Optimizing the charging infrastructure design of a regional airport in support to electric aviation demands

Master of Science Thesis

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Rotterdam The Hague Airport

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by

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Preface

After the completion of my Bachelor Marine Technology in Delft I was looking for a new challenge. Completing the Minor Airport of the Future at the Faculty of Aerospace Engineering triggered my excitement for aviation. With an additional interest in logistics and operations, the choice was easily made for the Control and Operations Master of Aerospace Engineering track, with Air Transport Operations as specialization. In the past period, I learned a lot about airport and aircraft operations and got the opportunity to become a member of the STATO student association board. Next to this, I moved to Barcelona for an internship. In this period, I came into contact with a new culture and got to experience working in a new environment. In the last year, I performed my Master Thesis in preparation for my graduation in Delft. Last but not least, I embraced a new challenge starting September 1st as KLM Management Engineering & Maintenance Trainee, for which I am really excited.

This thesis would not have been possible without the help and support of a number of people. First of all, I want to thank Rotterdam the Hague Airport for offering me a graduation intern position, together with additional guidance and support. Daan van Dijk, thank you for helping me every step along the way in my thesis and for all the meetings and fun conversations. Also a big thanks for all my colleagues at Rotterdam the Hague Airport and their support, whom I will miss. From the Delft University of Technology I especially want to thank Alexei Sharpanskykh for the great guidance during the past year. Your feedback has been beneficial to this project and I've learned a lot from your experience.

Ultimately, I want to thank my family and friends for all their support. I would like to give a special thanks to my parents Piet Hein and Nathaly, my grandmother Editha and my brother Joaquim for their never-ending support and love. Also, a sincere thank you to my boyfriend Matthew, who has been there through out my TU Delft journey, been along side all my decisions and was there to motivate and support me every step of the way.

Danique Horstmeier
Delft, July 2023

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Nomenclature

If a nomenclature is required, a simple template can be found below for convenience. Feel free to use, adapt or completely remove.

Abbreviations

Abbreviation	Definition
AC	Alternating Current
ACO	Ant Colony Optimization
AM	Airport Manager
ARES	Airport Recharging Equipment Sizing
ATC	Air Traffic Control
A2G	Aviation to Grid
BIP	Binary Integer Programming
BMS	Battery Management System
BPCs	Battery Plug-in Chargers
CAPSO	Coordinated Aggregated Particle Swarm Optimization
CCS	Combined Charging System
DC	Direct Current
DE	Differential Evolution
DES	Discrete Event Simulation
DP	Dynamic Programming
ESS	Energy Storage System
EV	Electric Vehicles
GA	Genetic Algorithms
GRASP	Greedy Randomized Adaptive Search Procedure
G2V	Grid to Vehicle
HA	Handling Agents
HEA	Hybrid Electric Aircraft
ILS	Iterated Local Search
IP	Integer Programming
kW	Kilowatt
LP	Linear Programming
MAS	Multi-agent System
MESS	Mobile Energy Storage System
MCS	Megawatt Charging System
MILP	Mixed Integer Linear Programming
MINP	Mixed Integer Nonlinear Programming
MIP	Mixed Integer Programming
MTOW	Maximum Takeoff Weight
PAX	Passengers
PHEV	Plug-in Hybrid Electric Vehicles
PSO	Particle Swarm Optimization
PV	Photovoltaic
RTHA	Rotterdam the Hague Airport
RTP	Real Time Pricing
SA	Simulated Annealing
SI	Swarm Intellegence
SOC	State of Charge

Abbreviation	Definition
TS	Tabu Search
UDP	Usage Based Pricing
VNS	Variable Neighborhood Search
VTOL	Vertical Take-Off and Landing
V2G	Vehicle to Grid

Symbols

Symbol	Definition	Unit
α	Resources set	-
β	Task set	-
γ	Objective function set	-
C_j	Completion time job j	-
d_j	Due dates	-
i	Machines	-
j	Jobs	-
p_{ij}	Processing time job j on machine i	-
r_j	Release dates	-
v_i	Machine speed	-
c_{ij}	Cost of charging aircraft i with charger type j	[€]
c_j	Procurement cost of charger type j	[€]
a_{ij}	compatibility of aircraft i with charger type j	-
a_{it}	Occupancy of aircraft i at time t	-
y_j	Number of chargers of type j	-

Part I

Scientific Paper

Optimizing the charging infrastructure design of a regional airport in support to electric aviation demands

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Abstract

Climate change poses a significant global challenge and the aviation industry, a major contributor to greenhouse gas emissions, must address its environmental impact. As the demand for air travel continues to rise, transitioning to sustainable forms of aviation becomes crucial. This paper focuses on the challenges and opportunities associated with implementing full electric aircraft at regional airports, using Rotterdam the Hague Airport (RTHA) as a case study. The research aims to determine the optimal infrastructure sizing of RTHA and provide insights into the integration of electric aviation. A novel mixed integer linear programming (MILP) model is proposed to optimize the charging schedule and determine the required number of charging stations and electricity grid capacity. The study considers different scenarios of electric aviation uptake, aircraft types, charger types, and spatial aspects of charging locations. The findings offer comprehensive recommendations for regional airport infrastructure planning and address uncertainties through sensitivity analysis.

Keywords: Electric aviation, sustainable aviation, regional airports, airport infrastructure, charging procedures, optimization, resource allocation

1 Introduction

Looking at our world today, climate change is one of the biggest and most complex global challenges. Combatting climate change is a global goal and major polluting industries like aviation should start mitigating their emission effects. While, on the other hand, flying, getting on a plane and reaching almost any location in the world has become a standard to our kind. It is expected that the aviation industry will continue to grow in the coming years. Combining these two somewhat contrary statements, on one hand the challenges of climate change and on the other the growing aviation industry being one of the major polluters, an increasing need and focus rises towards transitioning to new and sustainable forms of aviation.

In recent years, numerous programs and emission reduction goals for the aviation industry have been established by international aviation organizations such as the International Civil Aviation Organization (ICAO), the International Air Transport Association(IATA) and NASA (ICAO, 2016; NASA, 2021). Programs like Flightpath 2050 and Destination 2050 aim to achieve net-zero emissions in European aviation by 2050 (Destination 2050, 2022; Kallas and Geoghegan-Quinn, 2011). The Netherlands has also expressed its ambition to become a leader in sustainable aviation, focusing on (hybrid) electric flying. The Netherlands has set goals to achieve zero-emission domestic general aviation by 2050 and use fully electric aircraft for short distances (Ministerie van Infrastructuur en Waterstaat, 2022). Consequently, to meet these emission reduction goals, research and development of sustainable aircraft propulsion systems, including electric-powered aircraft, are underway. Electric aircraft have the potential to eliminate operational emissions and offer attractive operational expenses (Alfredsson et al., 2022). With the recent year's advancements in the electric vehicle industry, battery performance technology has progressed tremendously, for which many aircraft developers are now looking to introduce electric aircraft as the new chapter of aviation.

However, even tough electric aircraft have significant benefits over traditional fossil fuel driven aircraft, their development has been limited due to the energy density of batteries in comparison to kerosene (Doctor et al., 2022), which results in lower ranges and the size of the aircraft. It is therefore, that electric aviation will for the short to medium term, first make its entrance in the small and regional aviation markets (up to 400 km), with application for shorter range general aviation and pilot flight lesson training. With 2030 in prospect, larger electric aircraft are expected to enter the market, with ranges up to 550 kilometers and transporting around forty passengers. With the introduction of these sizes of aircraft, electric aviation has the potential to also become reality for the commercial aviation market.

Electric aviation offers a distinctive solution to environmental challenges and is already a reality on a small scale with the first certified electric aircraft, the Pipistrel Velis Electro, being utilized for pilot training flights. In the years to come, it is anticipated that electric aviation will increasingly be integrated into the aviation sector. However, introducing electric aviation will also pose challenges, especially from an airport point of view, for which the infrastructure and operations are tailored to traditional fossil fuel operations. In order for airports to accommodate electric aviation, adequate charging and electric infrastructure should be in place to accommodate the charging of the electric aircraft batteries which involves high energy demands and peak loads on the electricity grid.

This research paper aims to address the challenges and opportunities associated with the implementation of full electric aircraft at regional airports, using Rotterdam the Hague Airport (RTHA) as case study. As a regional airport, RTHA accommodates various aviation segments, including pilot training, general aviation, business and regional commercial air traffic. As electric aviation will impact all of these segments in the coming years, it is crucial to explore how the operation of electric aircraft can be integrated into the existing airport infrastructures and what investments are advised to make. It is important for airports to identify and invest in infrastructural changes well in advance, for which considering various scenarios presenting different infrastructural demands is advised. This research aims to determine the optimal infrastructure sizing of RTHA and provide insights into the implementation of electric aviation for regional airports. In addition to other relevant works in this field, the contributions of this research include that different uptakes of electric aviation are considered using various future scenarios. In order to assess what the infrastructure will look like, also spatial aspects of the charging locations will be considered by designing for different decentralized charging locations versus designing for a central charging location. Additionally, the required capacity of the electricity grid will also be assessed.

To address the goals of this research, the research proposes a novel mixed integer linear programming (MILP) model which determines i) the optimal charging schedule for the electric aircraft, ii) the optimal number of charging stations and iii) the capacity of the electricity grid, which are required to accommodate all electric flight movements on a reference day. Furthermore, various model scenarios will be included, which present different uptakes of electric aviation in the coming years rather than modelling for one fixed electric flight schedule. Also, five different electric aircraft types and different charger types are considered in this research. By examining different future time frames, a comprehensive overview of the infrastructural requirements for a regional airport can be made using the methodology proposed in this research.

The remainder of the paper is structured as follows. Previous works in the research field will be reviewed in section 2. In section 3 the concept of electric aircraft charging at an airport is explained. Next, the problem description and proposed approach will be provided in section 4. The formulation of the novel mixed integer linear programming model will be provided in section 5, followed by the model evaluation scenarios presented in section 6. Furthermore, before the model results will be presented, the verification and validation of the model is discussed in section 7, after which the results will be provided in section 8. In order to assess the uncertainties in the model outcomes to assumptions made in the research, sensitivity analysis have performed for which the results will be given in section 9. The discussion and recommendations for future work will be provided section 10. The conclusions will be given in section 11.

2 Literature review

Over the past few years, there have been several studies which focused on what will be the infrastructural impacts for airports when electric aviation becomes reality. With the first research published in 2018, the topic of electric aviation and the impact on airport operations and infrastructure is a relatively new field of research. In this section, a literature review of the previous studies in this research will be provided.

Most of the previous research focused on developing charging schedules and determining the optimal number of chargers. However, there are also topics which are covered by only a few researches. Hou et al. (2021) conducted research on flight rescheduling algorithms and did not consider determining the optimal number of chargers or batteries. In this research, the focus was on designing an optimization model which minimizes flight schedule displacements and peak power required for charging hybrid electric aircraft. Several studies, including Bigoni et al. (2018), Justin et al.(2020), Mitici et al. (2022), Salucci et al. (2019), and Trainelli et al (2021), determined the optimal number of chargers and batteries and developed charging schedules. The research of Guo et al. (2020) focused on determining the optimal airport charging infrastructure, including the number of chargers and batteries, but did not develop a detailed charging schedules.

The research of Doctor et al. (2022) is the only research which considered minimizing the operational impact of electric aircraft for an airport. Their research utilized a Discrete Event Simulation model to assess the impact of battery charging regimes on the airside stand capacity. The research of Doctor et al. focused more on the conversion of aircraft stands, while there are several other studies which focused on the actual required charging infrastructure. An important model in the research of electric aviation and the impact on airport infrastructure is the Airport Recharging Equipment Sizing (ARES) mathematical model (Trainelli et al., 2021). The ARES model gives the optimal solution to the airport battery recharging infrastructure problem, in which the model combines knowledge of the flight schedules to determine the number and type of charging points, batteries and aircraft required for the operations, while ensuring a minimization of peak energy demand, operational and procurement costs. The ARES model is based on a consolidation of the earlier studies of Bigoni et al. and Salucci et al. The research of Bigoni et al. was the first group investigating the problem of desired infrastructural sizing of the operation of electric aircraft. They developed a recharging and battery swapping scheduling, using a mixed integer linear programming (MILP) model similar to the one used in the ARES Model. The study performed by Salucci et al. consisted of a similar procedure in which they applied their research to Athens international airport.

A more recent study was published by Mitici et al; in which the focus also included, determining the required number of chargers, batteries and provide an optimal fleet allocation. The research proposed a two-phase MILP in which a flight schedule and battery recharge schedule was generated in the first phase, followed by the second phase which applied time discretization to determine the optimal sizing of charging stations, swap batteries and optimal charging times. Besides using similar concepts as plug in an battery swap (Bigoni et al., 2018; Salucci et al., 2019; Trainelli et al., 2021), a route specific energy consumption per electric aircraft was introduced as well.

Furthermore, most studies focused on a specific reference airport, except for the research of Justin et al; which considered a network of airports. Their research applied an optimization model formulated with a network flow representation. While there are some differences in the framework compared to the other studies, their approach shared many elements with the ARES model presented by Trainelli et al. For the other researches, most focused on applying their study to (regional) hub airports (Doctor et al., 2022; Guo et al., 2020; Hou et al., 2021; Mitici et al., 2022; Salucci et al., 2019; Trainelli et al., 2021). Only the researches of Bigoni et al. and Trainelli et al. considered a regional general aviation airport to analyse the impact of electric aviation. Additionally, in the literature a distinction is made between full electric and hybrid electric aircraft, and also the sizes of the aircraft used as references vary. Most studies focused on small regional aircraft carrying up to 19 passengers (Bigoni et al., 2018; Guo et al., 2020; Justin et al., 2020; Trainelli et al., 2021), while others considered larger narrow-body aircraft(Doctor et al., 2022; Salucci et al., 2019).

Now that the most important researches in the field have been elaborated on, several considerations will be briefly addressed due to their relevance to the research gap of this research. The majority of the researches focused on two electric aircraft charging concepts, namely battery swapping and plug-in recharging. The concept of battery swapping involves removing the batteries from the airframe and replacing them by a fully charged battery. In this concept, the charging of the aircraft battery thus happens remotely. Battery swapping is a concept which requires additional investment costs for specialized swapping equipment and adds additional operational complexity (Doctor et al., 2022). An alternative concept is the plug-in charging concept, which is similar to the current charging process of electric cars, namely that the batteries of the aircraft are integrated or fixed in the airframe, requiring the aircraft to be plugged into a power source to recharge the batteries. The research of Mitici et al; Bigoni et al; Trainelli et al; and Guo et al; all focused on both using battery swap and plug-in as charging strategies. For which the research of Guo et al. specifically focused on making a comparison between the two concepts, from which it was concluded that battery swap is more economic when the percentage of electric aircraft replacing current aircraft is below 10%, while for levels above 10% the plug-in charging system becomes the more cost-effective option. Justin et al. only considered the concept of battery swap as charging procedure for their research. The research of Hou et al. and Doctor et al. only considered plug-in charging. Lastly, the research of Guo et al. (2020) and recent study of Niek van Amstel (2023) included an energy storage as additional power source to charge electric aircraft.

Concluding, from reviewing the literature in the field of electric aviation and its impact on airport infrastructure, it is clear that it is a new field of research for which not many research has been published. Discussing the work, showed that a majority of the studies developed charging schedules and utilized optimization techniques. The majority of the research also focused on determining the optimal charging infrastructure of airports, while a minimization of operational and procurement costs of batteries and chargers was in place. Furthermore, it can be concluded that mixed-integer linear programming is dominant as methodology and applied to most of the works in this field.

Looking at the studies, several research gaps can be identified from which research opportunities present themselves. For example, the investment costs related to increasing the grid infrastructure capacity has not been considered yet. Additionally, including spatial aspects of the charging infrastructure layout was not included in any of the researches. None of the researches compared a centralized charging layout with a decentralized charging layout. Lastly, assessing potential future uptakes of electric aviation for various aviation segments (pilot training, general aviation, business aviation and commercial aviation), has not been done in any of the previous studies.

3 Electric aircraft charging at an airport

This section will provide insight in current considerations of electric aircraft charging concepts at an airport. The turnaround process for electric aircraft, similar to fossil fuel aircraft, involves passenger embarking/disembarking, aircraft cleaning and safety checks. However, a significant difference is that electric aircraft require battery charging instead of refueling, which is a more time consuming process. While refueling a small two-seater aircraft takes 3 minutes, recharging a similar electric aircraft with current charger and battery capacities takes around an hour.

To achieve compatible turnaround times with fossil fuel aircraft, fast charging or battery swapping are the main concepts considered for aircraft battery charging. Battery swapping involves replacing depleted batteries with fully charged ones, reducing turnaround time and potentially spreading out charging demand. However, the adaption of battery swapping faces challenges due to additional investment costs and added operational complexities, making plug-in charging the preferred choice for electric aircraft manufacturers (Diamond Aircraft, 2023; MAEVE, 2023). This method involves plugging the aircraft into a power source to recharge the integrated or fixed batteries, quite similar to current charging procedures of electric cars.

As in coming years, different electric aircraft types with varying sizes, battery capacities and ranges are expected to enter the market, the charging infrastructure will include different charger types with varying charging capabilities. Existing charging stations like the first standard and EASA approved SkyCharge station, with a strength of 40 kW, are suitable to charge electric aircraft with low battery capacities. However, to ensure charging within short turnaround times for future electric aircraft like the Eviation Alice, expected in 2027 with a 900 kWh battery capacity, there is a need for chargers in the scale of megawatts, which are currently in development (CHARIN, 2022).

In addition to the need for megawatt-scale fast chargers, airports must consider the power supply infrastructure behind the chargers. Charging electric aircraft with high energy demands from the electricity grid may require substantial grid connections. Evaluating the grid's capacity and potential congestion issues is crucial. Peak shaving techniques can help manage demand peaks and include smart scheduling of charging operations or inclusion of a battery storage system. These systems can be grid-powered or utilize renewable energy system such as solar panels and wind turbines, to avoid excessive grid demands. The manufacturer of the electric aircraft Maeve 1, expected to be introduced in 2030, is designing such an energy storage system to power the aircraft's batteries, thereby avoiding excessive demands on the grid. It is worth noting that battery energy storage system entail significant investment costs and that they particularly serve as viable alternative to grid charging when substantial power demands are required.

Concluding, for electric aircraft charging at an airport, the infrastructure should be in place, which includes making decisions about the concept of charging the batteries, either plug-in or swapping, and decisions regarding the power supply system. Additionally, for a regional airport serving various aviation segments at different locations, careful consideration should be given to the charging locations, enabling the design and investment in appropriate charging infrastructure. Centralized charging at one location and decentralized charging at multiple locations are options that can be considered, each offering distinct advantages. Designing for a central location simplifies infrastructure deployment and investment, while decentralized charging provides operational benefits.

4 Problem description and the proposed approach

To implement the concept of electric aviation, airports should ensure they have the adequate infrastructure in place to accommodate this new form of aviation. As a result this will likely involve fast charging, high energy demands and peak loads on the electricity grid. Furthermore, when investing in airport infrastructures, it is important to be forward-looking and account for likely growth trajectories in electric aviation (Hou et al., 2021). However, indicating how and to what extend electric aviation will be introduced in the future, comes with uncertainties, including dependence on battery technological developments and aircraft certifications.

The problem in this research focuses on determining the optimal number of charging stations and capacity of the electricity grid required for the future operation of electric aircraft at a regional airport. For which, various factors such as electric aviation uptake uncertainties, airport spatial aspects, and different types of electric aircraft and chargers will be considered. In order to account for likely growth trajectories and electric aviation uptake uncertainties, various modelling evaluation scenarios have been included. These scenarios are from now on referred to as the future scenarios, in which the expected uptake of electric aviation for the flight school, general aviation, commercial and business aviation segments for different future time frames of a reference airport are included. As electric aircraft charging concept, plug-in charging powered from the electricity grid is assumed. The study focuses on a reference airport, Rotterdam the Hague Airport (RTHA), which is a regional airport accommodating various aviation segments including pilot training, general aviation, business and commercial aviation. The airport's unique spatial characteristics are considered, and the research aims to determine the optimal sizing and placement of charging stations across five different locations within the airport premises, shown in Figure 1. By considering both centralized and decentralized charging configurations, the analysis accounts for the spatial distribution of electric aircraft operations.

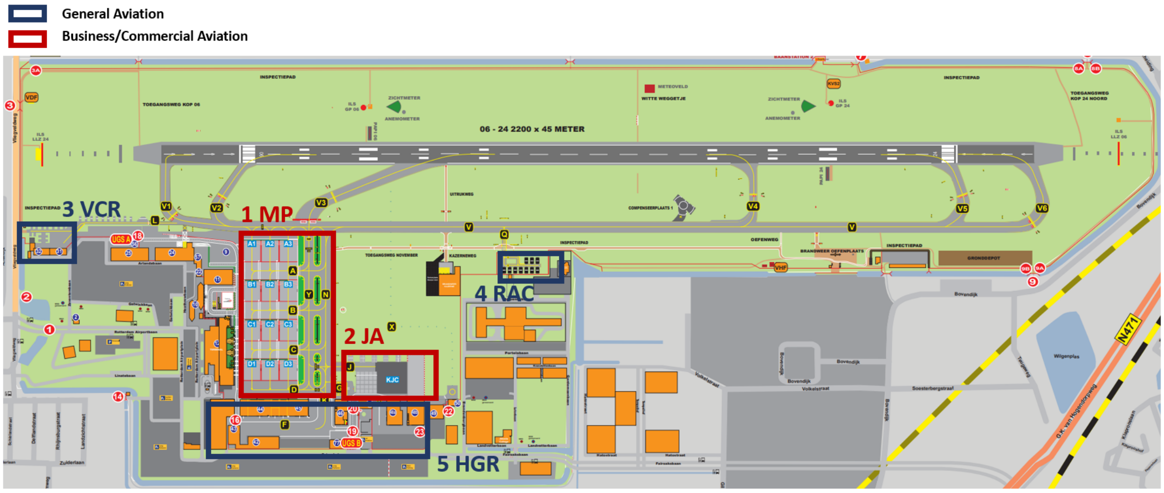


Fig. 1: Map RTHA indicating the five main airport locations: Main platform (MP), Jet Aviation (JA), Vliegclub Rotterdam (VCR), Rotterdamsche Aeroclub (RAC) and Hangars (HGR)

This research proposes a novel mixed-integer linear programming model, which given an electric flight schedule will determine the optimal number of charging stations, required electricity grid capacity and an optimal charging schedule, while minimizing the acquisition costs of chargers and the operational cost of charging. From the electric flight schedule, the set of charging events C_E is attained, for which each charging event is optimally assigned to one of the charging stations of charger set C_S. The model determines the optimal start time of a charging event $t_{s,i}$ and the end time $t_{e,i}$, for which the charging duration d_i is dependent on the required charging level and the charging rate $r_{c,i}$ of the charger i it is connected to. In this research, a bi-linear charging profile is assumed for which up to 80% of the battery state of charge (SOC), fast charging with a maximum of three times the battery capacity is allowed at a charging price $p_{c,k}$ which depends on the connected charger. Then, after 80% of battery state of charge is reached, the remaining SOC_2 of charging event i is slow charged at a rate of half the battery capacity at a charging price $p_{c,slow,i}$. The model will determine which charging event i is coupled to what charger k, given as $x_{i,k}$, for which decision variable r_k gives whether charger k is used for charging of electric aircraft. Concluding, the model will ensure optimal assignment of charging events to chargers while minimizing the following objective: $\sum_{k \in C_S} r_k * c_k + \sum_{i \in C_E} \sum_{k \in C_S} x_{ik}(p_{c,k} * SOC_1 + p_{c,slow,i} * SOC_2)$. As addition to the model, for the concept of charging at decentralized charging locations, the charging events C_E are restricted to be charged with chargers located at their designated parking locations.

Several main assumptions are included in this research:

- The requested energy during flight is estimated using the Brequed formula
- Battery of an electric aircraft is assumed fully charged before the first flight

- Charging infrastructure is assumed to be in place at other airports, for which returning aircraft depart from other airport with equal battery state of charge (SOC) as it departed from at RTHA
- Charging is only assumed to take place if battery state of charge is insufficient for next mission
- For a flight of which the flown distance is unknown (e.g. terrain trip), an average energy consumption of 60% is taken into account
- A battery reserve of 20% is always ensured for emergencies
- Flight movements resulting in the most demanding charging operations are prioritized for electrification
- For the centralized charging location, the entire turnaround procedure including (dis)embarking of passengers, cleaning, safety checks and charging of the electric aircraft are assumed to take place at one location
- For the decentralized charging locations, the entire servicing of an electric aircraft including charging is restricted to be performed at the designated handling location of the aircraft

Further elaboration of the electric aircraft types considered, the electric aircraft charging concept and the generation of the electric flight schedule and charging operations will be provided in subsection 4.1, subsection 4.2 and subsection 4.3, respectively.

4.1 Electric aircraft types

For this research, different electric aircraft designs have been considered, which are likely to serve different types of flights. Included is the Diamond eDA40 which will be used as flight trainer and the electric eFlyer 4 aircraft which is suitable to serve as general aviation aircraft. The Tecnam P-Volt and Eviation Alice are also included, which are electric aircraft likely to be employed as business aviation aircraft. Additionally, the design of the Maeve 1 electric aircraft has been taken as reference of a commercial aviation aircraft. An overview of the designs taken as reference aircraft to this research is given in Table 1. Note that the entrance years provided by manufacturers were used as a reference for this research. However, there is a chance of delays in delivery due to certification and technological advancements. Manufacturers often make frequent adjustments to their designs and characteristics, but the ones used in this research are based on their initial publications and remain unchanged. It is important to consider that characteristics may have been modified since then.

Table 1: Electric aircraft types used as model input

	Class 1 **Diamond eDA40**[4]	***Class 2*** **Bye Aerospace eFlyer 4**[5]	***Class 3*** **Tecnam P-Volt**[6]	***Class 4*** **Eviation Alice**[7]	***Class 5*** **Maeve 1**[8]
Year	2024	2025	2026	2027	2030
Seats	2	4	11	11	44
Range [km]	222	480	157/270[1]	463-**385**[3]	550
MTOW [kg]	1,300	1,542	4,082	8,346	45,000
Wingspan [m]	-	11.6	-	19.2	36
Battery capacity [kWh]	80	**250**[3]	275[2]	900	7,500
Max power [kW]	130	110	640	1,400	8,700
Cruise speed [km/h]	**285**[3]	370	222	480	488

[4] Source : Diamond Aircraft, personal communication, feb 2023 and Diamond Aircraft (2023)

[5] Source : BYE AEROSPACE (2022); FutureFlight (2021)

[6] Source : FlightGlobal (2021); Tecnam (2020)

[7] Source : Eviation (2023); FutureFlight (2023)

[8] Source : Maeve, personal communication, feb 2023 and MAEVE (2023)

[1] Manufacturer 2030 projection

[2] Using 0.27 kWh/kg

[3] Value determined to ensure 20% battery SOC as a reserve (using Equation 4)

As part of the electric aircraft model, the energy required to execute a mission is calculated by Equation 4. The total energy required during a mission is determined based on the energy consumption during different flight phases, namely takeoff, climb, cruise, descent and landing. The energy requested during descent and landing has been assumed to be negligible. The energy consumption during take-off and climb is calculated using the maximum power (P_{max}). The maximum time in which the electric aircraft can deliver this power ($T_{max,TO,CL}$) determines the energy consumption during this flight phase, for which the time during take-off and climb has been assumed to equal 10 minutes (see Equation 1).

The requested energy during cruise (ξ_b^{CR}) is estimated using the Breguet range equation which has been adapted for an electric aircraft (Hepperle, 2012), given in Equation 2. The specific energy of the battery is denoted by E_b^*, the battery mass W_b, g is the gravitational acceleration, η_b is the battery to propulsive efficiency (set to 0.9 (Raymer, 2012)) and L/D the lift to drag ratio (assumed to equal 16 for all eAC types considered (Babikian et al., 2002)). The maximum duration for which the aircraft batteries can deliver this energy consumption ($T_{max,CR}$) is calculated and the actual time spend during cruise (T_{CR}) depends on the range flown (R) and the cruise speed (V) of the aircraft, see Equation 3.

$$T_{max,TO,CL} = \frac{C_B}{P_{max}} * 60, \quad T_{TO,CL} = 10 \tag{1}$$

$$\xi_b^{CR} = E_b^* \cdot W_b = \frac{R \cdot g}{\eta_b \cdot L/D} \cdot MTOW \tag{2}$$

$$T_{max,CR} = \frac{C_B}{\xi_b^{CR}} * 60, \quad T_{CR} = \frac{R}{V} * 60 \tag{3}$$

$$E_{tot} = E_{TO,CL} + E_{CR} = (\frac{T_{TO,CL}}{T_{max,TO,CL}} + \frac{T_{CR}}{T_{max,CR}}) * 100 \tag{4}$$

4.2 Electric aircraft charging

In this research, the requirements for the operation of charging electric aircraft from an airport point of view are considered. In this subsection, the electric aircraft charging concept considered in this research is discussed in more detail. For which the focus will be on the charging mode, the charger types considered and the factors influencing charging duration.

For the plug-in charging concept, the use of seven different charger types are considered in this study. Given the nascent stage of electric aviation, indicating the aircraft charger market is difficult and therefore, the automotive industry has been used as reference to this research and the charger types considered. An overview of the different charger types included in this study is given in Table 2. Indications of the charger acquisition costs are also given in this table, as the proposed MILP model will minimize the required charging investment costs, these serve as important inputs to the model. Experts note that indicating the prices of the still underdevelopment megawatt chargers is difficult. Therefore, the price indications for the 1,000, 3,000, 4,000 and 9,000 MW chargers are based on the price to kW ratio of the 180 kW charger. The charging operational cost is also included as part of the optimization model objective, for which the considered charging prices are also provided in Table 2.

Table 2: Charger types considered in model, including cost (Ecotap, 2023) and charging price (ANWB, 2023)

	Charger types						
	1	**2**	**3**	**4**	**5**	**6**[1]	**7**[2]
Power [kW]	80	150	350	1,000	3,000	4,000	9,000
Cost [€]	24,200	43,375	94,680	270,000	810,000	1,080,000	2,430,000
Charging price [€/kWh]	0.4	0.5	0.65	0.8	0.9	0.8	0.9

[1] Reference of four 1MW chargers

[2] Reference of four 2.25 MW chargers, for maximum fast charging Maeve

Furthermore, the charging duration of an electric aircraft depends on the charging profile, the charging rate of the charger it is connected to and the required state of charge of the batteries. In the aviation industry, aircraft utilization and short turn around times are of high importance. Therefore, fast charging is essential, but this places high demands on the electricity grid and affects battery aging as this process operates at the boundaries of the physical limits of lithium-ion batteries (Wassiliadis et al., 2021). The optimal charging process for lithium ion batteries is known as the CC/CV (Constant Current/Constant Voltage) and consists of two phases, the constant current phase and the constant voltage phase (Bilansky et al., 2023). The charging profile for the electric aircraft lithium-ion batteries is assumed to follow the two phases of CC and CV, with a linear threshold occurring at 80% state of charge (SOC). The bi-linear charging profile assumed can be seen in Figure 2, which shows that after the battery reaches a state of charge of 80% the charging rate is decreased and the process goes into a slow charging mode. Fast charging is assumed up to 80% state of charge (SOC), with a maximum rate of 3C. The battery C-rate is a unit used to express the speed at which a battery is fully discharged or fully charged at a given current (Heubner et al., 2020). For which a 3C indicates a full charge realised in 20 minutes, which is thus assumed in this research in order to ensure compliance with regular turn around times and follows the expectations of electric aircraft manufacturers (Diamond Aircraft, 2023; MAEVE, 2023).

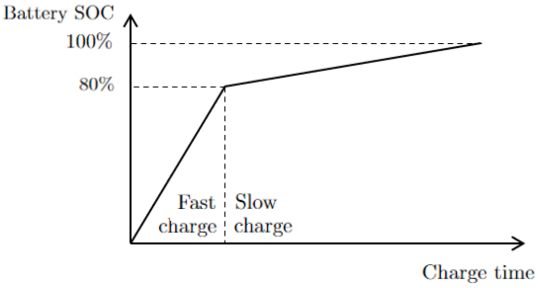


Fig. 2: Bi-linear charging curve

4.3 Selection electric flight schedule and associated charging events

As input to the novel infrastructure sizing model, first an electric flight schedule is generated from which associated charging events follow. The electric flight schedule generated in this research, is based on the flight movement data of 2022 at Rotterdam the Hague Airport. To determine which fossil fuel flight movements are eligible for replacement by electric aircraft, specific selection criteria have been established and these are further elaborated on during the explanation of the selection procedure discussed in this section. As mentioned, the research will include different time frames representing potential electric aviation uptake scenarios. For each of these scenarios, an electric flight schedule and the number of charging operations will be generated. Last, for this research the decision has been made to prioritize selecting the flight movements which result in the most demanding charging operations. For which, a charging operation is considered demanding when the turn around time is short and the required level of charging between arrival and departure is large. Selecting the most demanding charging operations is desired for the scope of this research, since reference airport RTHA, has the vision of accommodating the full demand of electric aviation in the future, and thus wish to know the infrastructural requirements to support this demand.

With this information, the final electric flight schedule was formed based on the following steps:
1. Total number of flight movements in the year 2022 at reference airport RTHA
2. Selection of reference day based on available data
3. Creation of potential electric flight schedule based on flights for which electric aircraft can fly required range and number of passengers
4. Creation of charging schedule based on flights from previous step, for which charging is required (battery SOC insufficient for next flight)
5. Selection of flights for final electric flight schedule dependent on potential uptake given by model scenario and those flights resulting in the most demanding charging operations

Concluding, the electric flight schedule consists of a number of flight movements, for which this number is determined by the scenario percentage. The flight movements are selected from the potential electric flight schedule, for which the flight movements resulting in the most demanding charging operations are prioritized for selection. As model input, in addition to the electrical flight schedule for the reference day, a flight schedule for the next day is also drawn up, in which the departures of the electric aircraft which have flown on the reference day are included. This because, for this research also the charging operations to ensure next day departures are included.

5 Infrastructure sizing model

After the electric flight schedule and required charging operations have been attained, these are fed into the infrastructure MILP sizing model. This model will determine the optimal infrastructural charging requirements in terms of number and types of chargers, while minimizing the charger acquisition and charging operational costs. In this section, the model formulation will be presented and explained. First, the model will be provided and elaborated on in subsection 5.1. The objective of the proposed MILP model is to minimize the acquisition costs of chargers and the operational cost of charging. Before a detailed model formulation of the objective and the constraints will be given, first the modelling sets, parameters and the decision variables will be discussed. Then, after the formulation of the model has been presented, an addition is made to the this model, which is used to model for the decentralized charging layout. This addition is presented in subsection 5.2. Note, that the model discussed in subsection 5.1, is utilized for the modelling of the central location.

5.1 Model

A discrete planning horizon T has been considered. The set of chargers is denoted by C_S for which the number of charging stations equals $|C_S| = c_s$. These chargers should fulfill the number of charging events c_e, for which C_E denotes the set of charging events. Every charging event has a time window in which charging needs to start, denoted by $[e_i, l_i]$. The start time of this window equals the arrival time $t_{a,i}$ with an added buffer time t_{sm} which ensures that charging of the electric aircraft (e-AC) can not start within the first 5 minutes after arrival. The end time of this window equals the departure time $t_{d,i}$ from which a buffer time t_{em} presenting a 10 minute time horizon before departure for which charging should be finished is subtracted. The duration d_i of the charging event is also subtracted from these two, resulting in $l_i = t_{d,i} - t_{em} - d_i$. An overview of the introduced decision variables is given in Table 3.

Table 3: Overview decision variables

Decision variable	**Type**	**Description**
o_{kti}	0,1	Charging station k is servicing event i at time t
u_{ik}^t	0,1	Charging station k starts servicing event i at time t
r_k	0,1	Charging station k is used at least once during planning horizon T
x_{ik}	0,1	Charging event i is serviced by charger k
b_{sit}	0,1	Time t is larger than start time of charging event i
b_{eit}	0,1	Time t is smaller than the end time of charging event i (incl. buffer time $t_{c,b}$)
$r_{c,i}$	$\mathbb{Z}$	Rate of charge for charging event i
d_i	$\mathbb{R}$	Charging duration of charging event i
$t_{s,i}$	$\mathbb{R}$	Start time of charging event i
$t_{e,i}$	$\mathbb{R}$	End time of charging event i

The goal of the optimization model is to minimize the investment costs for the acquisition of chargers and minimizing the operational charging costs. The charger acquisition cost (c_k) and the price for charging, including charging price with charger k ($p_{c,k}$) associated with the required charging energy in the first charging phase (SOC_1) and the price of slow charging ($p_{c,slow,i}$) which is applied to the required charging energy in the second charging phase (SOC_2), are thus minimized. The objective is therefore as follows:

$$minimize: \sum_{k\in C_S} r_k * c_k + \sum_{i\in C_E}\sum_{k\in C_S} x_{ik}(p_{c,k} * SOC_1 + p_{c,slow,i} * SOC_2)$$

The model is subjected to the following constraints:

$$\sum_{k\in C_s}\sum\nolimits_{t=e_i}^{l_i} u_{ik}^t = 1, \quad i \in C_E \tag{5}$$

$$\sum_{i\in C_E}\sum_{t\in T} u_{ik}^t \leq c_e * r_k, \quad k \in C_S \tag{6}$$

$$x_{ik} = \sum_{t\in T} u_{ik}^t, \quad i \in C_E, k \in C_S \tag{7}$$

$$\sum_{k\in C_s} A_{ik}x_{ik} = 1, \quad i \in C_E \tag{8}$$

$$\sum_{k\in C_s} \frac{1}{C_{ik}} x_{ik} = r_{ci}, \quad i \in C_E \tag{9}$$

$$d_i = SOC_1 * r_{ci} + SOC_2 * 1/r_{c,slow}, \quad i \in C_E \tag{10}$$

$$t_{si} = \sum_{k\in C_s}\sum_{t\in T} u_{ik}^t * t, \quad i \in C_E \tag{11}$$

$$t_{ei} = t_{si} + d_i \quad i \in C_E \tag{12}$$

$$t_{ei} \leq t_{di} - t_{em}, \quad i \in C_E \tag{13}$$

$$\sum\nolimits_{t=end,ops}^{start,ops} u_{ik}^t = 0, \quad i \in C_E, \quad k \in C_S \tag{14}$$

$$t \geq (t_{si} - 1) + \epsilon - M(1 - b_{sit}), \quad i \in C_E, \quad t \in T \tag{15}$$

$$t \leq (t_{si} - 1) + M * b_{sit}, \quad i \in C_E, \quad t \in T \tag{16}$$

$$t \leq (t_{ei} + t_{c,b}) + M(1 - b_{eit}), \quad i \in C_E, \quad t \in T \tag{17}$$

$$t \geq (t_{ei} + t_{c,b}) - M * b_{eit}, \quad i \in C_E, \quad t \in T \tag{18}$$

$$\sum_{k\in C_s}\sum_{t\in T}\sum_{i\in C_e} o_{kti} \geq x_{ik} + b_{sit} + b_{eit} - 2 \tag{19}$$

$$\sum_{k\in C_s}\sum_{t\in T}\sum_{i\in C_e} o_{kti} \leq x_{ik} \tag{20}$$

$$\sum_{k\in C_s}\sum_{t\in T}\sum_{i\in C_e} o_{kti} \leq b_{sit} \tag{21}$$

$$\sum_{k\in C_s}\sum_{t\in T}\sum_{i\in C_e} o_{kti} \leq b_{eit} \tag{22}$$

$$\sum_{i\in C_E} o_{kti} = 1, \quad k \in C_S; t \in T \tag{23}$$

The first constraint, constraint 5 ensures that every charging event must be exactly satisfied by one charger. Constraint 6 assesses whether a charging station is used. Constraint 7 sets decision variable $x_{i,k}$ such that it equals 1 if charging event i is serviced by charger k. Compatibility between an electric aircraft and a charger is ensured by constraint 8 (in which A is a compatibility matrix). Constraint 9 ensures that the charging rate equals the rate of the charger to which the eAC is coupled to (in which C is a charging rate matrix). The charging duration is given in constraint 10, which is dependent on the selected charger and the required state of charge of the aircraft. Two stages of charging are assumed, in which in the first phase (up to 80% SOC) the aircraft batteries can be charged with a maximum charging rate of 3C and in the second phase (above 80% SOC) the charging rate ($r_{c,slow}$) is restricted to slow charging at 0.5C (explained in more detail in subsection 4.2).

Constraint 11 converts $u_{i,k,t}$ to the start time of the charging operation. The end time of charging is determined by equation 12 which is equal to the duration plus the start time of the charging operation. The charging operation should be finished before departure of the aircraft including time margin t_{em}, this is ensured by constraint 13. Furthermore, it is assumed that charging of an eAC can not start during non-operational hours of the airport, which is ensured by constraint 14. However, it is allowed for a charging event to start before the airport closes and finishes the charging procedure within the non-operational hours. In which the start hour of operation ($t_{start,ops}$) at RTHA is at 06:00 and the end hour of operation ($t_{end,ops}$) at 23:00.

Also, it is important to ensure that a charger can only serve one charging operation at a time, for which constraint 23 is introduced. In order to set up this constraint it is important to assess whether a charging operation is being executed at a certain time. Therefore, constraints 15, 16, 17 and 18 were set up for which the first two constraints determine whether a time t is larger than the start time of a charging operation and the second two constraints determine whether t is smaller than the end time of the charging operation. For the latter, a buffer time for the charger ($t_{c,b}$) was included which ensures that after finishing an event the charger can not be occupied for the next 5 minutes. Then, constraints 19, 20, 21 and 22 ensure that decision variable o_{ikt} equals 1 only if event i is serviced by charger k and t is within the charging duration of this event.

5.2 Model addition, decentralized scenario

For the decentralized scenario, the MILP model given in subsection 5.1, stays the same, for which one constraint is added to ensure the electric aircraft is charged at a charger at the designated parking location. This constraint is given in Equation 24. In which loc_i presents the designated parking location of electric event i and loc_k presents the location of charger k.

$$\sum_{k \in C_s} x_{ik} * loc_i = \sum_{k \in C_s} x_{ik} * loc_k, \quad i \in C_E \tag{24}$$

6 Model evaluation scenarios

In this section, the model evaluation scenarios will be presented. Given the uncertainty of exact timing and the extend of electric aviation implementation in the future, the research takes into account different time frames representing potential electric aviation uptake scenarios. For each of these scenarios, the charging infrastructure sizing in terms of optimal chargers and required grid connections will be assessed by running the infrastructure sizing model. For setting up these scenarios, a comprehensive analysis of available data, industry trends and expert opinions has been performed. The scenarios will be discussed in subsection 6.1. Furthermore, as the infrastructure sizing model optimizes for a reference day, a suitable modelling day should be chosen. The selection of the modelling days is elaborated on in subsection 6.2.

6.1 Future scenarios

This research proposes four different time frame scenarios to assess the required airport infrastructure for electric aviation. For different aviation segments, flight schools (FS), general aviation (GA), business aviation (BA) and commercial aviation (CA), the expected future uptakes of electric aviation are given in Table 4. The future scenarios, presented in this table, are based on the expected introduction of electric aircraft and anticipated growth of electric aviation in the coming years. For which the expected uptake of electric aviation has been based upon communication with airport operators, internal communication with experts from RTHA and the trends expected in the electric aviation industry. The electric aircraft classes considered in the scenarios, are those presented in Table 1. It is worth noting that the long-term scenarios (2030 and 2035) do not account for advancements in range and passenger capacity of the initial Diamond eDA40 and eFlyer4 aircraft. Furthermore, the scenario percentages indicate the share of flight movements eligible for electrification (appropriate range and number of seats, elaborated on in subsection 4.3), rather than the total number of flight movements. For the flight lessons, discussions with RTHA's flight clubs revealed that around 75% of the flight lessons, have the potential to be performed with electric flight trainers (like the Diamond eDA40). Detailed explanations of the percentages considered in each scenario will follow in the subsequent subsections.

Table 4: Future scenarios electric aviation

2025				2027				2030				2035			
Class 1 & 2 e-AC				*Class 1, 2 & 3 e-AC*				*Class 1, 2, 3, 4 & 5 e-AC*				*Class 1, 2, 3, 4 & 5 e-AC*			
FS	GA	BA	CA	FS	GA	BA	CA	FS	GA	BA	CA	FS	GA	BA	CA
30%	0%	0%	0%	50%	5%	0%	0%	70%	15%	5%	0%	100%	50%	30%	10%

6.1.1 Scenario 2025

In two years, electric aviation is expected to start making a real entrance in the world of aviation, starting with the flight lessons for which the first electric flight trainer will be introduced in 2024. Investigating the ambitions of the flight clubs located at reference airport RTHA, revealed that both flight clubs have the ambition to purchase electric flight trainers (like the Diamond eDA40) in the coming two years. Considering these ambitions and the share of movements which then becomes electrified, the scenario percentage for the flight lesson movements has been set to 30 for the 2025 scenario (see Table 4).

However, in the 2025 scenario, no entrance of electric aircraft is expected for other aviation segments. This is because by then, only flight trainer and general aviation aircraft (eDA40 and eFlyer4) have enter the market. Also, for general aviation aircraft owners, it is not expected that for the short therm they will already change their fleet to electric aircraft (GA aircraft owners, personal communication, Feb 2023).

6.1.2 Scenario 2027

In 4 years it is expected that flight clubs continue to include electric aircraft in their fleet, for which the flight lesson movements which are eligible for electrification, are assumed to become electrified for 50% (RTHA, personal communication, Feb 2023). Considering the national ambitions of a 15% reduction of general aviation emissions in the Netherlands by 2030 (Ministerie van Infrastructuur en Waterstaat, 2022), it is expected that slowly electric aircraft will be adapted in the general aviation segment. Therefore, the assumption is made that in 2027, five percent of the general aviation flight movements which have the potential of electrification, are electrified.

6.1.3 Scenario 2030

In the year 2030, it is anticipated that all the electric aircraft considered in this research will have entered the market, including the at that time recently launched Maeve 01. However, since this first commercial electric aircraft has just entered the market, the share of electric commercial routes is still assumed to equal zero for this scenario. On the other hand, with the introduction of the Eviation Alice a few years prior, it is expected that such aircraft will have found their way into the business aviation sector due to lower operating costs and emission reduction ambitions.

Based on an analysis of business flight movements at RTHA and input from airport experts, it is assumed that 5% of flight movements qualifying for electrification will become electrified in the 2030 scenario. For flight lessons, a percentage of 70% has been assigned, indicating a significant electrification rate, while the general aviation (GA) segment is assumed to reach 10% electrification, aligning with the goals outlined in the Luchtvaartnota ambition.

6.1.4 Scenario 2035

In the long term, specifically in 2035, it is expected that commercial aviation will begin to adapt electric aircraft (Schäfer et al., 2019; Wroblewski and Ansell, 2019). However, estimating the commercial electric aviation movements, solely based on flight movement data of reference year 2022, which only contained fossil fuel aircraft with a passenger capacity of 150, would lead to an unrealistic scenario. This is because, given the 50-seat capacity of the Maeve aircraft, no flight movements would meet the criteria for replacement. Therefore, the focus of this research has shifted to assessing the market potential for electric commercial aviation. In collaboration with commerce and airline specialists from RTHA, a fictitious flight schedule was developed, taking into account destinations within the ranges of the Maeve aircraft and the passenger market share that would make these routes attractive for airlines. By applying this method, a more realistic output of the model can be realised, as it is assessed how an electric aircraft type will serve flight routes which based on historic flight data were not assumed to be electrified. The fictitious flight schedule is presented in Table 5.

For the 2035 scenario, a combination of the fictitious flight schedule for commercial aviation and reference electric flight movements from 2022 for flight lessons, general aviation, business aviation, and commercial movements was considered. Note that an overview of all future scenarios considered, was presented in Table 4. In this research, for the 2035 scenario, it is assumed that all flight lessons suitable to be performed with an electric aircraft will be performed with an e-AC. As advancements in battery technology will enable a MAEVE aircraft to carry 44 passengers over 550 kilometers, it is also anticipated that electric general aviation aircraft will improve. Therefore, more general aircraft owners will electrify their fleets, reaching an assumed percentage of 50% in 2035. With the introduction of the Maeve and increased operations of the Eviation Alice (or similar aircraft), the business aviation share is expected to increase with 25% compared to the 2030 scenario, reaching 30%. Finally, the commercial aviation share is estimated to be 10%, indicating that one tenth of the flight movements eligible to be electrified, are electrified.

Table 5: Fictitious electric flight schedule, Maeve operations, 2035 scenario

Flightschedule electric routes 2035 scenario operated by Maeve 01														
	RTHA		Hamburg			RTHA		London			RTHA		Stuttgart	
AC	Time	Code	Time	Code	AC	Time	Code	Time	Code	AC	Time	Code	Time	Code
PH-M1	07:00	D	08:15	A	PH-M2	07:00	D	08:00	A	PH-M3	07:00	D	08:30	A
PH-M1	10:20	A	09:05	D	PH-M2	09:50	A	08:50	D	PH-M3	10:50	A	09:20	D
PH-M1	14:00	D	15:15	A	PH-M2	15:15	D	16:15	A	PH-M3	13:15	D	14:45	A
PH-M1	17:20	A	16:05	D	PH-M2	18:05	A	17:05	D	PH-M3	17:05	A	15:35	D
PH-M1	18:10	D	19:25	A	PH-M2	19:15	D	20:15	A	PH-M3	18:05	D	19:35	A
PH-M1	21:30	A	20:15	D	PH-M2	22:05	A	21:05	D	PH-M3	21:55	A	20:25	D

6.2 Modelling day

In order to generate results from the optimization model and assess the infrastructural requirements in terms of chargers required for an airport in support to electric aviation, a suitable modelling day should be selected. For this modelling day, the electric flight schedule and charging operations are generated which serve as input to the infrastructure sizing model. As various future modelling scenarios are included and an assessment will be made for the infrastructural design of a central charging location versus decentralized charging locations, it is important to select modelling days for each location and each future scenario.

The objective of this research is to determine the necessary capacity of electric infrastructure in support to electric aircraft charging. For RTHA, innovation and sustainability are of high priority, for which they want to ensure that they are capable of accommodating the full demand of electric aviation in the future. Therefore, in this research, the day reflecting the most demanding charging operations is selected, since this day will result in the maximum required infrastructure.

For the selection of the modelling days, histograms have been generated which are used to show the frequency distributions of daily charging demand. The year 2022 has been selected as reference year, as it is the most recent year and the level of commercial and business aviation is similar to pre-covid year 2019, while the general aviation segment experienced an increase in number of flight movements compared to 2019. For each location an analysis of the peak days has been performed, for which the most demanding peak day of the year has been chosen. An overview of the selected modelling days is given in Table 6 and a total overview and elaboration of the selection of the modelling days for each location and future scenario, can be found in Supporting Work Chapter 1 (Horstmeier, 2023).

Table 6: Modelling days for maximum charging operation demand

	2025	**2027**	**2030**	**2035**
Central location	23-07-2022	23-07-2022	01-05-2022	23-07-2022
Main Platform	30-01-2022	30-01-2022	30-01-2022	30-01-2022
JetAviation	23-03-2022	23-03-2022	23-03-2022	23-07-2022
VCR	09-10-2022	09-10-2022	09-10-2022	09-10-2022
RAC	18-08-2022	18-08-2022	18-08-2022	18-08-2022
Hangars	26-02-2022	26-02-2022	26-02-2022	26-02-2022

7 Model verification and validation

To check for correct model implementation, several verification steps have been taken. Code verification has been applied by unit testing and resolving any errors which showed during running of the code. This has been done for both the first modelling phase in which the electric flight schedule and required charging operations are generated, as for the development of the infrastructure sizing model. Calculation verification has been performed by checking whether the results of the model match the manually computed results. This is a form of dynamic testing, the model is executed under different conditions and the obtained values were compared to manual exact values to see if the implementations of the models are correct (Sargent, 2010). A detailed elaboration of the verification of the infrastructure sizing model can be found in Supporting Work Chapter 2 (Horstmeier, 2023).

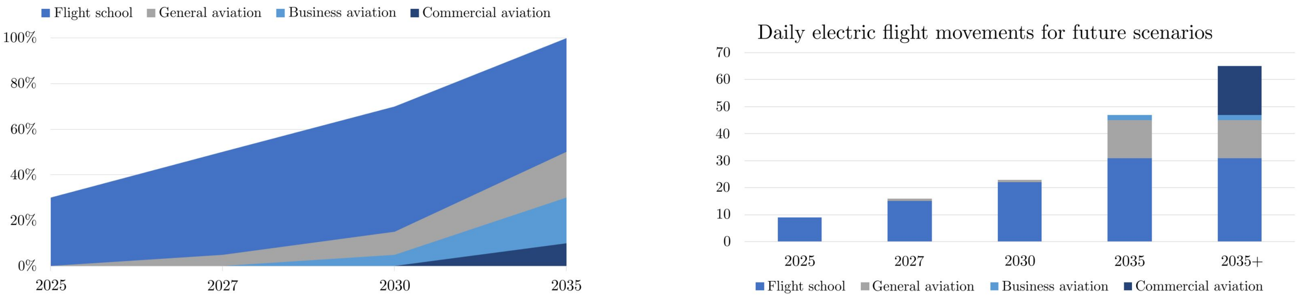
It is important to ensure that the model is an accurate representation of a real system, for which validation of the model has been performed using face validity. Face validity is one of the four main types of validity and is used to check whether a test appears to be suitable for the purpose. For this research, face validation is performed, since electric aviation and the charging of these aircraft is still in a nascent phase, for which no relevant data can be attained and thus no check with reality can be made. The validation has been performed by checking the model and the model outputs with experts in the field of electric aviation and seeing if these outcomes deemed to be reasonable (RTHA experts, personal communication, May 2023).

8 Results

In this section, the results of the infrastructure sizing model will be provided. The required charging infrastructure in terms of number and types of chargers will be assessed for the future scenarios, for each of the two spatial charging concepts, centralized and decentralized. The results will be presented in a few steps. First, the outcomes of the electric flight schedule and required charging events will be given in subsection 8.1, which presents the expected increase of electric aviation in the coming years. Then in subsection 8.2, the results of the infrastructure sizing model will be presented and discussed for the central and decentralized charging layout concepts separately. After which, it will be assessed to what extend expansions of the current grid infrastructure of reference airport RTHA are required, presented in subsection 8.3. The section will close with subsection 8.4, in which a comparison of the central versus the decentralized charging locations is given, including considerations from an operational airport point of view, weighing the costs and benefits of these two concepts.

8.1 Expected increase electric aviation in the coming years

Based on the assumptions and future scenarios considered in this research, the model generates the number of electrified flight movements and the number of charging operations required (as explained in subsection 4.3). In Figure 3 a comparison between the increase of daily electric flight movements and the percentage of electric flight movements which are considered to be electrified over time, is presented. The percentages illustrated in Figure 3a are the future scenarios as displayed in Table 4. The increase in daily electric flight movements for reference airport RTHA, is given for each of the future scenarios for the central location in Figure 3b. Comparing these two figures, it can be seen that the flight school movements are the first to be electrified, for which the first daily electric flight movements occur. From this point it can be seen that with an increase in future scenario percentages, the number of daily electric flight movements also increase.



(a) Percentage of flight movements considered to be electrified over time

(b) Increase in daily number of electric flight movements for future scenarios considered

Fig. 3: Comparison increase of daily electric flight movements versus the scenario percentage of flight movements considered to be electrified over time

8.2 Results infrastructure sizing model

The results from the infrastructure sizing model for both concepts, decentralized and central charging locations for the future scenarios are given together in Table 7. A distinction has been made between the two 2035 scenarios, for which the latter 2035* includes the fictitious routes of the Maeve as additional movements, which as discussed in subsubsection 6.1.4, has been set up as reference for the market potential of such electric aircraft. The model has been run for the modelling days given in Table 6. For each scenario, the number of electric flight movements and required charging events is given for every location, together with the optimal number and type of chargers. Additionally, the required grid connection for the optimal solution is given, which will be used in subsection 8.3, to check whether the current electricity grid of the reference airport locations, is sufficient to support the additional energy demand for electric aircraft charging. For every modelling run, the model outputs the optimal charging schedule for the modelling day together with figures presenting the requested energy and charging power during the reference day. A detailed overview of the outputs for every modelling scenario can be found in Appendix B ((Horstmeier, 2023)). Next, the model outcomes will be discussed for the central and decentralized charging location concepts, in subsubsection 8.2.1 and subsubsection 8.2.2 separately.

Table 7: Results model, for central and decentralized locations, for the different future scenarios and modelling days (given in Table 6)

		2025	**2027**	**2030**	**2035**	**2035***
Central location						
Electric flight movements		9	16	23	47	65
Number of charging events		4	7	10	14	23
	350 (kW)	1.0	1.0	1.0	1.0	1.0
	9 (MW)	0	0	0	1.0	2.0
Grid connection	(*Ampere*)	505	505	505	13,495	25,981
Total costs						
Operational costs (€/day)		291	345	428	8,734	40,475
Charger acq.costs (*1000 €)		94.68	94.68	94.68	2,524	4,954
Decentralized locations						
Main platform						
Electric flight movements		0	0	0	0	18
Number of charging events		0	0	0	0	9
Chargers	9 (MW)	0	0	0	0	2.0
Grid connection	(*Ampere*)	0	0	0	0	25,981
Jet Aviation						
Electric flight movements		2	5	8	6	6
Number of charging events		0	1	1	2	2
Chargers	150 (kW)	0	1.0	1.0	0	0
	9 (MW)	0	0	0	1.0	1.0
Grid connection	(*Ampere*)	0	216	216	12,990	12,990
Vliegclub Rotterdam						
Electric flight movements		6	10	14	21	21
Number of charging events		3	4	5	7	7
Chargers	350 (kW)	1.0	1.0	1.0	1.0	1.0
Grid connection	(*Ampere*)	505	505	505	505	505
Rotterdamsche Aeroclub						
Electric flight movements		2	5	6	10	10
Number of charging events		1	2	3	4	4
Chargers	350 (kW)	1.0	1.0	1.0	1.0	1.0
Grid connection	(*Ampere*)	505	505	505	505	505
Hangars						
Electric flight movements		3	7	12	22	22
Number of charging events		1	3	5	7	7
Chargers	150 (kW)	1.0	1.0	1.0	1.0	1.0
Grid connection	(*Ampere*)	216	216	216	216	216
Total costs						
Operational costs (€/day)		415	609	700	7,711	39,494
Charger acq.costs (*1000 €)		232.73	276.11	276.11	2,663	7,523

*2035 scenario including additional commercial movements

8.2.1 Central charging infrastructure concept

The results of the optimal infrastructure for the central location are presented in the first part of Table 7. From the results it can be concluded that for the first three future scenarios, the optimal infrastructure sizing in terms of installed charger capacity and grid connection remains the same. For reference airport RTHA, installing a 350 kW charger at the central location on the short term, will be sufficient to accommodate an increase in the daily electric flight movements for the coming seven years, until 2030.

Then, as business and commercial aviation become electrified and electric aircraft like the Maeve start operation routes and require charging in the 2035 scenarios, the results show that an increase in the capacities of the chargers, increased charger acquisition costs and as larger amounts of energy are charged, the daily operational costs are also increased. The results show that in order to accommodate charging for the Maeve aircraft operating the fictitious flights schedule (presented in Table 5), two 9 MW chargers will need to be in place. Providing power to these chargers from the grid, will require grid connections in the range of 25,000 Ampere.

8.2.2 Decentralized charging infrastructure concept

For the decentralized locations, the infrastructure sizing model has been run for the combination of modelling days as given in Table 6. From the results it can be concluded that for the flight school and general aviation locations of reference airport RTHA (Vliegclub Rotterdam, Rotterdamsche Aeroclub, Hangars), the required chargers and grid connection stays the same for all future scenarios. Investing in these infrastructure on the short term will ensure these airport locations are prepared to accommodate an increase in the amount of daily electric aircraft operations for the coming years. For the business aviation location, Jet Aviation, an upgrade of the installed charging infrastructure is required for the introduction of a Maeve charging operation in the 2035 scenario. The results show that for commercial aviation location (Main platform), no charging infrastructure is required until the introduction of a Maeve aircraft flying the routes of the fictitious flight schedule. Similar to the central location, an increase in required charging capacity, investment costs and charging operational costs can be seen in case an electric aircraft of the size of the Maeve requires charging.

8.3 Assessment of the required electric infrastructure

Next, the required grid connections attained from the model outcomes as given in Table 7 have been compared to the current infrastructure of reference airport RTHA. It is recommended for an airport preparing to accommodate electric aviation, to assess their current electric infrastructure in order to determine whether in time an increase in the capacity is required. A more detailed elaboration of the grid infrastructure in place at RTHA and the comparison made can be found in Supporting Work Chapter 3 (Horstmeier, 2023).

From the performed assessment for regional airport RTHA, it was concluded that the current electric infrastructure in place was not sufficient to accommodate the increase of electric energy demand for the introduction of electric aircraft charging in the coming years. Assuming that for all locations at RTHA a new connection to the grid should be realized, an indication of the investment costs is given in Table 8, for which price indications are attained from network operator Stedin (Stedin, 2023). For grid connections above 10.000 Ampere, Stedin states that the connection fee will be more specific for which a pre-calculated project indication will be made (Stedin, 2023). However, the high grid connection in the 2035 and 2035* scenarios for the central location, main platform and Jet Aviation locations are a result of charging the electric Maeve aircraft. In the future, it is likely that an energy storage system will be in place to facilitate the high power request during charging of these aircraft (MAEVE, 2023). This will results in less demanding grid connections. However, optimizing the operation of such an energy storage system is out of the scope of this research, for which determining what the required grid connection for that case should be is not possible in this research phase.

Table 8: Investment new grid connection indications

		2025 till 2035	**2035 +**
Central location	€*	25,059	>328.113
Main Platform	€*	0	>328.113
JetAviation	€*	25,059	>328.113
VCR	€*	25,059	25,059
RAC	€*	25,059	25,059
Hangars	€*	25,059	25,059
Total decentralized	€*	100,236	> 731,403

*Grid connection fee in € excl. VAT

8.4 Comparison of central and decentralized charging infrastructure concepts

For the comparison of the central and decentralized charging concepts, a high over cost benefit analysis has been performed. It is addressed what the investment costs for both concepts are based on the results of the model, but also considering additional investment costs in assets and infrastructure which were not considered in the model. These costs are compared to the benefits and disadvantages of both concepts in order to provide regional airport RTHA with an overview of the important considerations.

8.4.1 Comparison of the investment costs

Comparing central and decentralized charging solutions, Table 7 clearly showed that designing for a central location requires lower infrastructure investments compared to designing for decentralized locations. The cost comparison is focused on the investment costs in charging infrastructure up to the 2035 scenario, as it is difficult to determine the investment costs associated with either new grid connections or the installation of an energy storage system for charging the Maeve operations in the 2035 scenario.

From the results in Table 7 it is clear that for both the central location as for the decentralized locations, making an early investment for the 2025 scenario will result in an infrastructure which is suitable to serve electric aviation for the next 7 years, including the 2030 scenario. Combining the charger acquisition costs given in Table 7 and the investment costs of new grid connections given in Table 8, for the central location of reference airport RTHA, a total investment of approximately €120,000 is required. For the decentralized locations, the total investment costs are three times larger and equal a total of approximately €375,000. With a cost difference of €255,000, designing for a central location is the cost favorable concept. However, an airport should consider whether for the central location a new location will be designed for which investments in apron assets should be made. This is the case for RTHA, which results in additional investment costs for the central location which are not required for the decentralized locations since the charging stations will there be integrated in existing infrastructure. The height of these investment costs will depend on the airport decisions regarding the size of the apron and are excluded from this research, but it is an important factor to consider in case a new location will be designed.

8.4.2 Comparison of the benefits

For the comparison of the benefits of the two concepts, key performance indicators (KPIs] for an airport's airside operations are used as reference. The KPIs interesting for this comparison include aircraft turn around time, operational efficiency, taxiing distance and taxi time, passenger experience and safety incidents.

The operational concept of central charging included servicing the entire electric aircraft, including passenger (dis)embarkation, cleaning, and charging, at one location. However, in reality, regional airports like RTHA handle different passenger categories at their respective designated locations, such as flight clubs for pilots and visitors, and separate areas for private, business and commercial passengers. Including a central location for such airports, would either require passengers to (dis)embark fro the aircraft itself at designated locations or use shuttle buses to be transported from the central location to the designated locations, both increase ground movements and operational complexity. An increase in ground movements has the undesired effect of increasing the probability of aircraft or vehicle collisions on airside. In case the electric aircraft itself transports the passengers to the designated location, taxi distance and time are increased which is undesired as less time remains for servicing the aircraft within the turn around time. On the other hand, transporting the passengers with another service, like a shuttle bus, will lead to a decrease in passenger experience. Furthermore, implementing turnaround procedures at a new central location will lead to increasing operational expenses and under utilization of existing infrastructure and personnel, since rather than servicing the aircraft at locations where the assets are in place, additional resources should be realised in a new location.

Then, on the other hand, the decentralized charging locations concept includes that charging, together with the other turn around services takes place at the designated parking location of the aircraft. Looking at the key performance indicators, the aircraft turn around time is increased only for the charging operation duration it self compared to refueling of fossil fuel aircraft, but no additional time for taxiing to other locations is required. Also, the taxi distance and time remain the same. The chance of safety incidents in terms of additional aircraft movements remains unchanged since no additional ground movements are included in this concept. Also, passenger experience will in terms of additional taxi or on ground travel time, will not be impacted since the passengers will embark and disembark the aircraft at their preferred and designated locations.

Concluding, comparing the costs and the benefits of the two spatial charging concepts, the costs of equipping the five decentralized locations is for the next 7 years approximately €255,000 more expensive than the centralized investment costs. However, on the other hand, charging the electric aircraft at decentralized locations has significant benefits over the central location which leads to an increase in taxi distance and time, a decreasing operational efficiency and increasing probability of aircraft collisions due to additional ground movements.

As for Rotterdam the Hague Airport, they wish to limit the number of additional ground movements and prioritize handling of aircraft at their designated locations, the advise is to equip the decentralized locations with the optimal required charging infrastructure (as given in Table 7). For an airport questioning the required infrastructure sizing in support to electric aviation, it is advised to make a similar cost benefit analysis as presented by this research, for which the spatial aspects and preferences of the airport need to be taken into account to assess whether a central charging location or designing for various decentralized charging locations is more desirable.

9 Sensitivity Analysis

To study how the uncertainties in the model inputs affect the outcome of the model, various sensitivity analysis have been performed. The sensitivity analysis performed utilized a one at a time (OAT) method, in which one factor at a time is varied while keeping all other factors fixed at the original value. The OAT method is a local sensitivity analysis, since it studies the effect of one factor, the interactions amongst factors is less visible, as these are not varied simultaneously (Campolongo et al., 2011). However, since the model in this research is strictly linear, the OAT method is a valid approach (Saltelli et al., 2006).

Input parameters and modelling assumptions for which most uncertainty was included have been evaluated. Sensitivity analysis have been performed to see the effect of varying the modelling days and variations in future scenario percentages, presented in subsection 9.1 and subsection 9.2, respectively. Additionally, the effect of charging up to 80% battery SOC instead of the required SOC for next mission has been evaluated, presented in subsection 9.3. Last, variations in energy consumption's during flight lessons and excursion flights and variations in charger acquisition costs are analysed in subsection 9.4 and subsection 9.5, respectively. For all of the performed sensitivity analysis, a more elaborated and detailed description can be found in Supporting Work Chapter 4 (Horstmeier, 2023).

9.1 Varying the modelling days

In this research, the model was initially run for modelling days presenting the most demanding days in terms of charging operations for the reference year. In order to assess what the optimal charging infrastructure would be if reference airport Rotterdam the Hague would change their objective to an average day of electric aircraft operations, a sensitivity analysis has been performed. In Figure 4, a comparison for the central location and decentralized locations for each future scenario is presented in regard to installed charger capacity.

Looking at Figure 4, it is clear that the required installed charger capacity is generally lower for all locations, for all time frames, except for the 2035* central location scenario. Modelling for an average day instead of the maximum charging operation days, was found to result in lower number of electric flight movements in the flight schedule and less required charging events. As lower charging powers are installed, the required grid connections are also lower than in the maximum charging operation base case. Concluding, modelling for the average day, has a significant influence on the outcome of the model, as a decrease in required charger capacities, grid connections and lower investment and operational costs are found for generally all locations and future scenarios.

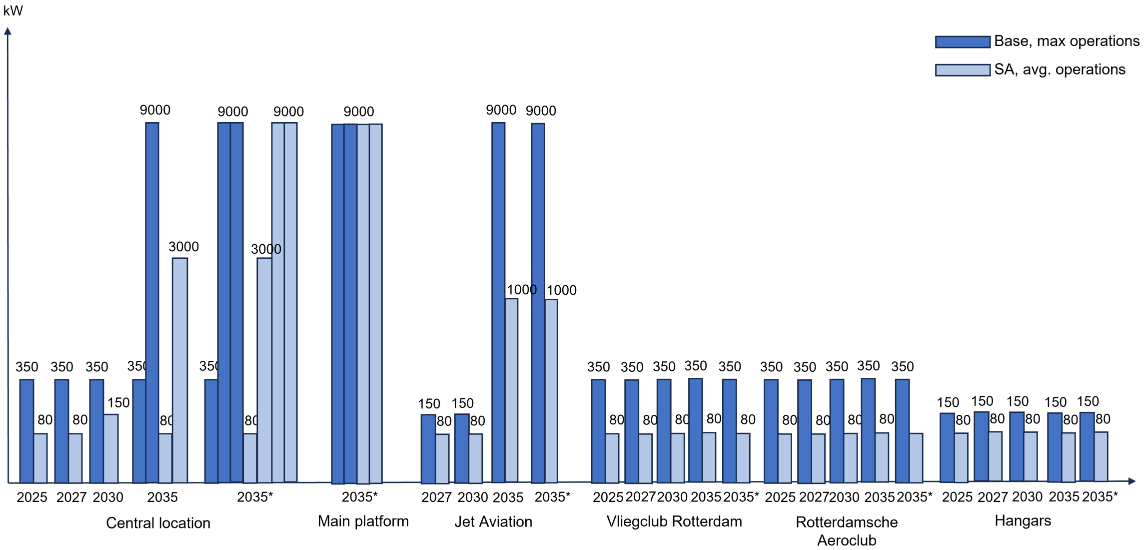


Fig. 4: Sensitivity analysis average modelling days versus maximum modelling days

9.2 Variations in future scenario percentages

While setting up the future scenarios presenting the expected uptake of electric aviation, various assumptions were included. In order to address the influence of these assumptions, sensitivity analysis have been performed for the parameters which include the most uncertainty. In subsubsection 9.2.1 the sensitivity analysis of varying the flight school percentage for the short term 2025 scenario, is presented. Additionally, the business aviation scenario percentages for the 2030 scenarios have been varied for which the results are discussed in subsubsection 9.2.2.

9.2.1 Varying the flight school percentage for the 2025 scenario

In two years, in the 2025 scenario, both the flight clubs located at Rotterdam the Hague Airport expressed their ambition to purchase and include an electric flight trainer aircraft, for which based on their current fleet, it was assumed that 30% of the flight school movements at RTHA would become electrified (see subsubsection 6.1.1). A sensitivity analysis has been performed to see what would be the impact on the required charging infrastructure for case study RTHA if the implementation of electric aviation at the flight schools goes slower or faster than expected.

From performing this sensitivity analysis it was concluded that varying the flight school percentage for the 2025 scenario, for lower uptake percentages for some locations resulted that no charging infrastructure is required. This was the case for the Rotterdamsche Aeroclub and Hangar locations of reference RTHA airport. For the central location and main platform locations this was only the case if the flight school percentage equaled 5%. From the results it was seen that for higher uptake scenarios, up to 45%, the optimal installed charger capacity for all locations remained the same as for the 30% base scenario. Concluding, a higher uptake of electric flight lesson movements (up to 45%) than initially expected, does not have a dominant influence on the outcomes. However, for lower number of electric flight lesson movements, the result for some locations is that no charging infrastructure is required.

9.2.2 Varying the business aviation scenario percentage for the 2030 scenario

In setting up the future scenarios, uncertainty was associated with the determination of the uptake of electric aviation for the business aviation segment. Therefore, it was decided to perform a sensitivity analysis to see to what extend variations in the expected uptake of this aviation segment will influence the optimal charging infrastructure requirements. For the sensitivity analysis, the base value of 5% for the 2030 scenario was varied from 0% till 15% as it might be that no implementation of electric aircraft in the business aviation segment occurs, but also a higher amount of implementation could take place. The uptake of electric aviation in the business segment will be dependent on the decisions of companies owning private aircraft and companies providing charter aircraft.

From the sensitivity analysis it was concluded that for the central location and the decentralized locations excluding Jet Aviation, no difference in optimal infrastructure sizing in terms of installed charger capacity and grid connection was found for variations in business percentages. Only for the Jet Aviation location, the location at which business aviation is executed, if the expected electric aviation uptake for the business aviation reaches a value of 10%, the required installed charger capacity increased with 567% from 150 kW to a 1 MW charger. This also leads to an increase in required electricity grid connection,charger acquisition costs and operational costs. Changing the business percentage for the 2030 scenario, was found to significantly influences the required charging infrastructure for the airport location where business aviation is handled, it does not influence the other airport locations. However, it should be noted that it might be that for this modelling day a more demanding charging operation was included which significantly changed the outcome, which might not be the case if another modelling day was selected.

9.3 Charging up to 80% SOC instead of required SOC for next mission

Furthermore, for this research, the assumption has been made that an electric aircraft would be charged up to the battery level required for the next mission. However, since electric aviation is still in development, it is difficult to estimate the operational regulations. Experts are questing what will be the effect on the optimal charging infrastructure, if instead of charging up to the required SOC for the next mission, a regulation would be imposed which states that charging up to 80% battery state of charge is required as minimum (RTHA personal communication, March 2023). Consequently, a sensitivity analysis was conducted, assuming a minimum charging SOC of 80%. Figure 5 illustrates the results of this analysis, comparing the optimal installed charging power with the base results, which involved charging up to the required SOC for the next mission.

Initially, it can be expected that if charging up to a minimum battery state of charge of 80% is set as requirement in stead of charging up to the required SOC for the next mission, that this will likely result in more demanding charging operations and potentially requiring higher charger capacities. From Figure 5 it can be seen that indeed for some of the locations and scenarios the charging capacity is higher for the 80% SOC minimum charging than for the base case. However, the figure also shows that for the central location for the 2027 scenario and the Rotterdamsche Aeroclub scenarios, the installed capacity is reduced. This is because, setting the requirement of charging to at least 80% battery SOC ensures that during the day an aircraft that was in the base case not charged during a turn around, does get charged. As a result, the total SOC upon the next arrival at RTHA is higher and less charging is required to get to 80% or required SOC for the next mission. In case of a short turn around time, the charging operation may turn out less demanding than in the base case and the final optimal installed charging capacity is lower. Concluding, setting the requirement of charging up to a minimum of 80% battery SOC, for sure influences the outcomes of the optimization model, for some cases it increases the required charging infrastructure, while for others the required charging infrastructure is decreased and for some cases the outcome remains similar to the base case of charging up to required SOC for the next mission.

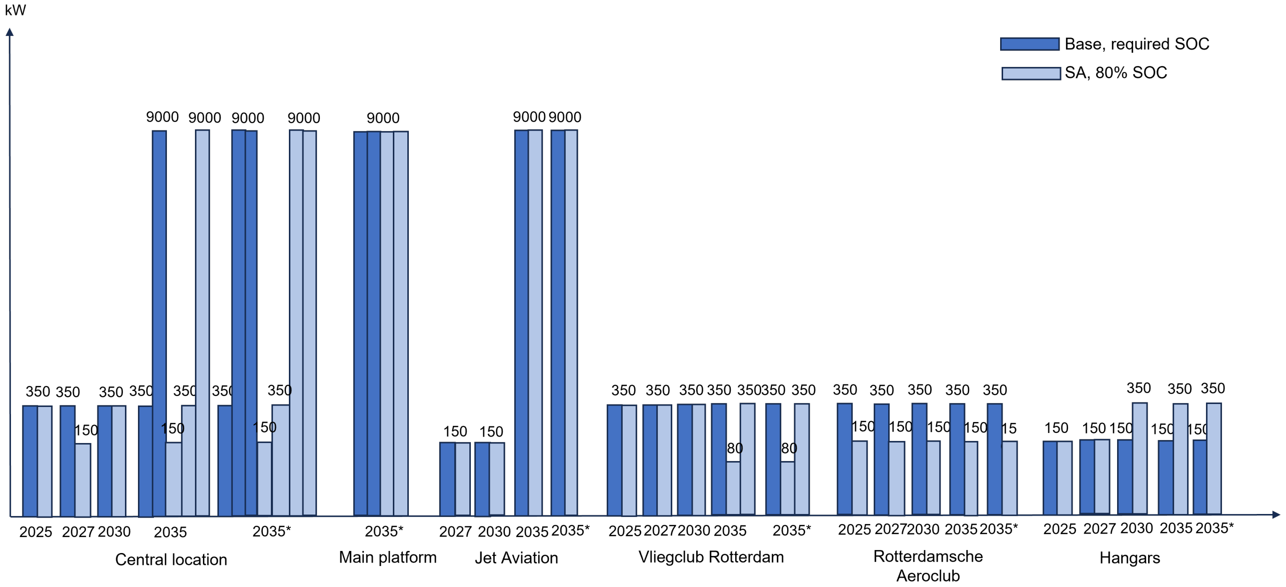


Fig. 5: Sensitivity analysis charging up to 80% SOC versus charging up to required SOC for next mission

9.4 Varying energy consumption of flight lesson and excursion flights

In this research, for the flight lessons and excursion flights performed at, for which the flown distance and flight duration is unknown, initially a 60% energy consumption during flight was assumed. This value was based on the average consumption of a one hour flight with the Diamond eDA40 and eFlyer4 which in this research were the electric aircraft types performing the flight lessons and excursion flights. However, the energy consumption will depend on the profile of the terrain trip, for which each terrain trip is different. The initial assumed one hour flight duration is based on the average duration provided by the flight schools, however in reality, some flights will have a longer or shorter duration. This results in a different energy consumption during flight, potentially impacting the model outcomes in terms of the optimal required charging capacity and grid connection installed. Therefore, a sensitivity analysis is included for which the energy consumption during the terrain trips is varied for the 2025 scenario. The ranges considered varied from 40 to 80%, for which 80% was taken as an upper bound as for this research a safety battery reserve of 20% is always included.

In Table 9, the results of varying the energy consumption during terrain flights are presented and compared to the 60% energy consumption base case. In this table, the central location and decentralized charging locations for which a change in optimal charging infrastructure occurs are displayed, the main platform and jet aviation are not included as no change in infrastructure occurred. In this table, a clear trend is visible between an increase in energy consumption and installed charging capacity.

Table 9: Results sensitivity analysis for variations in energy consumption during terrain trips in the 2025 scenario

Base	**Energy consumption** [%]	**Installed charging capacity**		**Base**	**Energy consumption** [%]	**Installed charging capacity**	
		Value [kW]	Change[1]			Value [kW]	Change[1]
Central location	60	350	-	RAC	60	350	-
	40	350	0%		40	80	-77%
	50	350	0%		50	150	-57%
	65	1150	228%		65	350	0%
	70	1350	285%		70	1000	186%
	75	1350	285%		75	1000	186%
	80	infeasible	-		80	infeasible	-
VCR	60	350	-	Hangars	60	150	-
	40	350	0%		40	80	-47%
	50	350	0%		50	150	0%
	65	350	0%		65	150	0%
	70	1000	186%		70	150	0%
	75	1000	186%		75	350	133%
	80	infeasible	-		80	infeasible	-

[1] Change with respect to base case

9.5 Variation in charger acquisition costs

In order to assess the sensitivity of the infrastructure sizing model outputs to the inputs of the charger acquisition costs, as these costs are dependent on technological development, these have been varied for a 20% increase and a 20% decrease.

Performing this sensitivity analysis showed that varying the charger acquisition cost, only resulted in a charger investment cost change and does not influence the optimal charging infrastructure in terms of installed charger capacity and required grid connection, neither does it change the operational costs of charging. This is inline with expectations as the model will optimize for a minimization in charger acquisition costs. When ratios between chargers remain equal, priorities will always be given to the charger that is least expensive.

10 Discussion and recommendations

The objective of this research included addressing the challenges and opportunities with the implementation of full electric aircraft at regional airports, for which the optimal infrastructure sizing for regional airport Rotterdam the Hague Airport was to be found in terms of number and types of chargers, required electricity grid capacity and considering the optimal layout regarding a decentralized versus a centralized configuration. A novel mixed integer linear programming model was proposed which given an electric flight schedule determines the optimal charging schedule, optimal number of charging stations and required grid infrastructure to support the charging operations of daily electric flight movements.

The contributions of this research to the field of electric aviation and airport infrastructure, included that spatial charging layout configurations were addressed by including modelling for decentralized versus a central charging location. Additionally, including various future electric aviation uptake scenarios ensures that a comprehensive overview of what is expected in terms of optimal charging infrastructure at an airport can be provided for different time frames. However, in order to build on these scenarios, it should be ensured that these scenarios accurately match the expectations of electric aviation at a regional airport. Performed analysis showed that variations in the chosen percentages of the scenarios resulted in different optimal infrastructure solutions.

The model and methodology proposed by this research can help regional airports investigate the infrastructure requirements for plug-in charging electric aircraft with the electricity grid as power source. By following the methodology discussed in this paper, airports can discover the number of electric flight movements, for which the considered electric aircraft types, reference flight data and future scenarios should be set. Then, using the electric flight schedule as input, the airport can utilize the infrastructure sizing model to assess the optimal number and types of chargers and grid electricity capacity required for different future time frames and location considerations. However, there are some limitations included in this research for which recommendations will be proposed next, in which a distinction is made between industry recommendations for airports presented in subsection 10.1 and academic recommendations for further research discussed in subsection 10.2.

10.1 Industry recommendations

In order for airports to prepare for the introduction of the operations of electric aircraft, it is recommended to keep track of the developments in the electric aviation industry, including following the entrance and characteristics of new electric aircraft together with collecting expertise about how this new form of aviation will develop. It is advised to adapt the scenarios given in this research accordingly to new insights in the market, such as new electric aircraft types, but also tailor the percentages to the expected uptake of electric aviation to the airport operations itself.

Furthermore, from the results of this research, it can be seen that for the chargers in the range of 80 to 350 kW grid connections of approximately 500 Ampere are required, which for reference airport Rotterdam the Hague Airport is in the same range of the capacity of some of the more large airport power stations.. For such grid connections, new or upgraded grid connections can be realized. It is recommended for an airport to investigate the current connections to the electricity grid, see where these are located and assess what the available capacity of these grid connections is. Using the infrastructure sizing model proposed by this research, the model will output the required grid connections and using a similar approach as in this research, the airport can assess whether the electric infrastructure in place is sufficient and to what extend and at what cost upgrading of this infrastructure is needed.

However, this research also showed that when the operation of electric aircraft like the Maeve becomes reality, charging from the grid will require grid connections in the range of 13,000 to 26,000 Ampere. Such grid connections are extremely high and realising such connections are not only costly but also due to congestion of most electricity grids in the Netherlands, it might be impossible to realise such connections. On the other hand, the manufacturer of the Maeve already is designing for an energy storage system in the form of containers from which the Maeve electric aircraft will be charged. Even tough the operation of such an energy storage system was out of the scope of this research, it is highly recommended for an airport to consider the inclusion of such a system, as it has the potential of realising peak shaving and resulting in lower required grid connections. Additionally, an energy storage system can be utilized to store renewable energy and therefore the system can ensure that renewable energy sources such as solar panels and or wind turbines can be integrated as power source for the charging of electric aircraft.

Additionally, this research included a cost benefit analysis of two charging layout configurations, a central location and various decentralized airport locations. After comparing the costs and benefits of the two concepts, for RTHA it was advised to design and implement charging infrastructure at five decentralized airport locations. For an airport it would be advised to investigate the operational feasibility of a central charging location and identify the preferences and key performance indicators such that a well overthought decision can be made.

Last, it is recommended for an airport to carry out a market research in which it is examined which future routes can be carried out with certain electric aircraft. In this study, this has only been done to some extend by including a fictitious flight schedule for the Maeve aircraft in the 2035 scenario. But it is considered a limitation of this research that the electric flight schedule is mostly based on historic flight movements performed by fossil fuel aircraft. For which a lot of movements were considered unsuitable for electrification since the fossil fuel aircraft which performed the route includes a high number of passenger seats. A market research can identify if there are certain routes which do have the potential of being executed with electric aircraft, which will increase the number of electric flight movements and required charging operations. Additionally, a limitation of this research is that the for the long-term and 2030 and 2035 scenarios, no advancements and developments in the range and passenger capacity of the first introduced electric aircraft were considered. While battery technology is expected to develop to such a level that an electric Maeve or Eviation Alice is going into service, it is likely that general aviation aircraft types such as the eFlyer 4 and Diamond eDA40 have longer ranges and can transport more passengers. Again, it is recommended for airports to follow the advancements of electric aircraft types and in case new designs are introduced, these can be included as input to proposed infrastructure sizing model.

10.2 Academia recommendations

For further research it is recommended to include an energy storage system as power source for charging the electric aircraft. Recent study published by (Niek van Amstel, 2023) already modelled for such a system, in which the energy storage system was powered by solar panels and wind turbines for Bonaire airport. Additionally, modelling for a mobile charging solution in the form of a mobile energy storage system could be of contribution to this research. Including such a mobile system will potentially change the layout of the optimal charging infrastructure of a regional airport. As in this research a central location was compared to various decentralized charging locations, it was found that charging at decentralized locations has significant benefits over the central location, except for the higher investment costs of acquiring more chargers and upgrading the electricity grid at various locations. The inclusion of a mobile energy storage system has the potential to keep the benefit of charging at designated locations but it tackles the need for the charging infrastructure to be in place. It is recommended to research how the operation of a mobile energy storage system can be included in this research proposed infrastructure sizing model.

Additionally, one of the limitations of this research includes that only strictly designing for a central or decentralized charging locations was considered and that no hybrid solution was modelled for. Including modelling for a hybrid option, in which electric aircraft are allowed to charge at various locations could be a valuable contribution to this research. In such a model it is advised that the effects on operational efficiency should be included as part of the objective.

Furthermore, a limitation of this research is that no detailed operations of the central location have been included. Various assumptions were made, including that the entire servicing of electric aircraft would take place at the central location. As discussed in subsubsection 8.4.2, modelling for a central location will potentially include either additional ground movements of the electric aircraft itself or movements of a sort of shuttle service. Including a more detailed operation of the central location, will provide more insights in associated additional ground movements and impact on other airport operations.

11 Conclusions

This study focused on evaluating the required infrastructure for regional airports in support to electric aviation, in which not only the number and types of chargers are determined, but also the required capacity of the electricity grid and optimal layout regarding a decentralized versus a centralized charging configuration have been included. A novel mixed integer linear programming model was introduced, which given an electric flight schedule, generates an optimal charging schedule, the optimal number and type of chargers and the required capacity of the electricity grid. Furthermore, various modelling scenarios were evaluated which included the introduction of different future time frames which presented various uptake scenarios of electric aviation in the future. The electric flight schedule is generated based on these modelling scenarios which include the share of electric aviation and considered electric aircraft types, for which total flight movement data of a reference year served as basis.

Concluding, the research gives an indication of what can be expected in terms of charging infrastructure requirements on a short to long term for reference airport Rotterdam the Hague Airport. For which on the short term to medium term including the 2030 scenario, the optimal infrastructure sizing of the airport locations including the installed chargers and grid connections required for the short term scenario are also sufficient for an increase of electric aviation in the 2030 scenario. It was found that the current electric infrastructure at RTHA is insufficient and would need to be upgraded. The results showed that on the long term, especially with the introduction of electric aircraft similar to the Maeve 01, an increase in required charger capacities and electricity grid connection is seen. The introduction of the Maeve and utilizing megawatt chargers leads to an extreme increase in required electricity grid capacity, for which it is advised for an airport to consider installing an energy storage system which will cover the high energy peak demands. Note that this will also introduce the opportunity to include renewable sources like solar panels and wind turbines into the powering of electric aircraft. With regard to the costs and benefits of the central versus the decentralized charging locations, it was found that designing for various decentralized locations include significant benefits with regard to key performance indicators as turn around time, taxiing distance, operational efficiency and safety incidents. It depends on the preferences of the airport itself, but for RTHA it was advised to design the charging infrastructure for five different decentralized location, even tough an increase of 250,000 euros of investment costs is included, the operational efficiency and other key performance indicators were deemed more important.

From the sensitive analysis later performed, it was found that variations in the percentages of the future scenarios influenced the optimal required charging infrastructure. Here, it was also found that the choice of reference day and changing the charging strategy influence the model outcome in terms of optimal charging infrastructure. As a result of the sensitivity analysis, the conclusion can be drawn that the assumptions made and assumed electric aviation uptake have a significant influence on the required charging infrastructure. Therefore, for airport's it is advised to closely keep track of developments in the world of electric aviation and adapt the considered input variables accordingly.

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Part II

Literature Study
previously graded under AE4010

1

Introduction

Looking at our world today, climate change is one of the biggest and most complex global challenges. Combatting climate change is a global goal and major polluting industries like aviation should start mitigating their emission effects. On the other hand, flying, getting on a plane and reaching almost any location in the world within 24 hours has become a standard to our kind. It is expected that the aviation industry will continue to grow and that the future of aviation is a bright one. Combining these two somewhat contrary statements, on one hand the challenges of climate change and on the other the growing aviation industry being one of the major polluters, an increasing need and focus rises towards transitioning to new and sustainable forms of aviation.

During recent years, various aspirational programs and reduction emission goals have been set in order to ensure a more sustainable future of global aviation. These goals and ambitions have been set by several aeronautical intuitions and stakeholders such as ICAO, IATA and NASA. One of the programs being Flightpath 2050 which was promoted by the European Commission in 2011. Recently in 2021, another program, Destination 2050 which presents a route to net zero European aviation in 2050 has been formulated by European aviation sector organisations. Furthermore, besides global and European ambitions, the Netherlands strives to be one of the international leaders in (hybrid) electric flying for which they have set ambitions goals for sustainable aviation as part of the Luchtvaartnota in 2020. These ambitions amongst others included, that by 2050 the domestic general aviation should be zero-emission. Consequently, in order to fulfill the goals and ambitions set for the aviation sector, there is a need for alternative aircraft technologies which include (hybrid) electric and hydrogen propulsion systems.

For this research the focus will be on the future entrance and implementation of full electric aircraft at regional airports, for which Rotterdam the Hague Airport (RTHA) is used as case study. RTHA has a special operational profile in which various forms of aviation are accommodated, including lessons and private flights, business flights and commercial traffic. The electrification of aircraft will impact all three of these segments, one earlier than the other.

Even tough electric aircraft have the potential of reducing the contribution of aviation to climate change, questions are posed on how the operation of these aircraft can be integrated in existing airport infrastructures. One of the challenges associated with the introduction of electric aviation at airports is the charging procedure of the aircraft, which is likely to involve high energy and peak demands on the electricity grid. Like other (regional) airports, RTHA wants to ensure that they are sufficiently equipped to allow for an increase of electric aviation and they question what will be the infrastructural requirements. This project will involve determining the optimal infrastructural sizing of the RTHA infrastructure, and give new insights on the implementation of electric aviation for regional airports. The cost-effectiveness of implementation of a centralized or decentralized charging layout configuration will be determined together with discovering the cost-effectiveness of a mobile charging truck as an alternative to fixed charging at an aircraft stand. Giving insights into electric aviation for regional airports and providing RTHA with an advise of how they should expand and adapt their current infrastructure to accommodate electric aviation in the future, is the goal of this research.

This literature study report is structured in the following way. First, in chapter 2 an introduction to Rotterdam the Hague Airport and electric aviation will be presented. The focus of this chapter is to highlight the operational profile of the airport together with introducing their visions and ambitions towards sustainable aviation. This chapter will also introduce the need of the aviation sector to mitigate their impact on global climate changes, the goals which have been set and the relevance of electric aircraft. Current and future expectations of electric aviation will be discussed and the scope of electric aviation entering RTHA will be provided. Then, in chapter 3 it will be addressed how electric aviation will become reality for RTHA and what will be the challenges involved. The different stakeholders of the airport, the airport layout, the concept of charging electric aircraft, the requirements of the airport and the subsequent model requirements will also be presented in this chapter. Then, a literature review will be executed in the research field of electric aviation and its impact on airport infrastructure, which will be addressed in chapter 4. In addition to studying similar studies related to charging of electric aircraft, also a literature review will be performed in the field of the electric vehicle charging scheduling. This will be done in order to create a more general understanding of charging scheduling related problems. Except for the vehicle type considered, the problem is quite comparable to the scheduling of electric aircraft charging, and therefore relevant to consider. Furthermore, since the focus of the project is finding the optimal infrastructure, optimized scheduling of electric aircraft charging operations will be involved. This ensures that the number of flights can be accommodated with the least amount of chargers. It is therefore that, a specific optimization problem which is concerned with the optimal allocation of resources over given time periods, namely scheduling theory which will be introduced in chapter 6. In this chapter also an overview of the most common and relevant modelling techniques utilized in the literature field will be given. With study done into the importance of electric aviation, its potential impacts on airports, the current state of the art in charging and a literature review of the studies in the relevant research fields, the research proposal will be given in chapter 7. Subsequently, the research methodology will be discussed in chapter 8 and the research planning of the project will be given in chapter 9.

2

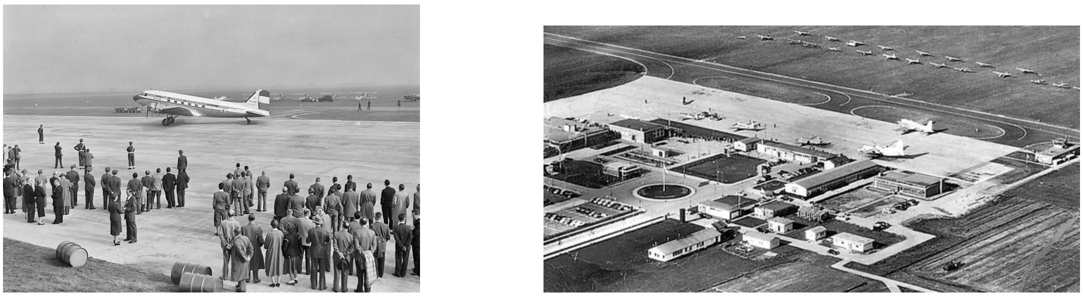
RTHA and Electric Aviation

In this chapter, an introduction will be given to Rotterdam the Hague Airport and to the world of electric aviation. The history, operational profile and visions of the airport will be discussed in section 2.1. Then, in section 2.2 insights will be given into the world of electric aviation. The ambitions and goals regarding mitigation of the impact of aviation on climate change will be discussed first. Then, electric propulsion will be discussed and the future expectations of electric aircraft will be presented. Additionally, it will be mentioned why the focus of this research will be upon electric propulsion of aircraft rather than hydrogen propulsion. The chapter will conclude with a short description of how electric aviation is expected to make its entrance at RTHA and an initial description of the research scope is given.

2.1. Rotterdam the Hague Airport

Rotterdam the Hague Airport serves as regional airport of the region Rotterdam and the Hague in the Netherlands, and as the reference case for this thesis project. The airport is part of the Royal Schiphol group and in numbers it is the Netherlands third largest airport facilitating air traffic to two million passengers annually (Rotterdam the Hague Airport, 2022).

Since 1783 aviation has been connected to Rotterdam, back then the first manned air balloon took off from the airport (Rotterdam the Hague Airport, 2022). In the 1920s and 1930s the pioneers of aviation really took off and the citizens of Rotterdam were proud of their local airport located in the Waalhaven. However, during the second world war the airport was destroyed completely. After the war it took quite some years before plans were made for a rebuilding. Eventually, it was agreed to build a new civil airport north of the city. It was on 1 October 1956 when the airport Zestienhoven opened at the same location it is located nowadays (Rotterdam the Hague Airport, 2022), of which pictures are shown in Figure 2.1. Over the years the airport operations expanded and since 2010 the airport is called Rotterdam the Hague Airport.



(a) Official opening airport Zestienhoven, 1956

(b) Aerial photograph, 1956

Figure 2.1: Pictures Zestienhoven airport in 1956

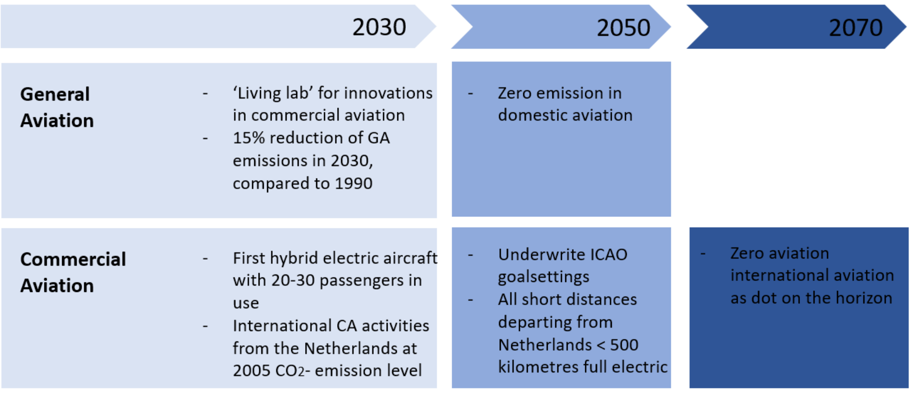
Nowadays, the operational profile of Rotterdam the Hague Airport centralizes around providing air traffic and service to both General Aviation and Commercial Aviation. In 2019 the commercial flight movements amounted 21.049. In the same year there were 31.390 general aviation movements, which include the movements of the flight clubs, business aviation and privately owned aircraft operations. Rotterdam the Hague Airport is home to two flight clubs, the Rotterdamsche Aeroclub and the Vliegclub Rotterdam. Business aviation at RTHA is executed by JetAviation and also the airport is home to a number of privately owned aircraft. The main business case however focuses on the commercial aviation executed by the airlines. The airport also has a social significance as the police and trauma helicopters are based at the airport.

Furthermore, RTHA as an organization has several different missions and visions they strive by. First of all, their mission is to connect the region. They provide infrastructure to accommodate air traffic and want to realise the ultimate experience for their travellers (Rotterdam the Hague Airport, 2022). Their vision is to ensure a cleaner future of aviation. They are therefore together with partners proactively committed to innovation and sustainability for both their own operation profile and the aviation sector itself. For example, RTHA wants to ensure that in 2030 their entire ground-based operations will be operated waste- and emission-free (Rotterdam the Hague Airport, 2022). Additionally, connected to their mission of accommodating air traffic, the airport is stimulating a sustainable fleet renewal of their stakeholders in which RTHA's part will be to accommodate the infrastructure needed for these more sustainable forms of aviation. In their mission statement the following is clearly stated: ”*Together with partners and the other airports from the Schiphol Group, Rotterdam the Hague Airport sees itself to be the international testing ground for sustainable and high quality innovation within the aviation sector*” (Rotterdam the Hague Airport, 2022).

2.2. Electric flight aviation

It is widely recognised that there is a need to mitigate global climate change and that reliance on burning fossil fuels for aviation and other sectors is unsustainable. In 2019, commercial aviation with 915 million produced tonnes of CO_2 was responsible for 2% of all human-induced CO_2 emissions globally (Air Transport Action Group, 2022). In recent years, several aeronautical institutions and aviation stakeholders have been proposing and formulating aspirational programs, such as the Flightpath 2050 and other programs by ICAO, IATA and NASA (Drake, 2012; ICAO, 2016; Kallas and Geoghegan-Quinn, 2011). The Flightpath 2050 was promoted by the European Commission in 2011 and stated several ambitions, including that by 2050 new procedures should allow for a 75% reduction of CO_2 emissions per passenger kilometer, a 90% NO_x reduction and that perceived noise should be reduced by 65% compared to typical new aircraft's in 2000 (Kallas and Geoghegan-Quinn, 2011). Recently in 2021, another program, Destination 2050 has been formulated by European aviation sector organisations. Destination 2050 presents a route to net zero European aviation in 2050 (Destination 2050, 2022).

Furthermore, besides global and European ambitions, the Netherlands strives to be one of the international leaders in (hybrid) electric flying. In 2020, the Netherlands has set ambitions for sustainable aviation as part of the Luchtvaartnota. In this nota, different ambitions for the commercial and general aviation in the Netherlands are stated in different road maps. For example, by 2030, all ground-based operations should be zero-emission and electric taxiing should be standard procedure (Ministerie van Infrastructuur en Waterstaat, 2022). Additionally, the road map states that by 2030 the first hybrid electric aircraft should be in use for 20-50 passenger aviation. Then, by 2050 the domestic general aviation should be zero-emission. Also, from 2050 all short-distance commercial flights departing from the Netherlands with distances up till approximately 500 kilometers should be fully electric (Ministerie van Infrastructuur en Waterstaat, 2022). An overview of the goals noted in the Luchtvaartnota is given in the road map presented in Figure 2.2 below.



	2030	2050	2070
General Aviation	- 'Living lab' for innovations in commercial aviation - 15% reduction of GA emissions in 2030, compared to 1990	- Zero emission in domestic aviation	
Commercial Aviation	- First hybrid electric aircraft with 20-30 passengers in use - International CA activities from the Netherlands at 2005 CO_2- emission level	- Underwrite ICAO goalsettings - All short distances departing from Netherlands < 500 kilometres full electric	- Zero aviation international aviation as dot on the horizon

Figure 2.2: Roadmap General and Commercial Aviation (Ministerie van Infrastructuur en Waterstaat, 2022)

Consequently, to fulfill the above mentioned goals, there is an increased focus on transitioning to more sustainable forms of propulsion technologies for aircraft, which include electrically powered and hydrogen powered aircraft. From these two, electrical propulsion is arguably the more mature since over the recent years a number of test flights have been performed for both pure-electric as hybrid electric aircraft (Doctor et al., 2022). Electrification has already demonstrated to be successful in road transportation in the form of electric vehicles and is thus now in the process of becoming more and more reality for the aviation sector. At Rotterdam the Hague Airport, they are invested in researching and participating in projects focused on airport related operations for both electric and hydrogen aircraft. However, they concluded that the research and steps currently being made by the airport towards electric aviation is far too limited and that they are still too much in a nascent phase. Since they do see the potential and feel the urgency of transforming the airport to accommodate this new form of aviation, they requested to focus this research on electric flight aviation and not take hydrogen aircraft into consideration.

Nowadays, the first and up to day only EASA certified pure-electric aircraft is flying for recreational purposes and pilot training's, the Pipistrel Velis Electro (Pipistrel, 2022). The Velis Electro has a range of 138 kilometers and can transport two people. Several manufacturers are working on different designs and electric aircraft types which will be entering the market in the coming years. In the course of 2023 new electric aircraft's will be launched by different manufacturers, including Pipistrel and Diamond. Eviation Alice is a full electric aircraft planned to be realised in 2025, it is currently flying test flights. The Eviation Alice has an operational profile with a range of 815 kilometers and can transport up to 9 passengers. Over the years, it is expected that the technology around electric aircraft will become more advanced and also regulations around the operations and safety will be specified. The expected trend is that in the coming years various full-electric and hybrid-electric aircraft's will enter the market. See Figure 2.3, in which a time frame overview of a selection of aircraft development programs is given.

The development of electric aircraft however, has been limited due to inferior density of batteries relative to kerosene (Doctor et al., 2022). Doctor et al., 2022 state that it is therefore that for the short to medium term until 2030, electric aircraft will probably become reality for shorter distance mission profiles (50-400 kilometers) operated by the small and regional aircraft market, as well as for pilot training and general aviation. Various studies such as in Schäfer et al. (2019) and Wroblewski and Ansell (2019) do predict that commercial aviation will adopt electric aircraft over the next decades (in the 2030-2050 time frame). However, the prospect of medium- and longer-range electric aircraft operating in the coming 10 or 20 years is limited for narrow body aircraft and almost impossible for wide body aircraft (Doctor et al., 2022).

Time will tell when and to what extend electric aviation will become available for the commercial aviation sector. It can be concluded that the first small electric airplanes are already available for the general aviation sector and that flight demonstrations are being executed and underway for the next generation of electric aircraft carrying around 10 passengers (Eviation Alice). After that the next step will be electric regional airplanes which accommodate 30-100 passengers (Hou et al., 2021).

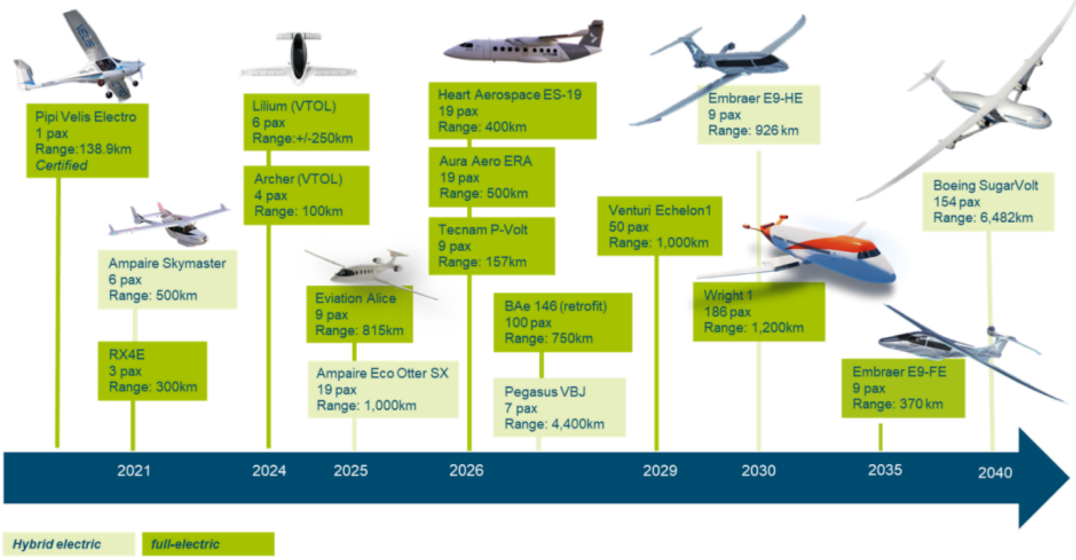


Figure 2.3: Selection of aircraft development programs with communicated Entry into Service year (Marlies Hak, 2021)

As for Rotterdam the Hague Airport, electric aviation is already reality on a small scale with a Pipistrel Velis Electro being based on the airport and performing flight movements. However, with the operational profile of RTHA being a regional airport with a large number of general aviation movements, the airport can expect a high increase in the number of electric flight operations in the coming years. In order to adhere to this increase, the goals set by the Dutch government and the ambitions of the airport itself, the airport should be prepared to facilitate the infrastructure and operations necessary to accommodate this new form of air transportation.

For the scope of this research, the focus will be on the electrification of aviation for the flight clubs, other general aviation, the business aviation and small commercial aviation segment. Uptakes of electric aviation in these segments will be considered for three different time frames, namely 2025, 2030 and 2035. These time frames have been decided on in close collaboration with RHTA and investigating for these scenarios will discover the impact of electric aviation at regional airports for the coming 15 years. The electrification of the narrow body aircraft operated by the airlines will not be included in the scope of this research. This has been decided because it is uncertain whether and in what time frame electrification of these aircraft is realistic and they will have a completely different operational impact and involved infrastructural requirements than the other aviation segments considered in this research.

3

Electric aviation at RTHA

After an introduction to RTHA and the world of electric aviation was given in the previous chapter, next it will be discussed how electric aviation will become reality for RTHA and what the challenges involved will be. First, a general description of Rotterdam the Hague Airport will be given in section 3.1. In this section, the layout, the airport users and an overview of the current ground operations at RTHA will be discussed. After the different stakeholders and locations of the airport have been identified, a description of the influence of electric aviation on the operations is presented in section 3.2. In this section, first it will be discussed when and where electric aviation is expected to become reality for RTHA. Then, before the ground operations of electric aviation can be discussed, the current state of the art for charging the batteries of these aircraft is discussed first. Section 3.2 concludes with the description of what the concept of the charging procedure of electric aircraft will look like. Then, as final part of this chapter, the requirements of RTHA and the subsequent method requirements will be presented in section 3.3.

3.1. General description RTHA

In this section a general description of the layout, airport users and ground operations at Rotterdam the Hague Airport will be given. First, in subsection 3.1.1 the layout of the airport is presented, followed by the airport users discussed in subsection 3.1.2. Concluding, a general description of the ground operations at RTHA is given in subsection 3.1.3.

3.1.1. Layout of the airport

Rotterdam the Hague Airport is home to various operations, which all slightly differ in terms of their operational profile. Figures from 2019 indicate that there were 31.390 smaller general aviation movements and 21.049 larger aircraft commercial aviation movements. Aircraft at RTHA land and depart from a single runway of 2.200 meters. In this subsection the layout of the airport will be discussed and the locations at which flight operations take place will be indicated. Figure 3.1 gives a map of the airport in which a distinction is made regarding the general aviation, business and commercial aviation locations.

The main focus of the airport is the commercial aviation operated by airlines such as Transavia and TUI. The handling of these aircraft is done at the platform in front of the main terminal building, see the demarcated area labeled with number 1 in figure 3.1. Only the passengers which arrive and depart with the commercial aircraft of the airlines are handled in the main terminal. Then, area 2 indicated in the figure is the Julliet platform, the location where JetAviation handles their private and business owned aircraft. JetAviation has their own small building which accommodates their passengers and clients. Furthermore, RTHA is home to two flight clubs, Vliegclub Rotterdam and Rotterdamsche Aeroclub, which are located at area 3 and 4 in the figure respectively. Both of these flight clubs have their own ”club houses” at which visitors and members enjoy a cup of coffee during their stay and from where they enter the airports airside. Additionally, there are several hangars at the airport grounds, which are located in area number 5. These hangars are home to several small privately owned jets and together with the aircraft movements of the flight clubs they form the general aviation segment operated at RTHA.

Besides locations at which flight movements take place, another part of the airport layout is worth to be noted, namely the solar park. The solar park located at the airport premises in parallel to the length of the runway, contains a total of more than 37.000 solar panels and with a surface of 7,7 hectares it is the largest solar park in the region. In this project, integration of power from the solar park as part of the charging procedure of electric aircraft will be investigated.

Figure 3.1: Map RTHA indicating general and business/commercial aviation locations (Rotterdam the Hague Airport, 2022)

From Figure 3.1, it is clear that there are four (excluding the hangars) main locations at which aircraft are handled and where aircraft movements take place. Further on in this chapter, in section 3.2, it will be discussed how and when electric aviation is expected to impact the different flight operations and locations of RTHA.

3.1.2. Airport users

In this section, the airport users are identified and both their general tasks and the tasks tailored for Rotterdam the Hague Airport are addressed.

Air Traffic Control (ATC)

Air Traffic Control (ATC) is responsible for the management of the civil airspace (LVNL, 2022). For airport operations, the ATC indicates a taxiway to an aircraft after landing and gives directions to reach the aircraft parking stand. The ATC also gives the take-off clearances, and thus influences the parking stand occupation time. Clearances for push-back and taxiing are also issued by the ATC (Skorupski and Żarów, 2021). At Rotterdam the Hague Airport there are no push-back operations involved, the ATC does give the engine-start clearance.

Airport Manager (AM)

The Airport Manager stakeholder usually has the tasks related to the apron management. This includes the allocation of parking stands to aircraft. Their work involves different time horizons, the stand allocation (SA) plan is prepared in advanced and adaptions are made in real-time due to disruptions. They also coordinate the ground movements on the apron. As discussed in subsection 3.1.1, RTHA is home to different flight profiles at different locations and for some this involves tailored airport manager tasks. Like, in specific cases the AM at RTHA also provides guidance to aircraft from the runway to the aircraft parking stands and vice versa. This happens in case the pilot is not familiar with the airport and this is standard procedure for visitors of the flight clubs, they will be only escorted to the flight club and do not need escort back to the runway for departure. Furthermore, at RTHA the airport manager also has the responsibility of supervising order and safety on airside along with involvement in emergency procedures.

Air Carriers

These stakeholders are the ones operating the aircraft. Since they need to organize ground handling and direct contact with their passengers, air carriers have a high interest in the location of the parking stand. This group is not uniform, due to different operating profiles and business models adapted. Therefore, their expectations in relation to stand allocation might also differ (Skorupski and Żarów, 2021). At RTHA, it are the airlines, JetAviation and flight clubs which are the major stakeholders operating the aircraft.

Handling Agents (HA)

This stakeholder group are entrepreneurs which perform ground handling services for the air carriers. For this organization, the location of the to be served aircraft is important, but also their availability for subsequent aircraft is important (Skorupski and Żarów, 2021). At RTHA the commercial aviation of the airlines is handled by Aviapartner. JetAviation handles their own flight movements and also the flight clubs handle their own flights and services.

Passengers (PAX)

For passengers the stand allocation determines the distances between for example the terminal and the aircraft (Skorupski and Żarów, 2021). At RTHA there are no gates which directly connect to the aircraft, passengers walk or are transported to the aircraft by buses. RTHA is home to different types of passengers which differ in preferences. For example, the visitors of the flight clubs, have the preference of relaxing and drinking a cup of coffee during their turn around at the airport. While, the passengers of the airlines and JetAviation are more pleased by keeping the walking distances between the terminal and the aircraft small. When determining an optimal charging configuration for electric aircraft, it is important to keep the different passengers and preferences in mind.

3.1.3. Ground operations at Rotterdam the Hague Airport

A general overview of ground operations flow at an airport is given in figure 3.2. This figure shows the process flow from the arrival of an aircraft to its departure. The ground operations at Rotterdam the Hague Airport will be explained using the flow presented in the figure.

An arriving aircraft on final approach receives landing approval form Air Traffic Control (ATC) and lands on the runway. The airports ATC also determines the runway exits. The taxiing starts when the aircraft enters the taxiway and travels to the aircraft stand. For the case of RTHA, as can be seen in figure 3.1 there are four different locations aircraft taxi to and park at. This is without considering the small number of privately owned aircraft located at the hangers (area number 5 in Figure 3.1). The stand allocation is generally determined by the Airport Manager (AM). For the commercial aircraft and the aircraft going to JetAviation, the stand allocation is always determined by the AM. For the flight clubs, the stand allocation is more free and they themselves determine where aircraft are being parked. For most airports it is the case that when the designated aircraft stand is not available yet, the aircraft can be parked at a holding area, also referred to as the apron. However, Rotterdam the Hague Airport does not have such an area.

After the aircraft arrives at the stand, the taxiing procedure is finished and the turn around process starts. The turn around process includes all operations performed while the aircraft is at the stand to get the aircraft ready for the next flight. This includes, the (un)loading of baggage, the (un)boarding of passengers, refueling and maintaining the aircraft, cleaning and catering and security checks. Figure 3.3 gives a clear overview of the process involved during the turn around. When the turn around process is finished the aircraft will taxi from the aircraft stand to the taxiway and make its way to the runway for departure. As mentioned in subsection 3.1.2, at RTHA push backs are not performed and are thus not as in Figure 3.2 part of the ground operations performed.

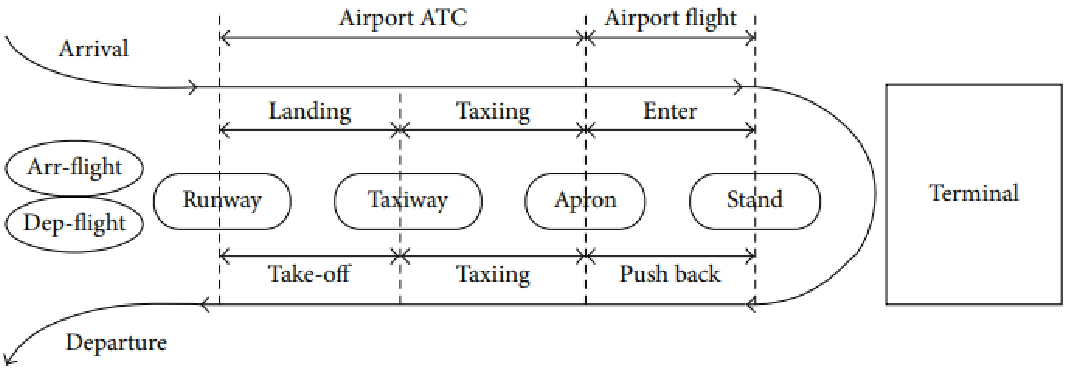


Figure 3.2: Overview ground operations flow at an airport, adapted from Jiang et al. (2013)

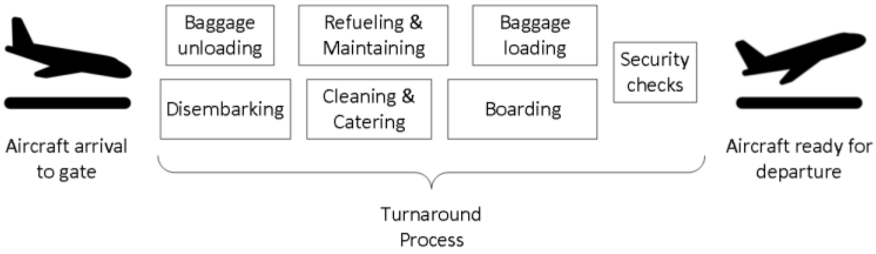


Figure 3.3: Overview turn around process, adapted from San Antonio et al. (2017)

3.2. Influence electric aviation on the operations at RTHA

Now that a general introduction to RTHA, the layout, the airport users and the ground operations have been presented, this section will focus on defining the concept of operations for electric aviation at Rotterdam the Hague Airport. First, in subsection 3.2.1 it will be described how and where electric aviation at RTHA is expected to impact the operations. Then, in order to gain more understanding of the charging process of electric aircraft, the current state of the art for charging electric aircraft will be discussed in subsection 3.2.2. Concluding, in subsection 3.2.3, the concept of electric aircraft charging for this project and thus tailored for RTHA will be described.

3.2.1. Impact of electric aviation on the operations of RTHA

In order to estimate the impact of electrification of aviation on the operations and infrastructure of an airport, it is first important to make an indication of when and where electrification of aircraft will become reality. For Rotterdam the Hague Airport, the first electric aircraft is already performing flights and due to their regional and operational profile and their strategy, a high increase in number of electric flight operations is expected. Forecasting the number of electric flight operations helps to create an understanding of what can be expected in terms of influences on the operations and impact on the airport infrastructure. The forecast however depends on several factors, including, the technological developments of batteries and electric aircraft, the strategies of the involved air carriers stakeholders, regulations regarding electric aviation and the time frame considered. The strategies of the stakeholders and the expected developments of electric aviation for the coming years at RTHA will be discussed in this subsection. The development of electric aircraft will initially emerge from the general aviation sector. Rotterdam the Hague Airport expects that three developments can be distinguished over time:

1. Electric general aviation aircraft;
2. Electric business/commercial regional aviation aircraft;
3. Further development of electric aircraft.

Electric general aviation

The general aviation profile is extremely suitable for the transition towards electric flight, the distances travelled are small and the Maximum Takeoff Weight (MTOW) of these aircraft is also relatively low. The Pipistrel Velis Electro is already stationed at RTHA and manufacturer Diamond is working on their electric variant of their Diamond D40 aircraft. This aircraft is planned to be certified at the end of 2023, have a range of 80 minutes, four seats and a charging time of 20 minutes. These type of aircraft are mainly intended for the use by flight schools. The strategies of the flight clubs located at RTHA have been investigated together with their vision towards electrification of their fleet.

The *Rotterdamsche Aeroclub* mentioned that at the beginning of 2024 they are expecting to acquire two Diamond eD40's and that in the upcoming years they will further electrify their fleet. The *Vliegclub Rotterdam* mentioned that it will only be a matter of time before one or two electric aircraft will be purchased. The hours which the flight club is currently dedicating to flight lesson can ideally be performed by electric aircraft. They are expecting to facilitate five charging locations from which three are for own use and two are for charging visitor aircraft. Their ambition is to also fulfill a role in handling recreational general aviation and providing visiting aircraft with electricity. Therefore, an inter-operable infrastructure at which different aircraft types can charge is required. Then, with an expected uptake in electric aircraft entering the market, there is a chance that also the privately operated aircraft at RTHA will become electric. These aircraft are located in the hangars at RTHA and refueling is currently performed at the central refueling station at the JetAviation platform. In time, when also in this segment more and more aircraft become electric, there will need to be a charging facility.

Electric business/commercial regional aviation

From 2024, the smaller regional 9 and 19-seaters will be entering the market, as well as the somewhat smaller Vertical Take-Off and Landing (VTOL) aircraft (see Figure 2.3). This will mean that from about the year 2024-2025 the impact of electric aviation will be noticeable in the business and commercial aviation operated at Rotterdam the Hague Airport. These will include smaller aircraft for private and or group use, but also for operators whom will be utilizing 9 and 19-seaters for operating new routes to regional destinations. Example of these aircraft is the Eviation Alice, a 9-seater aircraft with a range of 815 kilometers. Also the eFlyer 800, with a range of 900 kilometers and 6 passengers. The fact that these aircraft will in terms of size and weight be bigger and more heavy than the current maximum restriction of 2,000 kg MTOW and 13.5 meters wingspan and the fact that these aircraft will be operated commercially, means that these must be handled by either JetAviation or Aviapartner. JetAviation mentioned that they have not yet had concrete questions from their customers regarding electric aviation and therefore they are currently not considering operations of electric aircraft. However, they would like to accommodate this new type of aviation at RTHA.

In time, it is expected that operators will also use electric aircraft such as the Eviation Alice ES-19 for regular scheduled services. For example, MESA airlines which operates regional flights for United Airlines, has ordered 200 ES-10's. Other airlines such as Scandinavian Airlines (SAS), Braatens and Finnair are also interested in electric aircraft. That is why a route from Esbjerg to Rotterdam might become reality and operated by electric aircraft. It can be the case that these operators would like to handle the passengers via the main terminal of RTHA. Then, it should be questioned where these aircraft will be handled, either at Julliet or on the main platform. Either way, these aircraft will need to be charged and having an adequate electrical infrastructure is important.

Further development of electric aircraft

From 2030, the development of electric aircraft will continue. This includes aircraft with more efficient batteries, greater ranges and or more passengers or cargo spaces. However, indicating which aircraft and what will be the characteristics of these aircraft comes with high uncertainty.

Concluding, in the coming years, electric aviation will become reality for RTHA at different locations and to varying degrees. The electrification of the general aviation operation at RTHA will become reality in the coming 2-3 years. With the entrance of smaller regional electric aircraft to the market, expected from 2024, electric aviation will also become noticeable in the business and small commercial aviation operated at RTHA. Different electric and hybrid-electric aircraft types will be entering the market in the coming years. However, it should be noted that the promises of manufacturers shall not always be taken to literally since technical restrictions of batteries and certifications can slow down the realisation of the aircraft. It is important for RTHA to asses a solution for the infrastructure requirements which considers the future development in the electric aviation sector. How this will be implemented in the project will be later addressed in subsection 3.3.1.

3.2.2. Current state of the art for charging of electric aircraft

One of the major differences in terms of operation when comparing fossil fuel driven aircraft with electric and hybrid-electric aircraft is the time which it takes to get an electric aircraft ”refueled” before the next flight. The refueling process of fossil fuel aircraft generally takes 3 to 60 minutes depending on the size of the aircraft considered. However, recharging of electric aircraft takes a lot longer, generally while the refueling of a small sized 2 seater aircraft would take around 3 minutes, recharging of such an aircraft nowadays with the current charger capacities takes approximately an hour. It is important to consider different options and modes for charging which might result in lowering the demand from the electricity grid and investment in infrastructure. In this section, the basics about charging will be discussed together with the charging options which are currently discussed in the literature for charging electric and hybrid-electric aircraft.

Charging, the basics

For this research, going into detail about the technical characteristics of the batteries used in electric aircraft is out of the scope. However, it is necessary to be acquainted with the basics about battery charging. Regarding the charging of electric vehicles a lot can be learned from the automotive industry for which in the past years a lot has been developed regarding electric powered cars and the charging of these vehicles.

For the charging procedure of cars, all batteries use Direct Current (DC) for charging and discharging, while the grid delivers Alternating current (AC) (FASTNED, 2022). Therefore, an AC-DC converter is required which is part of what is called a charger. Chargers can be integrated in the vehicle as an onboard charger or chargers can be external to the vehicle, such as fast chargers. Nowadays, all electric vehicles have a small onboard charger which can be connected to a regular AC socket in for example your own garage like in Figure 3.4a (FASTNED, 2022). External chargers can be heavier, bigger, more complex and are more expensive than onboard chargers, but they are also a lot faster. A common fast charger (in the automotive industry) delivers 50 kW which chargers approximately 5 to 15 times faster than onboard chargers. Developments in fast chargers resulted in chargers delivering up to 175 kW and even chargers delivering 350 kW are currently used at the Fastned charging stations, see Figure 3.4b.

(a) Charging electric vehicle at home (Electrek, 2022)

(b) Fastcharger 350 kW (Athlon, 2022)

Figure 3.4: Difference slow and fast charging electric vehicles

Then, how does a charging process work? During charging there is a continuous communication with the battery management system (BMS) and the (fast) charger. The BMS instructs the charger to set the charge speed, which is usually expressed in kilowatt (kW). Power (expressed in Watts) is a product of current (Amps) and voltage (Volts). Charge speed is thus dependent on the voltage and current, from which voltage is a characteristic of the battery while the current is increased or decreased by the charger based on the instructions from the BMS. Besides voltage, there are other aspects which influence the charging speed, namely the battery pack capacity, the battery temperature and the state of charge (SOC) of the battery. Since the charging rate depends amongst others on the battery pack capacity, it should be noted that not all electric vehicles have the capability of being fast charged.

Charging electric aircraft

In the aviation sector, aircraft utilization and short turn around times are of high importance. This poses an increased importance on the utilization of fast charging for the charging of electric aircraft. The world's first standard electric airplane charging station which is EASA approved is the SkyCharge station produced by Pipistrel, which consists of two stations which both contain a strength of 20kW. Before electric aviation can literally "take off" it is of high importance that charging standards are developed and certified. Also, in order to ensure acceptable turn around times for aircraft entering the market, such as an Eviation Alice which has a battery capacity of 820 kWh, there is a need for chargers in the scale of megawatts (Schwab et al., 2021). Currently, the need to charge battery capacities at such scales with such rapid recharging speeds required, exceeds the current capabilities of the most powerful automotive sector chargers. In 2018, a charging interface task force CharIN was formed by industry actors which initiated the "Megawatt Charging System (MCS)". This taskforce set the goal to create a common solution for charging of electric heavy duty vehicles such as trucks and airplanes, within a reasonable time (CHARIN, 2022). The requirement of this initiative is to design a MCS up to 1,250 V and 3,000 A, resulting in 3.75 MW of peak power. Since the basis of the development of the MCS is the Combined Charging System CCS, the MCS can be seen as an extension of the CCS standard which can provide power up to 350 kW. Currently, the MCS is being tested and the publication of the final MCS standard is expected in 2024. From the tests it was shown that a working prototype of the MCS was able to deliver more than 1 MW of power to a Scania electric truck (INSIDEEVs, 2022).

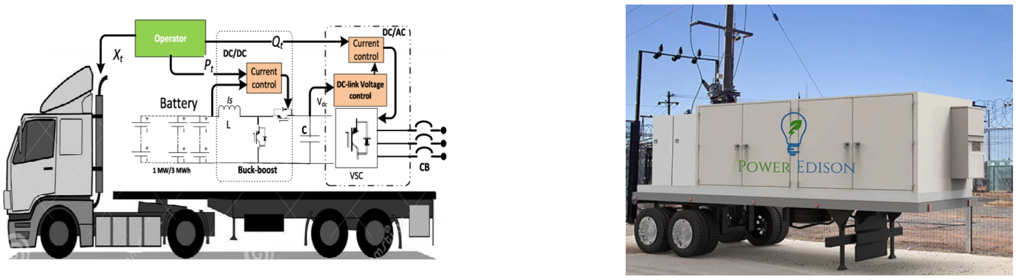
Besides the need for fast chargers in the scale range of megawatts, there are other challenges involved with the charging of electric aircraft. One of the main challenges is that charging electric aircraft will involve high energy demands from the electricity grid, especially when charging several aircraft simultaneously and at high charging rates. High charging rates are likely to be required in order to ensure compliance with the turn around times of the aircraft. Requesting high energy demands from the grid however, involve increased charging costs referred to as peak power pricing. Additionally, it should be considered whether or to what extend the grid can deliver high energy demands. One of the current issues in the Netherlands is that the national and regional power grids are becoming too congested (Nederland Netbeheer, 2022). It is therefore, that even tough airports and other companies which are looking towards electrifying their operations and willing to invest in accommodating charging infrastructure, should be considering that there might be restrictions posed on the amount of electricity which can be received from the grid. Netbeheer Nederland published and updates a capacity map of the electricity grid for which for all regions in the Netherlands it depicts to what extend the grid is in congestion, as shown in Figure A.1. From Figure A.2, it can be seen that for the location of Rotterdam the Hague Airport the grid is not highly and structurally congested, however there is a threat for scarcity. It is therefore, that for this project it is of importance to contact the provider of the electricity network and inquire the maximum capacity of the electricity grid. In addition, this project will also investigate what will be the investment costs associated with upgrading the grid.

In order to tackle/reduce the above mentioned challenges, smoothing of the demand peaks has to be applied which is generally known as peak shaving. Peak shaving can be realised by different options, including smart scheduling of the charging operations and inclusion of a battery storage system. Also, battery swapping is considered in most of the researches as an alternative to plug-in charging since it has the ability to spread out the charging demand. These different concepts will be addressed later in this section. Additionally, in order to become less dependent on the energy supply of the grid, investments can be made in the installation of local energy generation and storage components. These can be so called behind the meter systems such as wind turbines and solar panels. The extend to which inclusion of such generation systems will be included in this project will be addressed in the airport requirements in subsection 3.3.1.

Now that the challenges associated with the charging of electric aircraft together with possible solutions to reduce the impact of the challenges have been addressed, the current state of the art in charging electric aircraft will be discussed.

With regard to the (re)charging of the batteries of electric aircraft, there are several charging options discussed in the literature. Most researches considered two concepts, namely the concept of battery swapping and the concept of plug-in charging (discussed in subsection 4.1.4). The concept of battery swapping involves removing depleted batteries from the airframe of the aircraft and replacing them with fully charged batteries. The swapping of the batteries reduces the amount of time required to recharge an aircraft and has the potential of spreading out the charging demand. However, there are likely new specialist equipment required for replacing and moving the batteries around the airport which will add complexity to the existing airport operations (Doctor et al., 2022). Also, looking at what electric aircraft manufacturers are proposing for charging, Eviation (manufacturer Eviation Alice aircraft) states that they are expecting the charging to happen by mobile charging stations similar to current aviation fuel trucks and thus not considering battery swap. Furthermore, Rotterdam the Hague Airport mentioned that they currently have no interest in researching the concept of battery swapping and that solely plug-in options are considered. For these reasons, the concept of battery swapping will not be considered in this research and only the concept of plug-in recharging will be applied. Battery plug-in chargers (BPCs) are conceptually similar to fuel refilling stations. In the automotive industry many standards and connectors have been designed. Since electric aircraft and the operations of these are in the start up phase, the number of industry standards regarding BCPs is limited to a few models for the aviation sector, including the Pipistrel certified charging stations. For airports it is of importance that there will be a standard for the chargers and charging stations which is compatible with different kinds of aircraft and not as is currently the case for the Pipistrel aircraft, which can only be charged with the charger of Pipistrel itself. Therefore, SAE International is currently working on the AS6968-standard with which a standard is set for charging electric aircraft.

Concluding, battery plug-in is considered in this research for the charging of the batteries. There will be however, several variations considered in terms of the power system behind the chargers which provides the charger with power. The first one being a regular plug-in charger configuration in which the charger is connected to a charging station which directly draws the power from the electricity grid. This configuration is considered in most of studies in this literature field. A configuration which is less studied in the literature field is connecting the aircraft via a charger to an Energy Storage System (ESS). The aircraft then does not immediately charge from the grid but from the ESS, and the ESS can be charged during low hours and discharge to the aircraft batteries during peak hours or can be powered using renewable energy systems. The energy storage system is therefore perfectly fit to accommodate peak shaving ensuring that the electric demands required from the electricity grid are minimized. In addition, the ESS can be charged at times when aircraft are in the air or at night time when electricity costs are lower, ensuring a more optimal demand from the electricity grid. Including an ESS as power source is recommended to be studied by several of the researches which did not take this form of charging into consideration (Alfredsson et al., 2022; Doctor et al., 2022). Also, Teuge Airport, home to currently the most electric aircraft movements worldwide, is working on a design of a central charging plaza at which electric aircraft charge. Their design includes a large ESS in the form of a container consisting of several batteries, to which several aircraft can connect and charge from (Teuge Aiport, personal communication, 2022). Furthermore, as mentioned by the manufacturer of the Eviation Alice aircraft, another recharging option will be connecting the aircraft to a mobile charging truck similar to current aviation fuel trucks. An example of such a truck can be seen in figures 3.5a and 3.5b, which show that the truck consist of a large energy storage system. This system will have the advantages of adding mobility to the charging process together with the advantages of being an energy storage system. The potential of utilizing such a system has thus been recognised by electric aircraft manufacturers and additionally also regional airport RTHA sees the potential of utilizing such a system. It is therefore that the concept of a mobile charging truck will be included in this research and as presented later on, it will be one of the main contributions of the project. Concluding, as alternatives to charging directly from the grid, this research will include the option of charging from an ESS and charging from a mobile charging truck. The sizes of the ESSs of these concepts and the extend to which these can be charged by renewable sources such as solar energy, will be discovered later in the main body of this thesis.



(a) The schematic of a Mobile Energy Storage System (Wang et al., 2019)

(b) Example of a Mobile Energy Storage System

Figure 3.5: Mobile Energy Storage System

3.2.3. Concept of electric aircraft charging at RTHA

The ground operation process and the turn around process depicted in Figure 3.2 and Figure 3.3, will be slightly different for the operation of electric aircraft. Different from the turn around process explained in Figure 3.3 is that the refueling part is replaced by the charging of the batteries of the electric aircraft. As discussed in subsection 3.2.2, recharging generally takes longer than refueling and similarly to assumptions of other charging electric aircraft related literature, it is assumed that the charging duration will equal the turn around duration. Therefore, the focus of this research will be on the charging procedure and modelling all other turn around procedures is out of the scope. Thus, the other turn around processes presented in Figure 3.3 will not be considered and their durations are assumed to not influence the total turn around duration of an electric aircraft. In this subsection the charging procedure concept for electric aircraft as part of the ground operations of a regional airport, in specific for RTHA, will be described. Additionally, optimal scheduling the aircraft charging procedure is important in order to keep demands on electricity grid and large infrastructure investments to a minimum. Therefore, in the concept of charging it is also described how an optimal schedule will be included.

In its most basic form, the ground operations and turn around of electric aircraft can be described as an aircraft landing and ensuring that before departure the aircraft needs to be charged up to a required level for the mission. In this research, different scenarios will be discovered, including a scenario for which the infrastructural requirements will be determined for RTHA as a whole, and also a scenario in which for the different locations (flight clubs, Juliet platform and main platform) the infrastructural requirements will be determined separately. Additionally, another scenario considered is one in which charging of aircraft is allowed at another location than the required handling location and the last scenario is one in which a mobile truck is operating and utilized as additional charging option.

Consequently, all of these different scenarios will have a different impact on the ground operations. First, a general description for the turn around and ground operation of an electric aircraft at RTHA will be given. After that the differences in terms of operations for the various scenarios will be highlighted. In Figure 3.6, figure 3.2 has been adapted in order to explain the flow followed by an electric aircraft.

First, the basis scenario in which all aircraft are charged and handled at their preferred location will be discussed. After arrival of the electric aircraft on the runway, the aircraft is assigned to a location, which is either a regular aircraft stand (indicated in Figure 3.6 by ”apron”) or a tailored aircraft charging stand (indicated in Figure 3.6 by ”stand”). A tailored aircraft charging stand refers to a stand equipped with a fixed charger at which an aircraft can connect to. As explained in subsection 3.1.2, the stand allocation of aircraft to stands is performed by the Airport Manager. Thus, upon arrival the Air Traffic Control will first indicate which taxiway to use and then the AM will provide the aircraft with information of where to taxi to and at what stand to park at. The decision of whether an aircraft is initially assigned to an apron or immediately to a charging stand will be determined by an optimization model in which based on minimizing total cost (investment and operational) will determine the optimal charging times and allocation of the aircraft to a charger. Thus, also the duration of the aircraft charging procedure and occupation time of a stand results from the optimization model. The charging procedure starts the moment the charger is connected to the aircraft. The duration of the charging procedure depends on the battery’s state of charge (SOC) at the beginning of charging, the charging rate and the required battery’s SOC for the next mission. The SOC of a battery reflects the level of charge relative to the battery's capacity, 0% indicating that the battery is empty and 100% indicating that the battery is fully charged. Thus, the duration of the charging process depends on the SOC of the batteries of the electric aircraft upon arrival at the airport. The charging rate is optimized such that charging is finished within the turn around time available, while minimizing the cost related to charging. The maximum charging rate of a charger depends on the charger type, in this project, different charger types will be considered which have different maximum charging rates. The characteristics of these chargers will be decided on later in the project. Then, after the charging procedure is finished, the aircraft either waits at the stand or is moved to an apron at which it waits for departure. The aircraft thus makes its way immediately from the stand to the taxiway or has an in between stop at an apron. It should be noted that the process modeled does not include the other turn around processes (see Figure 3.3), but assumes that after the charging procedure is finished the aircraft is ready for departure.

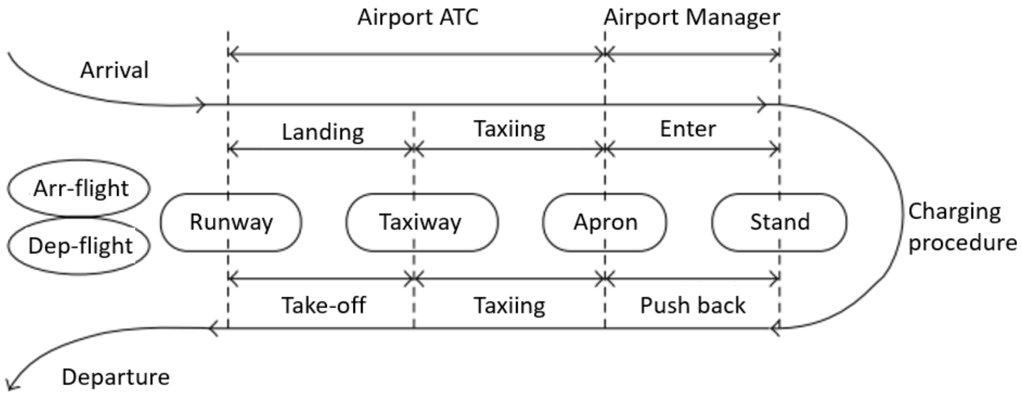


Figure 3.6: Overview ground operations flow electric aircraft RTHA, adapted from Jiang et al. (2013)

The ground operation process as described above is for the case that all aircraft will be assigned to the required handling locations as attained from the flight schedule. As mentioned, another scenario will be run for which aircraft in contrary to the basis case are allowed to be allocated for charging at another location. This does involve some restrictions, these involve restrictions on the wingspan and maximum take off weight (MTOW). The taxiways to the flight clubs do not allow taxiing of aircraft with a wingspan larger than 13.5 meters and a MTOW heavier than 2,000kg. Therefore, aircraft exceeding these restrictions are restricted to be handled and allocated to platform Juliet at JetAviation. Similar restriction applies to aircraft which are used commercially, these are also assigned to Juliet. The allocation of aircraft to other locations will be done in case it leads to lower total investment and operational costs. These total costs include the cost of the charging rate at which the aircraft is charged (operational), the cost of investment in the electric infrastructure at a location (investment), investment in chargers (investment) and investment in a fixed or mobile energy storage system (investment). It is important that for reallocating aircraft to charge at other locations, a cost related to moving this aircraft should be considered, this cost will serve as a sort of penalty since these are additional movements which impact the other operations at the airport and possibly negatively influences the passenger preferences.

The scenario in which a mobile charging truck is used as an option to charge the electric aircraft slightly changes the ground operations compared to the basis case. The mobile charging truck can be seen as a truck at which an energy storage system (ESS) is located. The use of the mobile truck ensures that aircraft can remain at their preferred location and connect to a charger which draws the power from the energy storage system on the truck. Considering the flow presented in Figure 3.6, the aircraft will remain at a normal parking stand (apron) at which it can connect to the mobile truck, so the aircraft will not be allocated to a stand. In terms of cost, a cost of transportation of the mobile truck from one location to another location can be added to the total cost function.

Concluding, the ground operations for an electric aircraft will be different to fossil fuel aircraft since refueling will be replaced by recharging of the aircraft batteries. Recharging of electric aircraft can pose high impacts on the electric infrastructure of an airport and therefore optimizing the charging of these aircraft is important. This subsection gave an initial idea of what the to be modelled charging operation of electric aircraft will look like for the different scenarios and how the model should be developed to optimize the infrastructure of a regional airport and in specific, RTHA.

3.3. Requirements

In this section the questions and problem statements from Rotterdam the Hague Airport regarding the operation of electric aircraft will be discussed and translated to a set of method requirements. The airport requirements of RTHA are presented in subsection 3.3.1 and the model requirements are given in subsection 3.3.2. In the proceeding chapters relevant research fields will be discovered and methods used in these fields will be discussed. Defining the method requirements in this section will serve as a backbone to determine which are relevant methods and eventually which method is best suitable to solve for the problem of this project.

3.3.1. Airport requirements

While approaching a future with an increase of electric aviation, airports should ensure that they are sufficiently equipped to allow for these battery powered aircraft operations to take place. Even tough electric aircraft have the potential of reducing the air transport contribution to climate change, their characteristics pose questions on how the operations of these aircraft can be integrated in existing airport infrastructures (Doctor et al., 2022). Doctor et al. mentioned that the time of recharging the aircraft while on the ground should be considered without adversely effecting operational capacities and also it requires airports to install charging capabilities. Thus, investing in appropriate charging infrastructure should be investigated. It is important that investments in building such infrastructure must be forward-looking and account for likely growth trajectories of the electric aviation technology (Hou et al., 2021). Rotterdam the Hague Airport wants to ensure that they are sufficiently equipped to allow for an increase of electric aviation. Therefore, they question how electric flying will affect their airport infrastructure and the operations. In this section challenges incorporated with the introduction of electric aircraft to airports will be highlighted and concepts/tools which RTHA would like to discover for solving or minimizing these challenges will be presented. The airport requirements will be discussed from an infrastructural, operational and general view of Rotterdam the Hague Airport, which are presented in Table 3.1.

Centralized vs decentralized

Considering the impact on the infrastructure of the airport, RTHA questions what the infrastructure will look like and what resources will be required to facilitate the operation of electric aircraft. This involves determining the charging locations and the optimal number and types of chargers needed. As discussed in subsection 3.1.1 there are several locations at RTHA where electric aviation will become reality on a short to medium term. Therefore, the question arises whether it is most optimal to make a central charging location plaza at which all aircraft recharge, or that a decentralized solution is more appropriate in which all aircraft can charge at the location of their destination/operator. Another option would be a hybrid one in which the number of charging points will be optimized for all locations also considering a central location at which aircraft will be assigned to during peaks and busy periods in the schedule. This would for example be that the entire JetAviation fleet and their customers make use of the centralized location and that the flight clubs have charging locations of their own but at busy times aircraft can and will be assigned to the central location.

Fixed and mobile energy storage system

Furthermore, charging electric aircraft involve high energy demands on the electricity grid, especially when several aircraft are charged at the same time and at fast charging. A useful concept to lower the energy demands on the grid is the concept of peak shaving. As discussed, peak shaving can among others be achieved by the use of a battery energy storage system. Such a system can be charged during ”low” periods and be discharged to power systems/vehicles during on-peak times. Currently, Teuge Airport in the Netherlands is designing a central charging plaza for electric aircraft in the form of placing a container filled with batteries from which several aircraft can charge. Rotterdam the Hague Airport is also considering such a solution at which aircraft can charge and thus not charge at a charger which is directly connected to the grid. An energy storage system can also be used to store power generated by renewable resources, it is therefore that RTHA would like to investigate the possibility of powering the batteries of the ESS using the airport-based solar park. In case of implementing an energy storage system , the sizing of such system(s) will need to be determined together with the acquisition costs. Additionally, RTHA would like to discover the effectiveness of the use of a mobile charging truck, which is a similar concept as the container like construction filled with batteries but then placed upon a truck such that it can easily move from one location to another. In turn, this solution will have lower impact on the infrastructural needs since it can be charged at a central location and drive to the locations where charging is needed. For the implementation of a mobile charging truck the sizing of the ESS on the truck and the number of trucks should be determined.

Smart scheduling

Besides a battery energy storage system mentioned above, there are other options which can realize peak shaving. As shown by the research of Hou et al. (2021), smart charging of electric aircraft can substantially reduce peak power demands. The operation of electric aircraft entails the need to support timely recharges such that the aircraft is operational in time for the next mission. Optimally scheduling the charging operations of the electric aircraft will be crucial to ensure lower impacts on the airport electric grid infrastructure and lower costs. Therefore, optimizing the recharging schedules will be part of the research, which will include the times at which the charging process starts, the duration of the charging and the allocation of aircraft to chargers. Additionally, RTHA would like to discover the effect of deviating from the flight schedule. Deviations from the flight schedule allow to more optimally schedule the distribution of electricity demand from the grid which in turn has the potential to result in lower investment and operational costs.

Operational challenges

From an operational point of view, there are several challenges involved with electric aviation. First of all, guaranteeing the safest possible operation is crucial for an airport. Therefore, safety questions in terms of fire safety with the realisation of electric driven aviation are questioned. RTHA is committed to discussing and finding solutions to the challenges of safety and fire safety of electric flying. Conversations with the fire department at RTHA indicate that they are not yet prepared for an increase in electric flying which includes an increased probability of battery fires. Looking at the car industry, it can be seen that a battery fire has a completely different fire profile than a fossil fuel fire. Fire departments are placing cars in liquid baths for days/hours straight in an attempt to extinguish the battery fire. In some cases the cars starts burning again within an hour after removal from the bath. It is important for airports to discuss how the safety of electric aircraft operations can be guaranteed and also how the impact on other flight movements and operations can be minimized at the time of fire. However, after discussing with RTHA the decision has been made to leave the safety requirements out of the scope of this research. Nevertheless, this is surely a point that deserves attention internally and will be addressed as part of future research.

Secondly, as is well established in air transport literature is that especially for airlines but also for flight clubs and operators of business aviation, aircraft utilisation and efficient turnarounds are extremely important for their business models. Hence, the ability of electric aircraft to turn around in a time frame which is suitable for the operation is important. RTHA already received the requirement of the flight clubs that there electric aircraft should be able to turn around in 30 minutes.

Addressing a forward looking solution

Lastly, it should be mentioned that all questions discussed above depend on the amount of electrified aircraft and the flight schedule. It is important to make realistic assumptions regarding the growth of electric aviation of the coming years and how this is applicable to the flight movements at Rotterdam the Hague Airport. Therefore, it is proposed to analyse for different future scenarios which present different uptakes of electric aviation. These scenarios will for different time frames include specific electric aircraft types and different level of utilization of electric aircraft for the general aviation, business aviation and commercial aviation segments at RTHA. An overview of the above mentioned requirements is given in Table 3.1.

	Priority
Infrastructural	
I.1 Determine number and type of chargers	***
I.2 Determine number of charging locations (centralized vs decentralized)	**
I.3 Determine influence and sizing of energy storage system	***
I.4 Determine influence and number/size of mobile charging trucks	***
I.5 Determine energy consumption	***
Operational	
O.1 Minimize the number of additional ground movements	*
O.2 Charging duration should stay within Turn Around Time	***
O.3 Determine effect of deviating from flight schedule	***
O.4 Operational safety	-
General	
G.1 A future proof solution should be found	***
G.2 Minimizing the investment costs	***
G.3 Minimizing the operational costs	***

Table 3.1: Airport requirements overview

3.3.2. Model requirements

In this section, a first and initial description will be given of what the function of the model should be, in terms of what will be the input and what are the desired outcomes.

The first step of the model should entail the generation of a flight schedule. This flight schedule will be based on RTHA flight movement data from the year 2022, this year has been chosen since it provides the most recent data of flight movements, and the years before such as 2020 and 2019 are less representative years due to a decrease in flight movements as result of the COVID pandemic. The flight movements of 2022 will be evaluated on whether or not they were suitable to be replaced by electric aircraft. For this, it is important to note that in order to anticipate for different electric aviation future growth trajectories, several future scenarios will be drawn. These scenarios include different time frames (e.g., 2025, 2030, 2035), these time frames include a set of aircraft types based on when which aircraft type is expected to enter the market. Then, different growth scenarios will be drawn up, preferably a low, medium and high scenario which represent different uptakes of electric aircraft movements. Depending on the growth scenario and the time frame considered, a percentage of aircraft movements which is replaced by electric aircraft will be given for the categories general aviation, business aviation and commercial aviation.

Based on the scenario which is considered and the flight movements of 2022, a new flight schedule is created in which electric aircraft type replaces the current aircraft types on the flown missions of some day(s) in the year 2022. This flight schedule together with aircraft characteristics, charger characteristics, infrastructure details, standards for investment costs and standards for operational costs are used as input for the model. In turn, the models desired outputs are the optimal number and type of chargers per location, the optimal number and size of mobile and or fixed ESS and the minimum investment cost required to ensure compliance with the flight schedule. The desired inputs and outputs of the model are given in Figure 3.7.

Lastly, it should be noted that analysing the effect of different considerations in terms of locations, use of energy storage system, and deviating from the flight schedule is important for RTHA which results in modifying or including different concepts to the model. For example, the spatial aspect of the different locations at which RTHA is expecting to invest in charging infrastructure is of high importance to this project. As discussed in the airport requirements in subsection 3.3.1, RTHA would like to discover whether or not a central charging location is advisable and to what extend the layout will be decentralized/centralized. Therefore, different scenarios will be analysed which involve a different setting from the model. One setting in which it is not allowed or aircraft to charge at another location other than their home base or destination location and another in which this is allowed involving a sort of penalty in terms of cost for making additional aircraft movements. Furthermore, in order to assess the wish of RTHA to investigate the effect of allowing the solution to deviate from the flight schedule, another model setting will be implemented which allows the solution to find an optimal while deviating from the schedule is allowed. Additionally, the model should be constructed in such a way that including or not including an mobile and fixed energy storage system should be easy.

Then, summarizing some of the functions of the model discussed above together with what the model should be cable of doing, the model requirements have been set up and are listed below:

- The model should be based on available data within Rotterdam the Hague Airport;
- The model should be able to convert a daily RTHA flight schedule;
- The model should be able to determine which flight movements in the flight schedule are eligible to be replaced by electric aircraft, based on the range and number of passengers transported;
- The model should be able to solve for multiple electric aircraft types;
- The model should be able to simulate different future scenario's, which account for when and to what extend the stakeholders of RTHA will operate electric aircraft;
- The model should solve on an individual aircraft basis, such that it takes into consideration aircraft specifics, performed missions, next missions etc.
- The model should take into account aircraft to stand compatibility when assigning aircraft to stands, since due to size compatibility and flight requirements not all aircraft can be assigned to all stands;
- The model should optimize for the entire flight schedule and not on an individual aircraft basis;
- The model should account for several constraints;
- The model should be capable of analyzing the effect of different operations (mobile charging truck) and different locations (decentralized vs centralized);
- The model should output the energy consumption;
- The model should output the optimal recharging schedule;
- The model should output the optimal number of recharging locations/chargers
- The model should output the optimal sizing of a mobile and or fixed energy storage system
- The model should output the total cost of a specific solution, including operational and investment cost

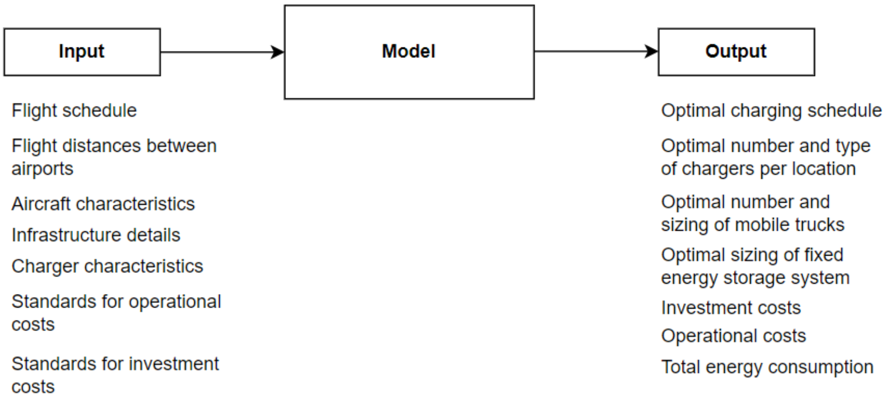


Figure 3.7: Overview initial model description

4

Previous studies on optimal infrastructural sizing for charging of electric aircraft

Electric or hybrid-electric aircraft offer the potential of replacing conventional aircraft in order to steer towards decarbonization of the air transport and reducing its contribution to climate change. With the increasing interest in electric aircraft, several questions regarding the operations and the influence of these new aircraft types on airport operations and infrastructure rise. In this chapter the research field considering optimal infrastructural sizing of airports for charging of electric aircraft will be reviewed. In section 4.1 the previous works in the research field of electric aviation and its impact on the operations and infrastructure of airports are addressed and discussed in detail. In section 4.2 the research gap is presented together with a conclusion of the lessons learned from previous work.

4.1. Research focused on the impact of electric aviation on airport infrastructure

Over the past few years, there have been several studies which focused on what will be the infrastructural impact for airports when electric aviation becomes reality. A general overview of the researches published in this field is given in Table 4.1. From this table it can be seen that the the topic of electric aviation and the impact on airport operations and infrastructure is a new research field with the first research published in 2018. The research of Bigoni et al. (2018) was the first group investigating the problem of desired infrastructural sizing for the operation of electric aircraft and of developing a recharging and battery swapping schedule, using a method which was based on models originally developed for electric vehicle recharge stations. The number of studies has been increasing over the last years but since it is a rather upcoming topic the number of researches published is rather limited compared to research topics which have been studied for years. In this section, the performed researches in this field of electric aviation and the impact on airports, will be discussed. The focus and outcomes of the researches will be highlighted in subsection 4.1.1, the objectives of the researches are discussed in subsection 4.1.2 and the methods used to solve the problems are presented in subsection 4.1.3.

4.1.1. Focus of the researches

In Table 4.1, nine different researches are displayed in which the details of the research in terms of focus, outcome, objective, method and application are presented. The first part of the table considers the focus and outcomes of the studies.

From Table 4.1 it can be seen that there are several topics which are covered by most of the researches such as the development of charging schedules and determining the optimal number of chargers, whilst there are also topics which are only covered by one or two of the researches. The research of Hou et al. (2021) focused on developing a flight rescheduling algorithm and did in contrary to the other researches, not take into consideration determining the optimal number of chargers and/or batteries. This research solved on a multi-objective basis in which the peak power was minimized while also minimizing the number of displacements to a flight schedule. The optimal number of chargers and/or swap batteries was determined together with the development of a charging schedule in a majority of the researches (Bigoni et al., 2018; Justin et al., 2020; Mitici et al., 2022; Salucci et al., 2019; Trainelli et al., 2021). Guo et al. (2020) focused on determining an optimal airport charging infrastructure including number of chargers and batteries but not including developing a detailed charging schedule providing the start times of battery swaps/charging. The researches of Alfredsson et al., Bigoni et al. and Trainelli et al. included determining the electrical consumption resulting from the solution to the problem. Additionally, besides determining infrastructural requirements, some of the research also included the optimal electric aircraft fleet allocation (Bigoni et al., 2018; Mitici et al., 2022; Salucci et al., 2019; Trainelli et al., 2021).

There is also a distinction made in the literature between considering full electric or hybrid electric aircraft (HEA). Also the sizes of the aircraft used as reference differ. The researches of Alfredsson et al. (2022), Bigoni et al. (2018), Trainelli et al. (2021), Justin et al. (2020) and Guo et al. (2020) all considered small regional aircraft carrying up to 19 passengers, from which Bigoni et al. and Trainelli et al. considered the HEA 4 pax Pipistrel Panthera and Guo et al. used the Eviation Alice as reference aircraft, both aircraft are prototypes which are expected to enter the electric aviation market. This makes that these studies made an effort to base their study on real expectations of what will be entering the market in the coming years. For the other studies of Doctor et al. (2022) and Salucci et al. (2019) considering narrow body aircraft of 48-78 passengers and especially for the studies which considered the larger narrow body aircraft, the prospect of such aircraft entering the market as electric or hybrid electric is much more uncertain and will most likely not be happening for the coming 20 years (Doctor et al., 2022).

Furthermore, most of the researches focused their models on a reference airport, except for the research of Justin et al. (2020). Their research was applied to two commuter airlines and the paper addresses some of the challenges which airlines will face when electric aircraft are introduced to their operations. The solutions in terms of the design for the supporting recharging infrastructure are thus not tailored for a specific airport but they considered a network of airports. Then, the other researches which do include reference airports differ in the type of airports considered. Most of the researches applied their study to (regional) hub airports (Alfredsson et al., 2022; Doctor et al., 2022; Guo et al., 2020; Hou et al., 2021; Mitici et al., 2022; Salucci et al., 2019; Trainelli et al., 2021). Only the researches of Bigoni et al. (2018) and Trainelli et al. (2021) considered a regional general aviation airport to analyse the impact of electric aviation. As will be discussed later in subsection 4.1.3, the research of Trainelli et al. (2021) is based on a combination of the researches of Bigoni et al. (2018) and Salucci et al. (2019). It is therefore that in the research of Trainelli et al. the same reference airports as in the study of Bigoni et al. and Salucci et al. were used, namely Milan's Bresso city airport and Athens international airport. Striking from these three researches is that they considered applying their case to reference airports which have a suitable operational profile that matches the type of airports for which electric flying will in time become reality. Milan's Bresso city airport is a regional airport and Athens international airport was chosen by Salucci et al. and Trainelli et al. because in Europe it was the airport with the highest number of propeller driven regional aircraft movements. Regarding the current characteristics of electric aircraft and the prospect of their short distance and operation in the regional aircraft market, their applicability to large hubs mainly operating the larger narrow body and wide body airplanes, is questionable.

4.1.2. Objectives of the researches

The objectives to which the researches optimized their problems are displayed in the second part of Table 4.1. The only research which considered minimizing the operational impact of electric aircraft for an airport is the study conducted by Doctor et al. (2022). Another study which considered something that the rest of the researches did not, was the one of Hou et al. (2021) in which the number of displacements to the flight schedule due to recharging activities were minimized. Keeping the peak energy demand to a minimum was focused on by several of the researches (Alfredsson et al., 2022; Bigoni et al., 2018; Hou et al., 2021; Justin et al., 2020; Salucci et al., 2019; Trainelli et al., 2021). The operational and procurement costs were objectives which were considered by the researches of Mitici et al., Bigoni et al., Salucci et al., Trainelli et al., Justin et al. and Guo et al.

4.1.3. Methods

An overview of the methodologies used in the researches is also provided in Table 4.1. The methods will be discussed for each research individually.

Optimization models

An important model in the research of electric aviation and the impact on airport infrastructure is the Airport Recharging Equipment Sizing (ARES) mathematical model. The ARES model gives the optimal solution to the airport battery recharging infrastructure problem. The formulation of the model is a mixed integer linear programming (MILP) problem solved with the commercial Gurobi solver. The model combines knowledge of the flight schedules together with the specifications of the aircraft fleet, to determine the number and type of charging points, batteries and aircraft required for the operations. The solution is attained by minimizing the total expenditures, including maintenance, procurement and electric energy costs, and provides a description of the optimal time scheduling of electric aircraft recharging. The ARES model is presented in the paper of Trainelli et al. (2021) and is based on a consolidation of the earlier studies of Bigoni et al. (2018) and Salucci et al. (2019). The research of Bigoni et al. presented a MILP similar to the one used in the ARES model, with alike inputs, outputs and the objective of minimizing the expenditures. The study performed by Salucci et al. (2019) consisted of a similar procedure in which they applied their research to Athens international airport.

Another research in which a mixed-integer linear program with a Gurobi solver was used, is the research of Mitici et al. (2022) in which a two phased MILP was proposed. The first phase focused on developing a schedule for flight and battery recharge for a fleet of electric aircraft. In the second phase, a time discretization was applied to determine an optimal sizing of the number of charging stations and swap batteries together with optimal times for battery charging.

Then, the research of Guo et al. (2020) focused on comparing the concepts of battery swap and plug in charging systems, in which also a mixed-integer linear program was used to solve for the optimal sizing of charging infrastructure for both concepts.

Hou et al. (2021) focused on designing an optimization model which jointly minimizes the displacements of flights from their schedule while flattening the power profile required to charge hybrid electric aircraft(HEA). This research showed that smart management of charging schedules of HEA can help to significantly reduce peak power demands.

Furthermore, an optimization model formulated by a network flow representation was presented in Justin et al. (2020). Except for some differences in the framework of the method, the research approach of Justin et al. shares many elements with the ARES mathematical model presented by Trainelli et al.

Simulation Optimization models

There are two researches in which simulation techniques are combined with optimization techniques, referred to in Table 4.1 as simulation optimization. The research of Doctor et al. (2022) applies simulation modelling in order to model and investigate the impact of both electric and hybrid-electric aircraft at a large hub airport. The battery charging regimes and their impact on the airside stand capacity have been analysed by Discrete Event Simulation (DES) models which were formalised through the queuing theory. Discrete Event Simulation is a methodology which is widely used in logistics and supply chain management. "DES models comprise of entities, attributes, events (modules), resources and queues where time is an essential component for describing the order in which modelled events take place" (Doctor et al., 2022). Queuing can be added to the model to manage the interactions of the entities presenting real process flows and delays (Doctor et al., 2022).The DES model generated by Doctor et al. was further used to determine the optimal number of aircraft stands required for different charging regimes, this was determined using computational metaheuristic based optimization strategies. The goal was to determine the number of single and dual purpose stands while keeping the number of stands close to a predetermined baseline and minimizing the congestion at the airport. The research applied a single solution based Tabu search and a population based scatter search algorithm as metaheuristic search driven strategies. Different metaheuristic methods including these, will be presented and discussed in more detail in subsection 6.2.1. The DES model of Doctor et al. was constructed by the AnyLogic software which is a simulation modelling tool supporting agent-based, discrete event and system dynamics simulation methodologies (Anylogic, 2022). It should be noted that the research of Doctor et al. did not take into account optimal scheduling of the charging of the aircraft (fixed charging times were considered starting immediately when aircraft stand was available) and that no requirements in terms of energy demand were taken into consideration.

Another research in which simulation modelling was used to investigate the impact of electric aviation on the infrastructure of airports is the research of Alfredsson et al. (2022). This research also makes a combination between simulation and optimization techniques. The simulation included flight data, the modelling of electric aircraft performance and charging simulations. Additionally, a 'smart charging' heuristic algorithm was developed to optimize peak power demands at airports. The logic behind the simulation was to follow the complete chain of movement of the individual aircraft during a specific period. The use of an aircraft identification number allowed to follow the chain of movement for that specific aircraft, and enable continuous simulation throughout the specified period(typically one day) for every aircraft. Thus, in contrast to the research of Doctor et al. (2022), this research is focused on continuous simulation. The charging of the aircraft was modelled in two consecutive steps. First, a "dumb" charging algorithm was used in which an aircraft starts charging as fast as possible after arrival and is permitted to obtain the full requested power from the charger. Second, a "smart" charging heuristic was used which redistributes the power given to each aircraft at points in time, with the goal of reducing peak power demand at the airport. By first simulating the dumb charging, the algorithm already knows the used charging curve and whether or not the charging process was finished before departure and thus if there was any spare time. Based on this the algorithm then strategically limits the power output for each charger to aircraft at every point of time.

4.1.4. Recharging and battery models

Regarding the (re)charging of the batteries of electric or hybrid-electric aircraft there are several options discussed in the literature. The majority of the researches focus on two concepts, namely battery swapping and plug-in recharging. The concept of battery swapping involves removing the batteries from the airframe and replacing them by a fully charged battery, so in this concept the charging of the battery of the aircraft happens remotely. The concept of plug-in charging is similar to the current charging process of electric car, namely that the batteries of the aircraft are integrated or fixed in the airframe, requiring the aircraft to be plugged into a power source to recharge the batteries. The researches of Mitici et al. (2022), Bigoni et al. (2018), Salucci et al. (2019), Trainelli et al. (2021) and Guo et al. (2020) all focused on both using battery swap and plug-in as charging strategies. The research of Guo et al. specifically focused on making a comparison between the two concepts, from which it was concluded that battery swap is more economic when the percentage of electric aircraft replacing current aircraft is below 10%, while for levels above 10% the plug-in charging system becomes the more cost-effective option. Justin et al. (2020) only took into consideration the concept of battery swap as charging procedure for their research. There are also researches which did not consider battery swapping as an alternative and only considered plug-in charging (Alfredsson et al., 2022; Doctor et al., 2022; Hou et al., 2021). Lastly, there is only one research in which an energy storage system is considered to be used as additional power source to charge an electric aircraft, which is the research of Guo et al. (Guo et al.). Their research additionally considered using power generated from an airport-based solar photovoltaic (PV) system to charge the batteries. The research also introduced the novel concept Aviation to Grid (A2G) which simulates a bi-directional flow between the electric aircraft charging system and the power grid in which the charging system is not only consuming electricity from the grid but can also supply excessive electricity back to the grid.

Furthermore, different strategies regarding the recharging process of (hybrid) electric aircraft are considered in the literature. The process differs in charging duration, assumptions regarding the battery state of charge, the energy consumption of the aircraft during flight and the charging rate are all factors influencing the charging duration.

Charging duration

The charging duration depends on several factors, including the ambient conditions, the current state of charge, and the charge/discharge rate of the battery (also referred to as the battery 'C-charging') (Doctor et al., 2022). Batteries with a C-rating of 1 can fully charge up to its capacity in 1 hour, for a 2C rating this is 20 minutes, and a battery with a 5C rating can be charged in 12 minutes (Buchmann, 2001). In the literature there are different concepts considered to determine the charging duration of the aircraft, which include different strategies of determining the charging rate and the battery's state of charge (SOC). The different considerations and assumptions made in the researches with regard to battery's SOC, energy consumption during flight and charging rates will be discussed below.

Battery's state of charge

The battery's state of charge (SOC) represents the level of charge of a battery relative to it's capacity, 0% indicating that the battery is empty and 100% indicates that the battery is fully charged. Mitici et al. (2022) consider the residual battery before re-charge represented by the SOC, such that in case the residual battery charge is sufficient for a next mission the recharging can be postponed. If the residual battery charge is not sufficient, the battery is charged up till the required battery's SOC for the next mission. Another research in which the battery's state of charge was accounted for is the one of Alfredsson et al. (2022), in which the SOC was dependent on the battery level at the start of flight and the amount of energy consumed during flight. In this research however, the SOC required for the next mission was not considered, instead charging until fully charged was performed.

However, the residual battery/the battery's state of charge was not taken into consideration by all studies presented in the literature. The research of Doctor et al. (2022) assumed that the electric aircraft arrive fully discharged after a mission and are fully charged at the aircraft stand, thus not taking into account residual battery charge. This was however acknowledged as limitation by the research. Similarly, Trainelli et al. (2021) considered that the battery SOC amounts to a minimum admissible value after completion of a flight and that during charging the batteries are fully charged. Furthermore, Hou et al. (2021) have not taken into consideration the battery's residual SOC either, they also assumed that each aircraft arrived with a depleted battery, but unlike Doctor et al. it did not consider charging fully but considered charging up to the level required by the next flight. A similar concept was applied in the study of Justin et al. (2020) in which the batteries were assumed to arrive discharged only containing the regulatory reserves and in which the batteries were also charged up to the required level for the next flight. The study of Guo et al. (2020) considered that each arriving aircraft only contained an energy reserve of 30% of the SOC to cover for emergency flights.

Energy consumption during flight

The energy consumption during flight was calculated by Hou et al. (2021) as a function of the number of passengers, flight distance and the battery energy usage per passenger mile for which the values were derived from Wroblewski and Ansell (2019). The assumption was made that the electrical power drawn from the batteries remained constant during the different flight phases.

In the research of Alfredsson et al. (2022) aircraft and flight simulations have been used to determine the energy consumption during the flight according to the different mission segments, e.g. take-off, climb, cruise, descent, holding, landing and taxi-in at destination.

The study of Justin et al. (2020) were able to calculate the energy consumption based on the design characteristics of their reference electric 9 passenger aircraft which contained for all phases of flight the power requirements. They used this to calculate the necessary SOC for the next flight.

Mitici et al. (2022) calculated the energy required to execute a flight mission by means of the Mission Analysis method, which is a method widely used during conceptual and preliminary design of aircraft to estimate the required fuel needed to carry out a mission. In this method approach, a weight fraction method together with a Breguet equation is used which have been properly adapted to take the differences between conventional aircraft and electric aircraft into account. The rationale behind the approach used by this research consisted of determining the amount of fuel used by a conventional aircraft and then calculating the corresponding amount of energy needed in case of an electric aircraft. The mission phases and the amount of energy needed during these phases have been addressed separately. The weight fraction method was used to determine the energy consumption during the take-off and climb segments of the flight and the Breguet Formula was used to determine the total energy needed during the cruise segment of the flight. Mitici et al. made the assumption that during descent and landing the requested energy is negligible.

Charging rate

Different concepts have been used in the literature to determine or set the charging rate at which the aircraft are charged. In some researches the charging rates have been optimized in order to minimize the electricity costs associated with the charging process (Bigoni et al.; Hou et al.; Justin et al.; Mitici et al.; Trainelli et al.). There are also studies which assumed the charging rate to be constant (Doctor et al.; Justin et al.).

The research of Justin et al. (2020) included both, a fixed power rate provided by the chargers was considered in the power optimization strategy proposed by the research while in the power investment strategy the charging rate was minimized. Doctor et al. (2022) only used a fixed power rate and thus fixed estimated time for charging and adjusted this duration to evaluate the effect of shorter or longer charging durations. A limitation of this research is that when setting up the charging times, the capacity of the grid infrastructure to support these charging times was not considered. In the research of Hou et al. (2021), a smart charging algorithm was introduced which aimed to lower peak power demands. This algorithm minimized the charging rate (power) drawn by the aircraft from the charging system, while ensuring that the aircraft finished the charging process before departure and that the charging rate can not exceed the capacities of the batteries. As a maximum, they considered C-charging of 10, considering that higher C-rates deemed unrealistic. Referencing this to the current developments in the automotive industry, they are currently targeting fast charging with a rating of 10C (Doctor et al., 2022). The researches of Bigoni et al. (2018), Salucci et al. (2019) and Trainelli et al. (2021) also considered the battery characteristics and the charging rate to determine the charging duration. In the researches of Bigoni et al. and Trainelli et al. the charging rate was optimized in order to minimize the energy costs involved with the charging procedure.

In order to better describe a charging process and make it more similar to the real life process, researches included a charging profile which varies the charging rate during the charging procedure. In the research of Mitici et al. (2022) it was considered that the charging duration/rate follows a bi-linear profile, indicating that for charging above 90% of the battery capacity the slope of the charging profile decreases. This behaviour reflects the charging behaviour of Li-Ion battery technologies nowadays used in the automotive industry (Mitici et al., 2022). The research considered that the nominal power of charge at a charging station had a maximum C rate of 6. Mitici et al. optimized the rate of charge considering minimization of the electricity cost of charging. Another study which considered a charging profile, is the research of Alfredsson et al. (2022). They also considered a charging curve at which at lower SOC levels the charging rate was higher and gradually decreased as SOC increased. This charging curve limits how fast it is practically convenient to charge the aircraft's batteries. In contrast to the 90% used by Mitici et al., Alfredsson et al. used a curve at which the C-rate was changed three times during a charging process, at 40%, 75% and 85% of the SOC. As discussed in subsection 4.1.3 Alfredsson et al. utilized two different charging algorithms, a ”dumb” one and a ”smart” one. In the dumb algorithm, the battery requests the maximum power of charge which has the behaviour described by the curve and depends on the SOC of the battery. In the smart algorithm the power of charge is optimized with the aim of lowering the peak power demand at the reference airport. Furthermore, the study of Justin et al. (2020) similarly to Alfredsson et al., considered a battery recharge process consisting of three phases. The first phase referred to as the pre-charge which is for batteries with low SOC, then a constant current fast charge phase followed by the final constant voltage charge for the high SOC.

	Mitici et al. (2022)	Alfredsson et al. (2022)	Hou et al. (2021)	Doctor et al. (2022)	Bigoni et al. (2018)	Salucci et al. (2019	Trainelli et al. (2021)	Justin et al. (2020)	Guo et al. (2020)
Develop flight (re)schedule	X		X						
Develop (re)charging schedule	X		X		X	X	X	X	
Plug-in charging		X	X	X					
Battery swap								X	
Plug-in and battery swap	X				X	X	X		X
Use of energy storage system									X
Optimal EA fleet allocation	X				X	X	X		
Optimal number of chargers	X	X		X	X	X	X		X
Optimal number of swap batteries	X				X	X	X	X	X
Optimal sizing BSS					X			X	
Determine electrical consumption		X			X		X		
(Min.) peak energy demand		X	X		X	X	X	X	
Min. displacements flight schedule			X						
Min. operational impacts				X					
Operational costs (maintenance, electricity)	X				X	X	X	X	X
Procurement costs (batteries, chargers, AC)	X				X	X	X	X	X
Mathematical optimization model			X						
Mixed-Integer Linear Program	X				X	X	X		X
Network flow optimization problem								X	
Simulation optimization		X		X					
Full electric aircraft	X	X		X				X	X
Hybrid electric aircraft			X		X	X	X		
Regional aircraft <19 pax		X			X		X	X	X
Narrow body 48-78 pax				X		X			
Narrow body >88 pax	X		X						
Regional GA airport					X		X		
(Regional) hub airport	X	X	X	X		X	X		X

Table 4.1: Literature review overview

4.2. Conclusions and research gap

From reviewing the literature in the field of electric aviation and its impact on airport infrastructure it is clear that it is a new field of research for which not many researches have been published. Discussing the works showed that a majority of the studies developed charging schedules and utilized optimization techniques. Most of the works also focused on determining the optimal charging infrastructure of airports. Reviewing the works also showed that different assumptions regarding charging procedures, objectives and applications have been considered by the studies. Furthermore, it can be concluded that mixed-integer linear programming is dominant as methodology and applied to most of the researches in this research field.

Looking at compatibility of the studies to the project of this MSc, the researches of Mitici et al. and Trainelli et al. (the ARES method) are the ones most compatible. This is because these researches provide the optimal number and type of chargers together with detailed recharging schedules while the total costs are minimized. Less compatible is the research of Justin et al. (2020) since this research only considers battery swap as main charging procedure which will not be considered in the research for RTHA, for which plug-in charge will be considered as charging procedure. Also, their research considered a network of airports for which for each airport the model is run, while for this project only one airport will be considered. However, Justin et al. did mention two alternative options in case the battery recharge schedule was not feasible for a certain number of batteries and chargers for the batteries, namely either relaxing the infrastructure constraint and thus adding more batteries/chargers or the relaxation of the flight schedule constraint in order to allow for delayed flights. Even tough this relaxation of the constraint was not applied in their research since disrupting the flight schedule was not allowed in their research, relaxing the flight schedule constraint is a useful comment which might be applicable to this research project for which RTHA would like to investigate the effect of slightly deviating from the flight schedule. Then, the research of Hou et al. (2021) focused on finding an optimal schedule which resulted in peak shaving and minimization of the number of displacements to the flight schedule. As mentioned, RTHA would like to know the effects of allowing deviations from the flight schedule, however this will not be the major goal of this project and thus extending a flight reschedule algorithm as proposed by Hou et al. to the project will not be needed. Furthermore, the work of Guo et al. (2020) does not extend well to the goals of this project since no generation of an optimal recharging schedule was considered. However, it is in fact the only research which considers an energy storage system as an additional power source for the charging of batteries. Also, the research solved for five different scenarios considering different electric aviation uptake scenarios. Since RTHA would like to discover the effects of a mobile energy storage system and implement different future scenarios to the research, looking at the research of Guo et al. can be used as an inspiration. The researches of Alfredsson et al. (2022) and Doctor et al. (2022) both did not consider optimizing for a charge schedule, but they both did consider only plug-in charging as a charging procedure which compares to the focus of the project for RTHA.

Concluding, some researches compare better to the project at hand than others, however lessons and ideas for modelling can be learned from all of them. There is not one of the works which is perfectly compatible to this MSc project. Looking at the studies, several research gaps can be identified from which research opportunities present themselves. For example, none of the researches considered the investment costs related to increasing the grid infrastructure capacity. For Rotterdam the Hague Airport it is important that the total expenditures are given which do include the investment cost required for upgrading the electrical infrastructure and thus not only considering the procurement of the chargers as investment cost. Furthermore, modelling a mobile charging truck as a charging option will be a contribution of this project which has not been done by the researches discussed and is to the author's knowledge the first research which discovers the effect of this alternative charging option for electric aircraft charging. Additionally, none of the researches compared a centralized charging layout with a decentralized charging layout. Performing the research for Rotterdam the Hague Airport is a special case in itself, since the airport has a rather exceptional operational profile in which all aviation segments are included. This includes that at various locations charging infrastructure will be required. Therefore, it is important to investigate the spatial aspects of implementing the charging infrastructure as well, which has not been done by any of the other researches. Another contribution of this project is investigating what will be potential future uptakes of electric aviation for different aviation segments (flight clubs, general aviation, business aviation and commercial aviation). Summarizing, the research gaps and the contributions of this project can be listed as follows:

- Modelling a mobile energy storage system (mobile truck) for the charging of electric aircraft
- Modelling for different electric aircraft charging locations, analysing the cost and benefits of centralized and decentralized charging layout configurations
- Including the investment cost of increasing grid infrastructure capacity
- Modelling for a regional airport which includes both flight lesson movements, other recreational general aviation movements and business/commercial flight movements

5

Literature study on electric vehicle charging scheduling

As discussed in subsection 3.3.1 one of the requirements of Rotterdam the Hague airport for this project is that an optimal recharging schedule should be provided. The literature study on the previous works (discussed in chapter 4) showed that various studies focused on determining an optimal charging schedule for the electric/hybrid electric aircraft. Additionally, in order to get the broadest view of the methods used in generating such charging schedules, also a literature review will be performed in the field of electric vehicle charging schedule. Which is presented in this chapter. An introduction to electric vehicle charging will be given in section 5.1. Different vehicle charging approaches will be also discussed in that section. Then, in section 5.2 the objectives and optimization methods in the field of electric vehicle charging scheduling will be given. Lastly, section 5.3 serves as a conclusion of the findings of the literature review presented in this chapter.

5.1. Introduction into electric vehicle charging

Electric vehicles (EV) have been introduced as alternatives to vehicles with internal combustion engines and their popularity has been increasing over the last years and it is expected that the number of EVs continue to grow rapidly the coming years. However, uncoordinated charging of these vehicles can result in severe problems for the electricity grid (Mukherjee and Gupta, 2014). Therefore, the need for solving the charge scheduling problems of EVs has grown and received increasing attention over the last years. The approaches and methods used in studies solving this problem will be discussed. The studies will be classified based on different characteristics.

The electric vehicle charging problem has a set of EVs, grid, users and aggregator parameters as input and outputs the charging schedule (start and end times of charging for all EVs in the set)(Mukherjee and Gupta, 2014). An aggregator has the function of acting as a mediator between the electricity users/customers and the system operator, ensuring mutual benefits for the electric vehicle owner and the power system (Sarker et al., 2015). The EV charging problem is an optimization problem in which different user, grid or aggregator parameters (or a mix of them) are optimized and subject to different constraints. A lot of studies have been presented in previous years considering this problem, even tough the problems have the same basis, there is a wide variation in terms of the parameters, constraints and methodology employed. First, the studies will be discussed based on different charging approaches. These include centralized versus decentralized charging control, unidirectional versus bidirectional power flow, static versus mobility aware charging, and integration of renewable energy sources. Then in section 5.2, various objectives utilized by the studies will be presented together with the used optimization methods.

5.1.1. Centralized versus decentralized charging control

The coordinated EV charging operation can be performed in two ways, namely using a centralized framework or a decentralized (distributed) framework (Amin et al., 2020). In a centralized charging control, the charging scheduling is done centrally at the aggregator which collects information from the EVs. The vehicles communicate information about their battery's state of charge, the maximum capacity of the batteries and charge rate to the aggregator. Then, based on the information collected from all EVs, the aggregator executes an optimization routine from which the charging schedule is generated ensuring that the energy requirements from all EVs are met (Mukherjee and Gupta, 2014). The computational complexity of this approach is higher since it involves large volumes of data (Amin et al., 2020). In contrary, in a decentralized approach the decisions about charging are distributed among individual EV customers. This approach empowers the customers to make the decision about the charging, however this might not guarantee the optimal solution. The centralized control has the ability of calculating the optimal schedule based on all the information that is available to it. In terms of scalability, the decentralized control is preferred, the penetration of a large number of vehicles is allowed (Mukherjee and Gupta, 2014). However, the lack of complete information at EV make the charging schedule attained suboptimal.

5.1.2. Unidirectional versus Bidirectional power flow

In unidirectional power flow models, the model considers that the power flow only flows from the grid to the electric vehicles while charging, also referred to as Grid to Vehicle (G2V) charging. In bidirectional power flow the flow is possible in both directions, also called Vehicle to Grid (V2G). However, simultaneous charging and discharging of the EV batteries is not allowed. The bidirectional flow has the advantage of providing more flexibility in the charging/discharging than the unidirectional model. Vehicle to Grid allows the electric vehicle to push back power to the grid and is thus able to balance variations in energy consumption. In fact, the batteries in this concept are used as energy storage systems. With the rise of electric vehicles and the challenges questioned with the impact to the grid, the concept of V2G is considered to enable the electric vehicles to become part of the solution and minimize strains on the power infrastructure.

The bidirectional/V2G power flow has received attention in many studies in the EV charging literature. Also, considering the traditional infrastructure layout, a lot of models focused on the unidirectional flow. There are also studies such as the study of Amin et al. (2020) which focused on the unidirectional flow (G2V) but concluded that for future work they would consider V2G characteristics. Regarding the electric aircraft charging literature, the study of Guo et al. (2020) introduced the novel concept of Aviation to Grid and thus was to their knowledge the first study in which A2G (similar to V2G) was considered when studying the charging of electric aircraft. In fact, the world's first standard and approved electric airplane charging station, SKYCHARGE, includes smart grid functionalities and enables vehicle to grid (Pipistrel, 2021). Concluding, the concept of V2G has also been introduced for the charging of electric aircraft.

5.1.3. Static versus mobility aware charging

In the review of Mukherjee and Gupta (2014) a distinction has been made in the literature considering static and mobility aware charging. In static charging a charging scenario in which the mobility of an EV is ignored is considered. The EV is modelled as a stationary load and do not include temporal properties related to the EVs mobility (Mukherjee and Gupta, 2014). Mobility aware charging on the other hand, considers the different mobility aspects of the EV such as the arrival and departure times at a charging station, trip history and unplanned departures of EV (Mukherjee and Gupta, 2014).

Taking into consideration the mobility aspects of the EV makes the problem more realistic. Charging request can be known before hand based on the expected arrival and departure times. Also, the effect of unplanned departures on the grid can be analysed. However, the increased flexibility of the mobility awareness concept requires a more complex problem formulation (Mukherjee and Gupta, 2014). In contrast, static charging results in a more simple formulation, and authors have utilized this concept to investigate the effect of other parameters on the grid. Both concepts have received considerable attention in the literature, as explained extensively in the review of Mukherjee and Gupta (2014).

5.1.4. Integration of renewable energy sources (RESs)

Additionally, the literature includes the integration of renewable energy sources in their electric vehicle charging scheduling problems. In the supply side, RESs such as wind and solar power have the potential of reducing emissions in the energy sector. However, these solutions are dependent on climatic variations which make the power generation from RESs highly stochastic (Mukherjee and Gupta, 2014). In the demand side, next generation of electric vehicles can reduce the the CO2 emissions (Saber and Venayagamoorthy, 2011). EVs with the ability of V2G can be integrated with RESs and reduce emissions. Therefore, charge schedule algorithms which can handle the integration of RESs are important. However, integration of RESs makes the problem more complex due to the uncertainty surrounding the power supply from these sources (Mukherjee and Gupta, 2014). There are several works in the literature which considered the integration of RESs specifically, for which the literature review of Mukherjee and Gupta presented the recent works in the EV scheduling up to that time. Furthermore, in the literature of electric aviation and the impact on airport infrastructure, the recent work of Guo et al., 2020 (2020) included using the power generated from airport-based solar photovoltaic system to charge the batteries and thus also in this field of research the use of RESs received attention.

5.2. Overview of objectives and methods applied in EV charging scheduling

The objectives used in the charge scheduling problem of electric vehicles are discussed in subsection 5.2.1. The methods used in this literature field are given in subsection 5.2.2.

5.2.1. Objectives used in charge schedule optimization

Various objectives have been used in the charge scheduling problem, depending on the goals of scheduling. The electric vehicle owners are concerned with the battery charging and attaining the desired SOC at the time of departure, while on the other hand the grid operator's focus is to maintain the grid's operational efficiency (Amin et al., 2020). Some researches focused on optimizing the grid benefits such as, minimizing financial cost of power supply, minimizing operational grid cost (including cost of hydro and wind power), maximizing profits of wind and thermal plants while minimizing energy trade risks. Other works focused on optimizing the electric vehicle benefits such as, minimizing charging costs, maximization of SOC of the EV batteries and maximizing user convenience. There are also works which combined optimizing grid and EV side benefits. The reviews of Amin et al. (2020) and Mukherjee and Gupta (2014) both give an extensive overview of the objectives used in the electric vehicle scheduling literature.

5.2.2. Methods used in charge schedule optimization

Different formulations of the EV charging schedule problem have been formulated and a wide variety of optimization techniques have been used to solve them. The review of Amin et al. (2020) is one of the reviews which did a comprehensive review on EV charging scheduling optimization (specifically under dynamic pricing schemes). Their review showed that classical, mathematical and intelligence based optimization techniques have been used to solve the EV charging optimization problem. A brief overview of various optimization methods used to solve for the EV charging scheduling problem will be given as follows:

Convex optimization

Convex optimization for electric vehicle charging scheme optimization has been discussed in the researches of Sortomme et al. (2010), Fan (2012), Taheri et al. (2013), Soltani et al. (2014), Crow and Maigha (2016), Martinenas et al. (2014), and Misra et al. (2014). For convex optimization, the solving method is similar to least square or linear programming (linear programming utilized in He et al., 2012; Sortomme and El-Sharkawi, 2011a, 2011b). After the problem is made convex it can be solved easily. However, the main limitation of this approach is the difficulty of formulating the problem as the convex optimization problem (Amjad et al., 2018). Mixed Integer Nonlinear Programming (MINP) is a non-convex optimization type. This type of optimization with Real Time Pricing (RTP) and Usage Based Pricing (UDP) reduces voltage irregularities and overloading of the distribution transformer (Korolko and Sahinoglu, 2015; P. Xu et al., 2017). Also, mixed integer stochastic optimization (Al-Awami and

Sortomme, 2011; Khodayar et al., 2012) and mixed integer linear programming (Jin et al., 2013; Melendez et al., 2020; Mirhoseini and Ghaffarzadeh, 2020) are also techniques considered in the literature of EV charge scheduling.

A mixed integer linear programming optimization model was also utilized in the work of Buitelaar (2022). Buitelaar developed an optimization model for finding the most cost-effective electric infrastructure as well as the optimal charging schedule of electric trucks for a distribution center. Renewable energy sources were also included and the sizing of these sources together with battery storage sizing were part of the optimization.

Dynamic programming

Dynamic programming can also be used for the optimal charging of electric vehicles, which has been done by various researches (Beaude et al., 2013; Clement-Nyns et al., 2009; Feng et al., 2013; Han et al., 2010; Y. Xu and Pan, 2012). In dynamic programming, the optimization problem is divided in different sub-problems which are solved and their solution is stored in a memory (Amjad et al., 2018). Problems which consist of various overlapping sub-problems and optimal substructures can be solved using dynamic programming.

Quadratic programming

In quadratic programming a quadratic function is generally optimized by considering linear constraints on its variables (Amjad et al., 2018). Solving the EV charging scheduling problem with quadratic programming has been done by the researches of Shrestha and Chew (2007), Clement-Nyns et al. (2009), Vandael et al. (2010) and Cai et al. (2013).

Game theoretic approach

The studies of C. Wu et al. (2011), Ma et al. (2010), Unda et al. (2014) and Sheikhi et al. (2013) are examples of studies which included a game theoretic approach for solving the EV charge schedule optimization problem. In game theory the logic is based on the cooperation and conflict of the participants, so in most applications it deals with the interaction of a group of people (Amjad et al., 2018). Depending on the interaction, two groups of game theory can be found in the literature, the cooperative and non-cooperative game theory.

Multi-agent systems

A multi-agent system (MAS) has been designed in the work of Vandael et al. (2010), to provide solutions for demand side management of plug-in hybrid electric vehicles (PHEVs). This research mentioned that in several research studies, multi agent systems were identified as the key technology in the Smart Grid future. Unda et al. (2014) also utilized a multi-agent system approach and presented an agent based control system which manages the battery charging of EV in power distribution networks. By the study of McArthur et al. (2007), distributed control has been identified to be one of the most promising applications of MAS in power system applications. With the main benefits of MAS being, the flexibility, fault tolerance, extensibility, open architectures and distribution (Unda et al., 2014). The research of Unda et al. integrated a game theoretic approach in their multi-agent system.

Fuzzy logic

Then, fuzzy logic for solving the optimization problem of EV charging is another techniques used in several studies (Boglou et al., 2020; J. Chen et al., 2017; Q. Chen et al., 2017; Rahman et al., 2016; Zakariazadeh et al., 2014). In contrary to Boolean logic in which there are only two states, 0 and 1, fuzzy logic provides the degree of partial truth instead of 0 and 1 (Amin et al., 2020). Fuzzy logic is used to test the degree of truth by combining many valued logics between 0 and 1. Fuzzy logic is also considered to be the infinite-valued logic for finding the optimal solution to the optimization problem (Amin et al., 2020).

Heuristics

Some heuristic methods were also used for solving the EV charging problem. Different heuristics methods were presented and utilized in the researches of Sortomme and El-Sharkawi (2010), D. Wu et al. (2011), Cao et al. (2011) and Mierau et al.(2012).

Particle Swarm Optimization (PSO)

The Particle Swarm Optimization technique has been applied to various studies discussing the EVs charging optimization (Hajforoosh et al., 2015, 2016; Moon and Kim, 2017; Saber and Venayagamoorthy, 2011; Savari et al., 2019; Yin et al., 2015). PSO is a stochastic metaheuristic method motivated by the phenomena of bird flocking and fish schooling. A global solutions are searched, starting with a random solution population and updating them until a final solution is attained (Amin et al., 2020). The research of Moon and Kim (2017) used coordinated aggregated particle swarm optimization (CAPSO) in order to minimize undesirable peaks and transformer overloading under variable charging rate. Another swarm intelligence (SI) technique used for determining the optimal charging schedule of EVs is the Ant Colony optimization strategy utilized in the research of Joo and Lim (2018).

Genetic algorithms

The Genetic Algorithm (GA) was also utilized in various studies debating optimal EV charging (Alonso et al., 2014; Huang et al., 2006; Lee et al., 2012; Mehboob et al., 2014; Srithapon et al., 2020; Yang et al., 2015). GA is one of the population-based metaheuristic techniques and the algorithm is bio-inspired in which searching the global optimal is performed by selection, recombination, and mutation process (Amin et al., 2020). Compared to other algorithms, the GA is the most robust in seeking the optimized solution (Amjad et al., 2018).

Cost-benefit analysis

Besides the mathematical modelling techniques described, some of the researches in electric vehicle charging involved determining the most cost-effective solution for which they included a cost-benefit analysis. One of these studies is the work of Ferguson et al. (2018) in which a cost-benefit analysis was performed in order to determine the optimal number of charging stations required for the charging of electric vehicles. Buitelaar (2022) conducted a cost-benefit analysis to see to what extent the cost and benefits of investing in renewable infrastructural components weighted up against buying electricity from the grid. Furthermore, a cost-benefit analysis was included in a multi-year hybrid planning method for implementation of smart charging strategies for electric plug in vehicles in the research of Mehta et al. (2017). They mentioned that the best course of action in order to make a decision for charging strategy was to conduct a cost-benefit analysis. Another research which focused on comparing two charging strategies was the work of Veldman and Verzijlbergh (2014). A cost-benefit analysis was included in this research to compare the two strategies, one for minimization of charging costs and the other for minimization network peak load.

Concluding, the importance of including a cost-benefit analysis is recognised to be important in the field of electric vehicle charging problems and it received attention in more and more researches over the years (Luo et al., 2013). The cost-benefit analysis in the above mentioned researches generally included generating results and graphs for different charging strategies (Mehta et al., 2017; Veldman and Verzijlbergh, 2014) and or scenarios (Buitelaar, 2022; Ferguson et al., 2018) and comparing these results.

5.3. Conclusion

Concluding, various objectives and methods have been used in solving the electric vehicle charging scheme problem. The problem is mostly formulated as a multi-objective problem and mostly treated as a real time optimization problem which requires a quick solution (Amin et al., 2020). For the conventional optimization techniques, even tough most work consider these techniques since they have easy implementation and low computational costs, it is hard to give precise solutions quickly. On the other hand, computational intelligence techniques (such as heuristics, particle swarm optimization and genetic algorithms) are more flexible to solve for multi-dimensional solution spaces which include non-linear constraints, however these techniques are computationally the more expensive choice (Amin et al., 2020). Thus, both conventional and intelligent techniques come with their own advantages and disadvantages. The relevant techniques mentioned in this chapter will be presented in more detail in the proceeding chapter 6. Furthermore, including a cost-benefit analysis has been done by various electric vehicle charging related researches for which the costs and benefits of charging strategies and investment considerations were compared.

In the next chapter, a specific type of optimization problem will be presented, namely scheduling theory. Also, an overview of the most common optimization techniques used in the literature will be given, specifically considering the methods used in the previous works of electric aviation charging infrastructure and the works on electric vehicle charging scheduling as discussed in this chapter.

6

Literature study Mathematics: Scheduling Theory and modelling techniques

In the previous sections, various modelling techniques have been mentioned to solve for electric vehicle scheduling problems and infrastructural sizing of electric aircraft problems. In this chapter the methods will be discussed in more details, such that the functions of the methods becomes known, as well as the advantages and disadvantages. Furthermore, a specific optimization problem which has high relevance to the project will be discussed, namely scheduling problems. Discussing the relevance of scheduling theory and the application of this theory will be presented first in section 6.1. Then, in section 6.2 the review on the methods discussed in previous sections will be given, which also present the most generally used methods used in scheduling theory.

6.1. Scheduling theory

From the literature review in the field of electric aviation charging problems (see chapter 4) and the studies in the field of electric vehicle charging (see chapter 5), it was noted that most of these problems involved generating optimal charging schedules. These schedules were in some of the studies used to determine optimal infrastructure sizing or in other studies used to for example minimize the peak demand from the grid. The goal in these studies was to determine the optimal allocation of for example the aircraft to chargers but also consider the optimal start and duration times (e.g. the schedule). Generating schedules and optimally allocating resources to tasks closely relates to the theory of scheduling.

Scheduling is a decision making process which is regularly employed in many industries. Scheduling deals with allocating resources to tasks over given time periods with the goal of optimizing one or more objectives (Pinedo, 2012). The resources and tasks can take many different forms, the resources may in the field of aviation be; runways at an airports, airport gates, flight crew, baggage handling vehicles, and so on. Tasks may include the take-offs and landings, maintenance jobs or turn around processes. Each task can have a certain priority level, certain amount of time to be completed or can be available only at a specific time window (Pinedo, 2012). Objectives can also take different forms, looking at the objectives used in the reviewed literature, some objectives focused on minimization of total costs, minimization of peak energy demand electricity grid, minimization of displacements from flight schedule, minimization of operational impacts and so on.

Scheduling theory is thus concerned with optimal allocation of resources to tasks over time, with the objective of optimizing one or more performances, which is looking back on the literature review sections closely related to what the researches have done. The tasks for this project involve the charging of the aircraft during the turn around and the resources will be chargers. With the objective of minimizing total costs which include investment and operational costs involved with the charging procedure of electric aircraft.

6.1.1. Notation and framework of scheduling theory

In this literature review, only a small part and a general overview of the scheduling theory can be discussed. Therefore, a framework will be given in which deterministic scheduling theory operates. Over the last sixty years a large amount of research effort has focused on deterministic scheduling (Pinedo, 2012). During these years a notation has evolved which captures the structure of many (but not all) of the deterministic scheduling models in the literature (Pinedo, 2012). A version of this notation will be presented (based on the explanation given in the work of Pinedo (2012).

First, it should be mentioned that a scheduling problem generally consists of three components, namely:

- A description of the set of resources
- A description of the set of tasks
- A description of the desired objective

Based on these three components, the scheduling problem is described with a triplet of characteristics: $\alpha|\beta|\gamma$. In which α presents information about the resources of the problem. The description and information of the tasks is presented in β and the objective function information is given by γ. The values of these fields present different considerations, the most relevant values will be discussed. The notations and values provided in this report are attained from the book of Pinedo (2012). The tasks and resources are in these notations labeled as jobs (j) and machines (i) respectively. The set of jobs is given by n and the number of machines is denoted by m. Each job has a processing time labeled as p_{ij} (and $p_j$if it is independent of the machines).

Some of the most relevant and possible values of the α/resources field are:

- Single Machine (1): only one machine is available, this is considered the simplest machine/resources environment
- Identical machines in parallel (P_m): There are m identical machines with exact same characteristics available. Each job j can be processed on any of the m machines.
- Machines in parallel with different speeds (Q_m): There are m machines with different speeds v_i available. Each job j can be processed by any of the machines, but the processing times for the jobs is given by $p_{ij} = p_j/v_i$
- Flow shop (F_m): m machines are available and each job has to be processed on each machine following a specific order

Then, the β field presents constraints and possibilities for the processing/tasks. This field may contain zero, one or multiple entries depending on the problem. Some of these values are:

- Release dates (r_j): Presents the release dates of the jobs. If a job has a release date, working on that job cannot start before r_j
- Due dates/deadlines (d_j): If a job has a due date, working on that job has to be finished before d_j. If not, a penalty can be included
- Preemptions ($prmp$): If preemption is allowed this implies that work on jobs may be interrupted to be resumed later

Finally, the field γ presents the to be optimized objective function. The following are examples of what can be considered in this field:

- Lateness related: The so called lateness of a job is given by the difference between the completion time of the job and the due date
- Completion time related: The completion time C_j gives the time at which the work on job j needs to be finished

Note: for more values in the different research fields and a more detailed overview of the framework, the author refers to the book of Pinedo (2012).

6.2. Modelling techniques

In this section an overview of the modelling techniques utilized in the literature of electric aircraft infrastructure requirement modelling and electric vehicle charging will be presented. It should be noted that the most relevant techniques used for solving scheduling problems will also be addressed. This is because scheduling theory is a specific optimization problem for which various optimization techniques such as networks, enumerate and heuristics have been used.

The literature review on the studies concerned with investigating the infrastructural requirements for the operation of electric aviation, showed that the majority of the studies utilized optimization techniques. There were however two studies (Alfredsson et al., 2022; Doctor et al., 2022 which used a combination of simulation and optimization (referred to as simulation optimization) to provide an optimal solution to their problems. In the research of Doctor et al., 2022 (2022) a discrete event simulation model with queuing was combined with metaheuristics in order to determine the optimal number of charging locations. This research focused on simulating the operation rather than finding an optimal charging schedule and/or considering impact of electrical consumption on the grid. Alfredsson et al. (2022) used simulation to follow the complete chain of movement of individual aircraft which involved the charging process. The charging process was later optimized by the use of a ”smart charging” heuristic.

The focus of this Msc project is providing insights into infrastructural requirements for electric aviation to RTHA which is still in an initial discovery phase with regard to this topic. Considering that the focus is more on a global level rather than already on an implementation level where there is a need for simulating the effects of electric aviation, it is decided that using simulation techniques is not applicable for the goal of this research. Therefore, simulation techniques will not be presented in this section and the further focus is on reviewing potential optimization techniques.

6.2.1. Optimization techniques

As discussed, the rather upcoming literature study field of electric aircraft charging operations and infrastructural sizing mainly focused on solving an optimization problem. Additionally, the electric vehicle charging problem is also an optimization problem. Generally, optimization problems can be used to find the best or a good enough solution to given problems. Optimization techniques are currently being utilized in different fields, from social problems, business, logistics and engineering. Solving an optimization problem involves modelling the problem by describing the variables in a mathematical form (Amiri et al., 2017). In this way, a mathematical model is constructed which represents the essence of the problem. To attain solutions to these problems, optimization techniques are required. According to the focus and properties of the techniques, there are different categorisations for the optimization algorithms, of which an overview is presented in Figure 6.1.

Deciding on a suitable optimization method is based mostly on whether the problem concerns linear constraint terms and bounds or non-linear terms and bounds (Sinha, 2020). Additionally, the classification of optimization methods is also based on the characteristics of the objective function. For example, in case of continuous and real number control values, the method is called continuous optimization. Similarly, for integers the problem is known as discrete optimization and when a combination of integers and continuous real number is made the optimization method is mixed integer (Sinha, 2020). Furthermore, the optimization method is referred to as quadratic, linear or non-linear in case the design variables are quadratic, linear or non-linear. Based on including or not including constraints the method is either a constrained optimization method or an unconstrained optimization method. Additionally, the problem is defined as a mono-objective optimisation problem if the optimisation is aimed to solve for a single objective. For optimising on a multi-objective basis the problem is considered as multi-objective. Many techniques are present which formulate the multi-objective in a single objective in order for it to be solved, these methods usually rely on generating a single weighted objective function (Luke, 2013). Lastly, the problem can be either static or dynamic based on whether or not the candidate solutions are tested at the end of each iteration (static) or the candidate solutions are tuned during the process (dynamic). Dynamic optimisation problems generally require more computational power.

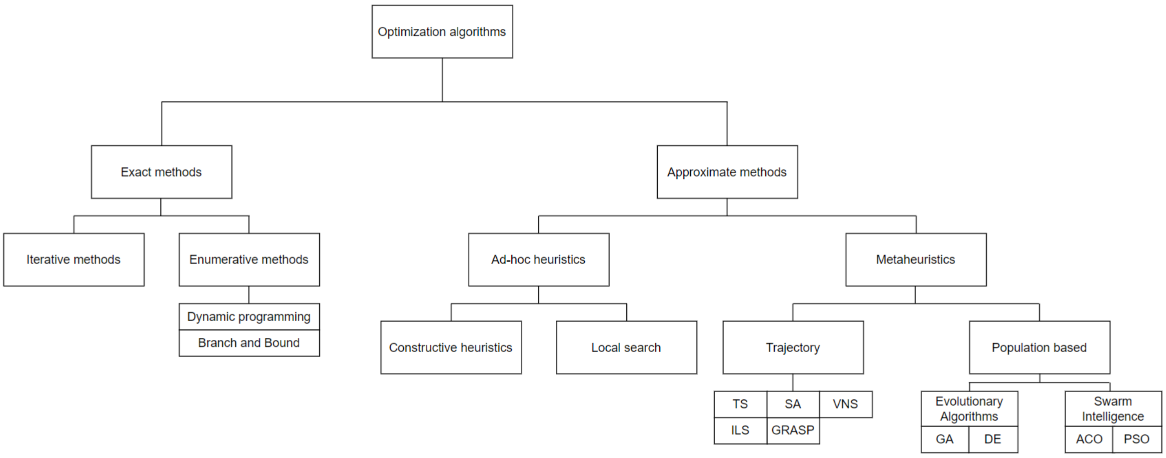


Figure 6.1: Overview of optimization techniques (combination of Amiri et al., 2017, De León-Aldaco et al., 2015 and El Alamin and Bouvry, 2010)

Exact methods

There are various algorithms which can be used to obtain optimal solutions for various kinds of optimization problems, including linear programming, nonlinear programming and integer programming models. These models guarantee that the optimal solution is found and therefore they are referred to as the exact methods. Different exact optimization methods will be discussed.

Linear Programming models

One of the optimization types is linear programming (LP) for which the models generally consist of an objective, constraints and a set of decision variables. The goal is that the values of the decision variables are chosen in such a way that the objective function is optimized while complying with constraints. These constraints are restrictions which limit the values of the decision variables (Hillier and Lieberman, 2010). Linear programming models must have a linear objective function which is subject to linear constraints (Hillier and Lieberman, 2010).

Linear programming models have emerged and changed over the years, especially with respect to restrictions on the decision variables. When the decision variables are restricted to integer values, the problem is an Integer Programming (IP) problem. If it is the case that some decision variables are restricted to have discrete (integer) values and others can remain continuous, the problem is said to be a Mixed Integer Programming (MIP) (Hillier and Lieberman, 2010). For the linear case, the model is a Mixed Integer Linear Programming (MILP) problem. Furthermore, in a Binary Integer Programming (BIP) model the decision variables are restricted to being binary values (0 or 1).

The advantage of using the mixed integer linear programming technique is that it is an exact method and finding an optimal solution is guaranteed (Evertse and Visser, 2017). However, on the other hand the solutions are often restricted to discrete values due to the binary or integer decision variables. This results in higher computational times, which makes the method less practical for larger problems. This is considered as one of the major limitations of this approach. The computational times can be reduced by limiting the complexity of the models. Generally, formulating the problem into a MILP is straight forward, some care should however be given in constructing the MILP since some formulation attributes can influence the effectiveness of the linear programming solver (Vielma, 2015). The MILP problem can be solved to optimality when solved by a solver (e.g. CPLEX, Gurobi), most MILP solvers are based on the branch and bound algorithms (Linderoth and Ralphs, 2005). The branch and bound technique will be discussed a little further in this section. The main components of the solvers generally involve a prepossessing phase, a cutting plane generation, sophisticated branching strategies, heuristics and parallel implementation (Linderoth and Lodi, 2010). Various solvers are available for which some are free non-commercial solvers (e.g. GLPK, BLIS) and others are more powerful solvers (e.g. Lindo, CPLEX, Gurobi) for which a license is required. For NP-hard problems the MILP problem can especially for the non-commercial solvers only solve for small to medium sized problems.

As seen from the review of the literature on the previous works presented in chapter 4 MILP was the dominant technique utilized by the studies for optimizing infrastructural and scheduling requirements for electric aviation at airports. The MILP problems where dominantly solved by the Gurobi solver (Hou et al., 2021; Mitici et al., 2022; Trainelli et al., 2021).

Dynamic programming
Dynamic programming is a mathematical technique useful for making interrelated decisions (Hillier and Lieberman, 2010). It presents a systematic procedure for giving the optimal combination of decisions. The name dynamic programming is by some considered slightly misleading and a better formulation would be ”recursive” or ”multistage” optimization because it interprets the optimization problem as multistage decision processes (Błażewicz et al., 2007). The problem is divided in different stages and at each stage a decision has to be made which impacts the decisions in later stages. The method breaks down the problem in several sub problems and then solve the sub stages one by one and the optimal solution to the sub problem is stored in a sort of memory. Unlike linear programming, there does not exist a standard mathematical formulation for the dynamic programming problem. Therefore, particular equations used must be designed to fit the situation. It should be noted that not all optimization problems can be described as a multistage decision process and that using this method is particularly not efficient for most integer programming problems (Hillier and Lieberman, 2010).

Branch and Bound
Another method which uses a kind of enumeration procedure for finding an optimal solution for a finite number of feasible solutions is the branch and bound technique (Hillier and Lieberman, 2010). This method has proven to be useful for finding optimal solutions to IP problems. As the name suggests, the branch and bound method consists of two procedures, namely branching and bounding. Branching is the procedure of dividing the larger problem into two or more sub-problems usually mutually exclusive (Błażewicz et al., 2007). The bounding process is involved with calculating a lower bound on the optimal solution value for each of the sub problems generated in the branching process. The branch and bound method can be summarized as an algorithm which iteratively builds a search tree of sub-problems (the branching procedure) and which is capable of determining the optimal solution. The main limitation of this procedure however is that for large-sized problems the tree becomes large and solving these problems requires large amount of computational effort.

Approximate methods
In contrary to the exact methods, there are some problems which are so complicated that it might not be possible to solve for an optimal solution (Hillier and Lieberman, 2010). Then, the approximate methods can be used to find a good feasible solution which is reasonably close to optimal. These methods sacrifice the guarantee that a optimal solution is found in favor of attaining a good satisfactory solution within a reasonable time. Heuristic methods can be used to find such solutions. Since heuristic methods are usually designed to fit for a specific problem and not for a variety of problems, they tend to be ad hoc in nature. Metaheuristics on the other hand, consist of a set of concepts which can be used to define heuristic methods which can be applied to a wide variety of different problems, in other words metaheuristics can be viewed as general algorithmic frameworks which can be applied to several different optimization problems without the need to make severe adaptions to fit a specific problem (Blum and Roli, 2003). Additionally, algorithms differ from each other in their search ability, there are local search algorithms leading to local optimum from which they do not have the ability to escape and there are global search algorithms which get the global optimum. Generally, for most cases metaheuristic algorithms are suitable to find the global optimum (Amiri et al., 2017).

As mentioned, metaheuristics can be used to find satisfactory solutions to a wide range of hard optimization problems without having to make deep adaptions to fit each problem. Hard optimization problems can be defined as ”problems that cannot be solved to optimality, or to any guaranteed bound, by any exact (deterministic) method within a ”reasonable” time limit” (Boussaïd et al., 2013). Most metaheuristics share common characteristics such as: they are nature inspired; they include stochastic components (involving random variables); they need several parameters to be fitted to the problem (Boussaïd et al., 2013). A metaheuristic will need to provide the right balance between exploration and exploitation, in order for it to be successful on a given optimization problem (Boussaïd et al., 2013). The terms exploration and exploitation are often also referred to as diversification and intensification respectively. Exploration (diversification) is the concept which identifies the regions with high quality solutions, while exploitation (intensification) provides the intensification of search in some promising areas. The balance between these two concepts is important to on one hand quickly identify regions within the research with high quality solutions and on the other hand to not waste too much time in regions where no high quality solutions can be found or which has already been explored (Blum and Roli, 2003).

As indicated by Figure 6.1, metaheuristics can be divided into two categories, namely trajectory and population based metaheuristics. The difference between these two is that in a trajectory based algorithm, a single agent is tracing a single path and iterations continue to attain the optimal solution, while in a population based algorithm multiple agents are tracing out multiple paths. The trajectory based category is often also referred to as the single-solution based metaheuristics. "Roughly speaking, basic single-solution based metaheuristics are more exploitation oriented whereas basic population-based metaheuristics are more exploration oriented" (Boussaïd et al., 2013). The population based metaheuristics can generally be classified into evolutionary and swarm intelligence algorithms.

The purpose of this section is to present a global overview of the different main metaheuristics used in the previously reviewed relevant literature (see chapter 4 and chapter 5). The trajectory (single-solution) based metaheuristics will be discussed firstly, followed by the presentation of the main population based metaheuristics. Simulated annealing and Tabu Search have been identified as optimization methods used in scheduling problems and therefore, even tough they have not been applied to problems in the literature reviews of electric aircraft and EV charging, these methods will be briefly discussed below. Furthermore, it should be noted that not a complete overview of all metaheuristic methods is given since only the methods considered in the relevant literature to this project will be addressed. Therefore, looking at Figure 6.1, the algorithms of Variable Negihborhood Search (VNS), Iterated Local Search (ILS), Greedy Randomized Adaptive Search Procedure (GRASP) and Differential Evolution (DE) are not included in the discussion of the methods below.

Simulated Annealing

Simulated annealing (SA) is often said to be the oldest metaheuristic and it was surely the first method which included an explicit strategy to escape local minima (Blum and Roli, 2003). The algorithm was first introduced by Metropolis et al. (1953). The approach was later applied to deterministic optimization problems by Kirkpatrick et al. (1983). Simulated annealing is based on the physical annealing process in which an alloy is gradually cooled down such that a minimal energy state is achieved. The SA algorithm transposes this annealing process to a solution of an optimization problem, in which the objective function of the problem just like the energy of the material, is minimized, by the introduction of a fictitious temperature T, which represents a simple and controllable parameter of the algorithm (Boussaïd et al., 2013). The algorithms starts with the generation of an initial solution and initialising the temperature parameter T. At every iteration, a solution $s^{'}$ is selected randomly from the neighborhood $N(s)$ of the current solution s. Depending on the objective function and the temperature parameter T, it is determined whether or not the new solution $s^{'}$ will replace the current solution s. The objective functions are noted as $f(s^{'})$ and $f(s)$ for the new solution and current solution respectively. If the new solution generates a better outcome ($f(s^{'}) \leq f(s)$) the new solution is adapted. However, in some cases the new solution is also accepted even tough the solution does not yield a better outcome, this happens with a probability $p(T, f(s^{'}), f(s)) = \exp - \frac{f(s^{'}) - f(s)}{T})$. During the simulation, the parameter T is decreased, meaning that at the beginning of the search the probability that deteriorating moves are accepted is high and this gradually decreases during the search process. The exploratory characteristic of the algorithm can be tweaked by playing with the rate at which the temperature parameter is decreased.

Concluding, the SA algorithm can converge to a solution s even if a better solution $s^{'}$ has been met during the search process. Basic improvements of the SA algorithm consists of saving the best solution during the search process (Boussaïd et al., 2013). Simulated Annealing has been successfully applied to both continuous and discrete cases, however, it has been found too greedy or unable to solve for some combinatorial problems (Boussaïd et al., 2013). The main limitations of this algorithm include that the algorithm may require too much computational time (Fouskakis and Draper, 2002), tailored work is required for the constraints and fine tuning of the algorithm can be rather delicate (Busetti, 2003), and finding the optimal solution is not guaranteed.

Tabu search
Tabu search (TS) is a method introduced by Glover and Laguna (1998). The Tabu Search is a widely used algorithm which is based on common-sense ideas and designed to manage an embedded local search algorithm. Local search algorithms take potential solutions and check the immediate neighbors to see if the solution can be improved. These algorithms have the tendency of getting stuck in suboptimal regions. The TS algorithm uses the history of the search, in order to enable the search to escape from local minima and to implement an explorative strategy (Blum and Roli, 2003). Unlike the simulated annealing algorithm which does not utilize a memory, the TS algorithm is able to learn from the past. Every application of TS includes a local search procedure as basic ingredient from which the algorithm starts exploring neighbouring solution, of which the best solution is selected and this solution is stored on the tabu list. The tabu list records the previous encountered solutions (or the attributes of them) and forbids these solutions (or solutions containing one of the attributes) from being visited again. This list can be seen as a short term memory. This use of a memory is a distinctive feature of tabu search. Furthermore, the length of the tabu list determines the concentration of the research, and thus the length of the tabu list influences the behaviour of the TS algorithm. A shorter tabu list results in a smaller area of search space while a longer list forces the search to explore a larger region of the search space. Varying the length of the tabu list during the search leads to a more robust algorithm, like the Reactive Tabu Search Algorithm (Battiti and Tecchiolli, 1994).

Tabu search has predominantly been applied to combinatorial optimization problems. However, applying TS to continuous optimization problems has been proposed (Chelouah and Siarry, 2000; Cvijović and Klinowski, 1995; Glover, 1994). The main limitations of this method is that it results in a large number of iterations, large number of parameters to be determined and does not guarantee finding an optimal solution.

Genetic algorithms (GA)
The genetic algorithm (GA) is one of the most well-known and most used evolutionary computation techniques (Boussaïd et al., 2013). The GA is an algorithm based on concepts of evolutionary biology. The basic GA formulation is very generic and different aspects can be implemented to the problem: selection strategies, representation of solution, mutation operators and type of crossovers (Boussaïd et al., 2013). Concepts of mutation, selection and cross over are used to generate new populations. The crossovers involve (mostly) two individuals to be selected and exchange some of their parts together. Subsequently, the individuals are subject to mutations which introduce some randomness into the search and prevents the process from getting trapped into local optima. Disadvantages from the GA include that it is unknown what the optimum parameter settings should be (Davis, 1991), for complex problems great computational effort is required (Pirim et al., 2008), premature convergence (Malik and Wadhwa, 2014), and there is no guarantee that the optimal solution is found.

Particle Swarm Optimization (PSO)
Particle Swarm Optimization (PSO) is another one of the population based metaheuristics. It is a stochastic metaheuristic technique motivated by the phenomena of bird flocking (Boussaïd et al., 2013). The algorithm randomly instantiates autonomous particles/entities in a search space, for which each particle represents a solution. The particles fly around in a D-dimensional search space and all have a velocity, location and a memory which is used to remember the previous best position. Limitations of this algorithm concern premature convergence and the process getting trapped in local optima (Boussaïd et al., 2013). Since it is an approximate method, again finding the optimal solution is not guaranteed.

Ant colony optimization (ACO)
Another swarm intelligence based population metaheuristic is the Ant Colony Optimization (ACO) algorithm which is based on the behaviour of real ants. It is a algorithm which is employed to solve for difficult combinatorial optimisation problems. The algorithm reflects the behaviour of ants, when ants are searching for food they initially explore the area by performing a randomized walk (exploration) and relieving a chemical pheromone trail on the ground to mark a favorable path (exploitation). After some time, the shortest path between the nest of the ants and the food is found. The algorithm uses this behaviour and is searching for the minimum cost path in a graph. However, there are some limitations involved in this algorithm which besides not having the guarantee of finding an optimal solution, include that the time to convergence is uncertain and that the search is experimental (Selvi and Umarani, 2010).

6.2.2. Review and comparison of modeling techniques

Now that the most relevant modelling techniques for this project have been discussed, an overview is provided in Table 6.1 from which a comparison of the techniques can be made and can be used to decide on the modelling technique applicable to the project. The research proposal will be presented in the next chapter followed by the research methodology in chapter 8, in which the modelling technique will be selected.

Algorithm	**Description**	**Benefits**	**Limitations**
Mixed Integer Linear Programming (MILP)	Exact method	Guarantees finding optimal solution with the use of a solver	For solving large problems the computational effort is high, using a commercial solver provides the best performance
Dynamic programming	Exact method	Guarantees finding an optimal solution	Not all problems fit multistage decision process. Method proven not to be efficient for most integer programming problems (Hillier and Lieberman, 2010)
Branch and Bound	Exact method which iteratively builds a branching tree of sub problems	Solves for an optimal solution	For large problems the tree becomes very large and results in high computational effort
Simulated Annealing (SA)	A randomized local search algorithm	Achieves global optimal solutions and has the ability to incorporate many cost functions (Parvin et al., 2021)	Sensitive to input parameters and takes long time to find a near optimal solution (Parvin et al., 2021)
Tabu Search (TS)	Metaheuristic which includes a local search procedure, using a tabu list (memory) to learn from previous moves	Fast and flexible convergence speed and delivers good quality solutions (Parvin et al., 2021)	Large number of iterations and various parameters to be determined. Optimal solution not guaranteed
Genetic Algorithms (GA)	Algorithm based on evolutionary biology using concepts of selection, mutation and cross over tot determine solution	Easy implementation and performs a parallel search in different regions (Parvin et al., 2021)	Does not guarantee optimal solution, optimum parameter setting unknown (Davis, 1991), and has slow convergence speed resulting in great computational times for larger problems (Pirim et al., 2008). Also may include premature convergence (Malik and Wadhwa, 2014)
Particle Swarm Optimization (PSO)	Algorithm based on the behaviour of bird flocking	Simple execution, fast convergence speeds and high efficiency (Parvin et al., 2021)	Premature convergence, difficult to set initial design parameters, getting trapped in local optima and not guaranteeing optimal solution (Boussaïd et al., 2013; Parvin et al., 2021)
Ant Colony Optimization (ACO)	Algorithm based on the behaviour of ants	Adaptability and guaranteed convergence (Parvin et al., 2021)	Duration of convergence is uncertain and no guarantee of finding the optimal solution

Table 6.1: Modelling techniques overview

7

Research proposal

After an introduction to electric aviation and Rotterdam the Hague Airport was given in chapter 2, the impact of electric aviation on RTHA operations was amongst others discovered in chapter 3. In that chapter, also the airport requirements were set from which the model requirements evolved. Then, the current state of the art in the research field of electric aviation and its impact on airport operations and infrastructure was discovered in the literature review presented in chapter 4. It was found that the first study in this research field which was published in 2018, based their method on models in the electric vehicle charging field. Because the field of electric aviation has developed in recent years, an additional literature review was performed in the field of electric vehicle charging scheduling, presented in chapter 5. Based on the findings and modelling techniques used in these research fields, the scheduling theory was elaborated on in chapter 6. Additionally, the modelling techniques utilized in the literature were also discussed in more detail in this chapter. With study done into the topic of electric aviation together with its potential impacts on airports, the current state of the art in charging electric aircraft and a literature review of studies in relevant research fields, a research proposal can be presented.

This chapter presents the research proposal for this project. The proposal is specified through a research objective presented in section 7.1 and several research questions listed in section 7.2.

7.1. Problem statement and research objective

With the increasing need to mitigate global climate change, there is an increasing focus on transitioning to more sustainable forms of propulsion technologies for aircraft, of which electric propulsion is one. The adaption to (hybrid) electric aircraft however, is expected to have a considerable impact on the operations and infrastructures of airports. In the near future electric aircraft are expected to first make their entrance in the small and regional aviation segment, including pilot training's and general aviation. The commercial aviation segment and business aviation is expected to follow with the introduction of larger and longer range aircraft, like the Eviation Alice with a range of 815 kilometers and carrying 9 passengers. The focus of this research is on the future entrance and implementation of electric aircraft at regional airports, for which Rotterdam the Hague Airport is taken as case study. RTHA has a special operational profile, it is home to different operational profiles operating in the general, business and commercial aviation segment for which electric aviation will become reality to different extends and in different time frames. The recharging process of electric aircraft and especially the requirement that the charging process has to be completed within the regular TAT of aircraft, will pose high demands on the electricity grid. This is especially the case when the number of electric aircraft increases.

It is therefore that RTHA would like to ensure that they are sufficiently equipped to accommodate electric aviation. Therefore, it is the goal to discover what the infrastructural requirements of charging of electric aircraft will be. Considering the airport requirements stated in subsection 3.3.1, it is clear that it is the preference of RTHA to investigate the use of different concepts. Additionally, it is of high importance that different future scenarios will be considered such that a forward-looking decision can be made. This is especially important due to the uncertainty associated with identifying how electric aviation and the introduction of electric aircraft types will evolve.

In terms of operational scenarios, the use of a mobile energy storage system truck will be included as an alternative charging option in addition to direct grid-plug-in charging. Also, the effectiveness of a central charging location versus decentralized charging locations will be investigated. Both these implementations have not been addressed in any of the previous works in this research field so far and a model which accounts for these concepts will be developed. Last, it is desired that the scenarios as described above will also be modelled for a case in which deviating from the flight schedule is allowed. In conclusion, finding the optimal infrastructure sizing and layout for different future and operational scenarios will provide Rotterdam the Hague airport with a broad overview for the best strategy towards upgrading their infrastructure and accommodating electric aviation. For each scenario the number and types of chargers per location, the sizing of the energy storage systems and an optimal charging schedule are the desired outcomes.

Based on the problem statement described, the research objective is formulated as follows:

> *Design an optimization model which given a flight schedule, provides the optimal electric infrastructure composition in terms of number of chargers, sizing of fixed and mobile energy storage systems and optimal layout regarding a decentralized versus a centralized configuration, to accommodate electric aviation at regional airports*

7.2. Research questions

The main research question is formulated as follows:

> *What is the optimal electric infrastructure composition for a regional airport in support to various increasing demands of electric general and electric commercial aviation for the coming 15 years, considering the costs and benefits of a centralized, decentralized airport charging configuration and the operation of a mobile charging truck?*

In order to answer the main research question, several key questions have been established, each of them supported by several sub-questions.

1. Which input variables will be used for the aircraft fleet and charger types?
   (a) Which electric aircraft types are expected to enter the market and in which time frames?
   (b) What is the current state of the art in electric aircraft technology and what will be the aircraft characteristics of the aircraft types?
   (c) What is the current state of the art in charging?
   (d) What chargers will be modelled and to which aircraft types will these be compatible?
2. What will be the different sample scenarios?
   (a) What flight data can be obtained from Rotterdam the Hague Airport?
   (b) How can this flight data be used to generate flight schedules for electric aircraft operations?
   (c) Based on which criteria is a historic flight movement eligible to be replaced by an electric aircraft?
   (d) Which sample day/sample period will be modelled?
   (e) What are relevant scenarios and how will the expectations of future electric growth be incorporated?
   (f) What will be a relevant scenario which include new flight routes executed by electric aircraft which are thus not part of the historical flight schedules?
3. What are the costs included in the model and how can these be set up?
   (a) What will be the costs of investing in upgrading of the electricity grid infrastructure, for the different considered charging locations at the airport?
   (b) What are the acquiring costs for the different chargers?
   (c) What are the electricity prices for different times during the day?
   (d) How can the acquiring cost of an energy storage system and or mobile ESS truck be determined and what do these amount to?

    (e) What will be the investment cost of connecting the airport based solar panels to the electricity grid?

4. How will the optimisation model be constructed?
    (a) What will be the objective function?
    (b) What will be the constraints?
    (c) What will be the decision variables?
    (d) How can we allow the optimization to deviate from the flight schedule?
5. Based on a cost-benefit analysis and the results of the model, what will be the optimal configuration of charging locations, is a centralized or decentralized configuration more effective and cost efficient?
6. What will be the effect of including a (mobile) energy storage system as part of RTHA's charging infrastructure?
    (a) How can solar energy generated from the solar parks at the airport be used and stored in an energy storage system to charge the electric aircraft batteries? What will be the involved costs for connecting the solar panels to electricity grid of RTHA?
    (b) What will be the optimal sizing of the fixed and/or mobile energy storage system?
    (c) How can the use of a mobile truck and or energy storage system be implemented in the model?
7. What will be the effect of allowing deviations from the flight schedule and what is advised based on a cost-benefit analysis?
8. Based on a cost-benefit analysis, which sample day should be used as model input (for each model scenario)?
9. How do variations in the models input affect the outcomes of the model?
    (a) What is the effect of variations in the input costs of the model?
    (b) What if the procedure of selecting which aircraft and flight movements of 2022 are assumed to be replaced by electric aircraft, changes?
    (c) What will be the effect if the maximum grid capacity is lowered/increased?
10. With regard to the scope of this research, will it be relevant to take into consideration hybrid electric aircraft and if so, how will the obtained solutions change when hybrid electric aircraft are considered?
    (a) What is the current state of the art for hybrid electric aircraft types?
    (b) What will the concept of operation for charging and refueling of hybrid electric aircraft look like?
    (c) Is hybrid electric relevant to take into consideration in the scope of this research?
    (d) If yes to the previous question, what will be the changes to the mathematical model?
    (e) What (additional) infrastructure changes are expected when accounting for hybrid electric aircraft?
11. What conclusions can be drawn from the obtained results from the model and cost-benefit analyses?
    (a) How can the outcomes be best presented such that differences in the modelling scenarios are displayed clearly?
12. What recommendations can be made for a regional airport and in specific for RTHA in terms of upgrading and investing in their infrastructure to accommodate different uptake scenarios for electric aviation? What will be the optimal infrastructure layout for which there is a balance between investment costs and capacity?

8

Research methodology

In this chapter the research methodology used to fulfill the research objective and research questions presented in chapter 7 will be presented. Firstly, in section 8.1 the proposed modelling technique will be discussed. The scope of the research together with the assumptions is presented in section 8.2. After this, the model development representing the steps which will be taken during this MSc study are explained in section 8.3. Finally, section 8.4 discusses the to be performed analysis.

8.1. Modelling technique

From the research proposal presented in chapter 7 the problem of this project is clear and involves determining the optimal number of chargers and infrastructure layout given a flight schedule of electric aircraft. Keeping the goal of this project in mind and looking at the different modelling techniques discussed in section 6.2, a suitable modelling technique can and will be selected in this section.

As stated in the research objective, an optimization model which provides the optimal sizing and layout of the charging facility for electric aviation of Rotterdam the Hague Airport should be developed. In order to successfully fulfill this objective, selecting the appropriate optimization algorithm is essential. Considering the problem of this project an initial idea of the objective function, decision variables and output can be conceptualized. As stated by the research objective, the solution of the model should per location provide the number and type of chargers, the number and sizing of Energy Storage Systems (either a fixed or mobile concept) and the total costs which include the charging operational costs and the involved investment costs. Then, some of the decision variables in the model will for example include, the number of chargers of a certain type (integer value), the availability of a charger at a specific time (binary value), the charging power of charger at a specific time (real value) and the batteries state of charge (real value). Considering these decision variables it is clear that a mixture of Boolean, integer and real variables are involved. Furthermore, the objective will be linear and have the focus of minimization of total cost related to the charging procedure of electric aircraft, which include the operational cost of the charging process and the investment cost required to facilitate the charging process. Concluding, due to the linearity of the objective function (and constraints) and the mixture of decision variables, the problem considered is a Mixed Integer Linear Programming problem.

Looking at the techniques used in the literature field of charging electric aircraft (chapter 4), it was seen that a Mixed Integer Linear Programming was the dominant formulation of the problem. As discussed in section 6.2, MILP problems are solved using solvers and the majority of the problems in the literature were solved using the powerful Gurobi commercial solver. Furthermore, the review of modelling techniques presented in subsection 6.2.2 showed that using a Mixed Integer Linear Programming formulation guarantees finding the optimal solution, it is an effective method especially when the problem is not too large.

Considering the formulation of the model, the dominant technique used in the literature which proves the effectiveness of the MILP method for similar problems and that developing new techniques for solving the electric aircraft charging problem is not the goal of this project, the decision has been made to utilize mixed integer linear programming with a Gurobi solver as modelling technique for this project.

8.2. Research scope

In this section the assumptions that are made and will be made in this project are discussed in subsection 8.2.1. Note that these assumptions will be extended and might be slightly adapted during the development of the model. Furthermore, in subsection 8.2.2, the scenarios used in the project will be discussed, with specific focus on setting up the future scenarios.

8.2.1. Assumptions

General assumptions

- Full electric aircraft are considered, hybrid electric aircraft are not included as part of the main scope, but relevance will be touched upon by answering sub question number 9
- Only the charging demand of charging electric aircraft will be considered and thus not including the power demand of other airport processes (such as electric ground power units (eGPUs), electric busses, terminal power etc.)
- Rotterdam the Hague Airport is used as case study
- The flight data from 2022 of Rotterdam the Hague Airport will be used as data basis
- Investment costs of upgrading the electricity infrastructure will be tailored and based on the cost indication of RTHA's electricity provider
- The general aviation, business aviation and commercial aviation segments of RTHA are considered to include electric aircraft in their future operations, excluding the commercial narrow body aircraft operated by the airlines
- Assumptions will be made in setting up the different future scenarios of electric aviation uptakes (including assuming the aircraft characteristics and the number of movements of GA, BA and CA at RTHA)

Infrastructure assumptions

- Three locations are considered to be modelled as charging locations, these include the Juliet platform, the Vliegclub Rotterdam and the Rotterdamsche Aeroclub location (see locations 2, 3 and 4 in Figure 3.1 respectively)
- All modelled commercial and business aviation flight movements are assumed to be handled at the Juliet platform of JetAviation
- Restrictions on wingspan and MTOW of aircraft to the flight clubs are posed
- Restrictions will be included on the available number of electric aircraft stands/charging stands for each of the three locations

Aircraft/flight operation assumptions

- Single trips are assumed, thus the assumption is made that aircraft are charged at other airports and that the other airports also have sufficient charging infrastructure in place
- The energy consumption during flight will need to be included in order to determined the aircraft batteries state of charge upon arrival and the required SOC before takeoff. Assumptions and or equations will be used for the calculation of the energy consumption during flight
- Deviating from flight schedule is assumed to be allowed in some modelling scenarios

Charging procedure assumptions

- Battery swapping is not considered as charging option in this research, only plug-in charging is considered
- The assumption will be made that the charging duration reflects the total turn around time of an aircraft and that thus the other turn around processes are assumed to finish within this time
- Operations other than the charging procedure are not included in the model, e.g. taxiing, cleaning, (un)boarding passengers etc.
- Rather than assuming depleted batteries, the residual battery SOC will be assumed at the start of the charging process
- The required battery SOC for the next mission of the aircraft is the level to which the batteries are charged

- In order to better describe reality, a charging curve will be included which varies the charging rate during the charging procedure
- Mobile and fixed energy storage systems are included as additional charging options besides grid plug-in charging
- Power generated from airport based solar panels assumed to be used if cost-effective

8.2.2. Scenarios

Various scenarios will be considered in this project, including different future scenarios, the centralized vs decentralized scenario, the mobile energy storage system scenario and the deviating from flight schedule scenario. For the latter scenarios, thus excluding the future scenarios, the scenarios will result in different mathematical model settings, which will be discussed further on in subsection 8.3.2. Setting up the different future scenarios however, will involve making assumptions about the future and an indication of how these scenarios will be set up, is presented in subsection 8.3.1. In addition, to the scenarios which are based on the historical data of 2022, an additional scenario will be set up, which will consider other possible future flight movements rising due to the characteristics of electric aircraft. This will include, that there is a potential for new routes to be flown and setting up these scenarios will be done in cooperation with RTHA.

8.3. Model development

This section presents the main steps which will be taken for the model development of this project. Firstly, it will be mentioned what is required before the model can be developed in terms of input parameters, which is presented in subsection 8.3.1. Then, in subsection 8.3.2 an initial basic model will be discussed and described what will need to be added to this model in order to construct the final mathematical model. It should be noted that this is an initial draft of the modelling concept and that further development of the model is one of the main focuses of the proceeding master thesis phases. After the construction of a model, it is important that it gets verified and validated, the verification and validation process is discussed in subsection 8.3.3.

8.3.1. Setting up and gathering model input

Before the model can be developed and results can be attained, first the model inputs should be set. In this subsection, the different inputs required for the model will be discussed and it will be described how the values of the inputs will be acquired.

In general, the following steps need to be taken before the model can be developed:

- Setting up and collecting the input variables for operation and investment costs
- Setting up charger characteristics
- Setting up the electric aircraft characteristics for different aircraft types
- Setting up different scenarios presenting different expected uptakes for electric aviation
- Generating and collecting the flight schedule for case scenario based on RTHA 2022 flight data and the to be modelled scenario

Costs

The costs involved in the model for this project can be distinguished as operational or investment costs. Investment costs include the investment associated with upgrading the electric infrastructure capacity, investment in chargers and energy storage systems. On the other hand, the operational costs include the cost associated with the charging procedure of the batteries of the aircraft, for which the electricity prices will be dominant and for the ESSs a cost will be included which accounts for the service life up to replacement of the batteries.

The investment costs for the infrastructure will include determining what will be the cost for upgrading the electricity grid at the three different locations of RTHA. These costs will be obtained from internal contact with the airport and their net service provider, Stedin. It is important, to obtain realistic values for this group of investment cost, since it will greatly influence the decision regarding a decentralized or centralized charging layout configuration. Additionally, in order to include power generated by the airport based solar panels as power source for the charging of the electric aircraft, the solar panels should become connected to the electricity grid of the airport which will include investment costs. These costs will also be requested from Stedin or another infrastructure partner of RTHA.

Then, the investment costs of the chargers and the energy storage systems(fixed and mobile), will be decided on based on a combination of prices of existing chargers/ESS, internal discussions with RTHA partners, literature review and looking at current automotive industry standards.

The electricity prices will be obtained from RTHA/Stedin which include varying electricity prices during the day and night. Also the peak electricity price will be requested. It should be noted, that in the model the electricity price will reflect the mode of charging, for which at a fixed charger the electricity price corresponds to the price at that time of day, while for connecting with an energy storage system, the electricity price reflects the price at which the batteries of these systems have been charged before. Lastly, for the price reflecting the degrading of the batteries of the mobile truck and the fixed ESS, the literature will be investigated.

Generating flight schedule and future scenarios

For the generation of the flight schedule, different steps are involved. First, the flight movement data from 2022 will need to be obtained from RTHA. This will include determining a case day/period which will be studied. Then, the flight schedule used as input for the model is a result of the scenario which is considered. An indication of the generation of the future scenarios and how the values used in the scenario will be set, will be discussed.

Three different scenarios will be used, which present three different time frames, namely 2025, 2030 and 2035. Included in each of these three scenarios will be three sub scenarios, presenting different levels of uptakes in electric aviation. These levels will indicate a low, medium or high uptake. Table 8.1 below gives an indication of the future scenarios. It should be noted that the percentages and aircraft types stated in this table are not representative for what will be used in the model, since these values are just randomly chosen and not yet based on any future expectations. The percentages in the table indicate the percentage of flight movements in a specific aviation segment (general (GA), business (BA) or commercial (CA)) in the year 2022 which will be replaced by electric aircraft. Furthermore, aircraft classes will be used to indicate the electric aircraft characteristics presenting the AC types which are expected to enter the market in the coming years.

Setting up these scenarios is an important part of the project and deciding on the aircraft classes and the percentages will be done with caution. Deciding on these will be based as much as possible on scientific and market expectations regarding electric aviation uptake in the coming years. This will involve combining discussions and views of innovation partners of RTHA, researchers of the TU Delft and discovering the designs of electric aircraft manufacturers. Determining the aircraft classes and the characteristics of these aircraft in terms of battery capacity, MTOW, wingspan, etc will thus be done based on combining scientific and electric aviation market expectations. Also, the characteristics of the charger types considered will be decided on in a same matter.

	2025			2030			2035		
	AC class A			AC class A & B			AC class A, B & C		
	GA	BA	CA	GA	BA	CA	GA	BA	CA
Low	10 %	0 %	0 %	40 %	10 %	2 %	80 %	30 %	10 %
Medium	20 %	2 %	0 %	60 %	15 %	4 %	90 %	40 %	20 %
High	40 %	5 %	0 %	80 %	25 %	8 %	100 %	60 %	25 %

Table 8.1: Future scenarios indication

8.3.2. Model construction

In this subsection the model construction plan will be described. In developing a model, it is a good approach to start with constructing a very simple version and build and expand this basic model to move towards more elaborate models (Hillier and Lieberman, 2010). Therefore, first a simple basic model will be designed from which in every step more complexity will be added in order to eventually attain the final mathematical model which describes the complexity of the real problem.

An initial basic model has been designed which is derived from a simplistic gate capacity model. Note that notations might be changed along the way. The model below will optimize for connecting electric aircraft i to charger type j for a set of all electric aircraft I and considering a set of charger types J. The objective is as follows:

$$minimize: \sum_{i\in I, j\in J} c_{ij}x_{ij} + c_j y_j$$

Subject to the following constraints:

$$\sum_{j\in J} a_{ij}x_{ij} = 1, i \in I \tag{8.1}$$

$$\sum_{i\in I} a_{it}x_{ij} - y_j \leq 0, j \in J, t \in T \tag{8.2}$$

With the following decision variables and parameters:

- c_{ij} = cost of charging aircraft i with charger type j [€]
- c_j = procurement cost of charger type j [€]
- a_{ij} = compatibility of aircraft i with charger type j (0,1)
- a_{it} = occupancy of aircraft i at time t (0,1)
- y_j = number of chargers of type j

As explained, the model presented above is a basic model which is developed to form a basis from which construction of the final model can be started. It might be that later on, while constructing the model, the basic model is changed or made more aligned with the models used in the literature or models from scheduling theory. However, it is a good basis to start from and it can be used to identify which steps will need to be taken next.

The displayed model is concerned with a basic concept for the charging operation. The aircraft is assigned to a charger only considering a fixed cost of connecting that aircraft to a type of charger and the procurement cost of chargers. The first constraint given in Equation 8.1 presents that an aircraft should be assigned to one charger which it should be compatible with. The second constraint in Equation 8.2 determines the decision variable y_i, presenting the minimum number of chargers of type j needed to charge all aircraft. However, the basic concept of charging designed does not take into consideration a lot of important factors which are needed in the mathematical model to be more representative of the complexity of the infrastructure sizing problem. For example, the optimal charging duration is not considered, neither are the required SOC of the batteries and the SOC at the start of the charging process, or the costs of drawing power at peak moments, nor the limits of the capacity grid and all scenarios will need to be included. Concluding, a lot of constraints and variables will need to be added.

A draft of steps which need to be taken in order to develop the model will be discussed below. It should be noted that it are initial ideas made in the initial phase of the project and that concepts and ideas of the model configuration are likely to change over the course of the thesis. Additions and expansions of the model will include:

For general mathematical model:

- Constraint on compliance with flight schedule, thus finishing charging within turn around time
- Battery SOC should be included, it will determine the starting point of the charging process and the level up to which charging is required
- Charging rate included as decision variables, it influences the charging cost and the occupancy time of an aircraft at a charger and thus impacts the capacity in terms of number of chargers needed
- Constraint presenting that aircraft can not be charged above their maximum charging rate
- Constraint presenting maximum energy supply from electricity grid
- Constraint which ensures the charging process is finished at once and can not be interrupted
- Charging costs should account for the charging rate
- Charging costs should be based on varying electricity costs, different rates during the day/year periods
- Charging costs should also include peak pricing

- Investment costs should besides the charger procurement costs include investment in upgrading the electricity grid capacity
- Decision variable presenting the start time of the charging procedure
- Decision variable presenting the end time of the charging procedure

For decentralized vs centralized scenario:

- Constraints associated with aircraft being limited to charge at designated charging location
- Constraints on infrastructure configuration of Rotterdam the Hague Airport
- Inclusion of additional cost variable in objective function, which represents a sort of penalty for reallocation of aircraft to charge at other location
- Investment costs should include investing in upgrading the electricity grid, given for different locations and different grid capacities

For fixed and mobile energy storage system scenario:

- Investment cost included for connecting the airport based solar panels to the electricity grid of the airport
- Decision variable added which determines the optimal sizing of a fixed and mobile energy storage system
- Operational cost included accounting for the life time of the batteries
- Decision variable presenting the start time of the charging process of the battery storage systems
- Decision variable presenting the end time of the charging process of the battery storage systems

For deviating from flight schedule scenario:

- Relax the constraint which ensures compliance with the flight schedule

8.3.3. Verification and validation

After the mathematical model has been constructed it is important that it gets verified and validated in order to scientifically test the credibility before applying it to a real world problem. Verification is concerned with the process of determining if the model implementation accurately represents the conceptual description of the models developer and additionally verification is also concerned with finding and fixing model errors (Thacker et al., 2004). Validation on the other hand, is concerned with evaluating and reviewing how the model works and ensuring that it represents the real world system it intends to simulate (Carson, 2002). In short, verification concerns the mathematics associated with the model and validation deals with the physics of the model (Thacker et al., 2004).

Verification and validation of the mathematical model will be performed to check for the model's correctness and or accuracy for addressing the problem of this research. After construction of the model, it first will need to be verified. Verification will likely be performed by the use of a simple numerical test. Since with the use of a numerical test it can be verified that the results of the model accurately represent the mathematical model. In order to make the calculations the input variables will be more simplified than in the case study such that it makes checking whether the outcomes of the model based on the input parameters makes sense. Then, after verification has been done, the model will be validated. The validation will be based on a prepared case study. In this process the main question is whether the model accurately presents the case study and if the outcomes make sense based on real world scenarios.

8.4. Analysis

After the model has been developed and an optimal solution has been retrieved, different postoptimality analysis will be conducted. A postoptimality analysis is an important part of optimization studies and is an analysis done after an optimal solution has been found (Hillier and Lieberman, 2010). This analysis is sometimes also referred to a what-if analysis because it includes answering questions about what would happen to the solution if other assumptions are made. Additionally, a part of the postoptimality analysis is the sensitivity analysis, which includes determining which parameter(s) of the model are the most critical in order to determine the solution. Since RTHA, like most other (regional) airports, is still at a beginning phase when it comes to electric aviation, investigating various charging operational and infrastructure considerations is important. In order to create a more general understanding of the costs versus the benefits of these various considerations, different cost-benefit analyses will be included in this project. In subsection 8.4.1 it will be discussed how sensitivity analyses will be included and in subsection 8.4.2 the use of cost-benefit analyses as part of this research will be elaborated on.

8.4.1. Sensitivity analyses

Sensitivity analysis is a method which is concerned with measuring how the uncertainties of input variables can result to uncertainties in the output variables (Pichery, 2014). The analysis thus focuses on quantifying the importance of the models input parameters on the behaviour of the system. Sensitivity analysis should and will be part of the cost-benefit analyses, discussed in subsection 8.4.2. This is because, the sensitivity analysis will determine how benefits and costs will change if specified parameters are varied. In this subsection it will be discussed for which parameters and concepts sensitivity analysis will be performed.

Generally, some typical sensitivity analysis questions are (Hall and Posner, 2004):

1. What are limits to changing a parameter such that the solution remains optimal?
2. Given a specific parameter change, what is the new optimal cost?
3. Given a specific parameter change, what is the net optimal solution?
4. If a constraint is added to the model, how does it change the solution?

In this project, sensitivity analysis will be used to study the effect of input parameters on the outcomes of the model. This will include evaluating the influence of cost input parameters, such as the electricity pricing, procurement costs of chargers and (mobile and fixed) energy storage systems. Studying the sensitivity of the model to these input parameters will create an understanding of how robust the solution will be to changes in future prices. Also, the effect of the amount of available power from the solar panels and from the electricity grid will be interesting to analyse.

Lastly, the procedure of selecting which aircraft and flight movements of the 2022 data are replaced by an electric aircraft is important and the effect of changing this selection procedure will be analysed as well.

Summarizing, the sensitivity of the model will be at least tested for the following:

- Selection procedure of which aircraft and flight movements of 2022 data are replaced by electric aircraft
- Electricity pricing effect
- Charger procurement cost effect
- Energy Storage System procurement cost effect
- Effect of available power from solar panels
- Effect of changing maximum electricity capacity of the grid

8.4.2. Cost-benefit analyses

A cost-benefit analysis (CBA) will be performed for various concepts and charging considerations. A CBA is the analytical and systematic process of comparing costs and benefits in order to evaluate the desirability of a program or project (Mishan and Quah, 2020). Cost-benefit analyses will be included in this project, to evaluate different concepts of charging operations and charging infrastructure considerations. These include, evaluating decentralized versus centralized charging layout configurations, also the inclusion of a mobile charging truck, deciding on the sample day to use and the effect of deviating from the flight schedule. The basis of why a CBA is applied to these concepts, is that the benefits or disadvantages of these concepts can not be translated into a cost. The mathematical model, however optimizes for minimization of costs, therefore the CBA will be used to evaluate the costs of concepts to the benefits involved, such that RTHA can be provided with a comprehensive advise which includes finding an optimal between costs and benefits. In order to perform a complex CBA , a sensitivity analysis will be involved and be part of the cost benefit-analyses (Adam Hayes, 2022). As mentioned, this is because the sensitivity analysis will determine how benefits and costs will change if specified parameters are varied.

For this project, gathering managerial insights in terms of what the influence of various charging operations and infrastructure concepts might be is of importance. This includes deciding on a decentralized or centralized charging layout configuration for which a cost-benefit analysis will be performed. In this CBA, the costs relate to the infrastructure investment costs. The benefits for a decentralized location relate to that there will be no need for additional aircraft movements, which minimizes the impact on other airport operations. Additionally, the decentralized configuration will also ensure a better customer experience due to the fact that the allocation of the aircraft is at the preferred and final location. The costs however involved with a centralized location will most likely be lower since the investment in electric infrastructure upgrade is only required for one location. The cost-benefit analysis will weigh the costs to the benefits and it will be analyzed what will be the most optimal configuration. Depending on the desires of the airport itself, based on the CBA it can be decided what favors the most, lower investment costs but more additional ground movements of aircraft and a decrease of passenger experience, or higher investment costs but favorable passenger experience and less influence on other airport operations. The outcome might be a partly central and partly decentralized solution in which a number of flights are accommodated to charge at their preferred location and a number of flights are reallocated to a central location.

Additionally, one of the contributions of this project is analyzing the effectiveness of a mobile charging truck. A cost-benefit analysis will be performed to weigh the benefits of including a mobile truck as charging alternative, to the costs associated with the investment in such a mobile energy storage system. Benefits of a mobile truck are that a form of decentralized charging can be accomplished without actually investing in infrastructure at these decentralized locations. The mobile truck can drive to the locations and connected to charge aircraft at normal parking stands. The costs of the mobile truck will include the acquiring costs, operational charging costs of the batteries and a cost presenting the degradation of the batteries. In fact, the optimization model designed for this project, will output the optimal sizing of the mobile truck for which the costs of the truck versus the benefit of not needing to invest in decentralized location is taken into consideration. It might be the case that the model outputs that in terms of cost minimization it is not optimal to use a mobile truck. However, the cost-benefit analysis will focus on the preferences of RTHA in terms of operational benefits of utilizing a mobile truck which can not be translated to a cost form. Therefore, performing a cost-benefit analysis for this concept will ensure that a comprehensive decision can be made in whether or not to include a mobile charging truck, for which also the benefits have been considered.

Furthermore, deciding on a suitable sample day is important. This is because, modelling for the ”worst” day in terms of high number of flight movements will be very different than modelling for a relaxed ”best” day with a low number of flight movements. In the ”worst” day case the model will output a solution which is likely over sized in terms of capacity for regular days and similarly, for the ”best” day the infrastructure sizing will be undersized for regular days. Therefore, after the model has been constructed, it is important to analyse what is the best sample day/sample period in terms of comparing the investment costs of a charging infrastructure solutions to the benefits it has. The benefits in this analysis will be related to the amount of flight movements which the solution is able to accommodate. A cost benefit-analysis will be performed in order to recommend the sample day to be used, which concerns an optimal decision while comparing the costs versus the benefits . It should be noted, that this will be done for each of the different future scenario cases considered in the project.

Lastly, analysing the effect of deviating from the generated flight schedule is an important consideration in the project. In order to analyse and determine the most optimal investment strategy in which complying to the schedule is weighted against additional investment costs, will involve another cost-benefit analysis. In which the costs relate to investing in the capacity of the electric infrastructure of the airport and the benefits relate to complying with the flight schedule. Deviating from the flight schedule will in the model either be implemented as loosening the constraint of flight schedule compliance and seeing the effect of adapting this constraint to meet various values (sensitivity analysis). The cost-benefit analysis can then be performed by analysing various graphs which are generated from the outputs of the model. Another option might be to reconstruct the objective of the model and solve for a multi-objective which minimizes the displacements for the flight schedule while also minimizing the total investment and operational costs. Solving for a multi-objective model has the goal to return a set of mutually non-dominant solutions, for which the solutions are called Pareto optimal (Daş et al., 2020). The Pareto optimum has been found when an improved value in one objective is found without worsening the performance in any other objective. Therefore, solving the multi-objective model including the objective of minimizing costs and minimizing deviations from the schedule, will output an optimal solution for which the Pareto optimum is found.

Summarizing, a cost-benefit analysis will be performed at least for the following concepts:

- Centralized vs decentralized charging configuration
- Inclusion of a mobile charging truck
- Sample day, influence of considering an average day, worst day or best day
- Deviating from flight schedule

As discussed in subsection 5.2.2, the cost-benefits in these researches were generally performed by comparing graphs and outcomes of various scenarios and strategies. For this research, for now at least, it is expected that by generation of the outcomes of the model for different scenarios as discussed above and presenting these in graphs, a sufficient cost-benefit analysis can be performed. For the deviating from the flight schedule scenario it will be investigated whether loosening of a constraint or solving a multi-objective function will be included and to what extend a Pareto optimum can be found.

Furthermore, it can be concluded that to this project it is important to analyse the effect of making individual changes to parameters or constraints rather than varying them simultaneously. A suitable method for the sensitivity analyses would therefore by the one at a time (OAT) method which is a local sensitivity analysis method studying the effect of one factor (Campolongo et al., 2011). It is a simple and commonly used method which evaluates the effect of changing a factor on the output. A local method such as the OAT method is generally performed by using partial derivatives or linear regression. One of the downsides using this method is that interactions amongst other factors are less visible since they become evident when inputs are varied simultaneously (Campolongo et al., 2011). However, for this project using a local one at a time method will most likely be suitable and has the ability of providing insights into the effects on infrastructural layouts and total costs when inputs will be changed. If, later on it is decided that analysing the interactions among factors is important, global sensitivity analysis techniques can be used. A wide range of global methods is available, ranging from qualitative screening methods to quantitative techniques involving variance decomposition (Campolongo et al., 2011).

9

Research planning

In this chapter an overview is given of the planning for this thesis in Table 9.1 and Figure 9.1.

Research planning	
Data collection	**4 weeks**
Gathering flight data	1 weeks
Aircraft type selection	1 week
Charger type selection	1 week
Setting up different future scenarios	1 week
Model building	**6 weeks**
Generating flight schedule	2 weeks
Set up of objective, constraints and decision variables	1 weeks
Configuration of MILP algorithm	2 weeks
Model finalization	1 weeks
Analysing model performance	**2 weeks**
Model verification and validation	1 week
Postoptimality analysis	1 week
Working out scenarios	**4 weeks**
2025, 2030, & 2035 scenario	1 week
Deviating from flight schedule scenario	1 week
Decentralized vs centralized scenario	1 weeks
Mobile truck scenario	1 weeks
Project finalization	**10 weeks**
Research paper	4 weeks
Concept report	4 weeks
Greenlight meeting preparation	2 weeks
Final report	2 weeks
Graduation preparation	2 weeks
Total time	**26 weeks**

Table 9.1: Research planning

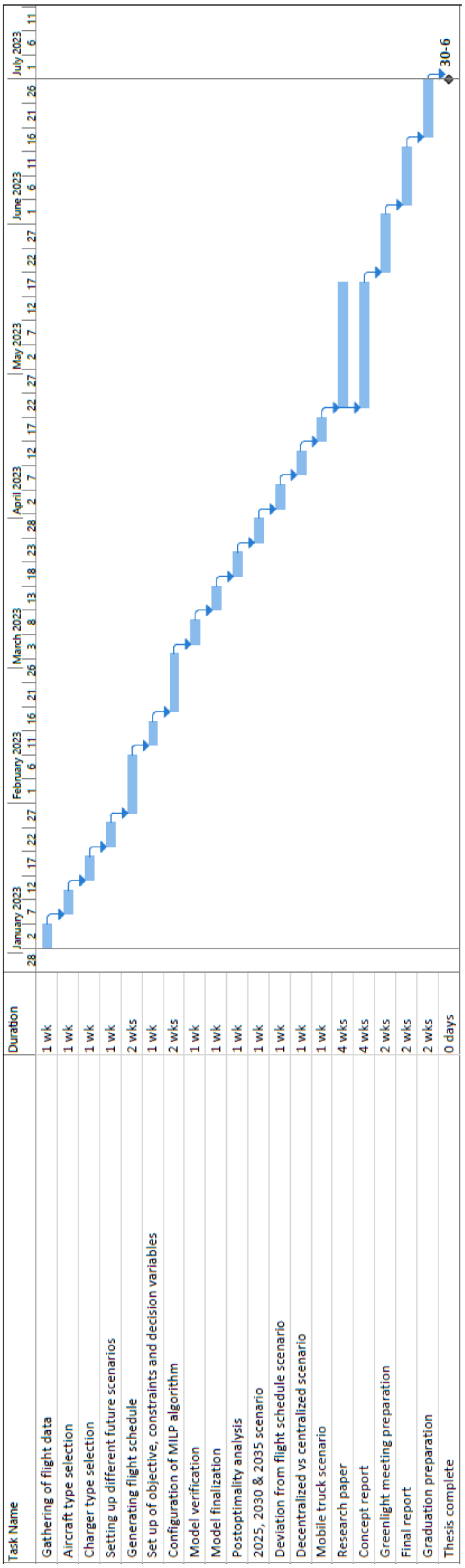


Figure 9.1: Research planning

Part III

Supporting Work

1

Modelling day

In order to generate results from the optimization model, a suitable modelling day should be chosen. For which first, a reference year will be decided on in section 1.1. Then, in section 1.2 the procedure of selecting a suitable modelling day is elaborated on. In section 1.3 the selection of the modelling days for each future scenario will be discussed.

1.1. Reference year

The flight movement data of the years 2019, 2020, 2021 and 2022 have been attained for regional airport RTHA. In order to determine which year will be used as reference to this research, the flight movements of these years have been analysed. The data has been analysed for different aviation segments, namely, the flight lesson movements, general aviation, business aviation and commercial aviation. In Figure 1.1, the aircraft movements at RTHA for the years 2019 to 2022 are displayed, for which it can be seen the year 2022 reached approximately the same level of flight movements as in 2019. However, during the Covid period years, which were mostly 2020 and 2021, a drop in especially the scheduled commercial aviation was seen. The pilot lesson flights and private general aviation flights actually increased over the last three years when compared to 2019. Since the level of commercial and business aviation is for 2022 as it was in 2019 and the general aviation segment actually experienced an increase, the decision has been made to model for the most recent year, 2022.

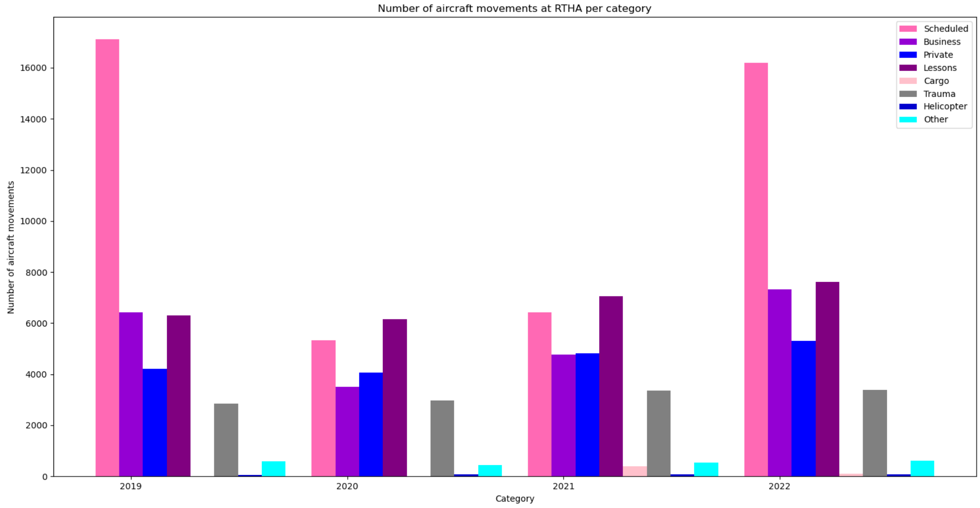


Figure 1.1: Categorized aircraft movements at RTHA for the years 2019 to 2022

1.2. Modelling day selection procedure

Then, in order to assess the infrastructural requirements of an airport in support to electric aviation, it is important to select a suitable modelling day. Since in this research, various future scenarios are considered, it is important to analyse the data and representative days for all of them. Additionally, this research assesses the infrastructural design of a central charging location versus the infrastructure of various decentralized charging locations. Therefore, different modelling days have been selected, one for each location and each future scenario.

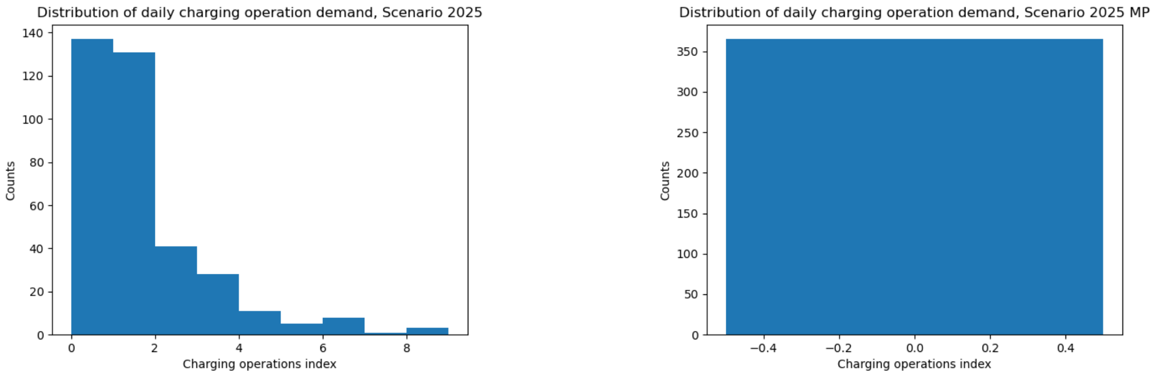
Furthermore, since in this research the objective is to address the required capacity of the electric infrastructure, it is important for the modelling day to reflect the day for which the maximum infrastructure is required. For RTHA, innovation and sustainability of aviation are high on the agenda and part of their strategy. It is important for the airport to ensure they have the infrastructure in place which is capable of accommodating the full demand of electric aviation in the future. It is therefore, that in this research the most demanding operations for each of the future scenarios is modelled for. First, it is important to consider what makes a day a peak day in terms of highest infrastructure demand, it might be a day with the most number of electrified movements, but this is not necessarily the case, since it might be that another day has less electric movements but does include a movement which poses a high charging demand. Therefore, similar to the procedure of attaining the flight schedule and associated charging events, it is decided to select for each location and for each future scenario, the modelling day which includes the most demanding charging operations for the year 2022.

1.3. Data Analysis and chosen modelling days

In order to decide on a representative peak day for the various airport locations amongst the different scenarios, histograms have been generated which are used to show the frequency distributions of charging demand indices. These demand indices have been set up and are calculated by dividing the required amount of charge (in kWH), by the available turn around duration. For instance, if 80 kWh needs to be charged within 40 minutes, the index equals 2 and in case of 80 kWh within 10 minutes, the index equals 4. So, the higher the index, the more demanding the charging operation is considered. On a daily basis, the charging indices of the operations were added and the values presented in the histograms thus present the combined indices for a day. The selection of the chosen modelling days for each scenario will be discussed in the following subsections.

1.3.1. Scenario 2025

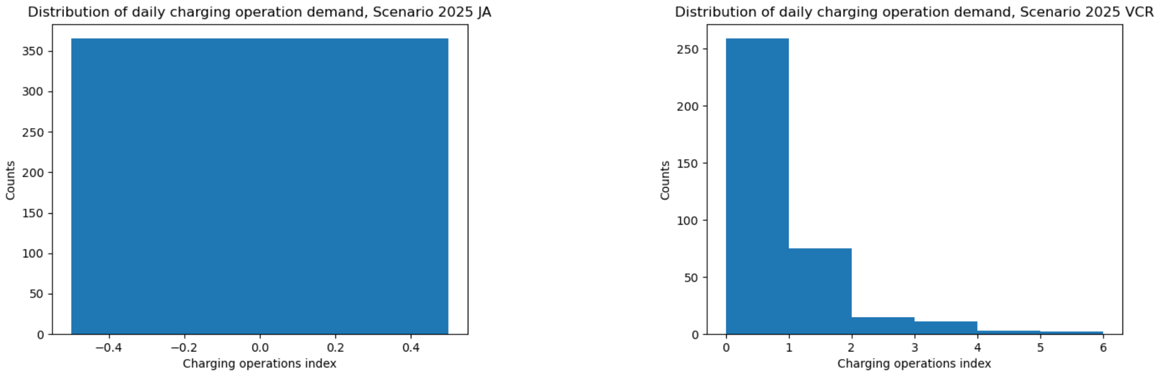
For the central location, see Figure 1.2a, the maximum charging operation occurs at date 23-07-2022, which has been chosen as modelling day. For the Main Platform, for the entire reference year, no charging operations occur, for which date 30-01-2022 has been chosen as modelling day. Similarly, for Jet Aviation (see Figure 1.3a), no charging operation of electric aircraft are assumed for the entire year. Date 23-03-2022 has been chosen for this location since in other future scenarios this is one of the peak days. Then, for the Vliegclub Rotterdam, the distribution of daily charging operation demand is given in Figure 1.3b, for which a maximum demand occurs at selected modelling day 09-10-2022. For the Rotterdamsche Aeroclub, peak day 18-08-2022 has been selected as modelling day (see maximum in Figure 1.4a). Then, for the Hangars, the distribution is given in Figure 1.4b for which a peak in daily charging operation demand occurs for selected modelling day 26-02-2022. An overview of the selected modelling days is presented in Table 1.1.



(a) Histogram central location

(b) Histogram Main Platform

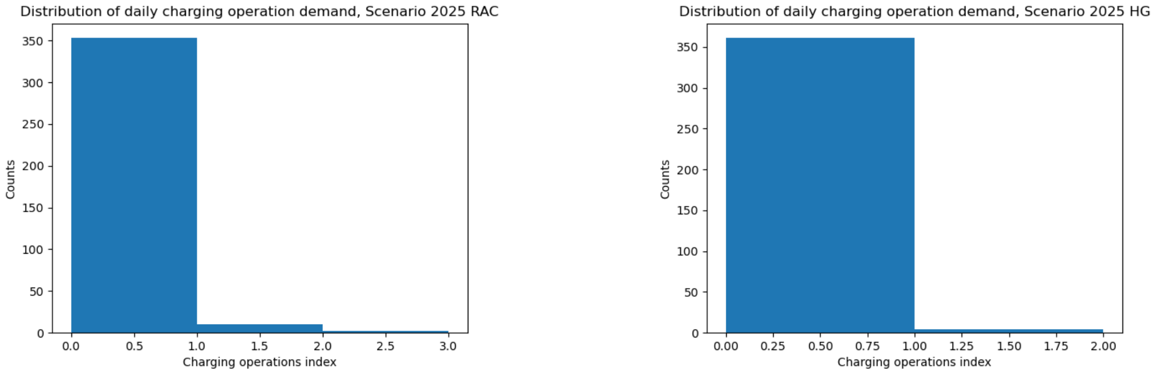
Figure 1.2: Histograms central location and main platform for 2025 scenario



(a) Histogram Jet Aviation

(b) Histogram Vliegclub Rotterdam

Figure 1.3: Histograms JA and VCR for 2025 scenario



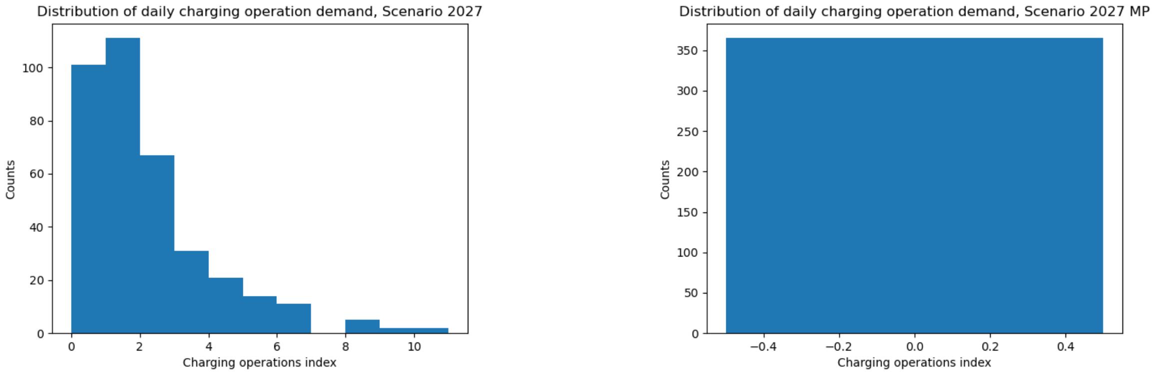
(a) Histogram Rotterdamsche Aeroclub

(b) Histogram Hangars

Figure 1.4: Histograms RAC and Hangars for 2025 scenario

1.3.2. Scenario 2027

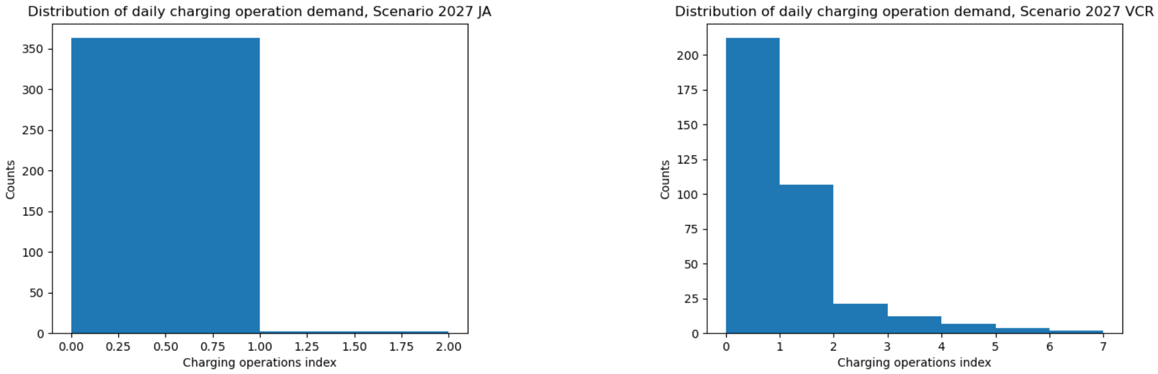
For the central location, a maximum charging operation demand can be seen in Figure 1.5a which occurs at selected modelling day 23-07-2022. Again, since no charging operations occur for the Main Platform (see Figure 1.5b), modelling day 30-01-2022 has been chosen. For Jet Aviation, electric flight movements and charging operations are expected to occur for the 2027 scenario, for which the histogram can be seen in Figure 1.6a. modelling day 23-03-2022 has been chosen since it reflects a maximum of daily charging demand. For Vliegclub Rotterdam the maximum charging demand occurs for selected modelling day 09-10-2022 (histogram in Figure 1.6b). For the Rotterdamsche Aeroclub and the Hangars, respectively in Figure 1.7a and Figure 1.7b, the maximum modelling days have been selected which are 18-08-2022 for the RAC and 26-02-2022 for the Hangars. In Table 1.1 the selected modelling days are displayed.



(a) Histogram central location

(b) Histogram Main Platform

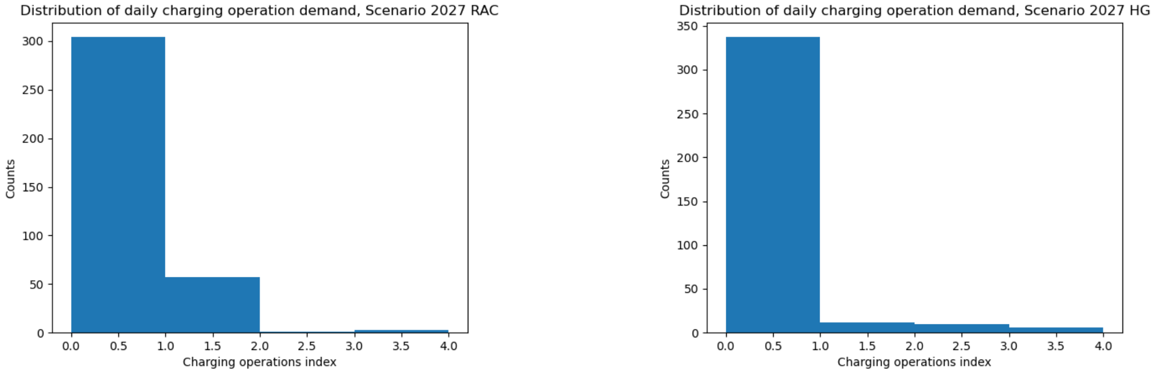
Figure 1.5: Histograms central location and main platform for 2027 scenario



(a) Histogram Jet Aviation

(b) Histogram Vliegclub Rotterdam

Figure 1.6: Histograms JA and VCR for 2027 scenario



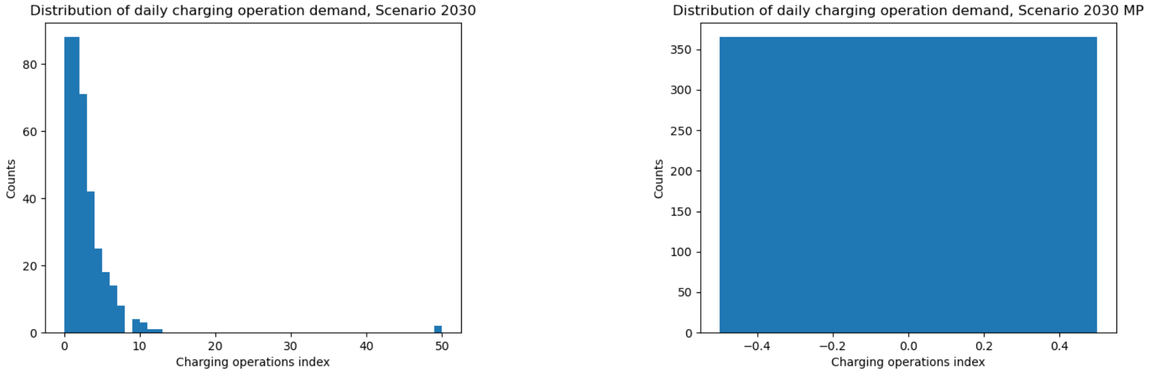
(a) Histogram Rotterdamsche Aeroclub

(b) Histogram Hangars

Figure 1.7: Histograms RAC and Hangars for 2027 scenario

1.3.3. Scenario 2030

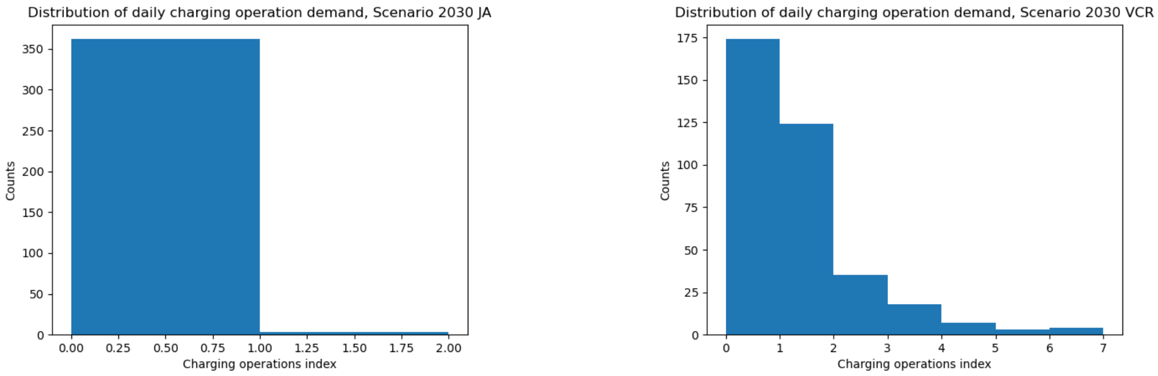
In Figure 1.8a an outlier can be seen for the maximum daily charging operation demand at the central location, this outlier occurs for modelling day 23-07-2022. However, modelling for such an outlier will result in over sizing the infrastructure, since this outlier only occurs once a year, it is assumed that with appropriate scheduling, such outliers can be avoided. Therefore, modelling day 01-05-2022 has been chosen for the central 2030 scenario which presents the second peak day. Once again, no electric flight movements and charging operations are expected for the main platform in this scenario. Date 30-01-2022 is again selected as modelling day. For Jet Aviation, the maximum charging demand as given in Figure 1.9a, occurs for selected modelling day 23-03-2022. For the Vliegclub Rotterdam and Rotterdamsche Aeroclub, modelling days 09-10-2022 and 18-08-2022 has been chosen respectively, since they both present the maximum charging demand (see Figure 1.9b and Figure 1.10a). For the distribution of the Hangars, an outlier can be seen in Figure 1.10b, the decision has been made not to model for this outlier to prevent over sizing of the infrastructure. The second peak day, 26-02-2022 has been selected which in the figure has the value of approximately 5 for the daily charging operation demand. In Table 1.1 an overview of the selected modelling days is provided.



(a) Histogram central location

(b) Histogram Main Platform

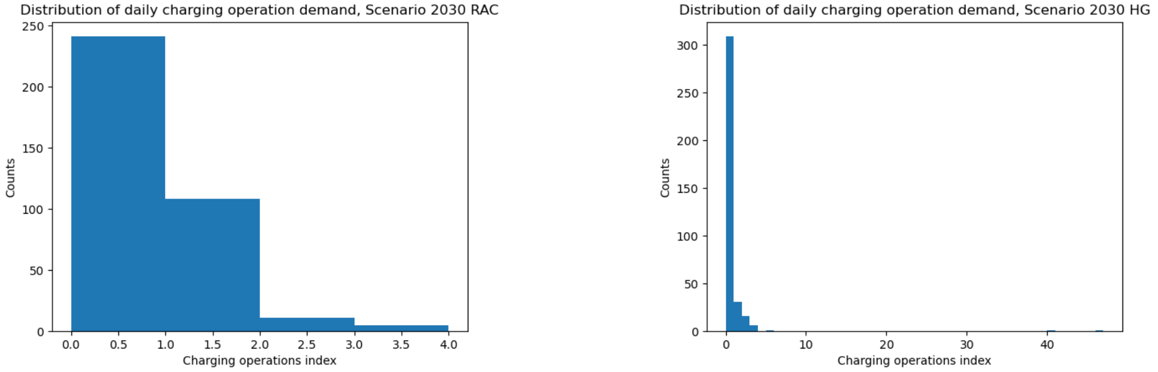
Figure 1.8: Histograms central location and main platform for 2030 scenario



(a) Histogram Jet Aviation

(b) Histogram Vliegclub Rotterdam

Figure 1.9: Histograms JA and VCR for 2030 scenario



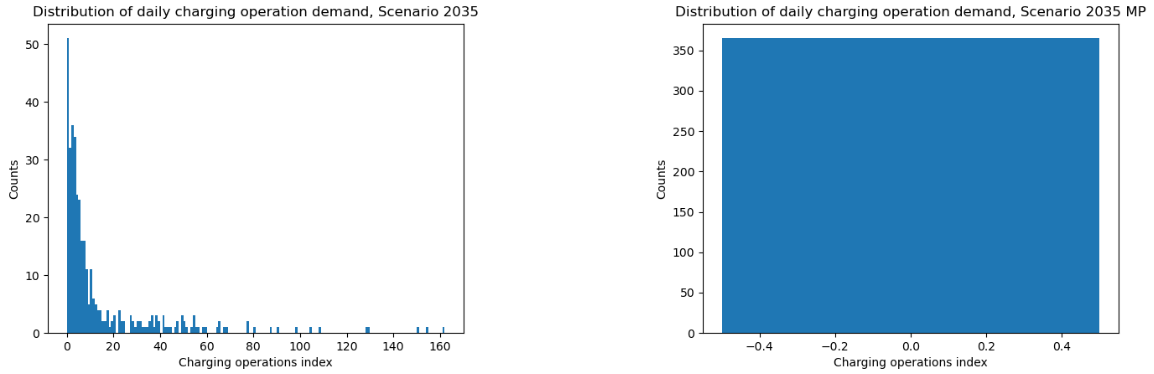
(a) Histogram Rotterdamsche Aeroclub

(b) Histogram Hangars

Figure 1.10: Histograms RAC and Hangars for 2030 scenario

1.3.4. Scenario 2035

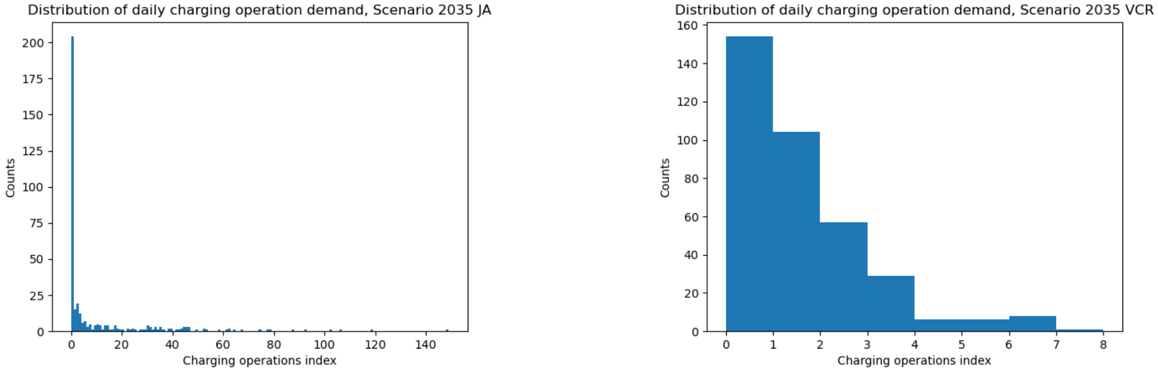
For the 2035 scenario, the daily charging operation demand for the central location is widely distributed (see Figure 1.11a). As mentioned before, choosing one of the outliers will most likely result in over sizing of the infrastructure. Therefore, not one of the three most extreme outliers has been chosen, however since 23-07-2022 was one of the most occurring modelling days for the central location in the other scenarios, this modelling day has been selected once again. It should be noted that it does reflect an operation demand of approximately 129 and is thus one of the outliers in the figure. For the Main Platform, 30-01-2022 has been selected, no charging operations occur for the 2035 scenario. However, for the 2035 scenario, additional commercial aviation movements performed with the Maeve aircraft are assumed in this research for which a fictive flight schedule has been set up. The charging operations and turn around procedures of these aircraft will be performed at the main platform, these operations will be added to the operations of the selected modelling day as input for the model. For the Jet Aviation platform, a wide distribution can be seen from figure Figure 1.12a. Similar to the modelling day of the central location, 23-07-2023 has been selected. This is a deliberate decision, since it is one of the days for which a maximum charging operation demand occurs for the Jet Aviation platform. But additionally, since for the central location a maximum peak day has been chosen, from a comparison point of view it has been chosen to select the same modelling peak day for both of these locations. Just as in the other future scenarios, for the Vliegclub Rotterdam and Rotterdamsche Aeroclub the maximum charging demands occur for 09-10-2022 and 18-08-2022 respectively. The distribution of charging operation demand for the hangars in the 2035 scenario is displayed in Figure 1.13b. For which three outliers occur, the decision has been made to follow the modelling day 26-02-2022 of the previous scenarios which is also the fourth peak day for the 2035 scenario and thus not one of the extreme outliers.



(a) Histogram central location

(b) Histogram Main Platform

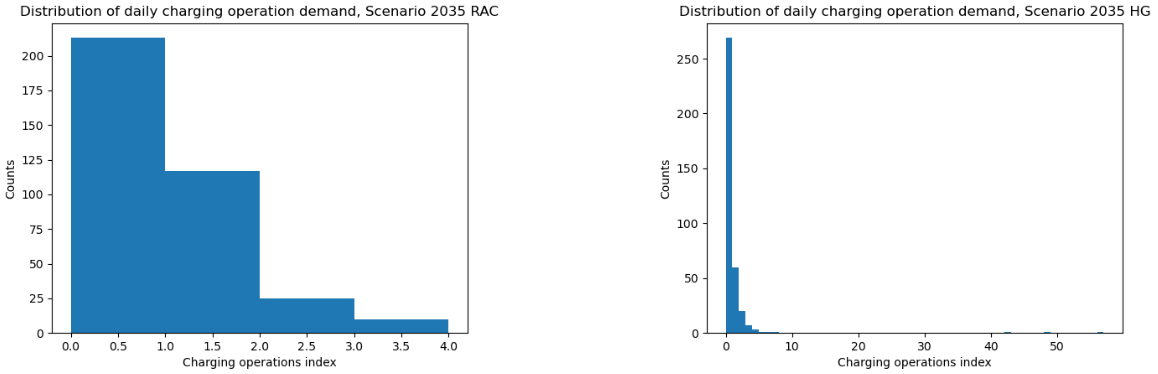
Figure 1.11: Histograms central location and main platform for 2035 scenario



(a) Histogram Jet Aviation

(b) Histogram Vliegclub Rotterdam

Figure 1.12: Histograms JA and VCR for 2035 scenario



(a) Histogram Rotterdamsche Aeroclub

(b) Histogram Hangars

Figure 1.13: Histograms RAC and Hangars for 2035 scenario

1.3.5. Overview selected modelling days

After the explanations of which modelling days were selected for the various locations and for each scenario, an overview of the selected modelling days is provided below in Table 1.1.

	2025	**2027**	**2030**	**2035**
Central location	23-07-2022	23-07-2022	01-05-2022	23-07-2022
Main Platform	30-01-2022	30-01-2022	30-01-2022	30-01-2022
JetAviation	23-03-2022	23-03-2022	23-03-2022	23-07-2022
VCR	09-10-2022	09-10-2022	09-10-2022	09-10-2022
RAC	18-08-2022	18-08-2022	18-08-2022	18-08-2022
Hangars	26-02-2022	26-02-2022	26-02-2022	26-02-2022

Table 1.1: Modelling days for maximum charging operation demand

2

Model verification

Both models have been verified for implementation of every modelling step along the way. Code verification has been applied by unit testing and resolving any errors which showed during running of the code. Also, calculation verification has been done by checking whether the model matches manually computed results. For the MILP model, three verification sets have been created for which in this chapter the results are checked to see if an expected outcome was reached.

First, a simple flight schedule has been set up, consisting of four flights and displayed in Table 2.1. All four flights are performed with electric aircraft eFlyer4, containing a 250 kWh battery capacity. The schedule displayed gives the required charge for the battery which equals 75 kW for the first and third flight and 125 kW for the second and fourth flight. The eFlyer4 aircraft is assumed to be compatible with three chargers, the 80 kW, 150 kW and 240 kW (maximum 3C charging). Since compliance with the flight schedule and thus turn around times is a hard constraint, the second flight cannot be charged with the 80 kW slow charger since this will result in a duration of approximately 1.5 hours which is not within the TAT of the flight. Furthermore, another special case is flight number 4 which has an arrival on the reference day at 22:45 and departs the next day at 6:30. As all flights in the schedule do not show critical overlaps, it is expected that the model will output one charger, which will be the least expensive charger complying with the constraints of the turn around of the aircraft.

Verification set 1									
	Model input					*Model output*			
Flight	**e-AC**	**Arrival**	**Departure**	**SOC$_{arr}$**	**SOC$_{dep}$**	**T$_{start}$**	**T$_{end}$**	**Charger**	**Parking**
Flight 1	eFlyer-4	14:00	16:15	40	70	15:35	16:05	1 (150 kW)	Central
Flight 2	eFlyer-4	14:35	15:45	30	80	14:40	15:30	1 (150 kW)	Central
Flight 3	eFlyer-4	16:35	17:30	40	70	16:50	17:20	1 (150 kW)	Central
Flight 4	eFlyer-4	22:45	6:30	30	80	22:50	23:40	1 (150 kW)	Central

Table 2.1: Charging schedule, verification set 1

Looking at the results of the model to the verification input, given in Table 2.1, the model shows that one 150 kW charger is required to fulfill the charging of the four flights. In terms of complying with the flight schedule, flight number 2 poses the highest constraint on the model outcome, since for flight number 2 the TAT can only be realised with the 150 kW charger as minimum. Since we are modelling for a minimization of charger investment costs, is it as expected that instead of acquiring an additional 80 kW charger, the 150 kW charger is also used to service the other three flights.

From the results it can also be seen that all flights comply with the buffer times posed after arrival and before departure, for which charging can start 5 minutes after arrival and charging should be finished 10 minutes before departure. Furthermore, from flight 4 it can be seen that this flight complies with the constraint that no charging is allowed to start within the non-operational hours of the aircraft, which is between 23:00-06:00 the next morning. Also, the results show that the charging duration is determined by the chosen charger and the level of charge required for each flight. Additionally, it can be seen that the buffer of 5 minutes between charging events at a charger is adhered to (see time between end of charging flight 2 and start of charging flight 1). The optimal charging schedule of this verification set can be found in Figure B.1.

Then, in order to show the effect of minimization of charging operation costs (second part of the objective) and complying with the flight schedule and turn around time, an additional flight is added to the flight schedule, which together with the model results is shown in Table 2.2. The flight added (flight number 2), is similar to the first flight of the flight schedule. It is expected that since overlap between the first, second and fifth flight occurs, that an additional charger is required to ensure compliance with the flight schedule. From the objective of minimization of the costs involved with charging, which increases for charging at higher rates, it is expected that in case a slower charger is part of the results, flight 5 will be charged with this charger, as it has a turn around duration of several hours.

Verification set 2

Model input						*Model output*			
Flight	**e-AC**	**Arrival**	**Departure**	**SOC_{arr}**	**SOC_{dep}**	**T_{start}**	**T_{end}**	**Charger**	**Parking**
Flight 1	eFlyer-4	14:50	16:15	40	70	14:55	15:51	2 (80 kW)	Central
Flight 2	eFlyer-4	14:50	16:15	40	70	15:35	16:05	1 (150 kW)	Central
Flight 3	eFlyer-4	14:35	15:45	30	80	14:40	15:30	1 (150 kW)	Central
Flight 4	eFlyer-4	16:35	17:30	40	70	16:50	17:20	1 (150 kW)	Central
Flight 5	eFlyer-4	22:45	6:30	30	80	22:50	00:23	2 (80 kW)	Central

Table 2.2: Charging schedule, verification set 2

From the results of the second verification set, it indeed is the case that a second charger is required to ensure that all flights are serviced within their turn around time. Since flight 1 has enough TAT to be charged with the 80 kW charger, this charger is acquired since it has the lowest cost relative to the other compatible chargers of this eAC. Furthermore, since minimization of charging costs is also included in the objective of the model, the ”night” flight, flight 5 is now being charged with the 80 kW charger instead of the 150 kW charger which is also available but at a higher operational charging cost. The optimal charging schedule of this verification set can be found in Figure B.2.

Lastly, a third verification set is used to check the functioning of the constraint which ensures charging at the designated parking location of an aircraft. Additionally, it is used to test whether the model ensures that slow charging occurs for charging above 80% of the battery capacity of an electric aircraft.

Verification set 3

Model input							*Model output*		
Flight	**e-AC**	**Arrival**	**Departure**	**Parking**	**SOC_{arr}**	**SOC_{dep}**	**T_{start}**	**T_{end}**	**Charger**
Flight 1	eFlyer-4	14:00	16:15	VCR	50	90	14:56	16:04	VCR1 (80 kW)
Flight 2	eFlyer-4	14:00	16:15	VCR	50	90	14:56	16:04	VCR2 (80 kW)
Flight 3	eFlyer-4	14:35	15:45	JA	30	80	14:40	15:30	JA1 (150 kW)
Flight 4	eFlyer-4	16:35	17:30	RAC	40	70	16:40	17:10	RAC1 (150 kW)
Flight 5	eFlyer-4	22:45	6:30	JA	30	80	22:52	23:42	JA1 (150 kW)

Table 2.3: Charging schedule, verification set 3

The results in Table 2.3 clearly show that the flights are being charged at their designated parking locations, which verifies that for the decentralized concept, the constraint of charging at own location is complied with. Also, the first and second flight require charging above 80% of their battery capacity, for which slow charging at 0.5C is required. Comparing the results of this third verification set to the outcomes of the second set, it can be seen that the charging durations for these first two flights indeed increased. The optimal charging schedule of this verification set can be found in Figure B.3.

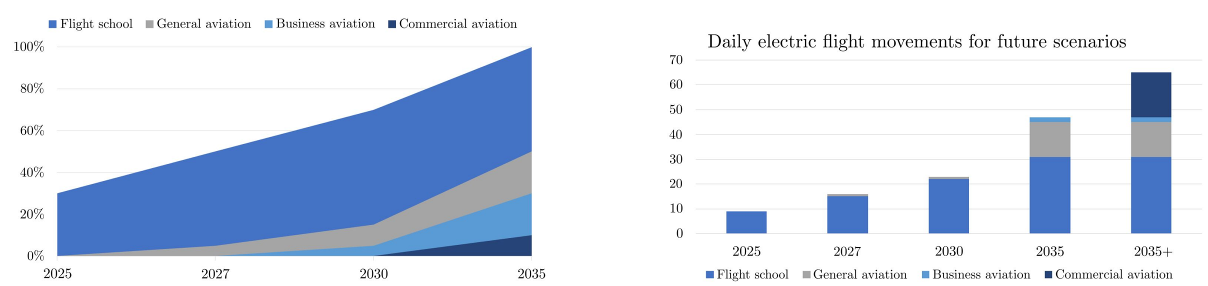
3

Results and advise for Rotterdam the Hague Airport

In this chapter, an overview of the results of the infrastructure sizing model will be provided, for which in addition to the research paper, a more detailed description of the results and advise for Rotterdam the Hague Airport will be given. In section 3.1 the expected increase of electric aviation in the coming years is presented. Followed by the results of the infrastructure sizing model given in section 3.2. An assessment of the current and required electric infrastructure at Rotterdam the Hague Airport will be presented in section 3.3. Last, the comparison of the central and decentralized charging infrastructure concept is discussed in section 3.4.

3.1. Expected increase electric aviation in the coming years

Based on the assumptions and future scenarios considered in this research, the model generates the number of electrified flight movements and the number of charging operations required. In Figure 3.1 a comparison between the increase of daily electric flight movements and the percentage of electric flight movements which are considered to be electrified over time, is presented. The percentages illustrated in Figure 3.1a are the future scenarios percentages. The increase in daily electric flight movements for reference airport RTHA, is given for each of the future scenarios for the central location in Figure 3.1b. Comparing these two figures, it can be seen that the flight school movements are the first aviation segment to become electrified and thus present the first number of daily electric flight movements (see Figure 3.1b). For the general aviation segment, the scenarios include a slow increase and this increase can be seen in daily electric flight movements from 2027 in figure Figure 3.1b. A significant increase in the number of daily GA movements can be seen in the year 2035 (see Figure 3.1b). Business electric flight movements appear for the first time in the 2035 scenario. For the commercial aviation, it can be seen that the model does not assume any electric flights, however since a fictive flight schedule is included, there is a share of electric commercial flight movements in the 2035 * scenario.



(a) Percentage of flight movements considered to be electrified over time

(b) Increase in daily number of electric flight movements for future scenarios considered

Figure 3.1: Comparison increase of daily electric flight movements versus the scenario percentage of flight movements considered to be electrified over time

3.2. Results infrastructure sizing model

The results from the infrastructure sizing model for both concepts, decentralized and central charging locations for the future scenarios are given together in Table 3.1. A distinction has been made between the two 2035 scenarios, for which the latter 2035* includes the fictitious routes of the Maeve as additional movements, which has been set up as reference for the market potential of such electric aircraft. For each scenario, the number of electric flight movements and required charging events is given for every location, together with the optimal number and type of chargers. Additionally, the required grid connection for the optimal solution is given which will be used later in section 3.3, to check whether the current electricity grid at RTHA is sufficient to support the additional energy consumption for the charging of electric aircraft. For every modelling run, the model outputs the optimal charging schedule for the modelling day together with figures presenting the requested energy and charging power during the reference day. A detailed overview of the outputs for every modelling scenario and location is given in section B.2. The model outcomes will be discussed for the central and decentralized charging location concepts, separately.

		2025	**2027**	**2030**	**2035**	**2035***
Central location						
Electric flight movements		9	16	23	47	65
Number of charging events		4	7	10	14	23
	350 (kW)	1.0	1.0	1.0	1.0	1.0
	9 (MW)	0	0	0	1.0	2.0
Grid connection	(*Ampere*)	505	505	505	13,495	25,981
Total costs						
Operational costs (€/day)		291	345	428	8,734	40,475
Charger acq.costs (*1000 €)		94.68	94.68	94.68	2,524	4,954
Decentralized locations						
Main platform						
Electric flight movements		0	0	0	0	18
Number of charging events		0	0	0	0	9
Chargers	9 (MW)	0	0	0	0	2.0
Grid connection	(*Ampere*)	0	0	0	0	25,981
Jet Aviation						
Electric flight movements		2	5	8	6	6
Number of charging events		0	1	1	2	2
Chargers	150 (kW)	0	1.0	1.0	0	0
	9 (MW)	0	0	0	1.0	1.0
Grid connection	(*Ampere*)	0	216	216	12,990	12,990
Vliegclub Rotterdam						
Electric flight movements		6	10	14	21	21
Number of charging events		3	4	5	7	7
Chargers	350 (kW)	1.0	1.0	1.0	1.0	1.0
Grid connection	(*Ampere*)	505	505	505	505	505
Rotterdamsche Aeroclub						
Electric flight movements		2	5	6	10	10
Number of charging events		1	2	3	4	4
Chargers	350 (kW)	1.0	1.0	1.0	1.0	1.0
Grid connection	(*Ampere*)	505	505	505	505	505
Hangars						
Electric flight movements		3	7	12	22	22
Number of charging events		1	3	5	7	7
Chargers	150 (kW)	1.0	1.0	1.0	1.0	1.0
Grid connection	(*Ampere*)	216	216	216	216	216
Total costs						
Operational costs (€/day)		415	609	700	7,711	39,494
Charger acq.costs (*1000 €)		232.73	276.11	276.11	2,663	7,523

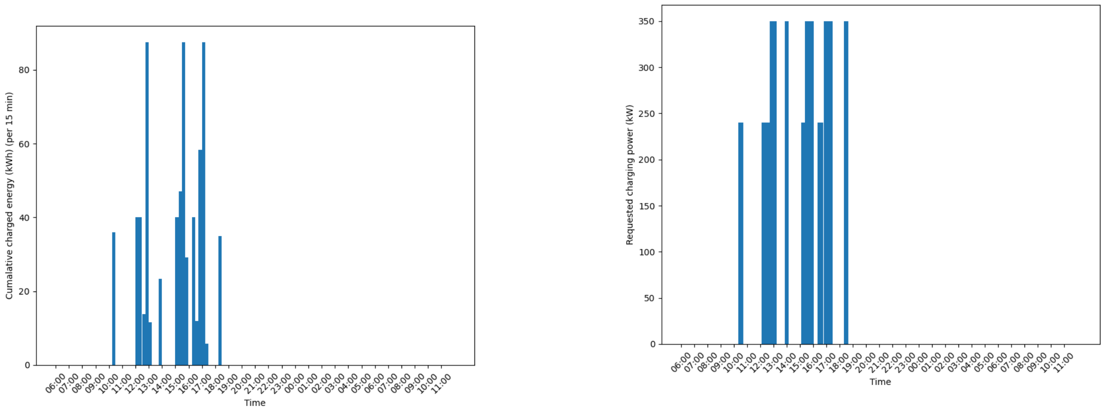
Table 3.1: Results model, for central and decentralized locations, for the different scenarios and modelling days (given in Table 1.1)

3.2.1. Central charging infrastructure concept

The results of the optimal infrastructure for the central location are presented in the first part of Table 3.1. For the short term 2025 scenario, the infrastructure sizing model gave a 350 kW charger as optimal solution. For the 2027 scenario, an increase in the number of electric flights and charging operations is seen from the results in Table 3.1 and Figure 3.1b. For this scenario the 350 kW charger again provides the optimal solution for the problem. This is also the case for the 2030 scenario, in which the 350 kW accommodates the 23 electric flight movements and 10 charging events. It can be concluded, that for the central location, for the first three future scenarios, installing a 350 kW charger will be sufficient to accommodate the daily electric flight movements for the reference days with the most demanding charging operations.

Then, as business and commercial aviation becomes electrified and electric aircraft like the Maeve start operating routes for which charging operations are required, an increase in the capacity of the charger type is seen from Table 3.1. A 9 megawatt charger should be in place to be able to accommodate the turn around times of an electric aircraft like the Maeve. It can be seen that in order to accommodate all electric commercial aircraft, in the scenario 2035* the optimal solution includes two 9 megawatt chargers additionally to the 350 kW charger. From the results in Table 3.1 it can be seen that including a 9 MW charger, significantly increases the required grid connection.

For illustration purposes, the outcomes of the model for the central 2030 scenario are displayed below. Based on the optimal charging schedule (displayed in Figure 3.3), the requested charging energy and power during the day can be attained. Figure 3.2b shows the requested power for electric aircraft charging during the day. From the requested power in (kW) the required grid connection in Ampere can be calculated by dividing by the voltage and a correction for three phase voltage. The required grid connection in Ampere is given in Table 3.1 for all scenarios. These results will be used to assess whether the current grid infrastructure in place at regional airport RTHA is sufficient and to what extend upgrades are required. This will be discussed in section 3.3.



(a) Requested energy during reference day, central location 2030

(b) Requested charging power during reference day, central location 2030

Figure 3.2: Energy and power requested charging operations at central location, 2030 scenario

Figure 3.3: Optimal charging schedule, 2030 scenario

3.2.2. Decentralized charging infrastructure concept

For the decentralized locations, the infrastructure sizing model has been run for the combination of modelling days as given in Table 1.1. Looking at the results of the model presented in Table 3.1, it can be concluded that the required chargers and grid connection, for the Vliegclub Rotterdam, Rotterdamsche Aeroclub and Hangar locations stay the same for the short, medium and long term scenarios. This indicates that investing in these infrastructures on the short term will ensure these airport locations are prepared to accommodate an increase in the amount of daily electric aircraft operations for the coming years. For the Jet Aviation platform, on the short term till 2030, one 150 kW charger is advised to be installed. For which in the 2035 and 2035* scenarios an upgrade is needed to a 9 MW charger. Keeping the 150 kW charger in place is advised to ensure also smaller electric aircraft can be charged since only electric aircraft in the size range of the Maeve can be connected to such megawatt chargers.

Then, for the Main Platform, no charging operations and electric flight movements occur until the introduction of the fictitious electric flight movements of the Maeve flying three frequencies to Hamburg, London and Stuttgart in the 2035* scenario, for which a 9 MW charger is requested. Lastly, note from the results in Table 3.1, that the required grid connection to meet the power request from charging with the 9 MW charger is large when compared to the required connection for a 350 kW charger. However, manufacturer Maeve is designing an energy storage system to which the Megawatt chargers will connect to charge the aircraft. This indicates that no direct charging from the grid is required to accommodate these high powers, which will decrease the required grid connection. However, for this research it is important to indicate what might be the impact of facilitating a Maeve aircraft on the electricity grid and optimizing for an energy storage system was out of the scope of this research.

3.3. Assessment of required electric infrastructure

In this section, the required grid connection attained from the model outcomes given in Table 3.1 will be compared to the current electricity grid infrastructure at Rotterdam the Hague Airport. It will be checked whether or not an upgrade of the infrastructure is required and a price indication of upgrading the infrastructure will be given based on price indications of network operator Stedin (Stedin, 2023).

Together with Rotterdam the Hague Airport, an investigation of their current electric infrastructure on airside has been performed. It is recommended for an airport preparing to accommodate electric aviation, to assess their current electric infrastructure in order to determine whether in time an increase in the capacity is required. This is important because adapting electric infrastructure is a time taking process, in the Netherlands, a lot of regions are congested and acquiring a new or upgraded connection to the grid is time consuming and can take up to 1-2 years before the infrastructure is in place.

In Table 3.2 an overview of the current grid infrastructure in place at RTHA at the various airport locations is given together with the required grid capacity attained from the optimization model results (given in Table 3.1). The current grid connection in place for RTHA is mostly given as reference to what is currently used to power the locations. It should be noted that the current grid connections are for most locations already used to full capacity. For the central charging location, no grid connection is assumed to be in place, as designing for a new location is considered. While for Jet Aviation and the VCR the grid connection is not known. Furthermore, it can be seen that the grid connection of 240 Ampere in place at the RAC should be upgraded to accommodate an additional 505 Ampere for electric aviation charging in the coming years. Also, for the hangars an additional capacity of 216 Ampere is required to charge electric aircraft in the coming years.

	Current	**2025**	**2027**	**2030**	**2035**	**2035***
Central location	-	505	505	505	13,496	25,981
Main Platform	3x630A	0	0	0	0	25,981
JetAviation	-	0	216	216	12,990	12,990
VCR	-	505	505	505	505	505
RAC	3x80A	505	505	505	505	505
Hangars	3x35A	216	216	216	216	216

Table 3.2: Grid connection current infrastructure airport and required connection for future scenarios

From Stedin, an indication of acquiring a new grid connection can be attained. Assuming that for all locations a new connection to the grid should be realized, an indication of the investment costs is given in Table 3.3. For which the investment costs required up till 2035 are given for each of the locations. For grid connections above 10.000 Ampere, Stedin states that the connection fee will be more specific for which a pre-calculated project indication will be made (Stedin, 2023). However, the high grid connection in the 2035 and 2035* scenarios for the central location, main platform and Jet Aviation locations are a result of charging the electric Maeve aircraft. In the future, it is likely that an energy storage system will be in place to facilitate the high power request during charging of these aircraft (MAEVE, 2023). This will results in that a less demanding grid connection will be in place. However, optimizing the operation of such an energy storage system is out of the scope of this research, for which determining what the required grid connection is not possible in this phase.

		2025 till 2035	**2035 +**
Central location	€*	25,059	>328.113
Main Platform	€*	0	>328.113
JetAviation	€*	25,059	>328.113
VCR	€*	25,059	25,059
RAC	€*	25,059	25,059
Hangars	€*	25,059	25,059

Table 3.3: Investment new grid connection indications, * Grid connection fee in € excl. VAT

Concluding, it can be seen that up till 2030 the grid connections at regional airport RTHA should be either upgraded or new connections should be installed for which an indication of the investment costs are given in Table 3.3. A comparison of the investment cost for the central location and the decentralized locations is given in the next section.

3.4. Comparison of central and decentralized charging infrastructure concepts

For the comparison of the central and decentralized charging concepts, a high over cost benefit analysis has been performed. It has been addressed what the investment costs for both concepts are based on the results of the model, but also additional investment costs in assets and infrastructure which were not considered in the model, have been considered. These have been compared to the benefits and disadvantages of both concepts in order to provide regional airport RTHA with an overview of the important considerations.

3.4.1. Comparison of the investment costs

Comparing central and decentralized charging solutions, Table 3.1 clearly shows that designing for a central location requires lower infrastructure investments compared to designing for decentralized locations. The cost comparison will mostly focus on the investment costs in charging infrastructure up till the 2035 scenario, since as mentioned, it is difficult to determine the investment costs associated with either new grid connections or the installation of an energy storage system for charging the Maeve operations in the 2035 scenario.

From the results it is clear that for both the central location as for the decentralized locations, making an early investment for the 2025 scenario will result in an infrastructure which is suitable to serve electric aviation for the next 7 years, including the 2030 scenario. For the central location installing a 350 kW charger will be capable of accommodating electric flight movements for the coming seven years, resulting in a required investment cost of €94,680. While, for designing for decentralized locations, till 2030, two 350 kW chargers and two 150 kW chargers will need to be installed at four different locations (JA, VCR, RAC and Hangars), resulting in a total of €276,110 charger acquisition costs. Furthermore, besides investing in the charger stations, the electricity grid at the locations needs to be sufficient, for which the results in Table 3.3 provided the investment costs associated with upgrading and renewing the electricity grid. For the central location, €25,059 is required to ensure a new grid connection which is sufficient till the 2035 scenario. For the decentralized locations, this investment is four times higher and equals €100.236.

Concluding, for the centralized location a total of €94,680 is required for chargers and €25,059 for upgrading the electricity grid, resulting in a total of €119,739 to ensure charging infrastructure for electric aviation in the coming seven years. For the decentralized location, the investment costs are approximately three times larger and equal a total of €376,346 (incl. charger and electricity grid investments). A cost difference of €256,607 is the difference between designing for a central location versus equipping five different decentralized locations with charging infrastructure sufficient until 2035. Thus, the central location is the cost favorable concept. However, in the case of reference airport, RTHA, the central location is assumed to be a new airport location for which investments in apron assets should be made. Which does result in an additional investment cost for the central location which is not required for the decentralized locations since charging stations will be included in the current infrastructure. The height of these investment costs will depend on airport decisions regarding the size of the apron and are excluded from this research, but it is an important factor to consider in case a new location will be designed.

3.4.2. Comparison of the benefits

For the comparison of the benefits of the two concepts, key performance indicators (KPIs] for an airport's airside operations are used as reference. The KPIs interesting for this comparison include aircraft turn around time, operational efficiency, taxiing distance and taxi time, passenger experience and safety incidents.

The operational concept of central charging included servicing the entire electric aircraft, including passenger (dis)embarkation, cleaning, and charging, at one location. However, in reality, regional airports like RTHA handle different passenger categories at their respective designated locations, which are not the newly designed central charging location. For example, flight club visitors and pilots gather at the flight clubs during aircraft turnarounds, while private, business, and commercial passengers use different airport areas for boarding and disembarking. Including a central charging location at RTHA would require passengers to either be (dis)embarking from the aircraft at their designated locations or be transported back and forth to the central location by a sort of shuttle bus, both increasing ground movements and operational complexity. In case the electric aircraft itself transports the passengers to the designated location, taxi distance and time are increased which is undesired as less time remains for servicing the aircraft within the turn around time. Transporting the passengers with another service like a shuttle bus, will lead to a decrease in passenger experience. Also, an increase of ground movements leads to an increasing probability of aircraft or vehicle collisions on airside, which is an undesired effect as the aim is to minimize the chance of incidents and ensure safe airport operations. Furthermore, implementing turnaround procedures at a new central location will lead to increasing operational expenses and under utilization of existing infrastructure and personnel, since rather than servicing the aircraft at locations where the assets are in place, additional resources should be realised in a new location.

Then, on the other hand, the decentralized charging locations concept includes charging takes together with the other turn around services place at the designated parking location of the aircraft. Looking at the key performance indicators, the aircraft turn around time is increased only for the charging operation duration it self compared to refueling of fossil fuel aircraft, but no additional time for taxiing to other locations is required. Also, the taxi distance and time remain the same as the aircraft will go to the designated parking location. The chance of safety incidents in terms of additional aircraft movements remains unchanged since no additional movements are included in the decentralized charging location concept. Also, passenger experience will in terms of additional taxi or on ground travel time, will not be impacted since the passengers will embark and disembark the aircraft at their preferred and designated locations.

Concluding, comparing the costs and the benefits of the two spatial charging concepts, the costs of equipping the five decentralized locations is for the next 7 years approximately €250,000 more expensive than the centralized investment costs of €94,680. However, on the other hand, charging the electric aircraft at decentralized locations has significant benefits over the central location which leads to an increase in taxi distance and time, a decreasing operational efficiency and increasing probability of aircraft collisions due to additional ground movements.

As for Rotterdam the Hague Airport, they wish to limit the number of additional ground movements and prioritize handling of aircraft at their designated locations, the advise is to equip the decentralized locations with the optimal required charging infrastructure (as given in Table 3.1). This does require an approximate investment cost of 370,000 euros and is compared to the centralized concept, 250,000 euros more expensive. However, designing for a central location will lead to increasing operational complexity since either the aircraft itself will need to taxi back and forth from the designated parking location to the central location, or busses will need to be in place to ensure the passengers are handled at their designated locations. For an airport questioning the required infrastructure sizing in support to electric aviation, it is advised to make a similar cost benefit analysis as presented by this research, for which the spatial aspects and preferences of the airport need to be taken into account to assess whether a central charging location or designing for various decentralized charging locations is more desirable.

4

Sensitivity Analysis

To study how the uncertainties in the model inputs affect the outcome of the model, various sensitivity analysis have been performed. The sensitivity analysis performed utilized a one at a time (OAT) method, in which one factor at a time is varied while keeping all other factors fixed at the original value. The OAT method is a local sensitivity analysis, since it studies the effect of one factor, the interactions amongst factors is less visible, as these are not varied simultaneously (Campolongo et al., 2011). However, since the model in this research is strictly linear, the OAT method is a valid approach (Saltelli et al., 2006).

First in section 4.1 the model reference days will be varied. Next, in section 4.2 variations will brought into the scenario percentages. After this, an analysis will be done into a change to the required SOC in section 4.3. In section 4.4, the sensitivity of the energy consumption for flight lessons and excursion flights will be tested. Last, in section 4.5 the charger acquisition cost will be varied.

4.1. Varying the model reference days

In this research first the most demanding days in terms of charging operations for the reference year 2022 were chosen. In order to assess what the optimal charging infrastructure would be if RTHA would change their objective, a sensitivity analysis is performed on model reference days. First, average modelling days have been selected, utilizing the same procedure as elaborated on in chapter 1, but then for the day which presents an average of daily charging operation demand for the reference year.

The results of the model for the average selected modelling days are presented in Table 4.1, for which also the outcomes of the model for the maximum charging operation days are presented as base value. From the table, it can be seen that modelling for an average day instead of for the maximum days in terms of charging operations, generally leads to a decrease of the optimal installed charger capacity and the required grid connection. For the central concept, the central location for the coming four years including 2027 can serve the average operation days with a 80 kW charger, which is upgraded to a 150 kW charger in the 2030 scenario while for these three future scenarios the optimal charger to serve the maximum charging operations has a power of 350 kW. Then, for the 2035 scenario excluding the fictitious Maeve flight schedule, the model gives installing a 3 MW charger together with a 80 kW charger as optimal solution. In order to accommodate the electric flight movements of the Maeve (2035* scenario), two additional 9 MW chargers are required while the 3 MW and 80 kW charger still need to be in place. From Table 4.1 it can be seen that for each future scenario the investment costs for charger acquisition are significantly lower than for the base maximum charging operation case. Except, for the 2035* scenario for which the investment costs are higher due to the additional 3 MW charger which is required to be installed, this is the result of a flight movement executed with an electric aircraft which is not compatible with the 3 megawatt charger, for which the 1 MW charger is required to fulfill the turn around of that flight. Then, looking at the decentralized locations, table Table 4.1 shows that both the daily operational charging costs and the total charger acquisition costs are significantly lower than the optimal solution for maximum operation infrastructure. For the Vliegclub Rotterdam, the Rotterdamsche Aeroclub and the Hangars it is seen that for all scenarios installing a 80 kW charger at these locations will be sufficient to accommodate the charging demand. For the main platform, no difference is seen in the optimal charging infrastructure. For the Jet Aviation decentralized location, the results show that lower charging capacity is required resulting in less demanding grid connections and lower investment costs.

	2025		**2027**		**2030**		**2035**		**2035***	
	Base	SA	Base	SA	Base	SA	Base	SA	Base	SA
Central location										
Electric flight movements	9	9	16	**11**	22	**14**	47	10	65	**28**
Number of charging events	4	**2**	7	**4**	10	**4**	14	**4**	23	**13**
Charger 80 (kW)	0	**1.0**	0	**1.0**	0	0	0	**1.0**	0	**1.0**
Charger 150 (kW)	0	0	0	0	0	**1.0**	0	0	0	0
Charger 350 (kW)	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**
Charger 3 (MW)	0	0	0	0	0	0	0	**1.0**	0	**1.0**
Charger 9 (MW)	0	0	0	0	0	0	1.0	**0**	2.0	2.0
Grid connection (*Ampere*)	505	**115**	505	**115**	505	**216**	13,500	**4,330**	26,000	26,000
Total cost:										
Operational costs (€/day)	291	**28**	345	**52**	428	**72**	8,734	**503**	40,475	**32,286**
Charger acq.costs (*1,000 €)	94.68	**24.2**	94.68	**24.2**	94.68	**43.37**	2,524	**834.2**	4,954	5,694.2
Decentralized locations										
Main platform										
Electric flight movements	0	0	0	0	0	0	0	0	18	18
Number of charging events	0	0	0	0	0	0	0	0	9	9
Charger 9 (MW)	0	0	0	0	0	0	0	0	2.0	2.0
Grid connection (*Ampere*)	0	0	0	0	0	0	0	0	25,980	25,980
Jet Aviation										
Electric flight movements	2	**0**	5	**4**	8	**4**	6	**16**	6	**16**
Number of charging events	0	0	1	1	1	**1**	2	2	2	2
Charger 80 (kW)	0	0	0	**1.0**	0	**1.0**	0	0	0	0
Charger 150 (kW)	0	0	1.0	**0**	1.0	**0**	0	0	0	0
Charger 1 (MW)	0	0	0	0	0	0	0	**1.0**	0	**1.0**
Charger 9 (MW)	0	0	0	0	0	0	1.0	**0**	1.0	**0**
Grid connection (*Ampere*)	0	0	216	**115**	216	**115**	13,000	**1,443**	13,000	**1,443**
Vliegclub Rotterdam										
Electric flight movements	6	**5**	10	**6**	14	**12**	21	**13**	21	**13**
Number of charging events	3	**2**	4	**1**	5	**2**	7	**3**	7	**3**
Charger 80 (kW)	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**
Charger 350 (kW)	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**
Grid connection (*Ampere*)	505	**115**	505	**115**	505	**115**	505	**115**	505	**115**
Rotterdamsche Aeroclub										
Electric flight movements	2	2	5	**3**	6	**3**	10	**3**	10	**3**
Number of charging events	1	1	2	**1**	3	**1**	4	**1**	4	**1**
Charger 80 (kW)	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**
Charger 350 (kW)	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**
Grid connection (*Ampere*)	505	**115**	505	**115**	505	**115**	505	**115**	505	**115**
Hangars										
Electric flight movements	3	**0**	7	**3**	12	**3**	22	**6**	22	**6**
Number of charging events	1	**0**	3	**1**	5	**1**	7	**2**	7	**2**
Charger 80 (kW)	0	0	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**
Charger 150 (kW)	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**
Grid connection (*Ampere*)	216	**0**	216	**115**	216	**115**	216	**115**	216	**115**
Total cost:										
Operational costs (€/day)	415	**22**	609	**77**	700	**74**	7,711	**1,514**	39,494	**33,297**
Charger acq.costs (*1,000 €)	232.73	**48.4**	276.11	**96.8**	276.11	**96.8**	2,663	**342.6**	7,523	**5,202**

Table 4.1: Results model and sensitivity analysis, average modelling day

4.2. Variations in the scenario percentages

Another sensitivity analysis will be changing the scenario percentages within realistic limits and seeing what the effect will be on the optimal charging infrastructure. First in subsection 4.2.1 the flight school percentage for the 2025 scenario will be adapted. After this the effects of varying the business aviation percentage for the 2030 and 2035 scenario will be analyzed in subsection 4.2.2.

4.2.1. Adapting the flight school percentage for the 2025 scenario

In the 2025 scenario, both the flight clubs located at Rotterdam the Hague Airport expressed their ambition to purchase and include an electric flight trainer aircraft, for which based on their current fleet, it was assumed that 30% of the flight school movements at RTHA would become electrified. A sensitivity analysis has been performed to see what would be the impact on the required charging infrastructure for case study RTHA if the implementation of electric aviation at the flight schools goes slower or faster than expected. Note that this can be dependent on the market /technological developments and financial considerations.

The results of the sensitivity analysis in which the flight school scenario percentage has been varied for the 2025 scenario, are presented in Table 4.2. In the table, only the locations for which a change in installed charger capacity occurred are displayed. No changes are visible for the central location, expect for the 5% value. This is similar for the decentralized Vliegclub Rotterdam location. For the Rotterdamsche Aeroclub and the Hangar locations however, for a decrease in the number of electric flight movements it is seen that no chargers are required to install since no electric flight movements are assumed. Concluding, varying the flight school percentage for the 2025 scenario for some of the locations results in that no charger capacity is required to be installed since no charging operations are performed and for an higher uptake up to 45% the optimal installed charger capacity is similar for all locations as for the 30% base scenario percentage.

Base	**FS % value**	**e-movements**	**Charging events**	**Installed charging capacity**	
		Value [-]	Value [-]	Value [kW]	Change[1]
Central 2025 scenario	30	9	4	350	-
	5	1	0	0	-100%
	10	3	1	350	0%
	⋮	⋮	⋮	⋮	⋮
	45	14	7	350	0%
Vliegclub Rotterdam	30	6	3	350	-
	5	0	0	0	-100%
	10	2	1	350	0%
	⋮	⋮	⋮	⋮	⋮
	45	9	4	350	0%
Rotterdamsche Aeroclub	30	2	1	350	-
	5	0	0	0	-100%
	⋮	⋮	⋮	⋮	⋮
	20	1	0	0	-100%
	25	2	1	350	0%
	⋮	⋮	⋮	⋮	⋮
	45	3	1	350	0%
Hangars	30	3	1	150	-
	5	0	0	0	-100%
	10	0	0	0	-100%
	15	1	0	0	-100%
	20	2	1	150	0%
	⋮	⋮	⋮	⋮	⋮
	45	6	3	150	0%

Table 4.2: Results sensitivity analysis for variations in flight school percentage 2025 scenario, [1]: Change with respect to base case

4.2.2. Effects of varying the business aviation percentage for the 2030 and 2035 scenario

While setting up the scenarios, assumptions were made about the expected up take of electric aviation in the business aviation segment. Therefore, a sensitivity analysis is performed to check for the effect of varying the assumed electric aviation uptake percentages of the business aviation in the 2030 and 2035 scenario. The results of varying the business aviation percentages for the 2030 scenario are displayed in Table 4.3. In this table, the central location and the decentralized Jet Aviation location have been displayed, for the other decentralized locations no change occurred compared to the base value of 5%. From the table it can be seen that for the central location, varying the business aviation (BA) percentage value does not influence the optimal installed charging capacity, neither does it change the number of charging events and electric flight movements. For the Jet Aviation location, the optimal installed charging capacity is unchanged when business aviation electric movements turn out less than expected in the base case. However, when the business aviation share of potential flight movements is increased with 10-15%, the installed charging capacity increases to installing a 1 MW charger instead of a 150 kW charger. However, it should be noted that it might be that for this modelling day a more demanding charging operation was included which significantly changed the outcome, which might not be the case if another modelling day was selected.

Base	**BA % value**	**e-movements**	**Charging events**	**Installed charging capacity**	
		Value [-]	Value [-]	Value [kW]	Change[1]
Central location	5	23	10	350	-
	0	23	10	350	0%
	2	23	10	350	0%
	7	23	10	350	0%
	10	23	10	350	0%
	12	23	10	350	0%
	15	23	10	350	0%
Jet Aviation	5	8	1	150	-
	0				
	2	7	1	150	0%
	7	8	1	150	0%
	10	9	2	1000	567%
	12	9	2	1000	567%
	15	10	2	1000	567%

Table 4.3: Results sensitivity analysis for variations in business aviation percentage 2030 scenario, [1]: Change with respect to base case

4.3. Charging up to 80% SOC instead of required SOC for the next mission

In order to evaluate the optimal charging infrastructure in case charging up to 80% SOC would be required as minimum rather than charging up to the required level of charge of the next mission, a sensitivity analysis has been conducted for which the results are shown in Table 4.4.

Initially, it can be expected that if charging up to a minimum battery state of charge of 80% is set as requirement in stead of charging up to the required SOC for the next mission, that this will likely result in more demanding charging operations and potentially requiring higher charger capacities. From Table 4.4 it can be seen that indeed for some of the locations and scenarios the charging capacity is higher for the 80% SOC minimum charging than for the base case. However, the figure also shows that for the central location for the 2027 scenario and the Rotterdamsche Aeroclub scenarios, the installed capacity is reduced. This is because, setting the requirement of charging to at least 80% battery SOC ensures that during the day an aircraft that was in the base case not charged during a turn around, does get charged. As a result, the total SOC upon the next arrival at RTHA is higher and less charging is required to get to 80% or required SOC for the next mission. In case of a short turn around time, the charging operation may turn out less demanding than in the base case and the final optimal installed charging capacity is lower. Concluding, setting the requirement of charging up to a minimum of 80%

battery SOC, for sure influences the outcomes of the optimization model, for some cases it increases the required charging infrastructure, while for others the required charging infrastructure is decreased and for some cases the outcome remains similar to the base case of charging up to required SOC for the next mission.

	2025		**2027**		**2030**		**2035**		**2035***	
	Base	SA	Base	SA	Base	SA	Base	SA	Base	SA
Central location										
Electric flight movements	9	9	16	16	22	22	47	47	65	65
Number of charging events	4	4	7	7	10	**11**	14	**16**	23	**25**
Charger 150 (kW)	0	0	0	**1.0**	0	0	0	**1.0**	0	**1.0**
Charger 350 (kW)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Charger 9 (MW)	0	0	0	0	0	0	1.0	1.0	2.0	2.0
Grid connection (*Ampere*)	505	505	505	**720**	505	505	13,500	**13,710**	26,000	**26,700**
Total cost:										
Operational costs (€/day)	291	291	345	**451**	428	**647**	8,734	**12,056**	40,475	**45,089**
Charger acq.costs (*1,000 €)	94.68	94.68	94.68	**138**	94.68	94.68	2,524	**2,568**	4,954	**4,998**
Decentralized locations										
Main platform										
Electric flight movements	0	0	0	0	0	0	0	0	18	18
Number of charging events	0	0	0	0	0	0	0	0	9	9
Charger 9 (MW)	0	0	0	0	0	0	0	0	2.0	2.0
Grid connection (*Ampere*)	0	0	0	0	0	0	0	0	25,980	25,980
Jet Aviation										
Electric flight movements	2	2	5	5	8	8	6	6	6	6
Number of charging events	0	0	1	**2**	1	**2**	2	2	2	2
Charger 150 (kW)	0	0	1.0	1.0	1.0	1.0	0	0	0	0
Charger 9 (MW)	0	0	0	0	0	0	1.0	1.0	1.0	1.0
Grid connection (*Ampere*)	0	0	216	216	216	216	13,000	13,000	13,000	13,000
Vliegclub Rotterdam										
Electric flight movements	6	6	10	10	14	14	21	21	21	21
Number of charging events	3	3	4	**5**	5	**6**	7	**8**	7	**8**
Charger 80 (kW)	0	0	0	0	0	0	0	**1.0**	0	**1.0**
Charger 350 (kW)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Grid connection (*Ampere*)	505	505	505	505	505	505	505	**620**	505	**620**
Rotterdamsche Aeroclub										
Electric flight movements	2	2	5	5	6	6	10	10	10	10
Number of charging events	1	1	2	2	3	3	4	4	4	4
Charger 150 (kW)	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**	0	**1.0**
Charger 350 (kW)	1.0	**0**	1.0	**0**	1.0	**0**	1.0	**0**	1.0	0
Grid connection (*Ampere*)	505	**216**	505	**216**	505	**216**	505	**216**	505	**216**
Hangars										
Electric flight movements	3	3	7	7	12	12	22	22	22	22
Number of charging events	1	1	3	3	5	5	7	7	7	7
Charger 150 (kW)	1.0	1.0	1.0	1.0	1.0	**0**	1.0	**0**	1.0	**0**
Charger 350 (kW)	0	0	0	0	0	**1.0**	0	**1.0**	0	**1.0**
Grid connection (*Ampere*)	216	216	216	216	216	**505**	216	**505**	216	**505**
Total cost:										
Operational costs (€/day)	415	**352**	609	**683**	700	**938**	7,711	**7,880**	39,494	**40,951**
Charger acq.costs (*1,000 €)	232.73	**181.43**	276.11	**224.8**	276.11	276.11	2,663	**2,687**	7,523	**7,547**

Table 4.4: Results model and sensitivity analysis 80% charging

4.4. Varying energy consumption of flight lesson and excursion flights

For the terrain trips, including excursion flights and flight lessons, for which the flown distance and flight duration is unknown, the research initially assumes a 60% energy consumption during flight. This value is based on the average consumption of a one hour flight with the Diamond eDA40 and eFlyer 4 which are the aircraft types performing the round trips in this research. However, the energy consumption will depend on the profile of the terrain trip, for which each terrain trip is different. Initially, a one hour flight duration was assumed for these trips (average duration provided by the flight schools), however in reality some terrain trips will have a longer duration of 1.5 hours and some shorter. This will result in a different energy consumption during that flight, which potentially will impact the model outcome in terms of the optimal required charging capacity installed. Therefore, a sensitivity analysis is included for which the energy consumption during a terrain trip is varied. The ranges of the variations are from 40 to 80%, 80% is taken as upper bound, since for this research a safety battery reserve of 20% battery capacity is always included.

The results of varying the energy consumption during terrain trips for the 2025 scenario are presented in Table 4.5. In this table, the central location and decentralized charging locations for which a change in optimal charging infrastructure occurs are displayed, the main platform and jet aviation are not included as no change in infrastructure occurred. In this table, a clear trend is visible between an increase in energy consumption and installed charging capacity.

Base	**Energy consumption [%]**	**Installed charging capacity**	
		Value [kW]	Change[1]
Central location	60	350	-
	40	350	0%
	50	350	0%
	65	1150	228%
	70	1350	285%
	75	1350	285%
	80	infeasible	-
Vliegclub Rotterdam	60	350	-
	40	350	0%
	50	350	0%
	65	350	0%
	70	1000	186%
	75	1000	186%
	80	infeasible	-
Rotterdamsche Aeroclub	60	350	-
	40	80	-77%
	50	150	-57%
	65	350	0%
	70	1000	186%
	75	1000	186%
	80	infeasible	-
Hangars	60	150	-
	40	80	-47%
	50	150	0%
	65	150	0%
	70	150	0%
	75	350	133%
	80	infeasible	-

Table 4.5: Results sensitivity analysis for variations in energy consumption during terrain trips in the 2025 scenario, [1]: Change with respect to base case

4.5. Variation in charger acquisition costs

In order to assess the sensitivity of the model outputs to the inputs of charger acquisition costs, these costs were varied for a 20% increase and a 20% decrease. A decrease of 20% can be expected for when technology progresses quickly and the electric cars and buses chargers technology can be employed. On the other hand, an increase of charger acquisition costs can be expected when technology progresses slowly or that scarcity of components occurs, which causes the price to rise. These variations in charger costs have been applied to all future scenarios as considered in this research, for which the 2025 scenario is presented in Table 4.6. The table shows that varying the charger acquisition cost, only results in a charger investment cost change and does not change the required charging infrastructure in terms of installed charger capacity and required grid connection, neither does it change the operational costs of charging. Since, for the other scenarios the optimal infrastructure sizing remained the same and also only a change in charger acquisition investment cost was seen, only one of the scenarios (scenario 2025) was displayed for insight.

	20% increase				**20% decrease**			
	Central		**Decentralized**		**Central**		**Decentralized**	
	Base	SA	Base[1]	SA[1]	Base	SA	Base[1]	SA[1]
Installed charger capacity [kW]	350	350	850	850	350	350	850	850
Grid connection [A]	505	505	1226	1226	505	505	1226	1226
Operational costs (€)	291	291	415	415	291	291	415	415
Charger acq. costs (*1,000 €)	94.68	**113.6**	232.73	**279.28**	94.68	**75.7**	232.73	**186.19**

Table 4.6: Results sensitivity analysis for variations in charger acquisition prices for the 2025 scenario, [1]: Sum of installed charger capacity and grid connections amongst all five decentralized locations

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A

Figures

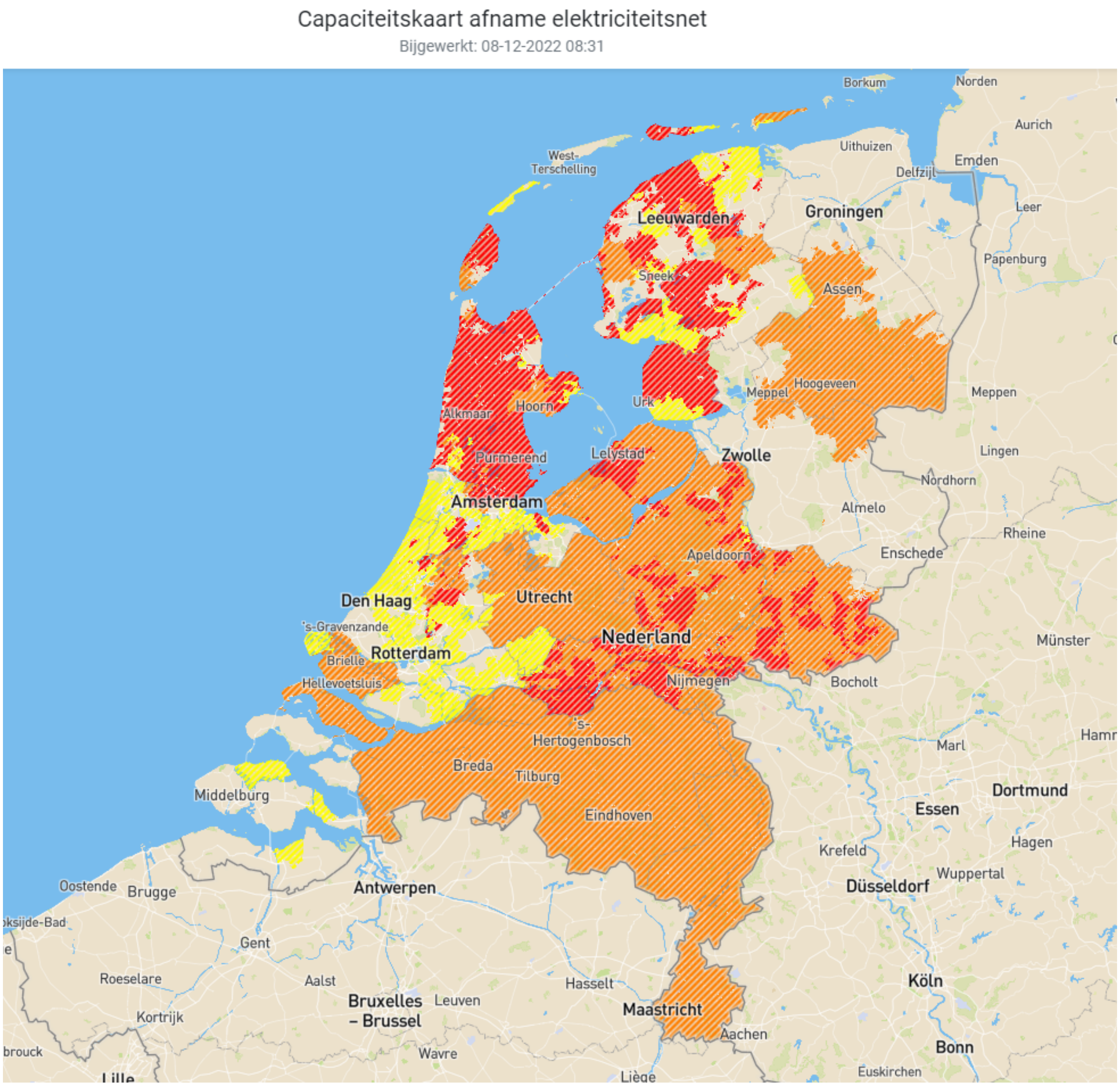


Figure A.1: Capacity map demand electricity grid in the Netherlands, attained from Nederland Netbeheer, 2022

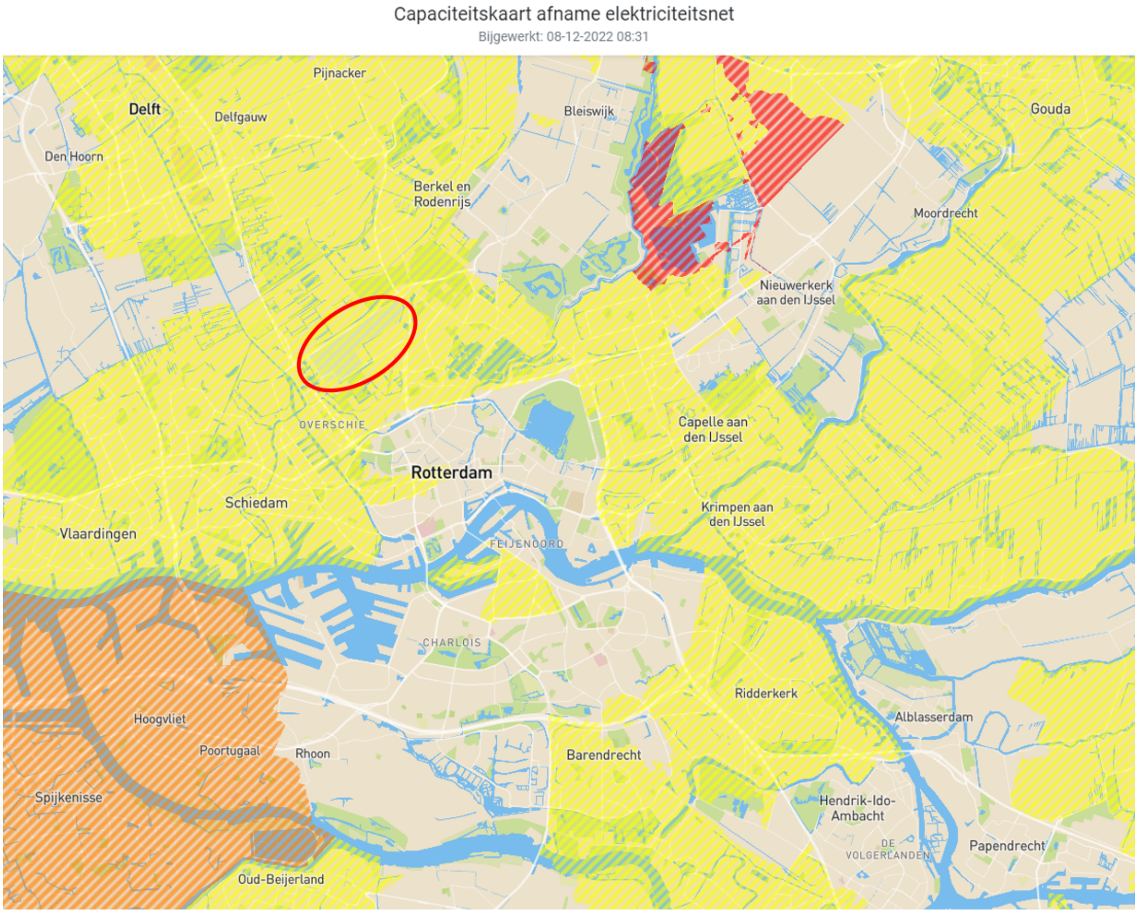


Figure A.2: Capacity map demand electricity grid in the Netherlands, indicating location of Rotterdam the Hague Airport, attained from Nederland Netbeheer, 2022

B

Additional results

B.1. Verification results

B.1.1. Verification set 1, charging schedule

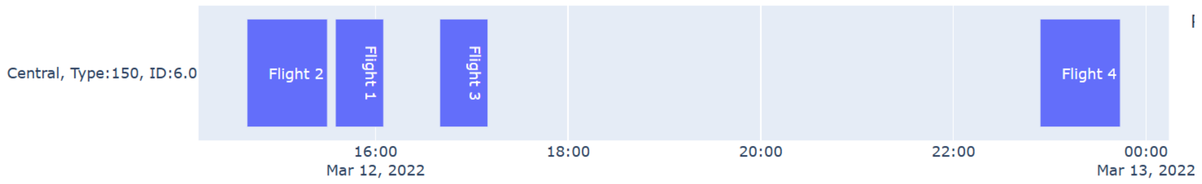


Figure B.1: Charging schedule, result of verification set 1

B.1.2. Verification set 2, charging schedule

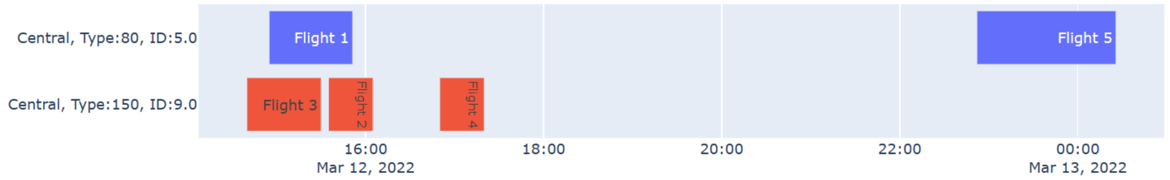


Figure B.2: Charging schedule, result of verification set 2

B.1.3. Verification set 3, charging schedule

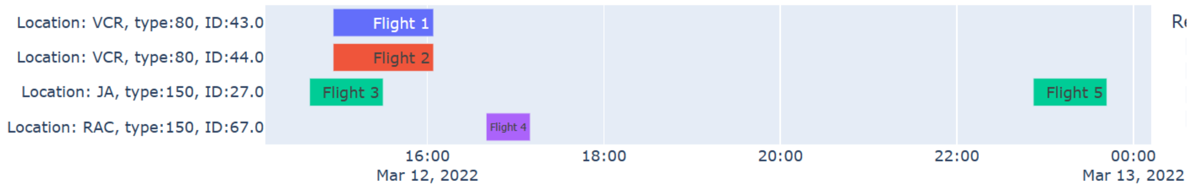


Figure B.3: Charging schedule, result of verification set 3

B.2. Infrastructure sizing model results

B.2.1. Central location, 2025 scenario

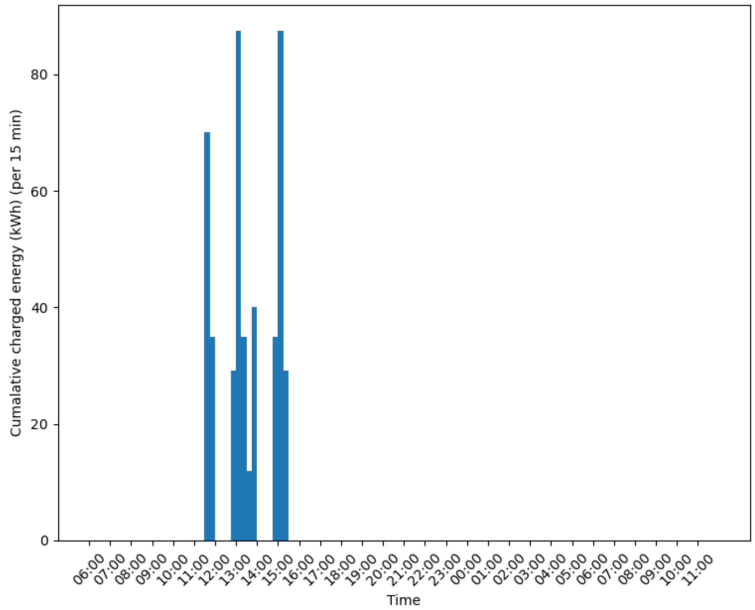


Figure B.4: Requested energy during reference day, central location 2025 scenario

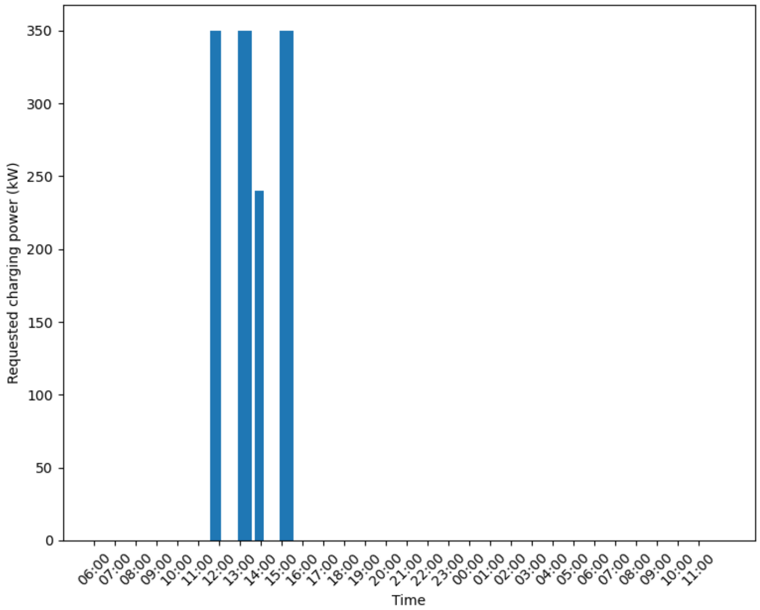


Figure B.5: Requested charging power during reference day, central location 2025 scenario

Figure B.6: Optimal daily charging schedule, central location 2025 scenario

B.2.2. Central location, 2027 scenario

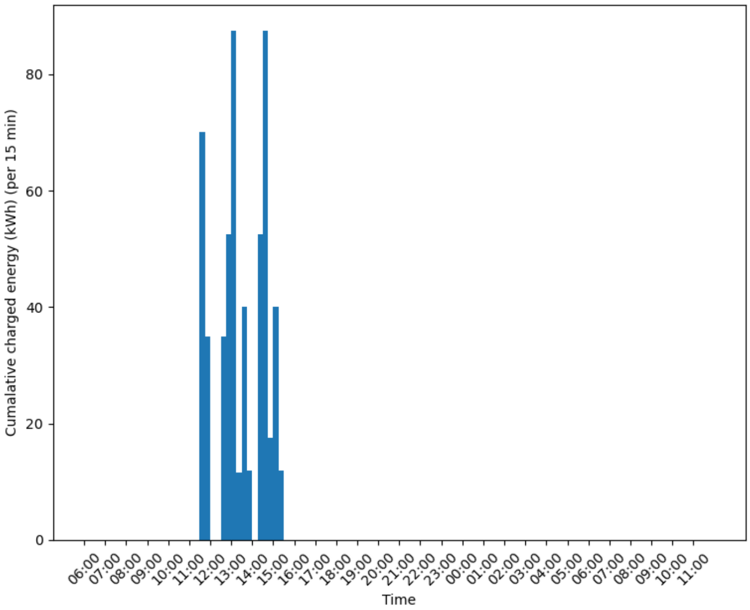


Figure B.7: Requested energy during reference day, central location 2027 scenario

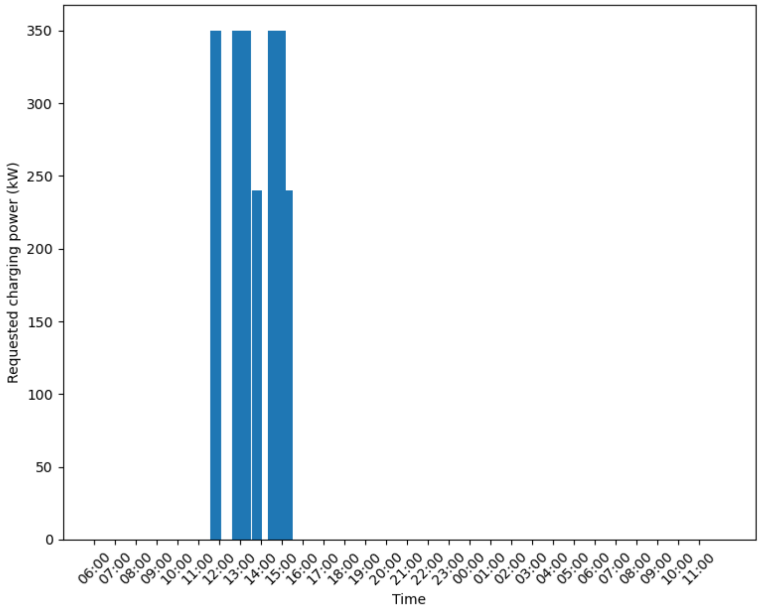


Figure B.8: Requested charging power during reference day, central location 2027 scenario

Figure B.9: Optimal daily charging schedule, central location 2027 scenario

B.2.3. Central location, 2035 scenario

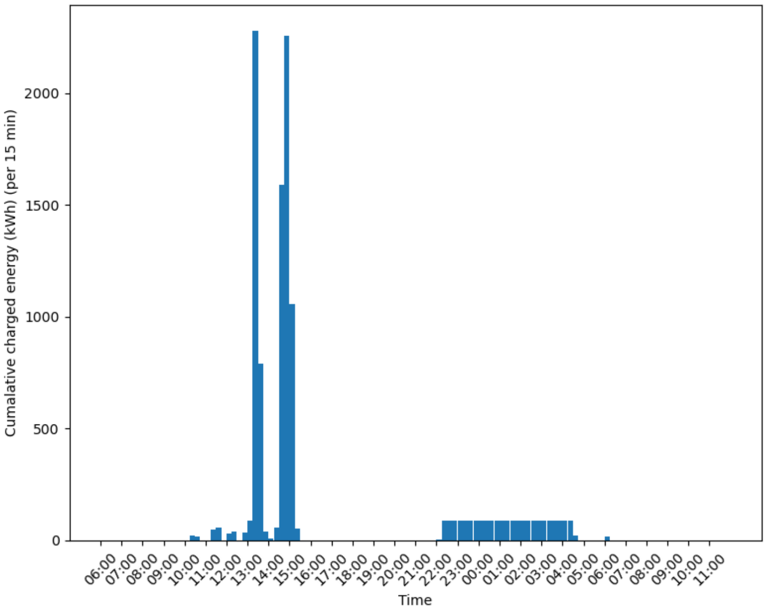


Figure B.10: Requested energy during reference day, central location 2035 scenario

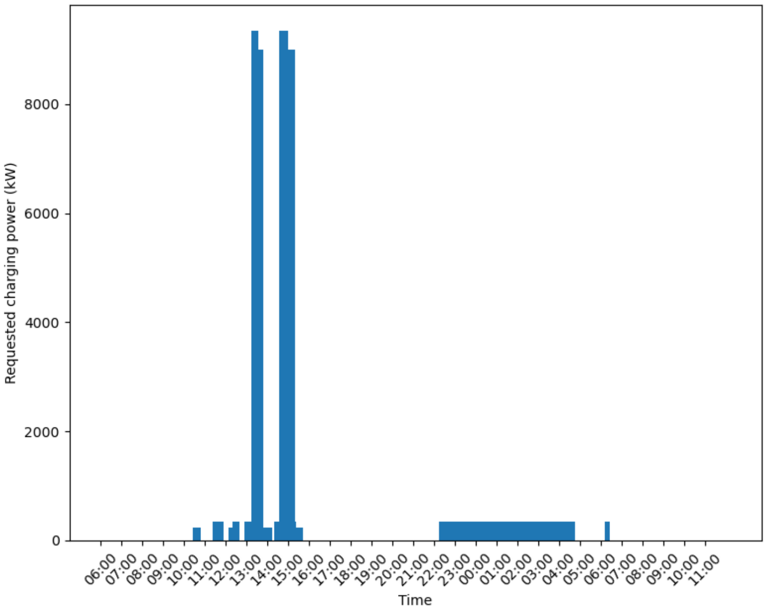


Figure B.11: Requested charging power during reference day, central location 2035 scenario

Figure B.12: Optimal daily charging schedule, central location 2030 scenario

B.2.4. Central location, 2035 scenario

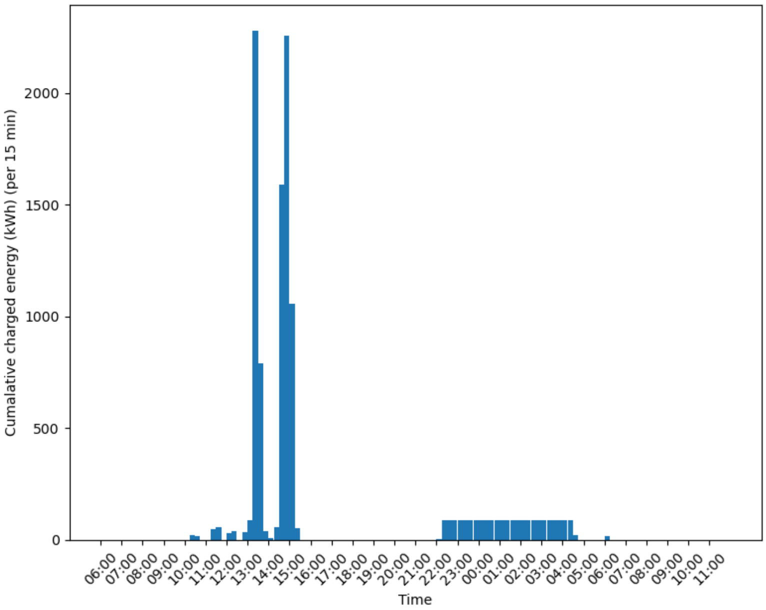


Figure B.13: Requested energy during reference day, central location 2035 scenario

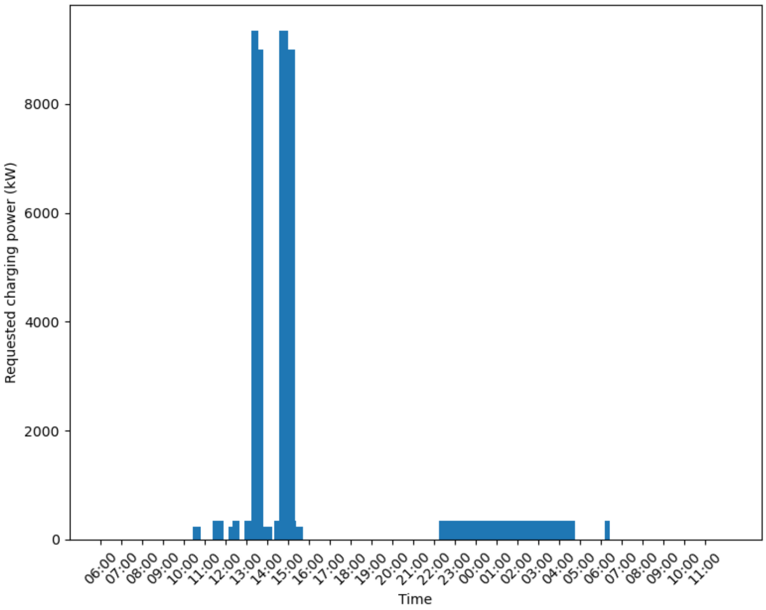


Figure B.14: Requested charging power during reference day, central location 2035 scenario

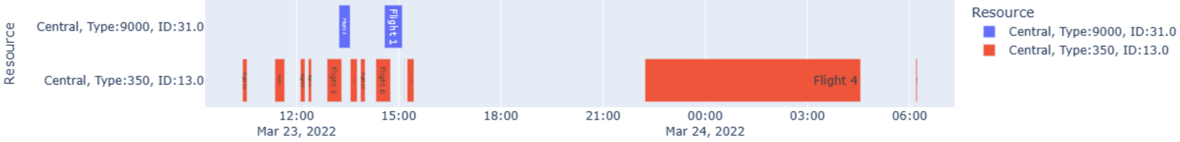


Figure B.15: Optimal daily charging schedule, central location 2035 scenario

B.2.5. Central location, 2035^* scenario

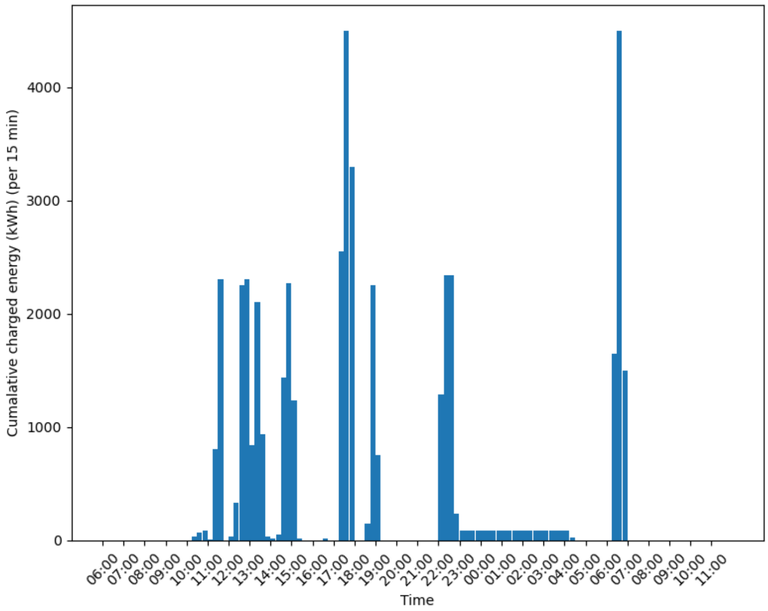


Figure B.16: Requested energy during reference day, central location 2035^* scenario

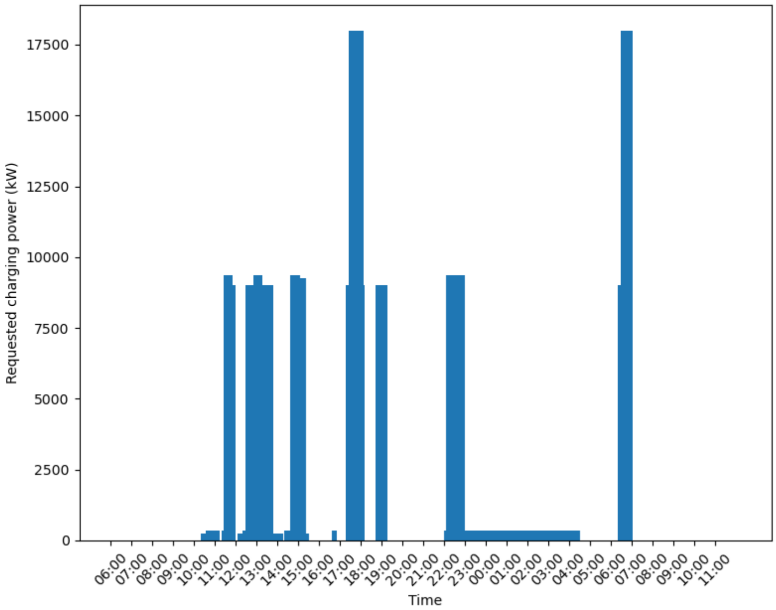
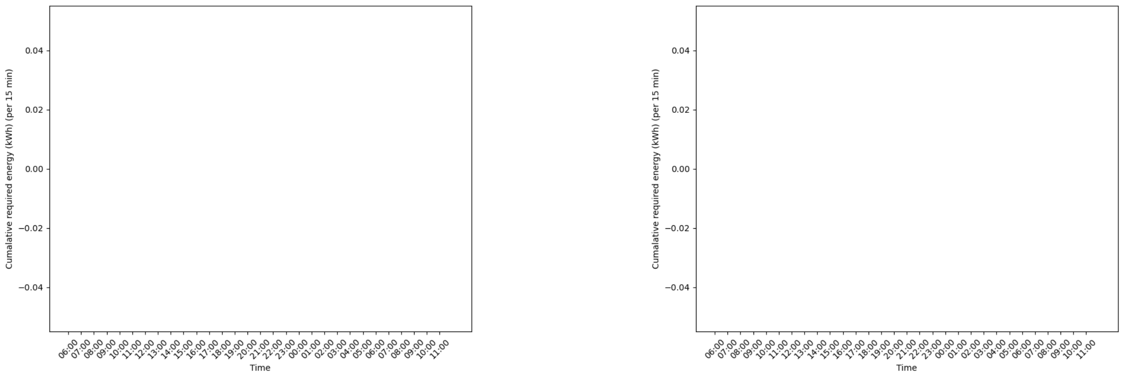


Figure B.17: Requested charging power during reference day, central location 2035^* scenario

Figure B.18: Optimal daily charging schedule, central location 2035* scenario

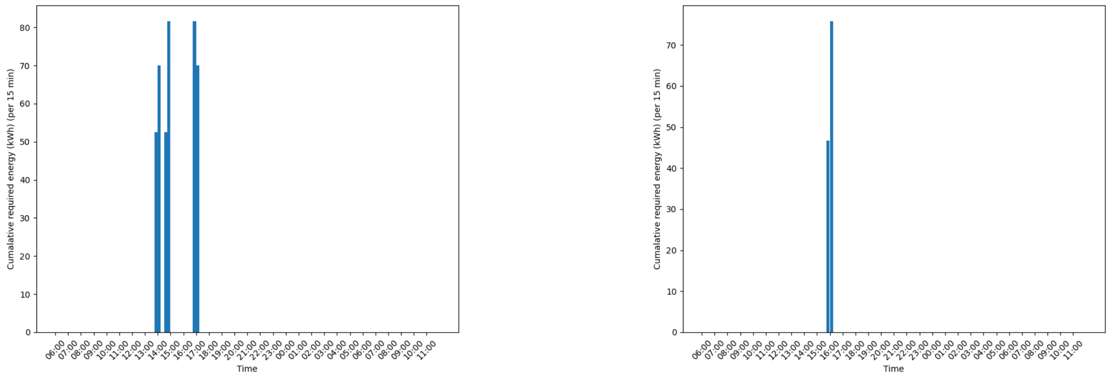
B.2.6. Decentralized locations, 2025 scenario



(a) Requested energy, Main platform

(b) Requested energy, Jet Aviation

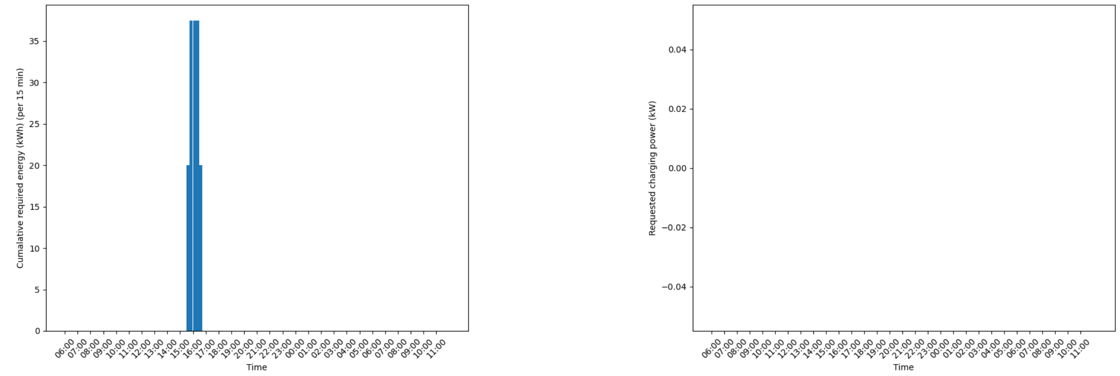
Figure B.19: 2025 scenario



(a) Requested energy, Vliegclub Rotterdam

(b) Requested energy, Rotterdamsche Aeroclub

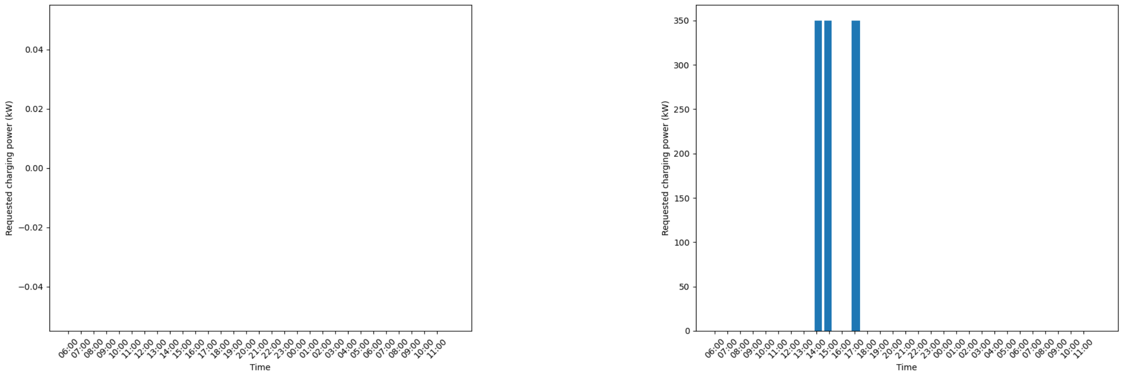
Figure B.20: 2025 scenario



(a) Requested energy, Hangars

(b) Requested power, Main Platform

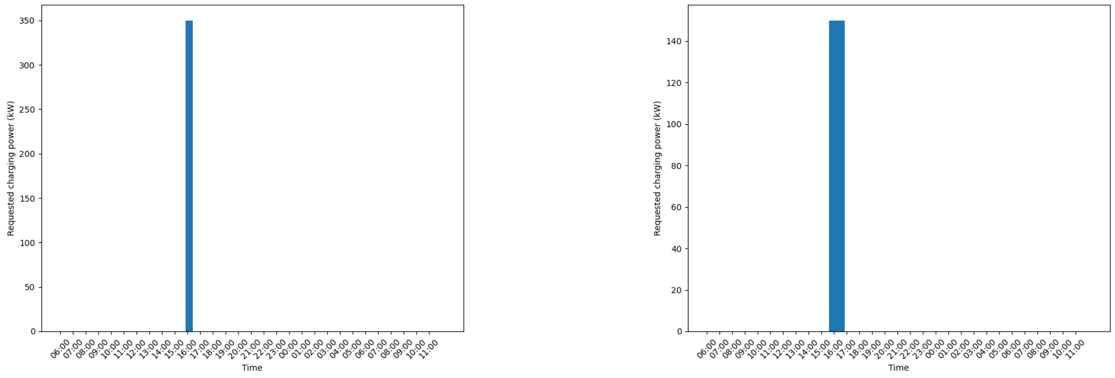
Figure B.21: 2025 scenario



(a) Requested power, Jet Aviation

(b) Requested power, Vliegclub Rotterdam

Figure B.22: 2025 scenario



(a) Requested power, Rotterdamsche Aeroclub

(b) Requested power, Hangars

Figure B.23: 2025 scenario

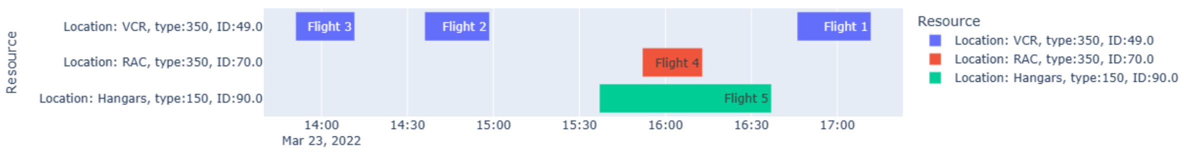
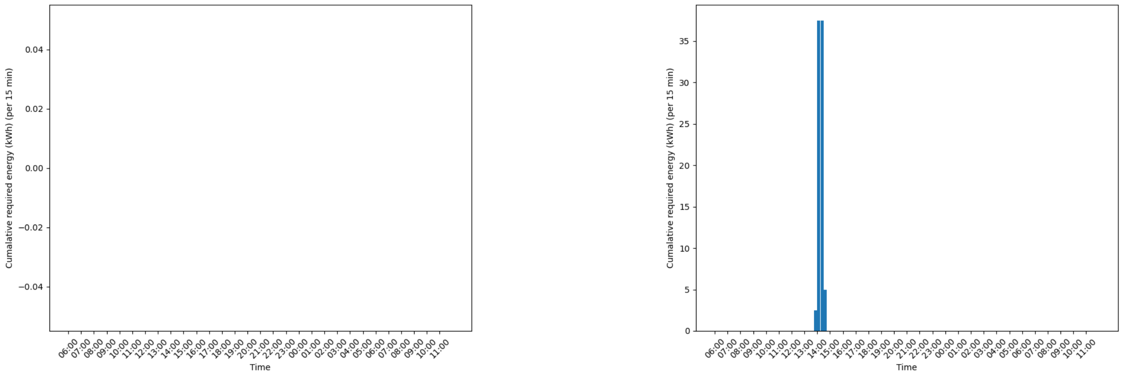


Figure B.24: Optimal daily charging schedule, decentralized locations 2025 scenario

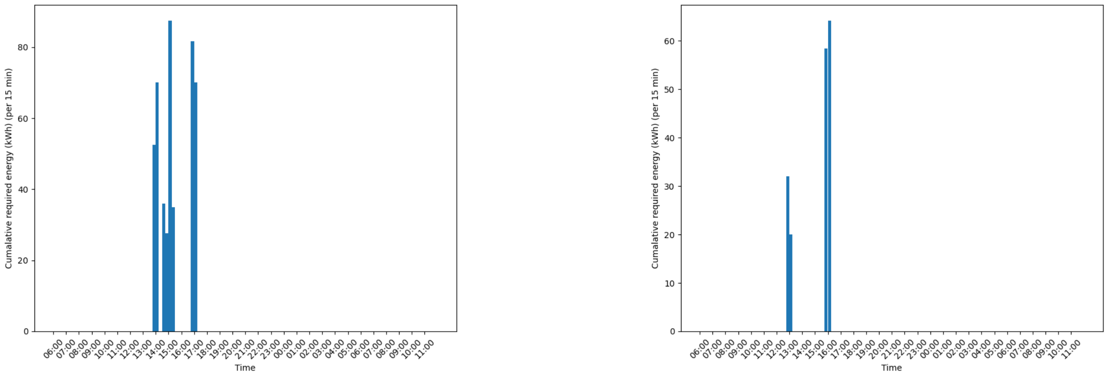
B.2.7. Decentralized locations, 2027 scenario



(a) Requested energy, Main platform

(b) Requested energy, Jet Aviation

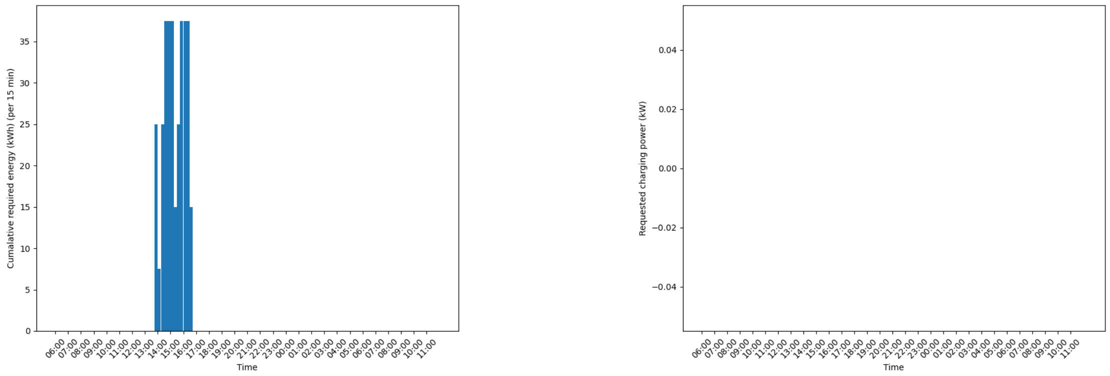
Figure B.25: 2027 scenario



(a) Requested energy, Vliegclub Rotterdam

(b) Requested energy, Rotterdamsche Aeroclub

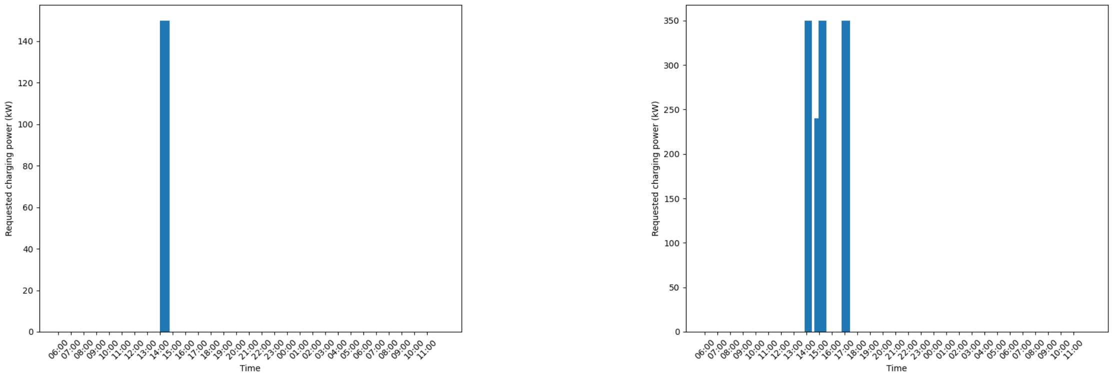
Figure B.26: 2027 scenario



(a) Requested energy, Hangars

(b) Requested power, Main Platform

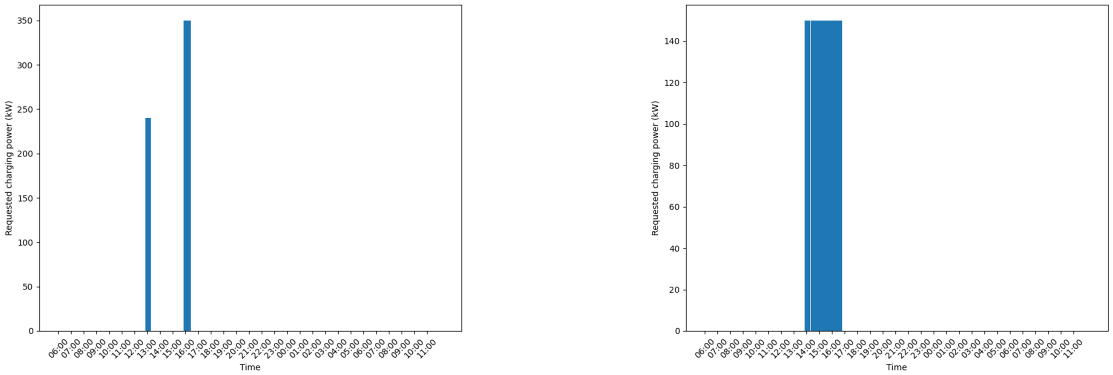
Figure B.27: 2027 scenario



(a) Requested power, Jet Aviation

(b) Requested power, Vliegclub Rotterdam

Figure B.28: 2027 scenario



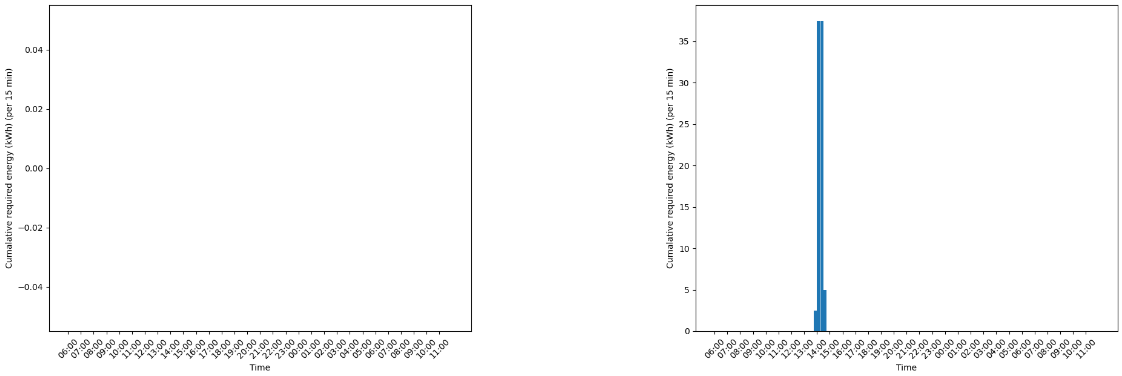
(a) Requested power, Rotterdamsche Aeroclub

(b) Requested power, Hangars

Figure B.29: 2027 scenario

Figure B.30: Optimal daily charging schedule, decentralized locations 2027 scenario

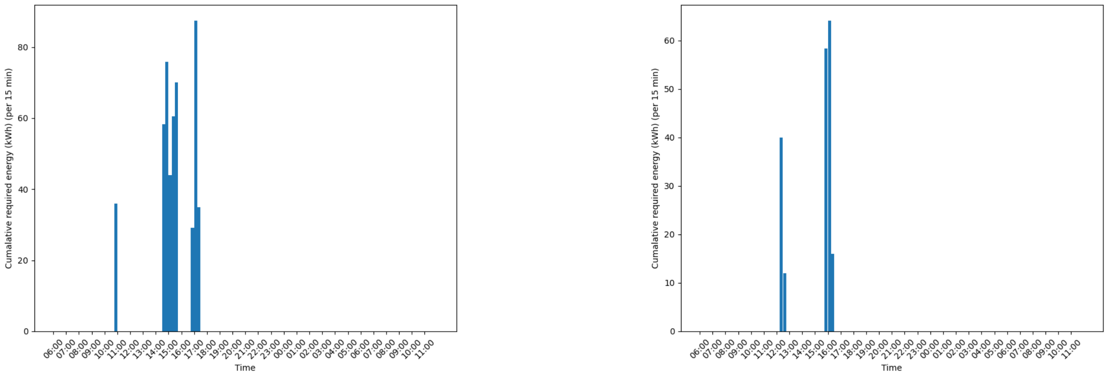
B.2.8. Decentralized locations, 2030 scenario



(a) Requested energy, Main platform

(b) Requested energy, Jet Aviation

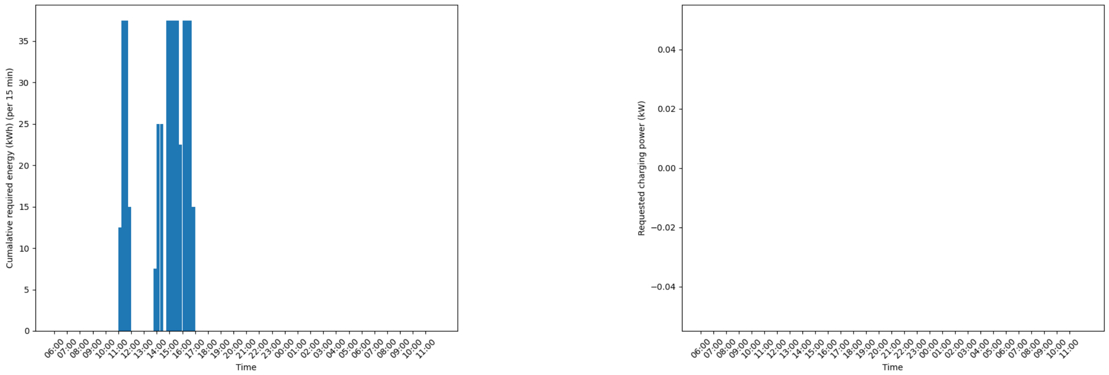
Figure B.31: 2030 scenario



(a) Requested energy, Vliegclub Rotterdam

(b) Requested energy, Rotterdamsche Aeroclub

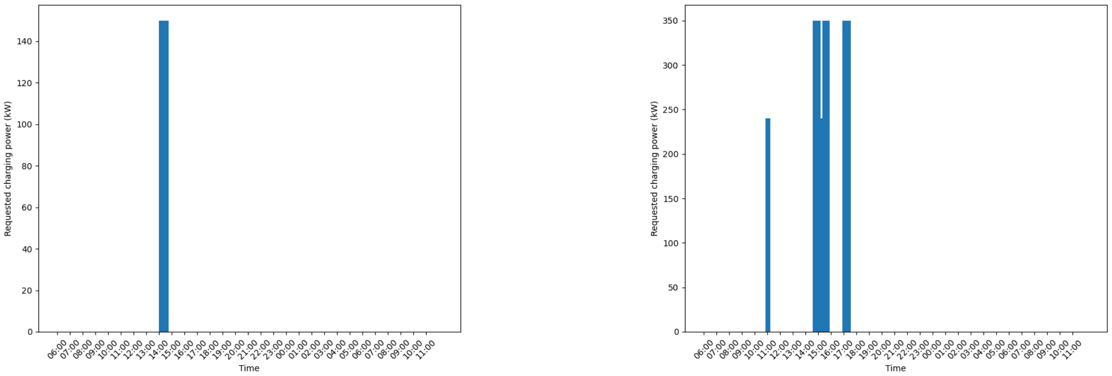
Figure B.32: 2030 scenario



(a) Requested energy, Hangars

(b) Requested power, Main Platform

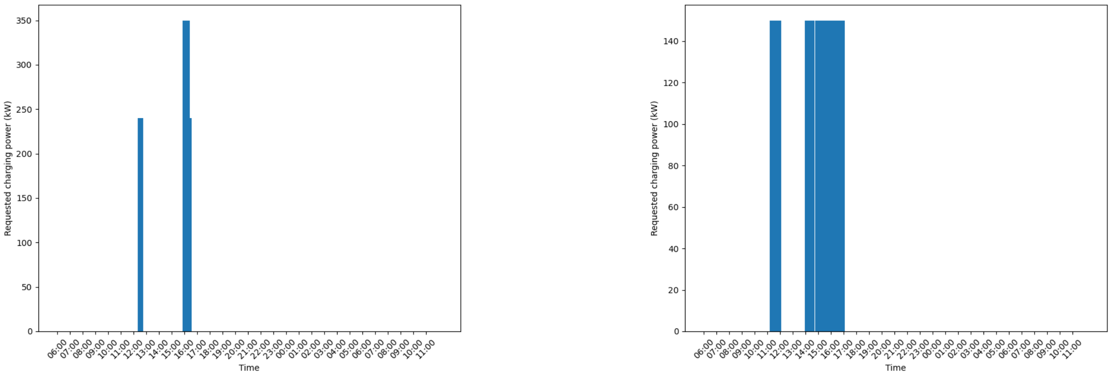
Figure B.33: 2030 scenario



(a) Requested power, Jet Aviation

(b) Requested power, Vliegclub Rotterdam

Figure B.34: 2030 scenario



(a) Requested power, Rotterdamsche Aeroclub

(b) Requested power, Hangars

Figure B.35: 2030 scenario

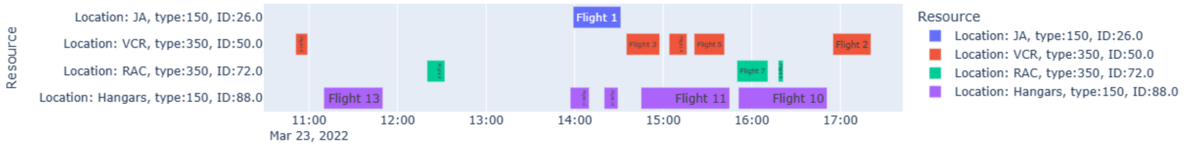
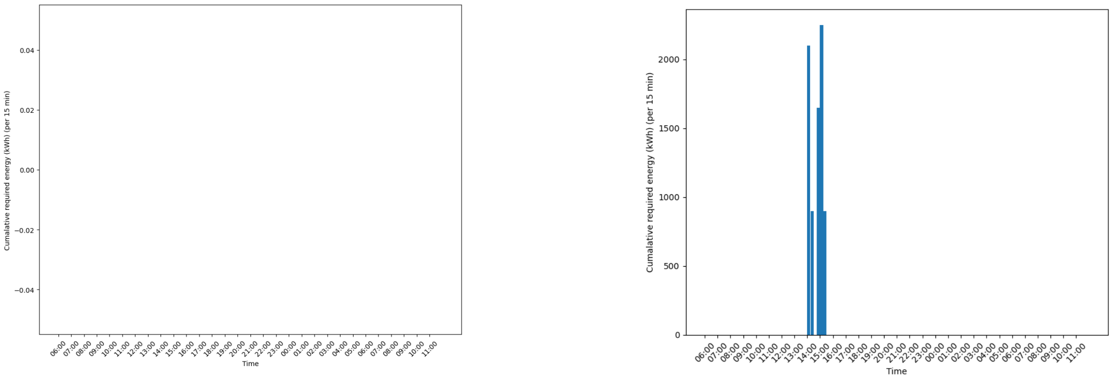


Figure B.36: Optimal daily charging schedule, decentralized locations 2030 scenario

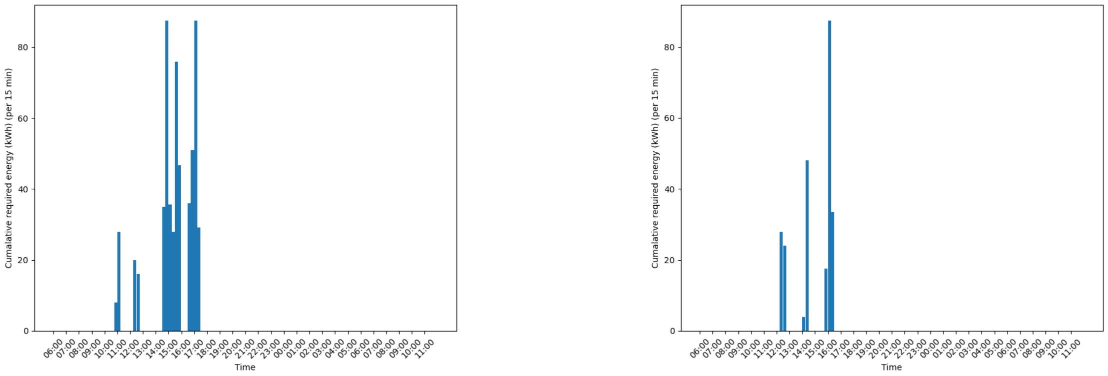
B.2.9. Decentralized locations, 2035 scenario



(a) Requested energy, Main platform

(b) Requested energy, Jet Aviation

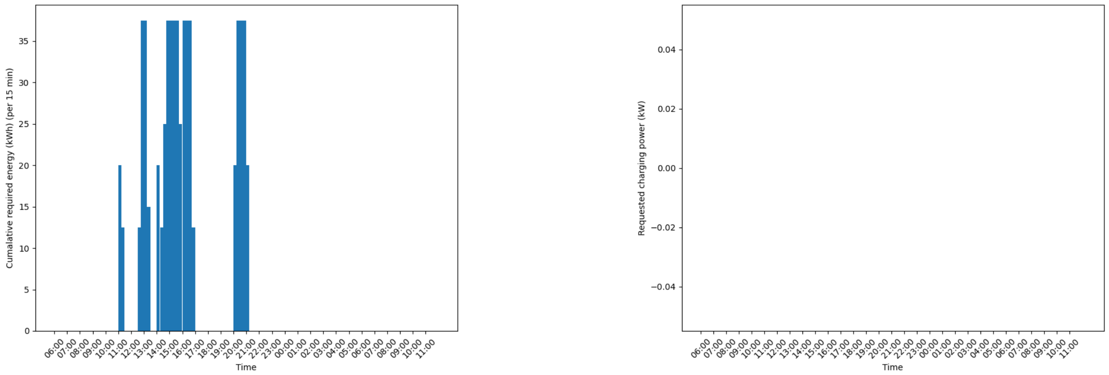
Figure B.37: 2035 scenario



(a) Requested energy, Vliegclub Rotterdam

(b) Requested energy, Rotterdamsche Aeroclub

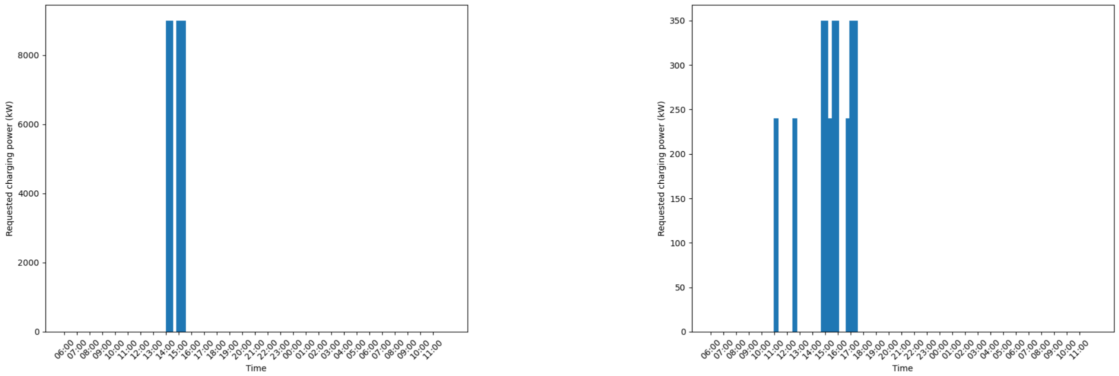
Figure B.38: 2035 scenario



(a) Requested energy, Hangars

(b) Requested power, Main Platform

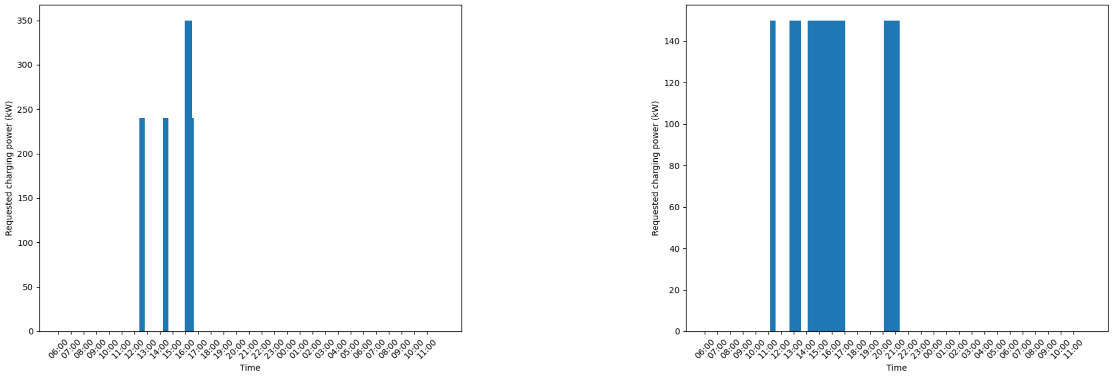
Figure B.39: 2035 scenario



(a) Requested power, Jet Aviation

(b) Requested power, Vliegclub Rotterdam

Figure B.40: 2035 scenario



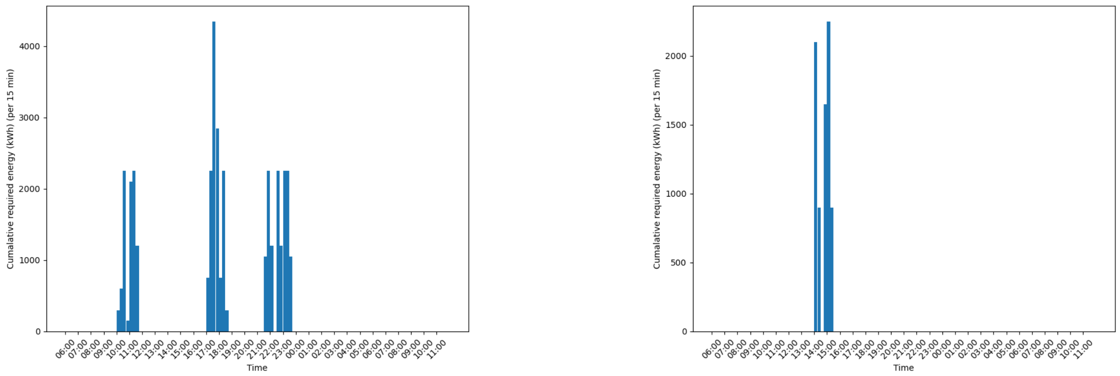
(a) Requested power, Rotterdamsche Aeroclub

(b) Requested power, Hangars

Figure B.41: 2035 scenario

Figure B.42: Optimal daily charging schedule, decentralized locations 2035 scenario

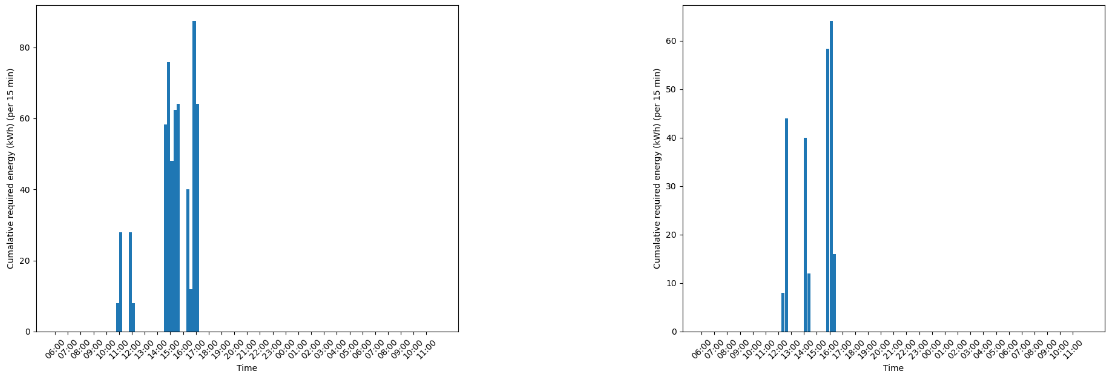
B.2.10. Decentralized locations, 2035* scenario



(a) Requested energy, Main platform

(b) Requested energy, Jet Aviation

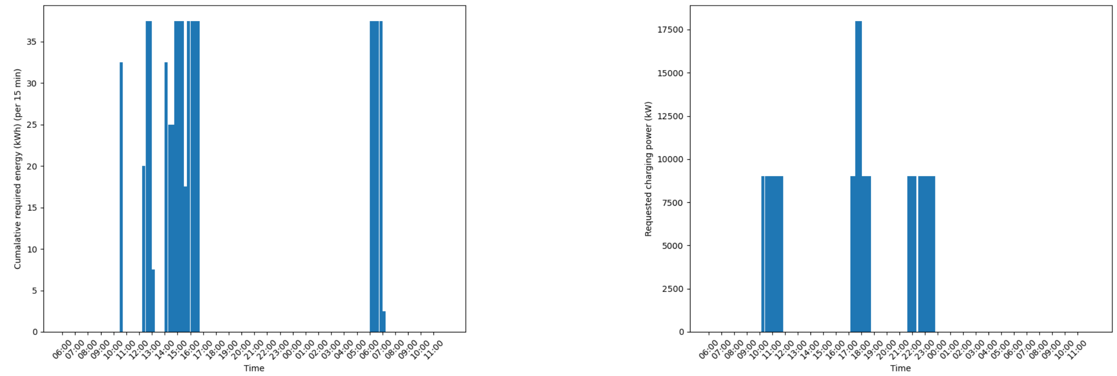
Figure B.43: 2035* scenario



(a) Requested energy, Vliegclub Rotterdam

(b) Requested energy, Rotterdamsche Aeroclub

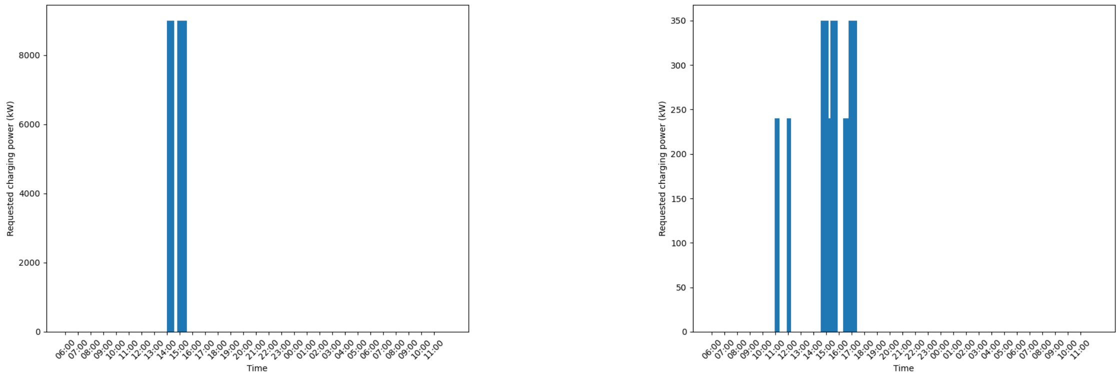
Figure B.44: 2035* scenario



(a) Requested energy, Hangars

(b) Requested power, Main Platform

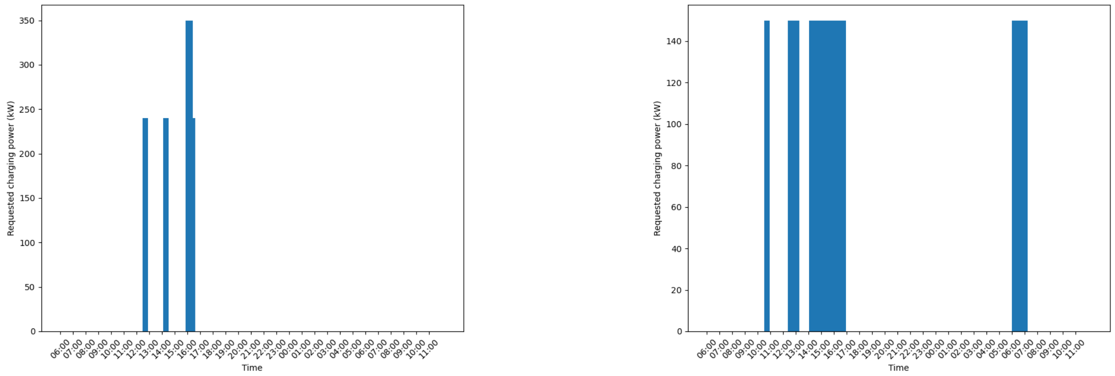
Figure B.45: 2035* scenario



(a) Requested power, Jet Aviation

(b) Requested power, Vliegclub Rotterdam

Figure B.46: 2035* scenario



(a) Requested power, Rotterdamsche Aeroclub

(b) Requested power, Hangars

Figure B.47: 2035* scenario

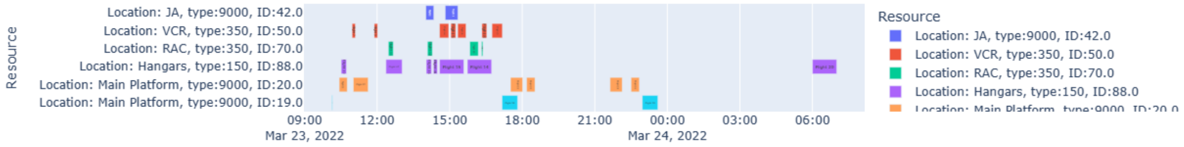


Figure B.48: Optimal daily charging schedule, decentralized locations 2035* scenario

Figure B.49: Optimal daily charging schedule, decentralized locations 2035* scenario (zoomed in on 10:00-18:00)