Optimizing the Energy and Charging Infrastructure Costs for Regional Electric Aircraft Operations

A case study in the Dutch Caribbean

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TU Delft
NACO
a company of Royal HaskoningDHV

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by

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Acknowledgements

Already at the beginning of the second year of my bachelor in Aerospace Engineering I knew that the Air Transport Operations master track would be the one for me. Starting it was a joy, however the middle of covid-19 sometimes made it a challenge. Having a strong group of friends and family around me helped, although I abandoned them for a second time to take the wonderful opportunity of doing an internship on St. Eustatius. It was during this internship that the early seed was planted that led me to this master thesis. At that time, I experienced first hand what NACO was capable of and that my scepticism towards consultancy maybe was a bit too exaggerated. A subtle hint by the director during a completely other purposed meeting then later on led the way to discussions on possible thesis topics. My Statia time may furthermore be seen as the kick-start of my professional career as it introduced me to the complete spectrum of aviation stakeholders especially for the Dutch Caribbean. Therefore a big thanks to the Statia team!

Although being mainly unaware of the electric aviation developments, the operational aspects in combination with the chance to develop more Dutch Caribbean expertise were pivotal to eventually start my master thesis at NACO. As part of my research, I even had the chance to attend the first conference on sustainable inter-island flights between the Dutch Caribbean. This was a goldmine of information and really inspired me during my research.

Moving on to more current practices, I would like to thank all experts and stakeholders I have spoken to. You were first of all very interested in my research and very willing to help in many ways. This really made my research even more relevant and my feeling of being useful was boosted again and again. From close colleagues at NACO and RHDHV to other Dutch experts, however, also not forgetting overseas BIA employees and other island stakeholders to voice the local challenges.

Lastly I would like to thank my two supervisors Christine Driessen and Paul Roling. Although you let me work very independently, I am very grateful that you gave me this space in which I could really find my own way and challenge myself. But when I needed your expert view or just needed to vent, you were always there. Your feedback directed me towards the final direction of my research, making it relevant, useful and high quality.

Niek van Amstel
Delft, March 2023

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General Abbreviations

ABC	Aruba, Bonaire and Curaçao
BES	Bonaire, Sint Eustatius and Saba
BIA	Bonaire International Airport
BMS	Battery Management System
CAA	Civil Aviation Authority
DCCA	Dutch Caribbean Cooperation of Airports
DEAC	Dutch Electric Aviation Centre
DOC	Depth of Charge
EASA	European Union Aviation Safety Agency
EIS	Entry Into Service
ESU	Energy Storage Unit
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
Li-ion	Lithium-ion (battery)
MARS	Multi-Aircraft Ramp Solution
MILP	Mixed-Integer Linear Programming
MTOW	Maximum Take-Off Weight
NACO	Netherlands Airport Consultants
NLR	Netherlands Aerospace Centre
OEM	Original Equipment Manufacturer
OLS	Obstacle Limiting Surface
PSO	Public Service Obligation
RHDHV	Royal Haskoning DHV
RUL	Remaining Useful Life
SOC	State of Charge
SOH	State of Health
STA	Scheduled Time of Arrival
STD	Scheduled Time of Departure
WEB	Water- en Energiebedrijf Bonarie

IATA Airport Codes

AUA	Aruba (Queen Beatrix) International Airport
BON	Bonaire (Flamingo) International Airport
CUR	Curaçao (Hato) International Airport
SXM	Princess Juliana International Airport St. Maarten

Aircraft Types

A333	Airbus A330-300
B1900	Beechcraft 1900
B38M	Boeing 737-MAX8
B738	Boeing 737-800
B77W	Boeing 777-300ER
BN2	Britten Norman Islander
CRJ200	Bombardier CRJ200
DHC-6	Twin Otter
E120	Embraer EMB 120 Brasilia
ERJ145	Embraer ERJ-145
SF34	Saab 340

Introduction

In the quest towards a more sustainable future, also air transport is doing their utmost to limit the emission of green house gasses as much as possible. Although completely new and more efficient aircraft models have been proposed, also the electrification of aircraft is now moving forward. Initially only smaller general aviation types were designed to fly on the power provided by batteries. Currently, these types are already capable of flying up to an hour. Other manufacturers are focusing on regional electrified commercial aircraft. However, given current batteries are relatively heavy, the range of such an aircraft is rather limited.

Besides the development of the electric aircraft itself, also other stakeholders must prepare themselves for the introduction of this new type of aircraft. To gain insights, NACO and NLR have made a roadmap[1] on behalf of the Dutch Government. This roadmap focused on inter-island flights between Aruba, Bonaire and Curaçao formed the basis of this research. However, from the start it was clear that more details were to be implemented to reach the set goals: lowering the peak power demand when electric aircraft are charging and gaining insights into (renewable) energy provision purposed for charging electric aircraft. By interviewing many experts and local stakeholders, a better and better picture was created. The conference aimed at sustainable inter-island flights in the Dutch Caribbean held on Aruba was therefore really worthwhile attending and inspirational for my research. All input was then translated into an optimization model that minimized the costs while adhering to particular airport operational and charging constraints.

Besides that this research contributes to the preparation of zero emission regional flights, it has a second social aspect that is experienced especially in the Dutch Caribbean: the lack of affordable air connectivity. As electric aircraft are expected to have lower operating costs, ticket prices might drop which will permit local people to visit family, a medical specialist or notarial services on a neighboring island more easily. Locally, this could thus also make a large impact.

The remainder of this thesis report continues with a technical research paper in Part I. Here the main models, assumptions, results and conclusions are presented. Part II provides a literature study performed in the beginning of the research outlining the state-of-the-art of other research on related topics. Finally, Part III will present the supporting work for this research. It includes some more detailed information on certain assumptions used in the research paper, more results that were generated alongside, model verification and a brief overview of certain energy storage types.

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[1] `https://www.rijksoverheid.nl/documenten/rapporten/2022/02/18/bijlage-2-roadmap-electric-flight-naco-nlr-report`

I

Scientific Paper

Optimizing the Energy and Charging Infrastructure Costs for Regional Electric Aircraft Operations:
A case study in the Dutch Caribbean

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Abstract

Commercial electric aircraft operations are foreseen in the coming five to ten years. For an airport to be ready for this introduction, energy infrastructure requirements have already been subject to various research topics. Most research in this field only focused on cost minimization of the number of chargers given a fixed flight schedule. This research however implements flexibility into the flight schedule and incorporates the energy provision in terms of renewable energy sources in combination with battery storage. Considering energy infrastructure costs as well as operational costs, the goal of the newly proposed Mixed-Integer Linear Programming model remains cost minimization. Besides a daily operational model, an additional energy balance focused optimization has been applied for data of an entire year. In this second model, energy from the local grid may be drawn and returned to come to a cost optimized solution. Both models have been run for a case-study on Bonaire International Airport where inter-island flights to and from its two neighboring islands were electrified. A combination of solar panels and battery energy storage was found to be most cost efficient while sensitivity analysis showed many insights into possible energy business cases for airports.

1 Introduction

On September 27th 2022, aviation sustainability history was written. Up to that date, no fully electric aircraft type with the capability of carrying up to nine passengers had ever taken off into the sky. Eviation's Alice did. However, it is far from the first fully electric aircraft that is flying around these days within the global quest of lowering emissions. With the Velis Electro, Pipistrel even already has a certified aircraft competing with non-certified ultralight electric aircraft. These smaller types mainly purpose pilot training. But besides future pilots and their instructors, business or even leisure travellers transported by electric aircraft is now one step closer. However, there are several caveats as many more steps are still to overcome. Although it sounds very promising that a purposed commercial electric aircraft has made its maiden flight, a critic will highlight that certification and thus commercial services will be at least five years ahead of us. What is more, battery technology will still need improvement before a commercially viable product could set foot in the market [Gates, 2022].

Nevertheless, the fact is that electric aircraft technology is advancing. The question is, how fast? While Original Equipment Manufacturers (OEMs) are busy working on their aircraft designs, other parties are preparing themselves in parallel for the introduction of electrified aviation. Mainly, this targets airports, energy providers and its infrastructure, and regulatory institutions. A recent focus lies on the determination of the charging infrastructure required to be present at an airport to charge future electric aircraft. Therefore several optimization models have already been created that minimize the total costs. Some of these models also schedule the charging times over the day. However, these models show two main limitations that will be addressed in this research. First of all, the energy provision from renewable energy sources and storage will be taken into account for a daily operational model and yearly energy model. Furthermore, flexibility in a daily flight schedule will be allowed to potentially lower the charging peak power demand on the electricity grid. This will all be done for fully electric aircraft being designed at the moment and not for hybrid electric or hypothetical retrofit aircraft.

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As in the Netherlands the government has the ambition to progressively act on electric aircraft developments and be prepared for its introduction, it requested Netherlands Airport Consultants (NACO) and the Dutch Aerospace Centre (NLR) to investigate the possibilities and opportunities. This resulted in a high-level road map for investments to be made by various stakeholders as well as regulatory gaps to be filled. They based their conclusions on a case study on fully electric inter-island flights between the Dutch Caribbean islands of Aruba, Bonaire and Curaçao (ABC) as the short distances between them (maximum 200 km) ideally fit the battery electric aircraft range. Furthermore, more affordable air connectivity made possible by electric aviation may even benefit local social-economical assets [van Buiren et al., 2018] besides not directly emitting any green house gasses. As this topic draws much attention from significant stakeholders involved these days, it was decided to take a more detailed look at a case study of these inter-island flights between the Dutch Caribbean ABC islands.

The goal of this research is to gain more insights into the electrification infrastructure required for fully electric regional flights and with it identify strategies for implementation and upscaling. This is done with a focus on minimizing costs of energy supply infrastructure, airline battery lifetime costs, charging infrastructure costs and operational costs for a case study of inter-island flights at Bonaire International Airport (BIA).

To achieve this goal, section 2 will discuss the current state-of-the-art literature of relevant topics and identifies a research gap. This research gap is then translated into a general problem scope in section 3. The methodology including optimization model is addressed in section 4 while section 5 will elaborate upon the Bonaire case study and the used parameters and assumptions. Section 6 shows the results of the case study and these results will further be discussed in section 7. Conclusions and recommendations will be provided in section 8 and section 9 respectively.

2 Literature Review

This research continues on the streamline of ground infrastructure needs for (hybrid-)electric aircraft that has evolved especially in the past years. An initial review on required ground infrastructure investments for (fast) charging hybrid-electric aircraft was already done by [Marksel et al., 2019]. Here, an overview of possible standardization of charging is shown. A more current, complete and more detailed review of the current electrical practices is made by [National Academies of Sciences, Engineering, and Medicine, 2022]. This review dove deep into possible changes in demand, economics and policy/legislation, while also addressing the more practical sides of implementation for airports. Even a dedicated assessment tool has been developed to provide insights into the requirements in case more than just aviation is electrified.

Moving more towards capacity needs, [Doctor et al., 2022] have researched the stand capacity of an existing hub airport by means of a discrete event simulation. They showed what percentage of stands should be redeveloped to be able to handle both conventional and electric flights. Airport operational efficiency and airside capacity were then not diminished with the proposed adaptations. Where this research focused on conversion of certain stands, three specific charging models have been published that focus more on the actual required charging infrastructure. The first model of [Justin et al., 2020] only included battery swapping to show a decrease in peak power demand of the local grid relative to the as-need power for two case studies of real airline networks. Although the prescribed machine scheduling model is able to facilitate the actual number of batteries and charging stations needed, the results mainly focused on the lowered peak power demand and cost savings. Alongside the fixed flight schedule, three different fixed power charging regimes were adhered to for a hypothetical fully electric aircraft.

The second and most extensive research combines intermediate publications of [Bigoni et al., 2018] and [Salucci et al., 2019] into one final paper by [Trainelli et al., 2021]. Using a Mixed-Integer Linear Programming (MILP) optimization model for cost minimisation, again a fixed flight schedule was used as input to now explicitly determine the number of charging stations, spare batteries and hybrid-electric aircraft to fulfill all scheduled flights. In addition to battery swapping, now plug-in charging was implemented as well, specifically for a general aviation airport and a regional hub airport using the existing local electricity grid as energy source. What is also different from the earlier research is that now battery lifetime is implicitly taken into account and that only maximum rated power may be drawn from a charging station.

More recently, [Mitici et al., 2022] published their research which incorporated several assumptions that were also addressed in the previous two studies. But besides the fixed flight schedule and combining plug-in charging with battery swapping using two fixed charging power modes, route specific energy per aircraft was introduced as well. Furthermore, all charges were scheduled over time given a two-phase MILP approach. This all resulted in a cost minimised number of hypothetical fully electric aircraft to execute specified regional flights (<350 km) at Amsterdam Airport Schiphol and the associated spare batteries and charging stations required.

Now that the most relevant research foundations have been elaborated upon, several subtopics that were also part of these studies will be briefly addressed as these will be directly linked to the research gap of this new research. Firstly, in all three discussed models, battery swapping was used. Where plug-in charging is very similar to charging electric cars or buses, battery swapping is a relatively new concept. When the (partially) empty battery is detached from an arrival aircraft, it is swapped with a sufficiently charged one to execute its next mission. The empty battery will then be brought to a special charging station where it will be charged until it is required again for another flight. Although this yields increased battery life time, it also requires extra investment costs for specialized swapping equipment and a dedicated charging station [Chau, 2014, Doctor et al., 2022]. However, the most inconvenient characteristic with respect to plug-in charging is the added complexity in terms of performing the actual swap as it is deemed an extra maintenance activity. This requires extra training for personnel and induces extra safety hazards [Marksel et al., 2019]. At the time of writing, it is unsure if battery swapping will be rolled out successfully as also future manufacturers will likely not adopt this technology in favor of plug-in charging [PIPISTREL, 2022, Heart Aerospace, 2022, Burns, 2021].

Another common characteristic of the three described models is the use of hybrid-electric aircraft and/or estimated hypothetical (hybrid-)electric aircraft. [Sahoo et al., 2020] reviewed the then current electric aircraft propulsion technology. However, in the past years, several design details have already been disclosed by electric aircraft developers. The most promising two include the Eviation Alice and the Heart Aerospace ES-30. Alice is a 9-seater fully electric aircraft with a battery capacity of 820 kWh, range (incl. VFR reserves) of 460 km and a maximum take-off weight (MTOW) of 8346 kg [Hemmerdinger, 2022, EVIATION, 2023]. The ES-30 is a larger 30-seater aircraft that in essence is hybrid-electric, however may also fly fully electric for 200 km using conventional kerosene as reserve fuel [Heart Aerospace, 2023]. Unfortunately, no other useful characteristics have been published of this larger regional aircraft at the time of writing. However, for its discontinued predecessor, the ES-19, sufficient data has been disclosed. The smaller version had a MTOW close to the CS-23 aircraft certification design limit of 8618 kg, range of 400 km using a battery capacity of 720 kWh [Northvolt, 2021, Heart Aerospace, 2022].

Lastly, some electrical and (power) charging background is outlined. These days, electrical mobility is almost always powered by lithium-ion (Li-ion) batteries. Trading off the cycle life and costs, this makes it a logical winner [Redondo-Iglesias et al., 2020, Micari et al., 2022]. Also as a bulk energy storage unit (ESU), Li-ion makes a very good candidate. However, the limiting factor for aviation still remains the energy density (kWh/kg) which currently lies at around 0.25 [Prapotnik Brdnik et al., 2022, Janovec et al., 2022, Marksel et al., 2019]. Charging a Li-ion battery will also induce extra degradation and thus reduced lifetime. However, certain guidelines may be followed to limit this degradation. By not charging with more than a 2C rate (charging power equal to capacity multiplied by 2), internal degradation processes are kept to a minimum [Xu et al., 2018, Yan et al., 2017]. Furthermore, it matters how much the battery is charged (Depth of Charge, DOC) and around what specific State of Charge (SOC, or simply battery level). The more the battery is charged, the more degradation takes places [Miao et al., 2019, Shchurov et al., 2021, Xu et al., 2016], and if the battery is charged starting with an SOC around mid-level, the battery is likely to degrade less [Bodeux et al., 2018, Shchurov et al., 2021]. Furthermore, above 80% SOC, fast charging should not be allowed as then safety hazards become a likely risk [Tomaszewska et al., 2019, Mussa et al., 2017].

In conclusion, three main charging models have already been published where battery swapping was included although it is questionable if this will see a market wide adoption. Furthermore, a fixed flight schedule was always adhered to. Specific airport (operational) constraints or current electric aircraft designs were in these studies not taken into account. Lastly, the energy needed for charging the aircraft in all three models originated from either the local electricity grid or was simply available against no cost.

3 Model Scope

As discussed in section 1, the focus of this research lies on the cost optimization of energy provision and energy infrastructure required to be able to handle electric aircraft at a regional airport. The research problem will be dealt with in two different ways. Firstly, a daily operational optimization model will be created to provide insights into the energy provision and infrastructure required given daily peak demand. Secondly, an entire year is subject to an optimization that focuses on the long term energy provision, demand and storage. In the following two sections, these two optimizations will be outlined in more detail. Section 3.3 will finally highlight some general considerations.

3.1 Daily Operational Model

In the daily model, a representative peak day will be optimized. On this day, pre-stored energy is not available at the start nor a connection to the local electricity grid is available. This may be seen as a worst case scenario. Furthermore, flexibility is introduced into the flight schedule by means of an arrival and departure time shift to be able to lower the peak power demand. With this, also some operational costs are associated. By also taking into account local weather data translated into (unit) energy supply, a cost minimization is performed to come to required infrastructural and energy provisional needs. This also includes a detailed charging schedule for all electric flights as can also be seen in the general overview of Figure 1. Please note that this model takes into account costs of various stakeholders and will minimize the total defined system costs and does not see any preference on minimizing for instance airport or airline costs.

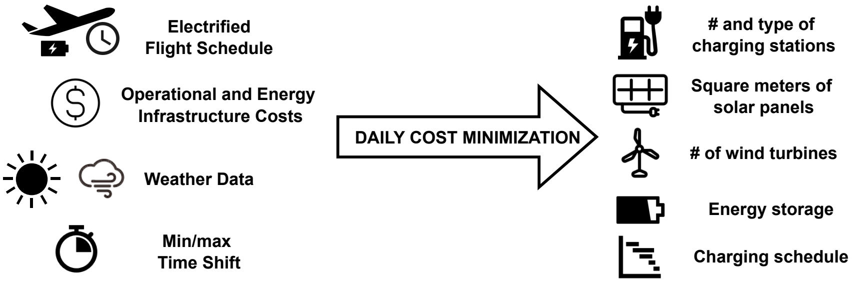


Figure 1: Daily operational optimization problem scope

3.2 Yearly Energy Model

Where the daily optimization is really focused on specific charging and operational details, it is, however, also important to look at the longer term energy provision and storage. Figure 2 shows the high-level flow of the second optimization model. Here, excess energy may be stored and used not only on the day of generation, but also on days further ahead in time when solar or wind energy might not be able to generate sufficient energy. In this optimization, a fixed flight schedule is adhered to while several charging and operational constraints are dropped. Furthermore, this model will include a connection to the local electricity grid. From this grid, energy may be drawn at all times. However, it will also be possible to return energy to the local grid when the storage capacity is full. The focus thus purely lies on the energy provision and demand.

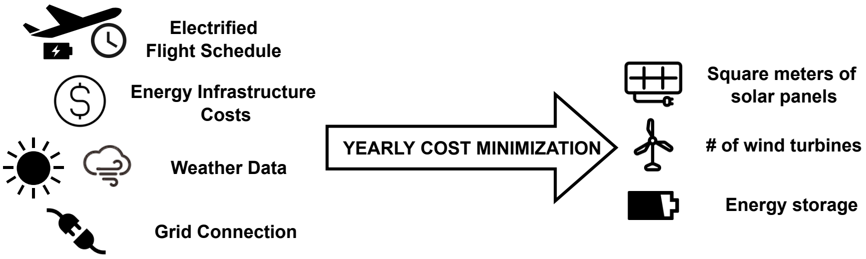


Figure 2: Yearly energy optimization problem scope

3.3 General Considerations

Diving more into the turnaround process that is envisioned for electric aircraft, there are still many uncertainties. It is believed that when an electric aircraft arrives at a parking position, it needs to be charged until sufficient energy has been transferred to its batteries to safely fly its next flight leg. The charging time may thus also be restrictive on the turnaround time. In section 2 the advantages and disadvantages of plug-in charging and battery swapping have already been addressed. For the remainder of this research, battery swapping is disregarded and therefore a physical cable is expected to be plugged into the electric aircraft when parked. What the exact infrastructure will look like is again unsure, but based on the principles of electric busses, it is likely that a certain main power charging station will be located close to, but not on the apron. From this main station, underground cables will then feed the energy towards the aircraft via a connection on the apron. Charging the aircraft battery will, however, induce certain (extra) degradation, especially when higher charging power are used. This can be translated into (battery) renewal costs to be paid by the airlines. Given the call for (more) sustainable aircraft operations, it is highly undesired that the energy used for charging is generated by (highly) polluting sources. Therefore, in the extent of sustainability, this research will only allow energy provision by renewable energy sources in the daily operational model. In the yearly energy optimization, however, a local grid connection is allowed as it then encompasses the larger energy system beyond the airport to enable extra energy availability when limited renewable energy sources are available. Extra caution should thus be exercised in terms of sustainability of the generation of the electricity of the local grid.

In addition to the above, in the entire research a conservative approach is adhered to. This has been decided as the technology is still in development and that currently, claims of electric aircraft OEMs are merely based on a hypothetical aircraft design that has not generated any flight data yet. Therefore, in the event of a flaw in the design, airports will still be ready for their introduction.

Lastly, as it concerns a preliminary research in order to provide insights, all electricity grid efficiencies have been neglected, unless otherwise stated. This would mean that all energy originating from a possible energy source will be able to be transferred completely to either energy needs or storage. Also drawing energy from the energy storage towards another means, is treated without any efficiency. Given that the overall efficiency in related research usually lies above 90%, it is expected that including the efficiencies will only add unnecessary extra complexity not encouraging the production of results.

4 Methodology

This section will discuss all aspects of the methodology that was used in this research. In section 4.1 the electrification of the flight schedule is elaborated upon. Next, the daily operational optimization model is addressed in section 4.2. Please note that the yearly energy optimization model will only be provided in Appendix A given the simplicity and high similarity with the daily operational model energy balance.

4.1 Flight Schedule Electrification Algorithm

The first step in the process is to prepare a given data set such that it can be used directly in the optimization of section 4.2. A graphical representation of this data preparation is shown in Figure 3. All input variables and requirements for the process have been summarized in Table 1 which will now be discussed in more detail.

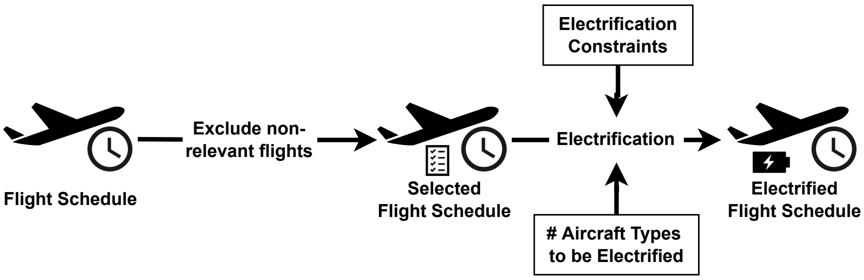


Figure 3: Flow representation of the Flight Schedule Electrification Algorithm

It all starts with a given flight schedule which should contain information as also specified in Table 1. Ideally this information is provided by an airport itself. However, it may also be possible to combine data from multiple other sources such as airlines.

From the flight schedule, it must then be decided per individual flight if the flight should be deleted from the schedule or not. This decision depends on the local situation and the goal of the research for that specific use case. Constraints may include for instance certain flight types or airlines. Given that the optimization is based on gate assignment, this must also be taken into account. For all flights present in the final schedule, flight times will be discretized according to the set model input parameter.

Now that only relevant flights have been selected, flights may be electrified. Per day, only the flights of unique aircraft of specific aircraft types will be eligible for electrification. The number of unique aircraft per type is set as model input parameter. If more than one unique aircraft of a to be electrified aircraft type is present, the aircraft with most eligible electric flights will be electrified first. Note that not all flights operated by a certain aircraft may be eligible for electrification. This again depends on electrification constraints such as specific routes. Table 2 shows an example flight schedule where on the left side only one aircraft of 'Type X' is electrified, while on the right side, two of 'Type X' are electrified. Note that in the example, airline constraints were not taken into account.

Table 1: Required inputs for electrification algorithm

Input Required	Comment
Flight schedule	Including: date, flight number, arriving and departing pax, origin, destination, aircraft tail number, aircraft type, arrival and departure time
Electrification constraints	Depending on local situation
# of aircraft types to be electrified	Depending on local situation
Aircraft specific route SOC estimation	Depending on routes and electric aircraft performance
Time discretization	May be varied, but fixed for this research at 10 minutes

Every electrified flight will be appended with data in the flight schedule with regards to the SOC on arrival and required SOC for departure (based on a return flight). This is dependent on the electric aircraft type with which the original aircraft is 'swapped', and the origin and destination airport. Leading for the arrival SOC is the reserve energy required for an electric aircraft. For a departing electric flight, an estimation must be made on how much energy is used to fly to the next scheduled airport. Together with the reserve energy, this then leads to a minimum required departure SOC. Note that also single flight legs may be electrified according to the same estimated SOCs. However, it depends on operational charging assumptions how this will fit into the desired research goals. Slight deviations may also be possible to take into account other aspects such as battery lifetime or foreseen charging operations.

Table 2: Example flight schedule for electrification of flights operated by aircraft 'Type X' (1x left, 2x right)

Flight #	A/C Type	Tail #	E-Flight	Flight #	A/C Type	Tail #	E-Flight
PT 237	Type X	REG-1	YES	PT 237	Type X	REG-1	YES
PT 357	Type Y	REG-2	NO	PT 357	Type Y	REG-2	NO
PT 239	Type X	REG-1	YES	PT 239	Type X	REG-1	YES
QY 589	Type X	REG-3	NO	QY 589	Type X	REG-3	YES
PT 393	Type Y	REG-2	NO	PT 393	Type Y	REG-2	NO
PT 551	Type X	REG-1	YES	PT 551	Type X	REG-1	YES
QY 221	Type X	REG-3	NO	QY 221	Type X	REG-3	YES

4.2 Daily Operational Optimization Model

After the flight schedule has been 'electrified', it is fed into the MILP model. This model uses the base model which will be described in section 4.2.1. An adaptation to the model is made in section 4.2.2 which implements the possibility of repositioning aircraft during their ground time. Note that besides the introduced inputs required for the electrification of the flight schedule an additional model input is required for the optimization. This extra input sets the minimum and maximum allowable time shifts of the flight schedule.

4.2.1 Base Model

The optimization model uses the decision variables as summarized in Table 3 with attributes belonging to sets shown in Table 4. Please note that x_{ESU_t} and $surplus_t$ cover the full daily time span. All variables related to a particular (E-)flight only cover possible time intervals t of this (E-)flight and thus also take into account possible time shifts. Additionally, the subset P_E represents all parking positions available for potential electrification. Furthermore, $x_{f,p,d1,d2}$ is the standardized notation for arriving and departing flights with arrival time shift $d1$ and departure time shift $d2$. This is implemented to allow flexibility in the flight schedule. Variations of these variable attributes remain possible with this formulation, depending on the type of flight and possible assumptions.

The objective of the optimization is to minimize costs. Equation 1 describes the mathematical formulation using the introduced decision variables and fixed parameters summarized in Table 5. The first line of Equation 1 introduces the costs related to the energy provision by means of wind turbines, solar panels and ESU. The second line composes the investment costs of an individual charging station and airport infrastructural costs (cables, ducts, asphalt cuts, etc.) per parking position. Next, every electric flight is linked with battery life time costs in terms of how much the internal battery is charged which is dependent on the aircraft type and route to be flown. Besides, a penalty cost is charged in case the aircraft is 'fast' charged. This penalty cost is divided by the total of time intervals of ground time for that specific flight as normalization. In the fifth line, the arrival and departure time shifts as well as the extension of the turnaround time induce extra costs. Lastly, the time shifts of electric flights could also increase the parking time at an airport such that a parking fee applies.

Table 3: Overview of used decision variables

Variable	Type	Attribute(s)	Description
esu	$\mathbb{Z}, \geq 0$	-	kWh of energy storage
sp	$\mathbb{Z}, \geq 0$	-	Square meters of solar panels
wt	$\mathbb{Z}, \geq 0$	-	Number of wind turbines
x_{ESU_t}	$\mathbb{Z}, \geq 0$	$t \in T$	Available kWh of ESU at time interval t
$surplus_t$	$\mathbb{R}, \geq 0$	$t \in T$	Surplus energy at time interval t
$x_{f,p,d1,d2}$	$\{0, 1\}$	$f \in F$; $p \in P_f$; $d1, d2 \in D_f$	Flight f with time shift $d1, d2$ is assigned to parking position p
$x_{CPi,p}$	$\{0, 1\}$	$CPi \in C$; $p \in P_E$	Charger CPi is coupled to parking position p
$fc_{f,t}$	$\{0, 1\}$	$f \in F_E$; $t \in T_f$	Flight f is fast charging at time interval t
$sc_{f,t}$	$\{0, 1\}$	$f \in F_E$; $t \in T_f$	Flight f is slow charging at time interval t
$tc_{f,t}$	$\{0, 1\}$	$f \in F_E$; $t \in T_f$	Flight f is terminal charging at time interval t
$nc_{f,t}$	$\{0, 1\}$	$f \in F_E$; $t \in T_f$	Flight f is not charging at time interval t
$pw_{FC_{f,t}}$	$\mathbb{Z}, \geq 0$	$f \in F_E$; $t \in T_f$	kW fast charging power for flight f at time interval t
$pw_{SC_{f,t}}$	$\mathbb{Z}, \geq 0$	$f \in F_E$; $t \in T_f$	kW slow charging power for flight f at time interval t
$pw_{TC_{f,t}}$	$\mathbb{Z}, \geq 0$	$f \in F_E$; $t \in T_f$	kW terminal charging power for flight f at time interval t
$slack1_{f,t}$	$\{-1, 1\}$	$f \in F_E$; $t \in T_f$	Slack variable for terminal charging of flight f at time interval t
$slack2_{f,t}$	$\mathbb{R}, \geq 0$	$f \in F_E$; $t \in T_f$	Slack variable for terminal charging of flight f at time interval t

Table 4: Overview of model sets

(Sub)Set	Description
C	Charger types
D	Possible time shifts (min/max set by model input)
E	Electric equivalent (subset) of specific set
F	Flights
P	Parking positions
S	Battery capacity
T	Time intervals

$$
\begin{aligned}
\textbf{minimize}\quad & wt \cdot C_{inv,WT} + sp \cdot C_{inv,SP} + esu \cdot C_{inv,ESU} \\
& + \sum_{CPi \in C} \sum_{p \in P} x_{CPi,p} \cdot (C_{inv,CPi} + C_{infra,p}) \\
& + \sum_{f \in F_E} \sum_{p \in P_f} \sum_{d1,d2 \in D_f} x_{f,p,d1,d2} \cdot DOC_f \cdot C_{DOC_f} \\
& + \sum_{f \in F_E} \sum_{p \in P_f} \sum_{d1,d2 \in D_f} \sum_{t \in T_{f,d1,d2}} fc_{f,t} \cdot x_{f,p,d1,d2} \cdot \frac{C_{FC}}{M_{f,d1,d2}} \\
& + \sum_{f \in F_E} \sum_{p \in P_f} \sum_{d1,d2 \in D_f} x_{f,p,d1,d2} \cdot ((|d1| \cdot G_{f_a} + |d2| \cdot G_{f_d}) \cdot C_{d1} + (d2 - d1) \cdot C_{d2}) \\
& + \sum_{f \in F_E} \sum_{p \in P_f} \sum_{d1,d2 \in D_f} H_{f,d1,d2} \cdot x_{f,p,d1,d2} \cdot C_{parking_f}
\end{aligned} \tag{1}
$$

The objective function of the MILP model is subject to constraints which basis is formed by a gate assignment model. This is then extended with 'electrification' constraints. Equation 2 reassures that every flight is assigned to 1 parking position while Equation 3 only allows at most one aircraft to be parked on a parking position at time interval t.

$$\sum_{p \in P_f} \sum_{d1,d2 \in D_f} x_{f,p,d1,d2} = 1 \quad \forall\ f \in F \tag{2}$$

$$\sum_{f \in F_{p,t}} \sum_{d1,d2 \in D_f} x_{f,p,d1,d2} \leq 1 \quad \forall\ p \in P;\ t \in T \tag{3}$$

As electric aircraft need to be charged with dedicated charging stations, Equation 4 ensures that only 1 charging station type can be fitted per parking position. Location wise, it may be beneficial to install or invest in 'electrified' parking positions in a certain order. Therefore, Equation 5 is implemented.

$$\sum_{CPi \in C} x_{CPi,p} \leq 1 \quad \forall\, p \in P_E \tag{4}$$

$$\sum_{CPi \in C} x_{CPi,p} \geq \sum_{CPi \in C} x_{CPi,p+1} \quad \forall\, p \in [0, ..., P_E - 1] \tag{5}$$

Once the aircraft is ready for charging, the model may choose either fast charging, slow charging, terminal charging (slow charging above 80% SOC) or no charging at all. This is reflected by Equation 6. By setting a threshold in Equation 7, the limits of fast, slow and terminal charging are defined together with the maximum available power per charger type in Equation 8. Additionally, the battery in the aircraft itself may impose limits to charging which is reflected by Equation 9.

$$nc_{f,t} = 1 - fc_{f,t} - sc_{f,t} - tc_{f,t} \quad \forall\, f \in F_E;\ t \in T_f \tag{6}$$

$$pw_{FC_{f,t}} \geq fc_{f,t} \cdot THR_{FC} \quad \forall\, f \in F_E;\ t \in T_f \tag{7a}$$

$$pw_{SC_{f,t}} < sc_{f,t} \cdot THR_{FC} \quad \forall\, f \in F_E;\ t \in T_f \tag{7b}$$

$$pw_{TC_{f,t}} < tc_{f,t} \cdot THR_{FC} \quad \forall\, f \in F_E;\ t \in T_f \tag{7c}$$

$$pw_{SC_{f,t}} \geq sc_{f,t} \quad \forall\, f \in F_E;\ t \in T_f \tag{7d}$$

$$pw_{TC_{f,t}} \geq tc_{f,t} \quad \forall\, f \in F_E;\ t \in T_f \tag{7e}$$

$$\begin{aligned} fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}} + tc_{f,t} \cdot pw_{TC_{f,t}} \leq \\ \sum_{p \in P_{E_f}} \sum_{CPi \in C} x_{f,p,d1,d2} \cdot x_{CPi,p} \cdot PW_{max_{CPi}} \quad \forall\, f \in F_E;\ t \in T_{f,d1,d2};\ d1, d2 \in D_f \end{aligned} \tag{8}$$

$$pw_{FC_{f,t}} \leq PW_{max,f} \cdot fc_{f,t} \quad \forall\, f \in F_E;\ t \in T_f \tag{9}$$

The aircraft can now be charged with variable power inputs. Attributed to the charging is the minimum required energy to be transferred from grid to aircraft battery. In Equation 10, a distinction is made between aircraft required to be charged above or below 80% SOC. But in no instance, the maximum capacity of the battery may be exceeded (Equation 11).

$$S_{start_f} + \sum_{t \in T_f} (fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}}) \cdot t \geq S_{min_f} \qquad \forall\, f \in F_E\ [if\ S_{80_f} \geq S_{min_f}] \tag{10a}$$

$$S_{start_f} + \sum_{t \in T_f} (fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}} + tc_{f,t} \cdot pw_{TC_{f,t}}) \cdot t \geq S_{min_f} \quad \forall\, f \in F_E\ [if\ S_{80_f} < S_{min_f}] \tag{10b}$$

$$S_{start_f} + \sum_{t \in T_f} (fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}} + tc_{f,t} \cdot pw_{TC_{f,t}}) \cdot t \leq S_{max_f} \quad \forall\, f \in F_E \tag{11}$$

Because of the distinction above and below 80% SOC due to fast charging allowance, Equation 12 is introduced. It determines by means of two slack variables if terminal charging is started or not. The translation from slack variable to terminal charging requires Equation 13.

$$\begin{aligned} S_{start_f} + \sum_{t=0}^{q} (fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}} + tc_{f,t} \cdot pw_{TC_{f,t}}) \cdot t - 0.8 \cdot S_{max_f} = \\ slack1_{f,q} \cdot slack2_{f,q} \quad \forall\, f \in F_E;\ q \in [..., T_f] \end{aligned} \tag{12}$$

$$slack1_{f,t} \cdot 0.5 + 0.5 = tc_{f,t} \quad \forall\, f \in F_E;\ t \in T_f \tag{13}$$

As all input energy due to wind, solar and battery power and output charging energy must be equal, the energy balance is formulated as Equation 14. Note that also a surplus variable is present to account for overshoot of energy when needed. The maximum energy storage capacity is set by Equation 15, while Equation 16 assures that no stored energy is available at the start.

$$x_{ESU_t} + wt \cdot E_{wind_t} + sp \cdot E_{solar_t} - \sum_{f\in F_E} (fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}} + tc_{f,t} \cdot pw_{TC_{f,t}}) \cdot t = x_{ESU_{t+1}} + surplus_t \quad \forall\ t \in T \tag{14}$$

$$x_{ESU_t} \leq esu \quad \forall\ t \in T \tag{15}$$

$$x_{ESU_{t0}} = 0 \tag{16}$$

Table 5: Overview of used parameters

Parameter	**Attribute(s)**	**Description**
C_{DOC_f}	$f \in F_E$	Cost per DOC charge of flight f
C_{d1}	-	Cost of altering arrival or departure time
C_{d2}	-	Cost of extending turnaround time
C_{FC}	-	Fast charge penalty cost
C_{infra_p}	$p \in P_E$	Infrastructure investment costs per parking position p
$C_{inv_{CPi}}$	$CPi \in C$	Investment costs for charging station of type CPi
$C_{inv_{ESU}}$	-	Investment costs for 1 kWh of energy storage
$C_{inv_{SP}}$	-	Investment costs for 1 square meter of solar panels
$C_{inv_{WT}}$	-	Investment costs for 1 wind turbine
$C_{parking_f}$	$f \in F_E$	Parking cost for flight f
E_{solar_t}	$t \in T$	Energy provided by 1 square meter of solar panel(s) at time t
E_{wind_t}	$t \in T$	Energy provided by 1 wind turbine at time t
G_{f_a}	$f \in F_E$	Passengers onboard arriving leg of flight f
G_{f_d}	$f \in F_E$	Passengers onboard departing leg of flight f
$\{H_{f,d1,d2}\}$	$f \in F_E;\ d1, d2 \in D_f$	1 if flight f with time shift d1,d2 is charged parking costs, 0 otherwise
$M_{f,d1,d2}$	$f \in F_E;\ d1, d2 \in D_f$	Number of time intervals per flight f with time shift d1,d2
PW_{max_f}	$f \in F_E$	Maximum allowable charging power for flight f
$PW_{max_{CPi}}$	$CPi \in C$	Maximum charging power of charger type CPi
THR_{FC}	-	Minimum power for fast charging

4.2.2 Reposition Adaption

Next to the base model, an extension is made to allow repositioning of aircraft while parked at the airport. This will introduce several new terms summarized in Table 6. Note that the presented repositioning model is based on only one allowed reposition, but this is easily extendable to a higher allowance.

Equation 17 is added to the general objective function for extra costs related to the operation of a reposition.

$$\sum_{f\in F_E} \sum_{k\in K} k \cdot y_{f,k} \cdot C_{repos} \tag{17}$$

In the set of constraints, some adaptations and additions are seen. From the base model, Equation 2 is adapted to Equation 18 to incorporate that every instance of a repositioned flight must be assigned to a parking position. To reassure that only 1 reposition option is chosen, Equation 19 is added. Equation 20 is the replacement of Equation 3 which merely is a substitution of the new flight decision variable type and its accompanying extra summations.

$$\sum_{p\in P_f} \sum_{d1,d2\in D_f} \sum_{r1\in R} x_{f,p,d1,d2,l,r1} = y_{f,k} \quad \forall\ f \in F;\ l \in [0, ..., K] \tag{18}$$

$$\sum_{k\in K} y_{f,k} = 1 \quad \forall\ f \in F_E \tag{19}$$

$$\sum_{f \in F_{p,t}} \sum_{d1,d2 \in D_f} \sum_{r1 \in R} \sum_{l \in [0,...,K]} x_{f,p,d1,d2,l,r1} \leq 1 \quad \forall\, p \in P;\; t \in T \tag{20}$$

Another new constraint that is added deals with the time sets of the new decision variables. Equation 21 makes sure that only the variables with the same reposition time could be used.

$$\sum_{p1 \in P_f} x_{f,p,d1,d2,l,r1} \geq \sum_{p2 \in P_f} x_{f,p,d1,d2,l-1,r1} \quad \forall\, f \in F_e;\; d1,d2 \in D_f;\; r1 \in R;\; l \in [1,...,K];\; if\ p1 \neq p2 \tag{21}$$

Lastly, similar to Equation 20, the substitution of the new variable into Equation 8 results in Equation 22.

$$\begin{gathered} fc_{f,t} \cdot pw_{FC_{f,t}} + sc_{f,t} \cdot pw_{SC_{f,t}} + tc_{f,t} \cdot pw_{TC_{f,t}} \leq \sum_{p \in P_{E_f}} \sum_{CPi \in C} x_{f,p,d1,d2,l,r1} \cdot x_{CPi,p} \cdot PW_{max_{CPi}} \\ \forall\, f \in F_E;\; t \in T_{f,d1,d2};\; d1,d2 \in D_f;\; r1 \in R;\; l \in [0,...,K] \end{gathered} \tag{22}$$

Table 6: Additional terms to the base model to allow for repositions

Added term	**Type**	**Description**
$x_{f,p,d1,d2,l,r1}$	Decision variable; $\{0,1\}$	Flight f with time shift d1,d2 is assigned to parking position p at instance l of repositioning at time r1
$y_{f,k}$	Decision variable; $\mathbb{Z}$, ≥ 0	k repositions are operated for flight f
C_{repos}	Cost parameter	Cost of operating 1 reposition
K	Model input parameter	Maximum allowed repositions
R	Model Set	Possible reposition times

5 Case Study

The two phase methodology introduced in section 4 will be used on a specific data set and under certain assumptions to be able to generate results and insights for the electrification of inter-island flights from Bonaire in section 6. Inputs and assumptions of the electrified flight schedule will be discussed in section 5.1. Section 5.2 will then dive deeper into the coefficients used in the daily optimization while section 5.3 lists the used operational assumptions. Lastly, an explanation and description of the chosen representative peak day and the yearly optimization is provided in section 5.4 and section 5.5 respectively.

5.1 Electrified Flight Schedule Inputs and Assumptions

Before the main airport flight schedule is electrified, several model input parameters must be defined. For the time discretization, a 10 minute interval is used. Furthermore, the number of aircraft types to be electrified is kept variable, but limited to the maximum per day (see also section 5.4). All other specific used inputs, assumptions and values that were used for the Bonaire case study will be discussed in the sections below.

Airport Flight Schedule

The main input for the electrification algorithm is the airport flight schedule. For this research, the tower log of BIA from 2019 was made available through NACO. This file was already pre-processed from raw data into the final provided electronic data file. During this pre-processing, several parameters were added, changed or deleted (mainly flight type). The basis of these changes was summarized and checked, and was not deemed to have a major if even any influence on the desired scenarios for this research. Unfortunately, several combinations of aircraft registration and arrival-departure combinations were physically impossible (two consecutive departures or arrivals) or deemed (operationally) unrealistic. Therefore, during the processing of the data by the author, in total 41 additional changes have been executed and logged. Some of these changes might have an influence on the final results if this adapted data is used. Given that this research only focuses on commercial and charter flights, all other flights were discarded from the flight schedule.

Electrification Requirements

After the identification of arrival-departure pairs or single arrivals/departures from the used tower log, electrification parameters are only added when two requirements are met. For this research, only inter-island flights between Aruba, Bonaire and Curaçao are considered. Therefore, only flights with origin Aruba/Curaçao and destination Aruba/Curaçao are able to be 'electrified'. Single arriving or departing flights may also be electrified if all other requirements are met.

Given the smaller size aircraft types that currently operate the inter-island flights and the fact that future electric aircraft are not expected to be expected to be much larger, only certain aircraft types may qualify for electrification. In this specific case study, only 9 and 19-seater aircraft will be considered for future electric aircraft replacement. These include: Britten Norman Islander (9 seats), Beechcraft 1900 and Twin-Otter/DHC-6 (19 seats). The 9-seaters will be replaced by the Eviation Alice while the 19-seaters will be replaced by the Heart Aerospace ES-19. Although the ES-19 has officially been discontinued in favor of the larger ES-30, the lack of information of the latter as well as better alignment with historic 2019 19-seater flights, has lead to the decision to continue with the ES-19.

Route SOC Estimation

Two methods have been used to estimate both the associated 30 minute reserve energy and the required energy to fly the BON-CUR and BON-AUA route. Firstly, the electrified version of the Breguet Range Equation, given in Equation 23, as per [Hepperle, 2012] is used. The battery density c_b is set to 0.25 kWh/kg, L/D to 16 and the efficiency η is estimated at 0.82. In addition to the simple equation, a more detailed approach is taken based on the performance model described by [Baerheim et al., 2022]. Hereby, the ground and in-air acceleration as well as with cruise power required were calculated with mission profiles inspired by `Flightradar24.com` data.

$$R_E = \frac{c_b}{g}\frac{C_L}{C_D}\frac{W_{batt}}{W_{TO}}\eta \tag{23}$$

The final SOC values that have been used in this research are shown in Table 7. Note that a distinction between four different electric flights is made. For all flight types, the battery levels have been chosen by also taking into account the battery lifetime and avoidance of levels above 80% as much as possible. Furthermore, the assumption is made that all single arrival flights will be fully charged on the day of arrival and that therefore a first flight of the day (early flight) sees different battery SOCs than the regular return flights. Although for some scenarios an early flight may not require charging, aircraft batteries were charged regardless due to possible battery degradation effects which require extra charging and operational ground handling habits.

Table 7: Battery SOC values for different flights per aircraft type

Electric Flight	**Alice**		**ES-19**	
	to CUR	to AUA	to CUR	to AUA
Regular (return)	40% → 60%	40% → 80%	40% → 65%	40% → 85%
Early flight out of AUA	50% → 65%	50% → 80%	45% → 65%	45% → 85%
Early flight out of CUR	60% → 65%	60% → 80%	55% → 65%	55% → 85%
Arrival only	40% → ≥ 98%		40% → ≥ 98%	

5.2 Costs & Coefficients

Aside from the general model inputs of the electrified flight schedule, multiple other fixed parameters are used in the optimization model. All of these inputs will be discussed in the following sections.

Energy Sources

All cost parameters in the objective function related to the energy provision are estimated based on published statistics. Although efforts have been made to extract Bonaire specific data, this was unfortunately not always possible. Also note that all costs are normalized per day as only a single day will be subject to optimization.

The cost of a wind turbine is mainly based on [International Renewable Energy Agency, 2022] which specifies the weighted average (USD/kW) of the Central American/Caribbean region. Furthermore, the agency states the operating and maintenance costs, just as in [Wisera et al., 2019]. Ultimately, a cost of 5.6 million USD is used for a wind turbine (3.45 MW peak, 15 year lifetime) along with 70 USD/kW yearly operating and maintenance costs. For solar panels, local market prices could be retrieved which led to a used cost of 375 USD/m^2 all inclusive (maintenance, cleaning, etc.) over a lifetime of 15 years. ESU costs are based on industrial Lithium-ion systems as per [Mongird et al., 2020, Feldman et al., 2021] which came down to 340

USD/kWh over a five year period, including second life opportunity costs, but excluding yearly maintenance costs of 1 USD/kWh.

Charging Stations

Costs concerning charging stations come in three types. First of all, the physical charging station itself induces direct investment costs. Based on prices of previous projects within RHDHV for electric bus fast charging, these investment costs could be extrapolated for Bonaire. The lifetime expectancy of the physical charging stations is estimated at ten years. For this research, only chargers with up to 600 kW of power in steps of 100 kW (thus six types in total) were considered.

Secondly, at this stage, it is expected that at least part of the electricity will be provided by the local grid. The costs of a new inverter station on the grid have been excluded as these costs are very hard to estimate and require expert engineering design as indicated by the local energy distributor of Bonaire. However, the fixed monthly connection fee for new larger connections ($>$ 76.1 kW) as well as the price per kWh have been published in their tariffs [Water- en Energiebedrijf Bonaire, 2022].

Lastly, the charging stations need a connection from a main power station close to where the aircraft will be parked. Underground cabling is then used to cause the least hindrance. The costs of this cabling along with resurfacing the apron were estimated based on similar projects within NACO/RHDHV.

Aircraft Battery Lifetime

Although battery lifetime is hard to estimate for current batteries and is different for all types, estimating the lifetime of future batteries is even harder. Therefore, very rough estimations have been made to implement these costs. The most important cost is the cost related to the Depth of Charge (DOC). In other words, how much the battery is charged per charging instance. Using the battery capacity, estimated battery cost per kWh (600 USD/kWh), an assumed maximum battery cycles of 1200 and an assumed maximum DOC per battery cycle of 0.8, the cost per charged DOC can be calculated. In this calculation, also a 10% margin has been introduced.

With this cost structure, the majority of costs are accounted for. However, this cost does not rely on any charging procedure. Therefore, a penalty is included in case fast charging is executed. This penalty of 75 USD will be fully charged in case the aircraft is charged exclusively using fast charging. However, it could also be that only a part of the charging time is dedicated to fast charging, hence the normalization term in Equation 1. Based on six charged flights legs per day, the battery lifetime of the two included aircraft types on the Bonaire-Curaçao/Aruba routes is estimated to be as depicted by Figure 4 for exclusive slow charging or fast charging.

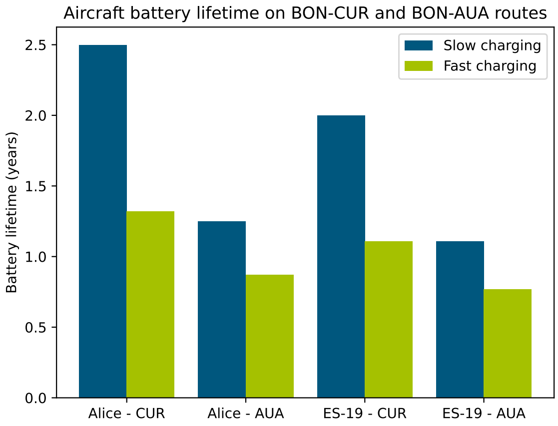


Figure 4: Estimated battery lifetime per route and aircraft type

Operational Costs

The last three cost coefficients in the objective function are of a simpler nature. Reposition costs have been published by BIA in their 2022 tariffs and equal 80 USD per pushback/pushforward [Bonaire International Airport, 2022]. Similarly, the parking fee is defined as 0.6 USD per ton MTOW with a minimum of 8 USD per 24 hours given a minimum parking time of two hours.

Costs related to the shift of scheduled arrival and departure times originate from delay propagation models. These costs are included as it is believed that the current flight schedule is optimized for the airlines (peak demand, transfers, etc.) and that any deviations would induce extra costs. A value of 0.11 $USD/PAX/min$ is used as per [Cook et al., 2012] based on the average of their found (soft) costs up to 30 minutes of delay.

In case the turnaround or ground time is increased by the model by means of the time shifts, an associated cost per block hour will be induced. This is calculated using an assumed yearly block hours of 960 for the ES-19 and 480 for Alice based on an average operational year of 320 days. Along with the acquisition costs, this directly translates to an estimation on the costs of ownership per block hour and thus a measure for coefficient C_{d2}. Given the acquisition costs for both aircraft are not officially published, this coefficient is a very course estimation.

Meteorological Data

Given Equation 14 which serves as energy balance, the input energy provision must be defined. The power provided by solar panels is directly related to the solar intensity received on the island. With the technology advancements of the recent years, it is estimated that current technology is able to convert 18% of solar radiation into grid power. This estimation was checked and approved by the local Bonaire energy distributor. Data on solar radiation (10 minute average) was available through the KNMI Data Platform [Koninklijk Nederlands Meteorologisch Instituut, 2022] which included the dedicated weather station of Bonaire located on the airport premises. The Data Platform also provides ten minute average measured wind speeds of the same weather station of an anemometer at a height of ten meters. Through the specific power curve of the wind turbine ([wind-turbine-models.com, 2022]), wind speeds could be converted to power. For this study, a wind turbine with a maximum peak power of 3.45 MW was chosen as this type will be used by the energy supplier of Bonaire as of 2024.

5.3 Operational Assumptions

Next to various assumptions with regard to input parameters, numerous operational assumptions are implemented which are highlighted briefly:

- Only electrified flights will be able to shift their scheduled arrival and/or departure time.
- The original turnaround time may never be decreased if the original turnaround time is shorter than one hour. In all other cases, the turnaround time may be decreased to one hour, provided it is allowed by the maximum shifts, set as $d1, d2$.
- In total four parking positions are eligible for a charging connection. These parking positions may handle up to code D aircraft. Parking position P1 will be the first one to be equipped with a charger. When needed P2, P3 and P4 may also be 'electrified' in that specific order. Two additional parking positions may only be used for conventional aircraft up to Code E.
- The threshold for fast charging is set at $\geq 100\ kW$.
- The maximum charging power is set to 1C (charging power equal to battery capacity).
- Fast charging is not allowed above 80% SOC.
- Charging stations are capable of providing a charging power that is lower than their maximum rated power output.
- Charging is only allowed during operational hours of the airport (06:00-23:00).
- Every day is optimized from 00:00 up to the latest possible time interval of that day.
- Repositions are only available for arrival-only E-flights and E-flights with an original turnaround time of two hours or more.
- Repositions may only take place at least 15 minutes after arrival or until 15 minutes before the departure time to assure proper time for ground handling services.

5.4 Modelling Day

Given the daily operational model, a particular representative day must be chosen to generate results. It has been decided to follow a parallel solution with airport terminal design sizing where the definition of an IATA representative peak day is often taken into account. The definition is originally based on peak hour passengers, however for this research, the number of electrified flights will be leading. By making use of this concept, over-sizing is avoided and a clear international standard is followed.

In more detail, this representative peak day has seen 21 return flights, 2 arriving and 2 departing flight legs as is also shown in Table 8. The majority of flights were inter-island flights originating only from Curaçao and only departing to Curaçao. No flights to or from Aruba were operated that day. In total, two unique 9-seaters and three unique 19-seaters have landed and/or departed BIA on this day. Of the two 9-seaters, one operates a return flight and an arriving flight leg that may be able to be repositioned. Also one 19-seater return flight is available for repositioning.

Furthermore, in terms of weather conditions, 0.79 kWh could be generated by one square meter of solar panel on the representative peak day. This is 25% less compared to the yearly average. With respect to the monthly average, a value of 12% lower was seen. For wind energy, the representative day falls within a three day dip and saw only a capacity of 44% compared to the yearly average and only 51% capacity with respect to the monthly average. In total, 11593 kWh of energy could be generated on the representative peak day by a single wind turbine.

The representative peak day will be subject to three optimizations given different electrified aircraft parameters to be able to tackle multiple aspects and variations of the imposed problem. The base scenario consists of possible combinations of unique electrified aircraft with a maximum allowable time shift of half an hour subject to ten minute intervals without making use of repositions. To be able to compare these time shifts, these results will be compared with the same scenario but then without the possibility of shifting flight times. The only problem that will then occur is that the model is infeasible as several required charging powers lie above the maximum set charger type of 600 kW as well as above the maximum allowable aircraft charging rate. Therefore, only for this 'D={0,0}' scenario, up to 1100 kW chargers were added next to the relaxation of Equation 9 as constraint. Lastly, the influence of allowing repositions will be analyzed for the base scenario.

Table 8: Overview of the type of flights on the selected representative peak day

Type	Return	Arrival-only	Departure-only
Conventional Flights	2	1	1
19-seater Flights	11	0	1
9-seater Flights	8	1	0
19-seater unique aircraft	3	0	1
9-seater unique aircraft	2	1	0
Reposition E-flights	2	1	0

5.5 Yearly Optimization Model Parameters

For the longer term optimization (for the model please see Appendix A), the full year of 2019 will be run according to the fixed ten minute discretized flight schedule with the same energy requirements, assumptions and coefficients as the detailed optimization model. Herein, all eligible flights will be electrified. However they will not be constraint by the parking position or charging constraints as the focus lies only on the general energy balance. Additionally to the battery energy storage, also a connection to the local electricity grid is included. This means that besides drawing energy from this grid against the local tariff ([Water- en Energiebedrijf Bonaire, 2022]) also energy could be returned to the grid for a certain return fee (0.01 USD). Note that now energy is only allowed to be returned to the local grid if the battery energy storage is full, given practicality. Moreover, only a maximum of 500 kW may be drawn from the grid per time interval as this was indicated by the local grid company to be the estimated power with which no significant investments to the grid should be made. Just like the daily operational model, energy provision in the form of solar panels and/or wind turbine(s) is available. More information on average monthly weather conditions may be found in Appendix B.

Unfortunately the complete year would now be too complex to run for a proper timely result, even with time intervals of 60 minutes. Therefore the twelve months of the year will be run separately using 60 minute intervals. However, this also means that no overnight storage would be possible between two consecutive months. To counteract this, a minimum of 275 kWh was set as storage end constraint. The final battery level will then thus be the starting level of the next month, except for January, where the battery level starts at 0.

6 Results

The results of both optimizations will now be presented. First in section 6.1, the daily operational optimization of the representative peak day will be discussed. Next, the optimized energy provision based on the entire year will be addressed in section 6.2. Lastly, section 6.3 presents the results of a sensitivity analysis based on potential costs changes and assumptions in the future. For all optimizations, the Gurobi Optimizer version 10.0.0 was used in combination with python under default settings, except for the NonConvex parameter that has been set to 2. All python scripts have been run on a server including two EPYC 7713 processors with each 128 cores and a total of 512GB RAM.

6.1 Representative Peak Day

Charging infrastructure minimum needs for the representative peak day have been summarized in Table 9. As can be seen in the scenario without any time shifts ($D = \{0, 0\}$), at least one charger capable of providing 1.1 MW of power should be installed to satisfy the original turnaround times. Alongside, two smaller chargers would be required. Energy is always provided by one wind turbine in combination with minimal battery capacity, except for the least demanding scenario where solar panels would see preference, again in combination with minimal battery capacity.

By allowing up to half an hour of time shifts for the arrival and departure time ($D = \{-30, 30\}$), the optimal solution for daily costs per scenario see significant lower values with respect to the scenarios without time shifts. This is mainly realized by the less powerful chargers required as turnaround times have been elongated and peak powers have dropped. Furthermore, the energy provision sees a shift from wind energy with minimal battery capacity to solar energy with significantly more battery energy storage. To dive more into detail, Table 10 shows the cumulative values of the provided solar energy, required charging energy and surplus energy for the complete peak day. As can be seen, always a significant part of the generated solar energy is not purposed to charge the electric aircraft.

Table 9: Results for the aircraft electrification possibilities on the reprensentative peak day for the base scenario and base scenario without time shifts

Electrified aircraft (9;19-seater)		**1;0**	**2;0**	**1;1**	**2;1**	**1;2**	**2;2**	**1;3**	**2;3**
Nr. of 9-seater E-flights (rtn;dep;arr)		*5;0;0*	*8;0;1*	*5;0;0*	*8;0;1*	*5;0;0*	*8;0;1*	*5;0;0*	*8;0;1*
Nr. of 19-seater E-flights (rtn;dep;arr)		*0;0;0*	*0;0;0*	*5;0;0*	*5;0;0*	*8;0;0*	*8;0;0*	*11;1;0*	*11;1;0*
D = {0,0} Repos = 0 T_{int} = 10 min	Charger types (kW)	1000	1000 200	1000 300	1000 300 200	1100 500	1100 500 200	1100 500 100	1100 500 300
	Wind turbine(s)	-	1	1	1	1	1	1	1
	Solar panels (m^2)	12000	-	-	-	-	-	-	-
	ESU capacity (kWh)	44	59	93	108	93	108	93	108
Base Scenario	Charger types (kW)	500	500 100	600	600 100	600	600 100	600 200	600 200
D = {-30,30} Repos = 0 T_{int} = 10 min	Wind turbine(s)	-	-	-	-	-	-	-	-
	Solar panels (m^2)	3715	7143	9883	13143	9883	13143	9883	13143
	ESU capacity (kWh)	105	431	437	876	437	876	617	1056
	Costs w.r.t. D={0,0}	-44.2%	-50.1%	-32.1%	-29.4%	-28.2%	-26.4%	-35.8%	-34.7%

Table 10: Total day energy balance values for the base scenario

Electrified aircraft (9;19-seater)	**1;0**	**2;0**	**1;1**	**2;1**	**1;2**	**2;2**	**1;3**	**2;3**
Solar energy provided (kWh)	2934	5642	7806	10381	7806	10381	7806	10381
E-Flight energy required (kWh)	697	1543	1489	2349	2036	2999	2658	3415
Surplus (kWh)	2237	4099	6317	8032	5770	7382	5148	6966

To see where exactly the surplus energy is seen, Figure 5 is presented. This figure shows the energy provision by solar energy (orange), charging energy required (red), surplus energy (blue) and energy storage level (green) per ten minute interval. Please note that the surplus energy and E-flight energy are stacked bars and thus cumulatively visualized. In the early morning, due to the worst case energy scenario no overnight energy storage is available. Therefore, all solar energy is needed for the charging of the first electric flights of the day. After that, all available energy is stored into the battery which is used again for the next morning flights. From that moment on, also surplus energy is seen, meaning that there is a certain amount of energy that will not be needed during the course of the day and thus may be used for other purposes. From around mid-day, the ESU level is constant and thus no more energy is needed to be stored for later use. During this time, it is seen that the solar energy exactly equals the required charging energy plus surplus. Towards the end of the afternoon, the energy storage is used again and finally fully loaded to serve the last electric flights when solar panels are not able to generate any energy.

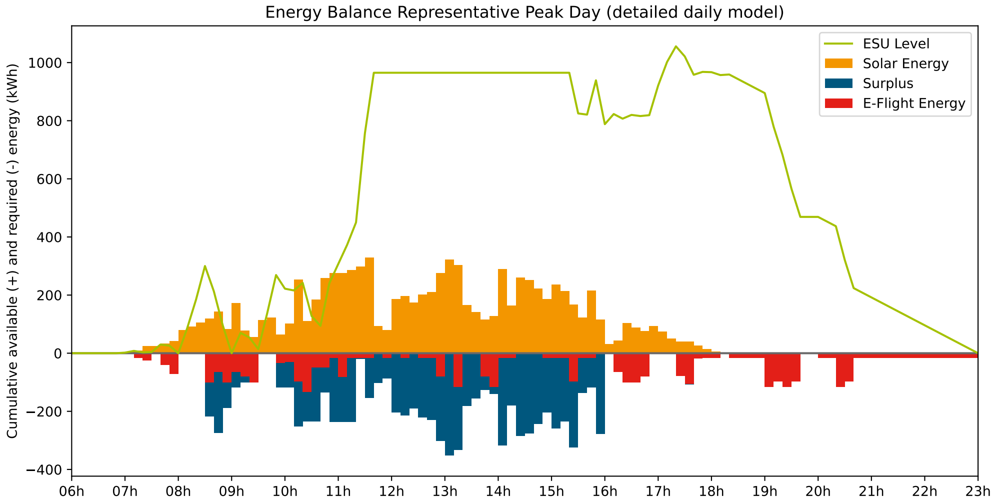


Figure 5: Available energy (solar & ESU), required charging energy and surplus energy of the representative peak day in 10 minute intervals as output of the daily energy model (base scenario, 2;3)

Now that the results of the base scenarios have been presented, it is also worthwhile to see if the allowance of repositioning the aircraft is beneficial in terms of daily costs. These results are shown in Table 11. Note that not all scenarios included flights able to reposition given the set constraints and assumptions. Furthermore, while running up to 48 hours, three scenarios did not come to a solution that was found optimal with 100% certainty. Although the found solution might still be the most optimal solution, Gurobi did at that point not have the time to check all remaining options of its algorithm, that might still include a better solution. However, it also provides an indication of the lower bound and thus the value up to which the solution might hypothetically still be decreased to, in case a solution complying to all constraints is found. This 'gap' between the lower bound and the current fount solution is also provided for these three scenarios.

Given the early morning and late afternoon/evening flights are still the same, the energy storage capacity as well as the solar panel area required are exactly the same as the scenarios without repositioning. For all scenarios that do not include flights able to be repositioned (<2 9-seaters, <3 19-seaters), all other results are the same as well. However, for the scenario where only two 9-seaters have been electrified, a slight decrease in costs with respect to its base scenario is seen. In absolute terms, this comes down to a value lower than $20, mainly contributed by the absence of a second charger. When one 9-seater and three 19-seaters are swabbed with electric equivalents, again one charger could be spared. Now, the cost reduction is more significant: slightly more than one hundred USD for this particular peak day. Given these two lower solutions, it is likely that all other reposition scenarios will eventually also show lower costs, however, given the solution gap, it is up for guessing to what extent a lower solution value might still be found.

Table 11: Results for the aircraft electrification possibilities on the reprensentative peak day for the base scenario including repositioning
**includes one or more flights available for repositioning*

	Electrified aircraft (9;19-seater)	**1;0**	**2;0***	**1;1**	**2;1***	**1;2**	**2;2***	**1;3***	**2;3***
	9-seater E-flights (rtn;dep;arr)	*5;0;0*	*8;0;1*	*5;0;0*	*8;0;1*	*5;0;0*	*8;0;1*	*5;0;0*	*8;0;1*
	19-seater E-flights (rtn;dep;arr)	*0;0;0*	*0;0;0*	*5;0;0*	*5;0;0*	*8;0;0*	*8;0;0*	*11;1;0*	*11;1;0*
D = {-30,30} Repos = 1 T_{int} = 10 min	Charger types (kW)	500	500	600	600 100	600	600 100	600	600 200
	Wind turbine(s)	-	-	-	-	-	-	-	-
	Solar panels (m^2)	3715	7143	9883	13143	9883	13143	9883	13143
	ESU capacity (kWh)	105	431	437	876	437	876	617	1056
	Repositions	0	1	0	0	0	0	1	1
	Costs w.r.t. Repos=0	0%	-1.8%	0%	0%	0%	0%	-3.1%	-0.3%
	Gap	-	-	-	0.6%	-	3.5%	-	9.5%

6.2 Yearly Energy Demand

Running the energy model for the entire year resulted in investments of only solar panels in combination with battery energy storage. Table 12 shows the results for every month presenting the energy infrastructure and the energy drawn from the local grid as well as the surplus energy returned to the grid. Looking at the number of solar panels, very similar results can be found for all months. Only November and December show slightly higher values as these were the peak months in terms of potential electric inter-island flights as well as the months with the least solar intensity (also see Appendix B). Similarly to the solar panels, also the two peak months show a slightly higher required battery capacity.

Besides using the sun as renewable energy source, the local electricity grid is also used. Relatively to the total energy used, it still remains a small portion. What is more significant is the surplus energy that is returned to the grid. At the starting of the year, the ratio of total input energy that is fed back lies at 11.5%, however this grows to a gross 20% in the summer months.

Table 12: Cost minimized energy provision infrastructure needs for 1 year optimization in 1 month, 60 minute intervals

Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Solar panels (m^2)	3069	2972	2948	2718	3139	2920	2873	3111	2904	2994	4153	3940
ESU capacity (kWh)	1362	1317	1154	1122	1154	1156	1195	1345	1400	1454	1397	1486
Solar energy (kWh)	94470	87057	98812	91140	107181	92817	92817	118230	98452	95390	114085	109937
Local grid (kWh)	3747	3239	4844	7809	3901	4557	4551	2824	6275	8269	4191	4355
Grid energy ratio	3.8%	3.6%	4.7%	7.9%	3.5%	4.7%	4.7%	2.3%	6.0%	8.0%	3.5%	3.8%
Surplus return (kWh)	11259	12602	18062	19957	24531	21059	21533	29768	15189	12184	27068	17605
Surplus ratio	11.5%	14.0%	17.4%	20.2%	22.1%	21.6%	22.1%	24.6%	14.5%	11.7%	22.9%	15.4%

A more detailed result with respect to the five energy parameters per 60 minute interval around the representative peak day from section 6.1 (Dec 09) is shown in Figure 6. Every day, the results show somewhat the same pattern: The energy stored overnight is used to charge the early morning flights. In case not sufficient energy could be stored overnight, energy is drawn from the local grid either in the late afternoon/evening or the next morning (seen on Dec 09 and Dec 12). During the rest of the day, the energy storage is filled up completely. On Dec 08, it however requires a small amount of stored energy as the charging energy demand is greater than the solar energy that could be provided during that mid-day hour. During this period, it now also becomes clearly visible that surplus energy is only fed back to the grid if the battery is at its full capacity. Later in the afternoon, when the solar energy is decreasing, the stored battery capacity is used again to charge the later arrivals of that day while also holding back some storage for the next morning flights.

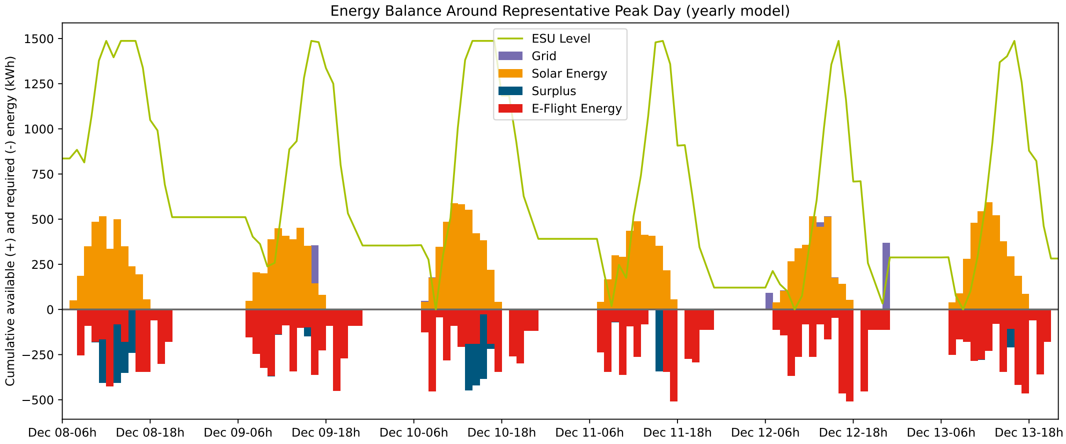


Figure 6: Available energy (solar & ESU), required charging energy and surplus energy of the representative peak day in 10 minute intervals as output of the yearly energy model

Although Table 12 already presents the monthly surplus energy and energy drawn from the local grid, this remains a rather large number without any further context. Figure 7 presents the boxplots of the daily surplus and grid energy of the complete year of 2019. As can be seen, the surplus energy varies widely per day. Furthermore, it indicates that half of the values lie lower than around 500 kWh while the other half shows more spread from around 500 kWh to 1800 kWh. For the energy drawn from the grid, it can be seen that around three quarters of all values lie below 250 kWh. What is more, in around half of all days almost no grid energy was used. Lastly, many outliers are visible representing days where a very significant amount of energy is drawn from the local electricity grid.

6.3 Sensitivity Analysis

In order to verify if the found solutions are robust and stable, a sensitivity analysis is performed for both optimizations. In this analysis, various parameters have been altered to see if this changes the final solution of the most demanding base scenario (without repositioning) or the presented yearly model. The parameter changes for the daily operational model have been chosen on the basis of likely future change and certainty of the actual value. Changes of the coefficients used in the yearly optimization have been chosen to allow more insights into possible energy business cases.

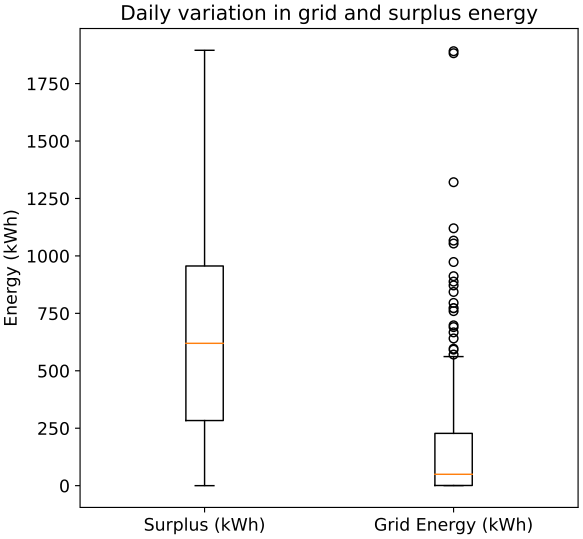


Figure 7: Surplus energy in kWh per day over 2019 given the yearly energy optimization

Daily Operational Model

For the results of the daily operational model sensitivity analysis, please see Table 13. Firstly, the cost of a charger has been decreased with 20% as it is expected that technology progresses quickly, just like with electric cars and buses. This change only shows marginal cost savings and does not change any of the energy provision infrastructure needs. Technology will also likely advance when it concerns the internal batteries onboard the aircraft. This is tested in three different changes of parameters. A total cost reduction of 25% on the battery price (thus cost per DOC) induces the most significant cost reduction. In case fast charging is better dealt with by the battery, and thus a lowering of the penalty price, also cost reductions are seen, just as for a higher threshold for fast charging. These three parameters mainly affect the costs for the operating airline. However, also for energy provision, cost savings were seen in the form of neglecting the flight schedule time shift penalties. This is done as a completely new flight schedule might be adopted when electric aircraft will be phased into the airline fleets, instead of adapting existing ones.

Table 13: Results for changed parameters with respect to the base scenario
** 1.9 % solution gap*

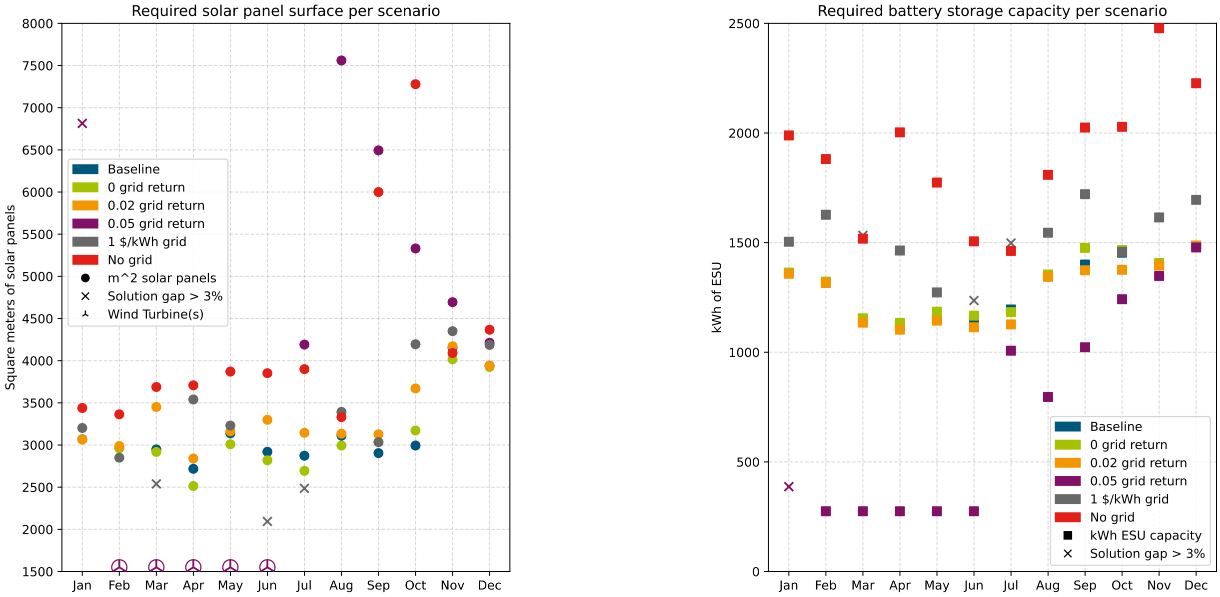
Parameter *Change*	$C_{inv_{CPi}}$ *-20%*	C_{DOC} *-25%*	C_{FC} *\$50*	$C_{d1}*$ *\$0*	THR_{FC} *200 kW*
Charger Types (kW)	600 200	600 200	600 200	600 200	600 200
Wind turbine(s)	-	-	-	-	-
m^2 Solar panels	13143	13143	13143	13143	13143
ESU capacity (kWh)	1056	1056	1056	842	1056
Costs w.r.t. base scenario	-0.5%	-14.5%	-8.5%	-10.7%	-4.2%

Yearly Energy Model

For the yearly model, two different coefficients (return fee and grid costs) have been varied to gain insights in possible changes in its solutions relative to the baseline solution. Results can be found in Figure 8 for the energy provision and the ESU capacity required, while Figure 9 shows the grid and surplus ratio. These ratios indicate how much energy is drawn from or returned to the grid relative to the total energy input (grid + solar). Please note that when one or more wind turbines are given as model output, on the lower y-axis of Figure 8 only the icon is presented. This does thus not represent solar panels and does also not indicate the number of wind turbines outputted by the model. Furthermore, solutions with an indicated optimization gap by Gurobi of larger than 3% are indicated with a different marker as well. For comparisons, these sub-optimal solutions have been neglected.

First of all, the fee which is obtained for returning one kWh of energy back to the grid is varied. The baseline already includes 0.01 *USD*, but now also 0, 0.02 and 0.05 have been subject to optimization. If no fee is to be received, the solar panel surface area and battery capacity do not differ that much for all months. Also for surplus ratio, the values do not show that much difference. For several months, the grid ratio does show slight variations. When the fee is increased slightly, in numerous months the solar panel area lies slightly higher which caused a lower grid ratio and higher surplus ratios in those months. The battery capacity is again very similar to the baseline scenario. In case of a 0.05 fee, more significant changes are seen. Most obvious are the investments in one or more wind turbines in February until June inducing very high surplus ratios and a zero grid ratio. But also in the other months, far more solar panel area is seen with respect to the baseline scenario, except for December. Looking at the battery capacity, the opposite holds in a less significant fashion as apparently less energy is required to be stored in combination with wind energy. For the grid ratio it means a lower value for the last six months of the year, while the corresponding surplus ratios are all higher, except again in December.

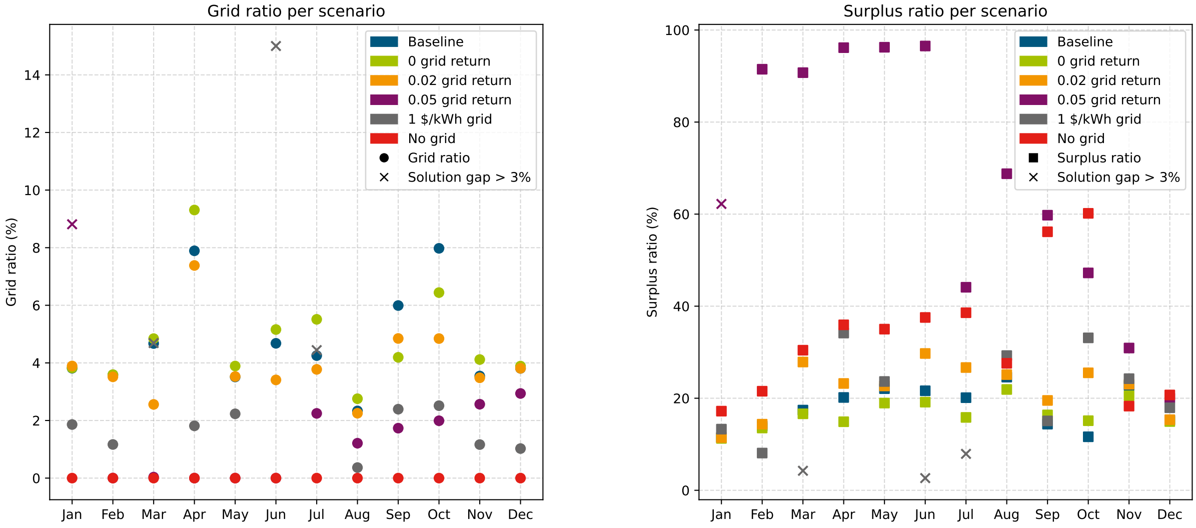
Besides the return fee, also the costs of drawing one kWh from the grid may see an increase in the future. Therefore, a cost of 1 *USD* is run which showed more required energy storage for all months. However, for the solar panel area, more variation is seen. Where some months show similar results to the baseline scenario (May, Sep), others show slightly higher values (Aug, Dec). In April and October, significantly more solar panel area is even seen. In terms of surplus, this is also reflected in higher ratios for the months of April and October. But for the grid ratio the higher price means structurally lower values. A cost increase will thus shift several parameters per month, however, in the extreme case that no grid energy is available (cost goes to ∞), even more drastic shifts are seen. In terms of solar panels, every month requires more surface area, which also induced higher surplus ratios. This changes from slightly more to far more in September and October. The same increase is seen with battery capacity, although here the variation is less varied, but always significantly higher.



(a) Solar Panels

(b) ESU capacity

Figure 8: Required energy provision infrastructure given a variation in grid return fee and grid electricity price



(a) Grid

(b) Surplus

Figure 9: Relative grid and surplus ratios given a variation in grid return fee and grid electricity price

7 Discussion

Analysing the results of the representative peak day, the difference between choosing a wind turbine or solar panels immediately becomes clear. Without any flexibility and without any energy stored overnight, one wind turbine would be the most cost optimized option. This is likely because of high peak power demand and the ability to generate high peak power during non sunlit periods. Energy storage would then only be required to cover periods without wind. By introducing flexibility and/or taking into account overnight energy storage, this advantage of possible 24 hour power generation fades away as a system of solar panels and battery energy storage is apparently less costly. Comparing the two former options, the shift to more storage capacity and less required energy provision makes perfect sense as this has introduced more flexibility into when energy could be used. Although the yearly energy model provides ample of surplus energy, it is logical as it is focused on providing sufficient energy on the most demanding day(s) which differ per month. Running the model for the entire year would harmonize these results better. This might also be a drawback of the model, as it can 'look into the future' which makes it fit for capacity calculations, but for practical reasons, it might be less relevant. In reality, it is impossible to exactly predict the weather of tomorrow (or further away) and thus how much energy must be stored the day(s) before. This is even amplified by current and future climate effects. Therefore, it might be that the found maximum capacity may not be sufficient in case of somewhat wrong weather predictions.

By looking more carefully to the detailed energy provision and needs per time interval, for both the daily model (worst-case scenario) and the yearly model, a trend may be identified. As no overnight energy is available in the daily model, all energy for the early morning flights must be generated by the solar panels at the exact same moment. This is thus a constraining factor as in the early morning the solar intensity is very limited. After that period, energy may be stored and thus the next set of morning flights will have less difficulty in being charged. While from the late morning on much surplus energy is seen, from around halfway the afternoon all energy is again used to charge the ESU to be able to handle all electric flights when solar energy is not any more available or to a lesser extent. The battery is then thus designed for the electric flights arriving in the late afternoon and evening. These two trends change when the yearly model results are reviewed. Now, the morning flights are not any more constraining on the number of solar panels as stored overnight energy is used. Now, the battery is still majorly constrained by the late afternoon and evening flights. However, additionally, now also the early morning energy demands must be taken into account in the form of overnight storage. Therefore, the battery is now constrained by the summation of both. Although this reasoning is sound, the price of the grid energy also has an influence. In case a larger battery is chosen, less grid energy is required and vice versa. But apparently, there is a turning point where adding battery capacity and using less grid energy will induce higher costs.

Besides the energy infrastructure, also the operationability of repositions may be questioned. For the airport, this means extra (outsourced) operations on its apron, but for the airline this likely means an associated cost. In conversation with BIA, it was pointed out that potential repositions are not especially desirable. Looking at the generated results, for the two reposition scenarios that reached their optimum, a slight decrease in daily costs was seen (up to ± 100 USD with respect to up to ± 3500 USD). However, given suboptimality of the more demanding scenarios, these savings may be higher depending on the flight schedule while also taking into account that the reposition costs used were deemed relatively high. Therefore it thus remains a decision for the airport, taking into account the workability of its operations and billing it to airlines, if repositioning is the preferred option.

Lastly, a short look will be taken into the practicality and reality of a possible implementation of the found results. If the maximum required infrastructure is chosen, the solar panel area of the daily operational model (13143 m^2) and the battery storage capacity of the yearly energy model (1486 kWh) would be implemented. This would be sufficient in the worst-case scenario, however, would also generate a lot of surplus energy. Given the area to the south of the runway at BIA is still open for development, this will easily fit all solar panels. Alternatively, roof mounted solar panels may be added on existing or future expansion terminal or maintenance building(s). Having executed a site visit, it is also deemed realistic that a potential battery may be placed within the existing airside support area. However, a problem arises when reviewing the legislative situation as now the return of energy to the grid is far from encouraged. What is more, supplying more back to the grid than taking from it is now even not possible, or the return fee is scrapped. Therefore, the sensitivity analysis nicely shows possibilities, however, local Bonaire legislation likely needs to change to support these sensitivity scenarios.

8 Conclusions

The goal of this research was to gain more insights into the electric infrastructure for electric flights. This was done by building a new Mixed-Integer Linear Programming model that minimizes the investment costs for the actual infrastructure (charging station(s), energy provision and storage) as well as airport and airline operational costs in the form of time shift, turnaround extension and battery charging penalties. By allowing up to 30 minute arrival and departure time shifts for flights to and from Curaçao and Aruba on the representative peak day of Bonaire International Airport, cost savings of up to 50% could be reached with respect to a fixed flight schedule. Depending on the number of flights and aircraft types to be electrified, these savings may be lower. Cost savings are also foreseen with technology advancements, however this did not majorly change the energy infrastructure needs. Also limited cost savings were seen by including the possibility of repositioning an electric aircraft during its ground time, although not all these scenarios had reached optimality. However, it remains an airport decision if repositions are to be implemented as operational complexity may be influenced.

For all these daily operational optimizations, a combination of solar panels and battery storage was seen. Wind turbines were thus not included in the final solutions, due to higher investment costs. The energy required for the early morning electric flights were seen to mainly drive the solar panel area whereas the late afternoon and evening electric flights drive the maximum capacity of the energy storage unit. This shifted to a slightly higher dependence on battery energy storage when a full year is optimized only in terms of energy provision and demand. Besides energy generated by solar panels, also the local grid was used on peak hours while surplus energy was only allowed to be returned to the grid when maximum storage capacity was reached. Sensitivity analysis on the grid return fee showed that above a certain threshold, the investments for a wind turbine would make sense in periods with ample of wind. Another analysis on increasing grid electricity prices furthermore showed the minimum energy infrastructure requirements and even for no grid connection if chosen for a airport micro-grid. However what energy business case is the most ideal for an airport is again highly dependent on the local situation taking into account legislation and energy infrastructure development plans.

9 Recommendations

As electric aircraft technology is far from advanced and not widely in commission at the time of writing, it remains highly advisable to closely follow the development of this new form of air transport. In case new information becomes available, this may easily be transferable as constraints or a change in constant(s) in the newly introduced model. Therefore, the model is very adaptable, also for potential other airports seeking to investigate the possibilities of electric flights. Given this specificity of the model, it however does not take into account the situation of other airports within the electric route network. In case of this research, integrating aspects of the total route network system (Curaçao and Aruba) could for instance introduce extra operational constraints for a daily aircraft flight schedule. In this way, a more complete solution could be obtained and insights could then be found in a wider spectrum. In terms of decision making, this may be beneficial for political or legislative plans or infrastructure investments.

One particular model aspect may be improved significantly. The battery model now is a highly simple reflection of costs per charge including a potential fast charging penalty. This is integrated as it would not significantly increase the complexity given all other charging and operational constraints. However, in real life, battery modelling is highly non-linear and very complex. Therefore, all costs related to the aircraft battery (charging) may be estimated better when a more advanced method of modelling battery charging is used. This will however also introduce more complexity into the model. Besides the battery dedicated to the aircraft, also the bulk energy storage, now taken as Li-ion battery, may be subject to further research. As other energy storage technology advances, it might very well be that in the (near) future other storage technologies such as hydrogen will be more cost beneficial than the current chosen Li-ion battery storage in both optimization models.

Lastly, two model improvements will also be recommended with respect to used assumptions. In future research it may be beneficial to investigate the switch from designated chargers per parking position to only one designated charger with a maximum capacity that could be shared among multiple parking positions. This might change the optimum costs in terms of civil or charging infrastructure. Secondly, the model now deals with the specific situation on Bonaire. As it may be that all or part of the power originates from the local electricity network, an extra penalty may reflect the charging of electric aircraft during the overall island peak (power) hour(s). In this way, less interference with the existing grid is seen at the most extreme situation, although electricity prices are fixed for all hours of the day. To lower the overall capacity by the airport on the grid, the complete grid supply and demand could also be taken into account in a future model.

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Appendices

A Yearly Energy Optimization Model

Objective:

$$\textbf{minimize} \;\; wt \cdot C_{inv_{WT}} + sp \cdot C_{inv_{SP}} + esu \cdot C_{inv_{ESU}} + \sum_{t \in T} (x_{grid_t} \cdot C_{grid} - x_{surplus2_t} \cdot C_{return}) \tag{24}$$

Subject to:

Energy balance

$$x_{ESU_t} + wt \cdot E_{wind_t} + sp \cdot E_{solar_t} + x_{grid_t} = E_{flights_t} + x_{ESU_{t+1}} + x_{surplus1_t} + x_{surplus2_t} \quad \forall\, t \in T \tag{25}$$

Only allow surplus2 when ESU is full

$$y_{surplus2\_allowed_t} - 1 \leq \frac{x_{ESU_t} + wt \cdot E_{wind_t} + sp \cdot E_{solar_t} + x_{grid_t} - E_{flights_t} - esu - x_{surplus1_t}}{M_1} \quad \forall\, t \in T \tag{26}$$

$$x_{surplus2_t} \leq (x_{ESU_t} + wt \cdot E_{wind_t} + sp \cdot E_{solar_t} + x_{grid_t} - E_{flights_t} - esu - x_{surplus1_t}) \cdot y_{surplus2\_allowed_t} \quad \forall\, t \in T \tag{27}$$

ESU max capacity

$$x_{ESU_t} \leq esu \quad \forall\, t \in T \tag{28}$$

ESU starting and end constraints

$$x_{ESU_{t0}} = ESU_{t0} \tag{29}$$

$$x_{ESU_{t\infty}} \geq ESU_{t\infty} \tag{30}$$

Only allow surplus1 as rounding

$$x_{surplus1_t} \leq 1 \quad \forall\, t \in T \tag{31}$$

Maximum power of grid without major adaptations

$$x_{grid_t} \leq PW_{grid\_max} \cdot t \quad \forall\, t \in T \tag{32}$$

Table 14: Overview of used decision variables of yearly energy optimization

Variable	**Type**	**Attribute(s)**	**Description**
wt	$\mathbb{Z}, \geq 0$	-	Number of wind turbines
sp	$\mathbb{Z}, \geq 0$	-	Square meters of solar panels
x_{ESU_t}	$\mathbb{Z}, \geq 0$	$t \in T$	Available kWh of ESU at time interval t
x_{grid_t}	$\mathbb{R}, \geq 0$	$t \in T$	Energy drawn from local grid at time interval t
$x_{surplus1_t}$	$\mathbb{R}, \geq 0$	$t \in T$	Rounding surplus energy at time interval t
$x_{surplus2_t}$	$\mathbb{Z}, \geq 0$	$t \in T$	Grid return surplus energy at time interval t
$y_{surplus2\_allowed_t}$	{0,1}	-	1 if surplus energy is allowed to be returned to local grid

Table 15: Overview of used parameters of yearly energy optimization

Parameter	Attribute(s)	Description
$C_{inv_{WT}}$	-	Investment costs for 1 wind turbine
$C_{inv_{SP}}$	-	Investment costs for 1 square meter of solar panels
C_{grid}	-	Costs of 1 kWh from the local grid
$C_{inv_{ESU}}$	-	Investment costs for 1 kWh of energy storage
C_{return}	-	Revenue for returning 1 kWh to the grid
ESU_{t0}	-	Energy available in ESU at the start of T
$ESU_{t\infty}$	-	Energy available in ESU at the end of T
E_{wind_t}	$t \in T$	Energy provided by 1 wind turbine at time interval t
E_{solar_t}	$t \in T$	Energy provided by 1 square meter of solar panel(s) at time interval t
$E_{flights_t}$	$t \in T$	Energy required to charge electric flights in time interval t
M_1	-	Large value (999999)
PW_{grid_max}	-	Maximum power to be drawn from the grid per time interval

Table 16: Overview of model sets of yearly energy optimization

Set	Description
T	Time intervals

B Daily Averages per Month

Table 17: Average daily (maximum) electric flight legs per month

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
E-Flight legs	28.0	28.8	29.6	27.3	30.2	27.1	30.0	32.6	33.6	33.8	34.5	35.0

Table 18: Average daily solar and wind energy per month

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar (kWh/m^2)	0.99	1.05	1.08	1.12	1.10	1.06	1.15	1.23	1.13	1.03	0.92	0.90
Wind (MWh/Turbine)	27.7	32.6	29.8	34.4	37.4	36.8	28.7	27.7	14.7	13.0	10.3	22.6

II

Literature Study

previously graded under AE4020

1

Introduction

In the current society, sustainability is a hot topic in all thinkable places. For some people, the overall worldwide climate effects are already experienced in tangible events such as immense bushfires in Australia, extreme draught, or the complete opposite, of extreme rainfalls and floods in several countries across the globe. Although not all these events might be directly linked to climate effects, some studies did show a likely correlation with the increasing temperatures for these extreme weather events [38, 55]. Given the communal response not to let the temperature rise by more than 2.0 degrees under the well known Paris Agreement [155], all industries are doing their utmost to limit their share in the emission of green house gasses.

This also holds for the transportation sector where electric vehicles are getting more and more common on the European roads [61]. Of course, its vehicle batteries and production must then be charged with 'green energy' for it to be fully sustainable. Especially electric cars are now making their move towards a sustainable transport solution on land. However, by air, developments can only be found in their childhood. Although intercontinental flights will likely never fly only using heavy batteries, for shorter flights, feasibility is a lot closer than one might think.

Given that the first commercial electric flight is yet to take-off, several countries together with the aviation sector are preparing themselves in advance for this special occasion and the years to follow. Also in the Netherlands several parties are collaborating to follow or advance the latest technology, including the Dutch Government. They have asked aviation consultancy NACO and the Netherlands Aerospace Centre (NLR) to prepare a road map to provide insights into the steps that need to be taken in order to successfully implement electric flights within the Kingdom of the Netherlands. Focusing on the Dutch Caribbean part of the Netherlands, inter-island flights between Aruba-Curaçao-Bonaire were identified as an ideal example market for a user case given their close proximity to each other. It was then quantified step-by-by what infrastructure investments would be needed to cater for these electric flights [79].

Although the introduced road map already provides a proper overview of several important factors in electrifying flights, it remains rather high-level. The goal of this literature review is to dive deeper into the Bonaire user case of electric flights in the Dutch Caribbean and consequently identifying a research gap. With this literature review, a more detailed overview will thus also be provided which will serve as the basis of a master thesis project, but could potentially also serve certain stakeholders.

To identify the research gap, this literature review will provide the current state-of-the-art background information. In chapter 2, the aviation sector of Bonaire is discussed with an emphasis on local flights to Curaçao and Aruba. Afterwards, also the energy infrastructure present on Bonaire is addressed in chapter 3. As electric aircraft will be provided with power out of a battery, their types together with charging characteristics are elaborated upon in chapter 4. The current and future electric aircraft developments will be summarised in chapter 5 where besides pure design features, also side factors are highlighted. chapter 6 will then combine theory with projected aircraft designs into a feasibility analysis. Afterwards, various optimisation models with respect to electric transport charging are presented in chapter 7. Lastly, in chapter 8, a conclusion is drawn including the identification of a research gap.

2

Bonaire Aviation

Bonaire International Airport (BIA), also known as 'Flamingo Airport', is the only aerial gateway to Bonaire and of great importance to the island and potential future electric air transport. This chapter will introduce the current airport operations (section 2.1) as well as a more detailed overview of the airport parking infrastructure (section 2.2). Furthermore, in section 2.3, the local flights to Curaçao and Aruba will be discussed. Lastly, also the more political debate regarding the air connectivity of the Dutch Caribbean is addressed in section 2.4, while section 2.5 summarises the future plans of stakeholders with respect to sustainable aviation.

2.1. BIA Operations

BIA is the largest airport of the three special municipalities (Bonaire, St. Eustatius, Saba; BES) of the Netherlands. However, compared to its nearby sister islands of Curaçao and Aruba, operations are a bit smaller. In the past three years (2019-2021), 484.4, 160.4 and 259.9 thousand passengers have made use of BIA using one of the 15.6, 7.8 and 10.0 thousand aircraft movements [40]. This means that in terms of Covid recovery, passenger levels in 2021 were 67,6% of pre-Covid 2019 levels.

Of all the passengers, 40.0% and 38.7% were classified as passengers that departed or originated from a 'local' flight in 2019 and 2020 respectively [33]. These only include routes to Aruba (190 km) and Curaçao (80 km), as verified by the 2019 BIA tower log [1]. On these routes, only two airlines are active at the time of writing (June/July 2022): Divi Divi Air and EZ Air. These two airlines mainly offer commercial scheduled flights, however also charters. Especially EZ Air offers frequent charter flights commissioned by the Dutch Government for so called 'ZVK' flights to St. Eustatius. These flights are offered twice a week and are only available to the citizens of St. Eustatius and Saba as on these small islands specialised health care facilities are not available.

About a third of the total passengers in 2019 boarded a KLM or TUI flight to or from Amsterdam. Both airlines currently operate daily flights. However, KLM flies its Bonaire route in combination with Aruba, while TUI merges its Bonaire route with either Curaçao, Aruba or Punta Cana. The majority of all other passengers mainly found themselves on a flight from the US. At the moment, the three big airlines of the US all fly to Bonaire out of Atlanta (2 weekly Delta Air Lines), Houston, Newark (both 1 weekly United Airlines) and Miami (3 weekly American Airlines) [24]. During the US holiday seasons, these flight frequencies are increased. Also KLM and TUI may increase their flight frequency during peak seasons. Only a very small portion of passengers flew to regional destinations such as St. Maarten (Winair) or Santo Domingo (Sky High).

In the past years, Saturday has always been the busiest day of the week regarding the number of handled passengers. This mainly is caused by the arrival of all US flights in combination with the two daily Amsterdam flights on the first day of the weekend. In terms of number of handled flights, Friday is especially busy with local Divi Divi Air and EZ Air flights to Curaçao and Aruba, see Table 2.1.

A look in the future learns that two airlines will (re)start routes to BIA. In combination with Curaçao, Air Belgium will connect Brussels with Bonaire two times a week [101], however, this has already been scaled down to only four return flights during the Christmas period [100]. WestJet will restart its Toronto flights only until the end of the year [23].

Table 2.1: Flight schedule including parking position appointment of Friday June 17th, 2022 [24]

Airline	Aircraft	From	STA	To	STD	Stand
EZ Air	SF34	CUR	07:15	CUR-AUA	07:35	3
Divi Divi	DHC-6	CUR	07:20	CUR	07:40	2
Divi Divi	DHC-6	CUR	08:50	CUR	09:15	2
Divi Divi	DHC-6	CUR	10:50	CUR	11:15	2
EZ Air	SF34	AUA-CUR	11:00	CUR	14:00	3
Divi Divi	DHC-6	CUR	12:25	CUR	12:45	2
Sky High	ERJ145	SDQ	15:10	SDQ	16:00	1
EZ Air	SF34	CUR	15:30	CUR-AUA	15:50	3
FEDEX	E120	CUR	15:38	CUR	16:08	4
Divi Divi	DHC-6	CUR	15:55	CUR	16:15	2
TUIfly	A333	AMS-CUR	17:20	AMS	18:30	5
Divi Divi	DHC-6	CUR	17:25	CUR	17:45	2
EZ Air	SF34	CUR	17:30	-	-	1
EZ Air	SF34	AUA-CUR	18:40	CUR	19:00	3
Divi Divi	DHC-6	CUR	19:15	CUR	19:40	2
KLM	B77W	AMS-AUA	19:45	AMS	21:00	5

2.2. Airport Parking Infrastructure

BIA has three aprons on which aircraft can be parked and serviced. The most western apron is only used for general aviation while the other two can accommodate commercial scheduled and charter flights. Given the 4E airport runway code, it is capable of handling aircraft up to the Boeing 777 series. According to the BIA Masterplan, parking positions 1 through 4 may be used by aircraft up to Code D which all have the capability of taxi-out, see Figure 2.1. Stands 5 and 6 are the only positions capable of handling Code E aircraft such as KLM and TUI wide bodies [116]. Practically, smaller size aircraft, typically Divi Divi Air DHC-6 Twin-Otter and EZ Air Saab 340, will almost always be parked on positions 1 through 4. Code C aircraft will preferably always be parked on the wide body apron when available. This is due to the set ICAO Annex 14 Obstacle Limiting Surface (OLS) which is infringed by the tail height of Code C aircraft when parked on stands 1-4. However, on Saturdays, three narrow bodies arrive in a short time frame after each other. Therefore, at least one Code C aircraft would need to be parked on the 1-4 apron. It must also be noted that when a wide body is parked on stand 5 or 6, it will always infringe the OLS.

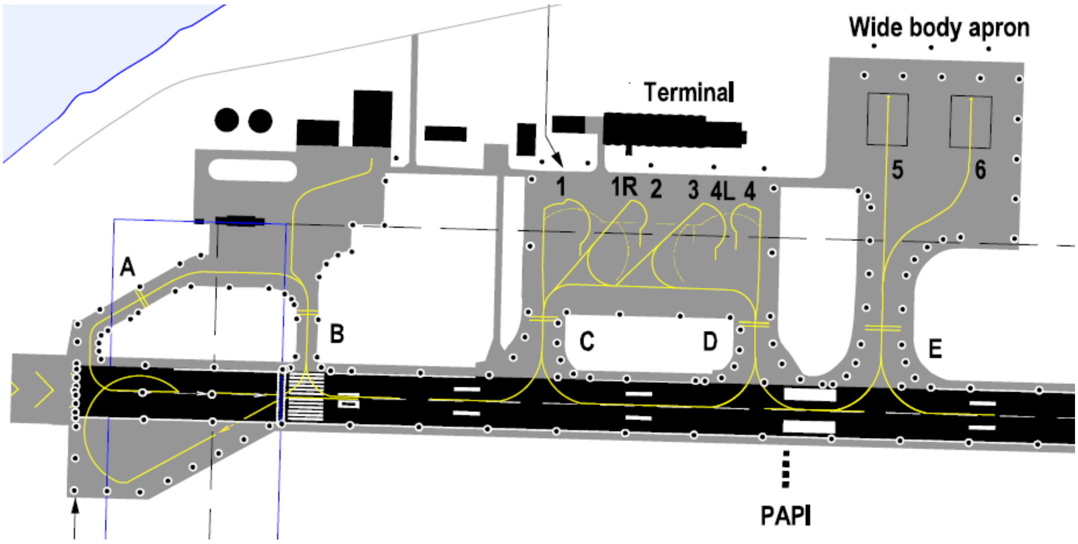

Figure 2.1: Overview of the current parking positions at Bonaire Airport (North ↑) [128]

Looking at various Aircraft Parking Position Planner schedules of the 2019-2021 time period [24, 25, 26, 27, 28], it becomes clear that on Saturdays, both on stand 1 and 3 a code C aircraft was planned to be positioned, next to one on stand 5. This could be due to practical reasons, for instance that stands 1-4 are located closer to the terminal or do not require pushback. What is more, when two narrow bodies were parked on stands 1 and 3, a Divi Divi aircraft was planned to be serviced on stand 2, see Table 2.2. In case only one or two narrow bodies arrive during weekdays, it was either positioned on stand 1, 3 or 5 without a clear preference. The real reasons for these decisions remain unknown for now. Also note that only the planned parking positions were provided and that changes during the actual operational hours are not known.

Table 2.2: Extract from flight schedule including parking position appointment of Saturday June 18th, 2022 [24]

Airline	Aircraft	From	STA	To	STD	Stand
Divi Divi	DHC-6	CUR	12:25	CUR	12:45	2
United	B738	EWR	13:27	EWR	14:40	1
American	B38M	MIA	13:33	MIA	14:34	5
Delta	B738	ATL	13:50	ATL	15:20	3
Divi Divi	BN2	CUR	13:55	AUA	14:30	2
Divi Divi	DHC-6	CUR	15:55	CUR	16:15	2

As already mentioned, the OLS causes certain restrictions due to international regulations. Non-compliancy with these regulations is not desired from a safety and regulatory point of view. The dashed line visible in Figure 2.1 marks the edges of the runway strip in which no static object may be placed. This strip extends 150 meters in parallel from the runway centre line. Beyond this runway strip, the OLS will induce height restrictions with a 14.3% slope [85]. In their BIA Masterplan Update (2019) [116], this item is also addressed which together with future expansion plans resulted in the proposed lay-out of Figure 2.2. In these plans, local and regional aircraft up to Code B are still catered from the existing apron (stands 1-4), however, the possibility exists that some of these planes might be serviced on the new narrow body apron. Code C aircraft will, in the proposed plans, be located on the existing wide body apron and an extension of it. Wide body (Code E) aircraft would see three new dedicated stands a bit further away from the runway centre line and will be a Multi-Aircraft Ramp Solution (MARS). These MARS stands can either locate one Code E aircraft, or 2 Code C aircraft (not illustrated in Figure 2.2). It must be noted that the runway strip width is reduced from 150 meters to 140 meters as ICAO has amended this value in its eighth edition of Annex 14 with respect to previous editions in which the old lay-out was designed.

Besides the proposed new apron design, BIA is currently also exploring the extension of the general aviation apron towards the middle apron. Although not officially published, the plans were brought up in a talk with a NACO project manager with experience at BIA. The new concrete or asphalt area would mainly prevent loose stones, pebbles and dust and would thus also serves as safety precaution. However, for electric aircraft it could mean extra space for potential charging stations.

Airport fees regarding landing and parking at BIA have been published on their website. Per ton of MTOW (or a part thereof) a landing fee of US$3.10 must be paid, with a minimum of US$10.50. For a Twin Otter this comes down to $18.60 and US$43.40 for a Saab 340. In case an aircraft remains longer than two hours on the apron for parking, a fee of US$0.60 per ton of MTOW per 24 hours (or part thereof) must be paid, with a set minimum of US$8.00. Furthermore, in case international flights are handled, a fixed fee of US$33.00 is to be paid due to waste management. Pushback services are available for US$80.00 per pushback [32].

Also ground handling services are offered at BIA through Swissport. This handler charges fees per requested service. For Bonaire, it is up to the time of writing unknown what these fees are, although the terminal handling charges of 2022 at Amsterdam Airport Schiphol have been made public [150].

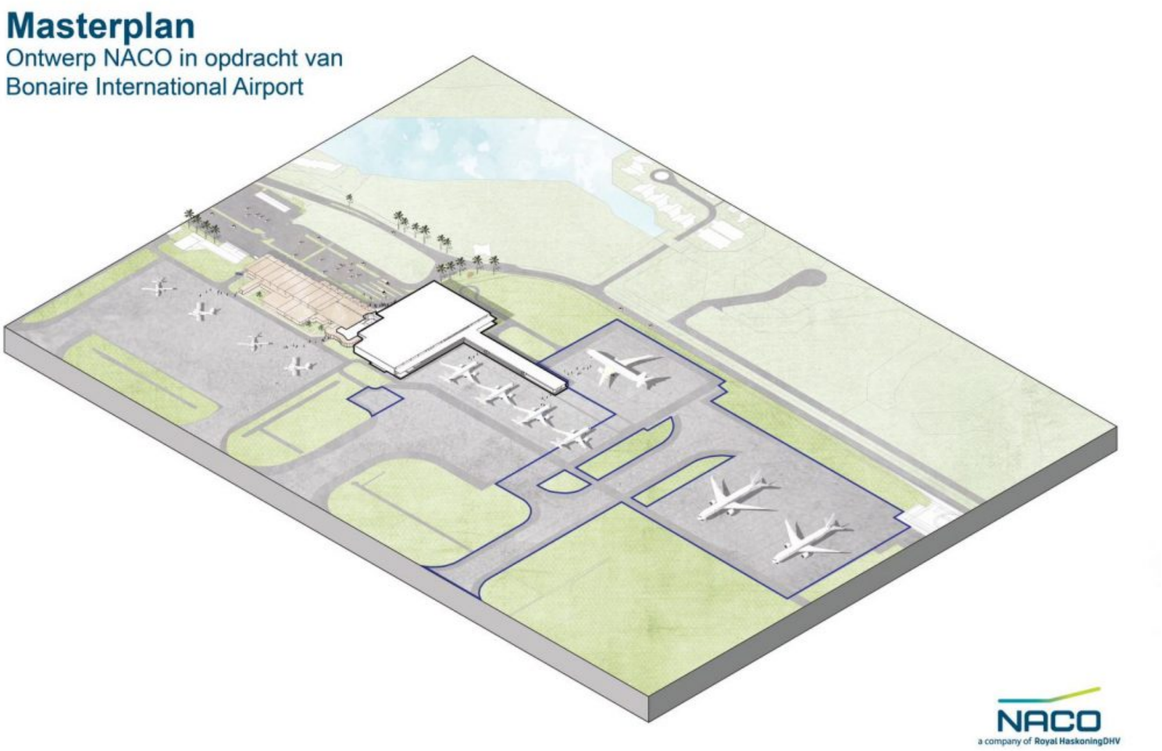

Figure 2.2: Illustration of future proposed apron Bonaire Airport [117]

2.3. Curaçao/Aruba flights

As in the preliminary road map became evident that inter-island flights could benefit from electric air transport [79], this section will zoom into the local routes to Curaçao and Aruba. First, the current situation is discussed after which 2019 and 2020 flight schedules are also addressed.

2.3.1. June 2022 Situation

At the time of writing, only two airlines operate flights to the two nearby islands: Divi Divi Air and EZ Air (see Table 2.3). Divi Divi has published its flight schedule on its website which states 77 return flights between Bonaire and Curaçao using their Twin-Otter aircraft (19 seats) and Britten Norman Islander (9 seats) [52, 53]. However, only 45 return flights appear on provided flight schedules by BIA (June 16th-22nd, 2022) [24] with scheduled turnaround times of 20 to 25 minutes. No direct flights to Aruba are offered, however because of the great availability of flights from Curaçao to both Bonaire and Aruba, transfers could be made easily.

EZ Air operated 47 weekly one-way flights (single flight legs) during the June 16th-22nd (2022) time period. Most of these flights went directly to or originated from Curaçao, however two flights arrived directly out of Aruba an one departed for Aruba. It must also be noted that for several EZ Air flights, Aruba is the final destination, however, a stop-over on Curaçao is made. The regular scheduled turnaround time varies from only 15 minutes up to half an hour. All EZ Air flights are executed by Saab 340 aircraft types which can accommodate 34 passengers.

Table 2.3: Scheduled flights from Curaçao to Bonaire June 16th-22nd, 2022 [24]

Airline	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Comment
Divi Divi Air	7	6	5	7	7	8	5	Return flights
EZ Air	8	6	8	9	9	2	5	One-way flights, 3 direct from/to Aruba

2.3.2. Historical Trends

As BIA is still recovering from the Covid-19 crisis, the presented flight schedule of 2022 might not show the full potential for electric flights. Therefore, this section further discusses two other time periods just before the worldwide pandemic: June 2019 [25] and February 2020 [26]. Note that due to Covid recovery, the flight schedules of 2021 are left out of this overview. From Table 2.4, it immediately becomes clear that far more flights have been operated in comparison with June 2022. For Divi Divi Air, this even is more than double. While Divi Divi still uses the same aircraft mix to fly its Curaçao route, EZ Air previously operated Beechcraft 1900 (19 seats) aircraft alongside a Britten Norman Islander (9 seats). Also EZ Air operated far more flights in the pre-pandemic period, in February 2020, roughly 50% more. It must be noted that in the analysed flight schedules, it only showed EZ Air flights to and from Curaçao, so no stop-over Curaçao-Aruba flights were seen.

Besides the two still operating airlines, in 2019/2020 two other local airlines were actively flying to Bonaire. National Aruban carrier Aruba Airlines in June 2019 even operated their Airbus A320 on the route alongside a CRJ200. Although the flight schedules showed limited weekly return flights, it however was the only direct route from Bonaire to Aruba. Several months later, the larger aircraft were swapped for a Dash 8-Q300 while remaining the flight frequency.

Next to flights to Aruba, also flights to St. Maarten (SXM) were operated by St. Maarten carrier Winair. Although far from all of Winairs ATR flights to Bonaire are given to originate or destined from/to SXM, this remains very likely. However, this could also be under a different flight number. This is of great importance as only fifth freedom rights have been agreed upon withing the Netherlands (BES), Aruba, Curaçao and St. Maarten [114]. In other words, only passenger traffic between SXM → BON, BON → CUR and BON → SXM is allowed and not CUR → BON on these BON-CUR-SXM stop-over flights.

Table 2.4: Historical local Curaçao/Aruba return flight frequencies at BIA for June 2019 and February 2020 [26, 25]

Airline	Route	Return Flights	Aircraft	Year
Divi Divi Air	CUR	70 weekly	DHC-6 / BN2 mix	June 2019
		87 weekly		Feb 2020
EZ Air	AUA	1 weekly	B1900	June 2019
	CUR	28 weekly		June 2019
		37 weekly	B1900 / BN2 mix	Feb 2020
Aruba Airlines	AUA	4 weekly	A320 / CRJ200 mix	June 2019
		4 weekly	DH8	Feb 2020
Winair	CUR(/SXM)	6 weekly	ATR42/72 mix	June 2019
		7 weekly	ATR42	Feb 2020

2.4. Local Air Connectivity

Although BIA is very important in bringing in tourists to the Dutch Caribbean island, the airport also serves a completely other purpose to the local community. The reason that around 150.000 passengers fly to Curaçao or Aruba has its origin in large social-economic factors. For instance specialist health care is not in all fields offered on Bonaire, however, it is offered on either Curaçao and Aruba. Therefore, air ambulance flights are very common. To map all these factors, SEO has conducted research in 2018 [36]. They concluded that given the decreasing trend in passenger numbers from 2012 to 2017, the route from Bonaire to Curaçao was slowly moving towards a 'thin route' (<100.000) and that a wealth loss of 1.8 million USD would be seen in the case of flight reductions of 10%. In order to guarantee connectivity, they proposed the use of a Public Service Obligation (PSO) in its 'open access' form where the government is able to impose certain minimum requirements for this route. The direct route to Aruba was already classified as a 'thin route' and it is also advised that an open access PSO would suffice here. However, wealth losses would only sum up to 0.1 million USD per month in case the route is not flown any more.

In the mean time, certain changes have taken place on the Bonaire-Curaçao/Aruba routes. Given the number of passengers have not really decreased since 2017 (neglecting covid-19) their conclusions may not yet be as relevant as they were four years ago. However, the political debate has ever since been active, mainly concerning the high costs of inter-island travel. From BES politicians [20, 21, 22] the call for cheaper airlift is considerable. However, also from BIA itself, the call for public transport-like financial subsidies on inter-island flights are made known to the public [157].

2.5. Stakeholder Future Ideas

As part of the process of the published road map, NACO conducted several interviews with stakeholders in the Dutch Caribbean region, the Netherlands and electric aircraft manufacturers. In these interviews, the stakeholders were asked to elaborate upon their future plans regarding sustainability and more specifically electric flights. This section will highlight communal goals and wishes, and details individual plans of Bonaire Airport [2], the Civil Aviation Authority (CAA) Aruba [3], Heart Aerospace [4], Winair [5], Air Ambulance [6] and the Dutch Electric Aviation Centre [7].

What all interviewees have in common is that they all foresee an infrastructural challenge regarding the electricity network. BIA mainly sees capacity and continuity issues on the current electricity network that provides the airport with around 1.5 GWh of electricity annually. They have the ambition to at least invest in their own partial power supply such as solar panels on top of their parking lot and/or energy storage facilities. Furthermore, they estimate that the current island electricity network could still handle an increased capacity for about four to five years. Other interviewees only briefly mention that proper electric infrastructure should be ready before the first electric flight.

Another common issue that was identified is the governance around electric flights with a focus on especially collaborations. CAA Aruba explicitly mentions the policy makers that should focus on specifics of electric flight regulations and proactiveness which is currently not the case. From Aruban Government to Dutch regulatory institutions and universities, they should all cooperate for the main goal of flying electrically as soon as possible. In case everyone is doing their own thing or waiting on someone, nothing concrete will happen. Moreover, they note the public awareness of electric aviation that must be increased to make it a success. BIA and Air Ambulance specifically mention a collaboration with the hospital as they also focus on energy continuity and are of course involved in medical flights.

Remarkably, major St. Maarten carrier Winair, does not have any plans for future electric aircraft as they want to await the moment it becomes available. They furthermore give none to zero input in the electrification debate. Air Ambulance does have a vision regarding sustainability and aims to operate 200 to 300 electric flights on an annual basis, when available. However, they indicate that they do not have the financial capital to invest in an entire new hybrid or all-electric aircraft, although they could cover operational costs and investments. The future aircraft should preferably be EASA certified as this would be easier for the Aruban Government to be taken over instead of FAA certification.

Other topics that have been addressed by the interviewees deal with the earlier discussed connectivity problem. Especially BIA, CAA Aruba and DEAC mention the importance of cheaper air fares that could partially be reached by electric aircraft operations. Also extra safety measures were mentioned with regards to electric fires and battery incidents by BIA and DEAC. Ideally this should be tackled internationally by means of the ICAO Annexes.

Lastly, the Dutch Caribbean Cooperation of Airports (DCCA) is worth mentioning. Although not interviewed as party, it was mentioned by BIA. The DCCA is a collaboration between all six Dutch Caribbean airports which agreed to work together on communal problems faced by all of them. Specifically, electric flights and the connectivity are focus points. The collaboration incentifies a more extensive sharing of information and knowledge as well as support. An excellent example of this collaboration is a joint event regarding future sustainable flights with an emphasis on electric aircraft, its operations and potential in the region.

3

Bonaire Energy Infrastructure

As the future electric aircraft will need power to charge its batteries, also the energy infrastructure must be reviewed. First, the current energy infrastructure and management is discussed in section 3.1. In section 3.2, two studies related to expansion of renewable energy sources on the island are summarised.

3.1. WEB

On the island of Bonaire, an energy network is operated for the exclusive use for Bonaire. Water- en Energiebedrijf Bonaire (WEB) is the local distributor of electricity and water and manages the energy supply chain. At this moment, diesel generators form the backbone of the power supply. However, renewable energy sources are also available in the form of thirteen wind turbines and a small solar park (792 panels). The wind turbines consist of one 330 kW unit alongside twelve 900 kW Enercon E-44 units with a base height of 45 to 55 meters. Its power to wind speed relation is given by Figure 3.1, while 'meteoblue' [108] and KNMI [91] provide data on the solar radiation and wind speed. These renewable sources made up 20.9% of the total 121 GWh energy supply in 2020 [162]. Although this renewable energy percentage has decreased from 2018, the aim is to increase this ratio to 60% in 2025 by expanding the wind and solar farms [160, 161]. According to an interviewee from Bonaire Airport, the current wind turbines will be replaced by larger more powerful ones and that an expansion of the solar park is not projected as WEB would see solar energy as additional source besides wind energy [2]. However, no other source could be found that acknowledges this.

What is also worth mentioning is the presence of a hybrid energy storage unit. This integrated system combines the inputs of diesel generators (22 MW), solar park and wind turbines (11 MW) and manages its energy flows [161]. Practically, the system can store some the surplus energy generated by renewable energy sources in case of abundance of wind and sun. According to information on their website, up to 6 MW of energy could be stored.

Furthermore, WEB has published their electricity rates. Numerous options are available from one-phase 25A connections up to three-phase 100A/380V connections. Every connection type has its own fixed monthly tariff starting from US$ 18.71 to US$ 569.98. For all connections, a variable usage fee of 0.4253 USD/kWh is charged. This also holds for all three-phase connections above 200A or 76.10 kVA of which a separate formula is used to calculate the fixed monthly fee [163].

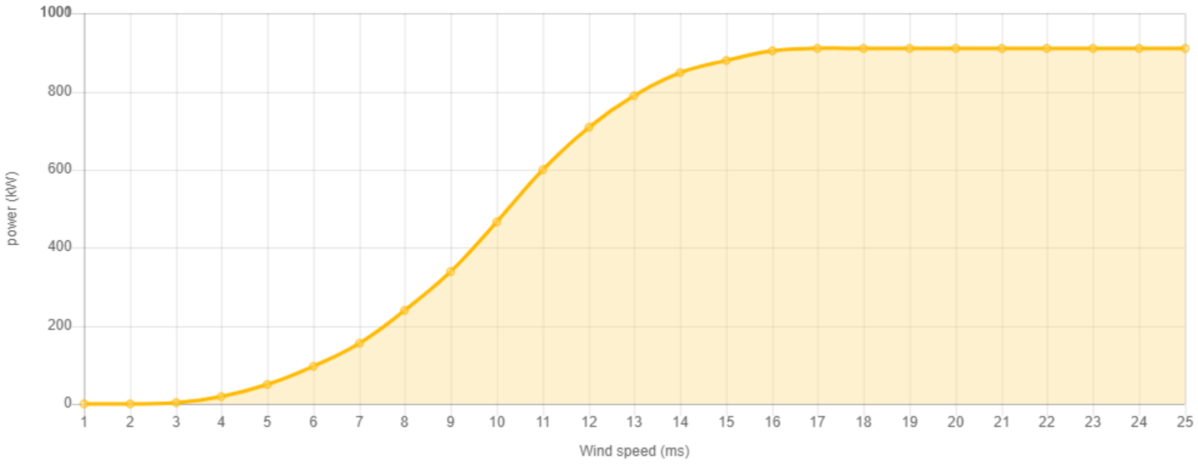

Figure 3.1: Power curve of the E44 wind turbine [167]

3.2. Expansion Plan Studies

Unfortunately, no more than just statements about expansion of renewable energy sources have been found. Therefore, it is yet unknown how Bonaire is concretely planning to increase their 'green' energy share. However, in 2016, Sun et al. already performed a feasibility study on the integration of a 6 MW solar park into the electricity network [149]. They proposed to place the new larger solar plant at the same location as the existing one as sufficient space is still available. According to the authors, by only including a second parallel cable (12.2 kV) the energy flows of the complete Bonaire energy network would be rated as 'healthy' also taking into account the power provided by the wind turbines.

More recently, Tariq conducted research into the possibilities of reducing the diesel generator power provision on Bonaire [151]. According to his baseline model, 34.22% of the total energy was provided by renewable energy sources. However, he argues that during the September-December period, the share of wind energy drops significantly. To counter this seasonal effect, he further proposed twenty new 1 MW wind turbines, a 42 MW solar park including 20 MW energy storage unit as well as a hydrogen plant including storage facility. These drastic measures would decrease the share of diesel generated power to only 0.53% over one year. Of course, these alternatives, especially the hydrogen plant, will require enormous investments, however, diesel import costs will also significantly decrease.

4

Battery and Charging Technology

Now that the current situation on Bonaire and its airport have been elaborated upon, this chapter will introduce the current state-of-the-art of battery and charging technologies. First of all, different battery types will be analysed based on different specifics in section 4.1 which also provides a short future outlook. section 4.2 will continue by discussing the degradation of batteries primarily caused by charging the battery. Lastly, the storage of energy is discussed in section 4.3.

4.1. Battery Types and Specifications

At this moment in time, almost everybody in the world in some way is dealing with any kind of battery. These batteries may vary in size from mini batteries in hearing aids up to massive industry style units. All these batteries may be composed out of different materials depending on the use case as a different battery composition leads to different specific energy performance. In Figure 4.1, six different conventional batteries are compared on the five most important design factors. Looking at the weight energy density, from an aircraft design perspective, it is desired to be able to store as much energy as possible in a low mass battery. This also holds for the volumetric energy density. Regarding the power density, there is a bit more flexibility. In case not much power is expected to be drawn from the battery, a battery type with a lower power density may be chosen, for instance because of lower prices per battery. Undoubtedly, both the cycle life, and thus life time, and the energy efficiency are always desired to be as high as possible.

Comparing the six batteries for the introduced specifications, it is clear that the lithium-ion (Li-ion) battery shows the greatest potential at this moment in time. What is more, these batteries are already used extensively across all industries including electric vehicles [129]. However, the main disadvantage of Li-ion is that with increasing specific power, the specific energy decreases a bit [90]. Over the past years, a lot of research has already been conducted into exploiting every potential of the Li-ion battery up to the specification levels we experience today. Although it is known that other factors might also be considered in choosing a battery type, this is deemed out of the focus of this research does not lie with extensive battery technology. Therefore, as Li-ion batteries show the best performance at this point, other existing batteries will be discarded from now on.

These days, Li-ion batteries can be made with a weight energy density of as high as 0.25 kWh/kg [34, 88, 106]. However, researchers are still exploiting its potential by proposing new adaptations to the existing Li-ion batteries with the goal of making it even a more reliable, longer lasting and higher capacity battery. Mainly, this is done by testing new combinations of anode, cathode and electrolyte materials in order to increase a specific characteristic of the Li-ion battery. Furthermore, thermal properties of these materials are also identified as key factors in the advancement of these batteries [110, 165]. Details of such researches are out of the scope of this research, however, the expected effects of these researches are of great importance for the future outlook of electric flights. In literature, there is still not one main commonly accepted outlook on how much current (Li-ion) batteries will improve. Forecasts vary from almost no improvements up to an energy density of 0.45 kWh/kg within five years [34, 92, 134].

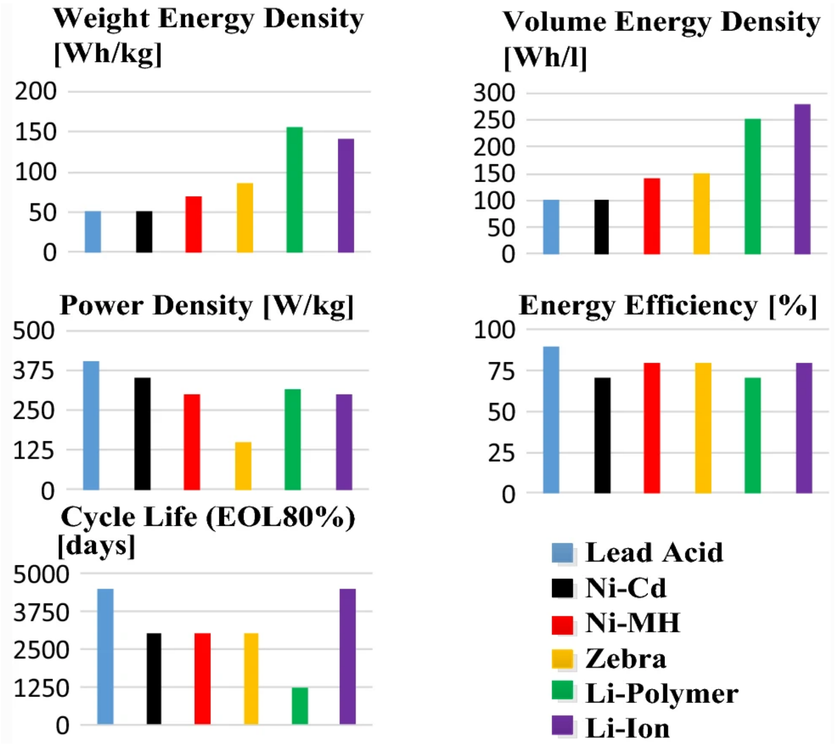

Figure 4.1: Battery comparison on five design characteristics [111]

Although Li-ion battery technology might thus advance in the (near) future, also some brand new technologies are currently being developed that might change the battery world significantly. Especially Metal-Air batteries may drastically lower the weight of batteries as the theoretical energy densities lie in the range of 1 kWh/kg to 3.7 kWh/kg [44]. However, practically, values up to 0.8 kWh/kg can now only be achieved [164]. Olabi et al. has written an extensive review on metal-air batteries and for the most common metals also provides an overview of advantages and drawbacks [119]. They furthermore concluded that the battery architecture and internal battery processes are far from optimised and especially not yet ready for safe implementation. Concerns mainly deal with unstable recharging, a very short life time and leakage. How long it will take before these 'new' battery types are sufficiently developed remains a mystery as in literature, authors are hesitant to make any predictions.

A second possible breakthrough in terms of batteries might come from the integration of battery cells into a structural component. In other words, the structure is the battery. Danzi et al. in 2021 reviewed the then state-of-the-art with the focus on the integration of existing Li-ion batteries into structures and multi-functional carbon fiber-based materials [49]. They concluded that also this new battery technology is far from mature and it too has to overcome numerous defects such as a faster degradation and lower capacity. Asp et al. even only showed a 0.024 kWh/kg energy density [13]. Although in recent years, large breakthroughs have been seen in this battery field, it is still unsure on when proper implementation will take place. Furthermore, the author of this literature review reckons that structural integrity within the aerospace industry is to be tested heavily and new techniques and materials must remain under strict regulations. This will also slow down the process in using structural batteries for aircraft.

4.2. (Fast) Charging Battery Degradation

Research into batteries has been going on for decades now, from space applications to the normal use car battery. However, again the electric automotive industry reestablished research into especially fast charging and the accompanying battery life time. Specifically for electric aircraft, no studies have been found up to the time of writing, therefore, mainly theory, tests and models will be discussed for electric vehicles. Although every specific battery has different specifications as tested and published by its manufacturer, there are several common grounds which are presented in this section.

Before a more in depth analysis is presented, first several general terms are introduced that are key in the discussed models. When charged, batteries will be able to provide the full energy capacity that it is designed for. This designed - as built - reference capacity is set as 100% State of Charge (SOC), or simply 'battery level'. As the battery is providing power, the remaining potential capacity drops and so does the SOC. All charging and discharging processes are also controlled by a Battery Management System (BMS). This system ensures that especially the internal battery cell processes are being monitored such that the degradation of the individual cells is limited.

This degradation of the battery cells is something that plays a huge role in the life time of a battery. With every (dis)charge cycle, cells are effected which in the end result in a slightly lower maximum achievable SOC. In literature, the condition of a battery is sometimes also referred to as State of Health (SOH). This remains a rather vague term and thus also estimations on the Remaining Useful Life (RUL) have been introduced in literature. The number of cycles up to which a certain threshold is reached for 'End of Life', for instance 80%, is defined as the RUL. While the aircraft manufacturers may be more focused on the energy provision of their electric motor(s) and its degradation, for this research it will be most interesting to know how charging influences the degradation and how to possibly optimise it.

4.2.1. Charging Rate

The power with which a battery is charged could differ from charging cycle to charging cycle. When the power is sufficiently high that a completely 'empty' battery is charged to its maximum battery capacity (SOC 0% $\longrightarrow$ 100%) in one hour, is called a 1C rate. A 2C rate equals a charge of a full battery of half an hour. Currently, chargers for electric vehicles can deliver charging power up to 350 kW [62, 67], while prototypes of 450 kW are being developed [127]. The charging rate has a high influence on the degradation of the battery cells. Tomaszewska et al. have made an extensive review on this subject as they indicated that fast charging technology would still need to be researched even more given the future plans with it [153]. The degradation of the battery by means of lithium plating was found to be leading in terms of higher charge rates, although also at lower rates than 1C it could occur [98]. Besides plating, also cracks in the internal battery cell structure could be induced. For charging rates up to 2C, no significant causal relationship was found [170, 171]. Furthermore, a lifetime prediction model as used by Liu et al. found that a 3C charging rate does not significantly reduce the battery cycle life compared to 1C and 0.5C rates, given their research boundaries [99]. For charging rates up to 10C, an increase in cracks was observed [95, 159]. Lastly, also the effects of ageing within the battery cells could be decreased by using lower C-rates [111].

4.2.2. Depth of Charge

While it may thus probably be better to charge the battery more slowly, the SOCs in between which is charged is also of relevance for the battery life time. First of all, above a certain threshold, fast charging is not recommended due to safety issues caused by too much voltage over the battery cells [153]. Typically, in literature, 80% SOC is mentioned as the threshold [115], although also 70% [105] and 90% [112] are used, be it under assumption. Under this threshold, specific regions of charging have also found to be better than others in terms of life time. Smaller or shorter charges show better performance than longer, bigger ones. For instance charging from 40% to 60% using a 1C charge rate shows about 2.6 more lifetime cycles (up to 90% SOC degradation level) compared to an SOC charge from 25% to 75% [110, 144, 169]. Thus shorter or smaller fast charges are preferred, but there is a caveat. Relatively high and low SOCs must be avoided as these short charges still show larger degradation over time than SOCs in the middle region. In other words, it is better to initiate (short) fast charging at 40% or 50% than 20% or 70% [30, 144]. It is even found in a Master Thesis of the Delft University of Technology that charging only up to the needed SOC for a drone flight shows a 5.7% and 20.1% improvement in terms of battery lifetime compared to always charging up to 80% SOC or 100% SOC, respectively [158].

4.2.3. Temperature

Another important influence is found with temperature. First of all, the higher the battery temperature, the lower the life time of the battery [99]. It thus also requires cooling systems in case of high ambient temperatures. But also the temperature at which the battery is charged is of great importance. The further away from the design temperature, the slower the charging can be performed and the life time will be shortened [153, 172]. Furthermore, it must be avoided to fast charge batteries at extreme low temperatures ($< 5C$) [106].

4.2.4. Other Influences

Certain other ageing processes in the battery cells will also play a part, for instance thermal effects or mechanical effects. The details of ageing processes are out of the scope of this research, however, for a thorough review on the most important mechanisms that degrade the battery cells, Atalay et al. [14] and Tomaszewska et al. [153] provide an overview. Besides internal cell ageing, also the way the battery is charged could be of influence. Different charging protocols are also addressed by Tomaszewska et al. [153].

4.3. Energy Storage

As wind turbines and solar panels cannot generate a continuous power given varying weather conditions, introducing these renewable energy sources into the existing electricity network will face some challenges. During the day, ideally, the ’green’ energy is used during all periods as much as possible. However, it could very well be that the supply of renewable energy is way higher during the day than the actual demand. Therefore, in case nothing is done, this renewable energy is simply wasted. Luckily, a simple solution was found which is already widely used around the globe. By placing an Energy Storage Unit (ESU), the surplus of renewable energy can be saved in this mega battery. These ESUs come in different capacities and forms, from smaller 15 kWh household ones [109] to gigantic 22 MWh industry style [50] or even mobile units in ten foot containers of 422 kWh [152]. Vattenfall even uses ESUs that are composed out of a large number of electric vehicle batteries [50]. Once the supply of renewable energy drops again below the demand, these batteries are thus still able to provide ’green’ energy which will then lower fossil fuel energy conversion processes. Another very useful feature of ESUs is that it enables large peak powers by helping in the energy provision next to the existing electricity network which may not be built for high power in a relatively short time period. Lastly, by using ESUs, the reliability of the network is improved as during a power outage the ESUs may be used to supply energy.

Existing ESUs are always placed close to renewable energy sources, however, this might not be the optimal place given the infrastructure, demand and supply. Several models have already been created to face this location problem, for instance by Celli et al. [39]. However, what is even more important is the management of energy streams over the network. As the network is extended with at least renewable energy sources and potential ESUs, the most optimal way needs to found to guide the energy provision and to also maximise the renewable energy potentials. Li et al. describes a model that optimises such microgrids for both the renewable energy provision as well as the charging schedules for ESUs [97]. They found that the proposed model has the potential to reduce costs next to enhancing reliability. Siemer, Schöpfer and Kleinhans presented a more general model to optimise charging times [145].

Besides large ESUs based on conventional battery technology, also alternatives have in recent years been developed for these large scale storage purposes in order to pursue the energy transition. Redox flow batteries are one of these developments. These batteries consist of two tanks which contain the two (liquid) electrolyte components which are pumped into a stack where an ion membrane is present. This membrane allows exchange of active hydrogen particles which create an electrochemical potential which through electrodes is translated into voltage and current. Sánchez-Díez et al. has thoroughly reviewed the advantages and disadvantages of flow batteries [138]. Main advantages that were found consist of high flexibility in terms of power and energy capabilities, high efficiency, long life cycle and above all far better cost-effectiveness than Li-ion batteries.

However, these lower costs can only be achieved due to scalability of the system. Furthermore, the energy density (weight and volumetric) may also only be beneficial when scaling the flow battery system to a large level. For example, current volumetric density lie ten times lower than Li-ion batteries at 0.025-0.035 Wh/L, due to large storage tanks. Therefore, for aircraft design, these batteries are currently far from suitable, however as ESU, facilities already exist of up to 60 MWh, although they occupy quite some space. To reduce the spatial footprint and to improve degradation as well as other factors, future research is needed to really mature this type of battery for better and more cost-effective use as ESU compared to current conventional ESUs (for instance Li-ion) [87].

A more mature form of gross energy storage exactly targets the differences in renewable energy source availability. Pumped hydroelectricity storage systems can already be found all over the world in places of natural mountainous terrain. The system is composed out of a lower reservoir, upper reservoir and a power/pump house. In case wind and solar energy provide too much power for a given demand, water is pumped from the lower to the upper reservoir. When the wind speed and solar power decrease and/or power demand increases, power may be generated through hydroturbines making use of the height difference. This form of storage currently forms the largest capacity energy storage possible [43], although, it is still a net energy consumer. Literature concerning pumped hydroelectricity storage is readily available, for instance into the possibilities and effects of using abandoned mines as lower reservoir [75, 31]. Although several relatively small hills exist on Bonaire, the absence of large height differences and underground mines make it a very unrealistic scenario, not to even mention large investment costs.

Next to new storage units, in literature also the ’vehicle-to-grid’ concept is widely researched. This concept uses the batteries of existing plugged-in vehicles which may be used for energy provision once needed in peak demands. Therefore, the vehicle batteries may be discharged to provide other sources with energy over the existing network. This will lower the fluctuation of the entire network [42]. Although this process will likely degrade the battery life time, it could still be beneficial for the owner of the vehicle from a financial point of view [148]. Also the ’aviation-to-grid’ concept has been explored by Guo et al. for five case studies using the bi-directional power flow enabled by the concept [78]. Especially when combined with the battery swapping concept, the ’aviation-to-grid’ concepts showed positive flexibility.

5

Electric Aircraft Developments

Within this chapter, a closer look will be taken to electric aircraft themselves. First of all, a quick insight will be given in section 5.1 on other future sustainable aircraft technologies in the light of the inter-island flights. Focusing on fully electric, section 5.2 will discuss several important design factors. Next, in section 5.3, electric aircraft that are flying today are summarised as well as their available specifications after which an overview of future electric aircraft is provided in section 5.4. Lastly, the certification and an analysis on battery swapping and plug-in charging is addressed in section 5.5 and section 5.6 respectively.

5.1. Future Sustainable Aircraft

Besides fully electric aircraft, also hybrid-electric and hydrogen powered driven aircraft are being developed to lower the footprint of the aviation industry. The high-level differences, advantages and drawbacks with respect to fully electric aircraft will now be elaborated for the introduced use-case of inter-island flights in the Dutch Caribbean.

Hybrid-Electric

Ideas and research into hybrid-electric aircraft has always preceded the research into fully electric aircraft. This is simply because of the reason that battery technology was still not up to par given weight restrictions for a completely electrified aircraft. Therefore, partially electric aircraft were sought as a solution. These hybrid-electric aircraft can be driven in a parallel, serial or serial-parallel manner. In a serial hybrid architecture, a combustion engine mechanically drives a power generator which is used for the provision of an electric motor. A battery could also be part of this architecture. In parallel, also both an electric motor and a combustion engine are present, however, these are now mechanically connected through a gear box [92, 107]. A battery and fuel tank are thus always present at the same time. The serial-parallel architecture is a combination of both, however the complexity adds too much weight to be realistically incorporated in aircraft design [88].

Where fully electric aircraft are rather limited in their range, hybrids can be deployed for somewhat different ranges. In a study regarding a hybrid training aircraft, Janovec et al. concluded that with an increasing percentage of electric propulsion, the range would decrease as well as the operating costs [88]. The hybridization of aircraft will also yield a fuel reduction. For a training mission, Frosina et al. concluded that up to 30% of fuel could be saved, or up to 20% for a typical transfer mission [73]. Also for larger commercial hybrid-electric aircraft, reductions in fuel may be significant as Fefermann et al. concluded [68]. Specifically, 39% savings could be achieved for a short range of 150 nm, 25% for 430 nm and up to 10% for 700 nm under the assumption of a battery energy density of 0.5 kWh/kg.

Regarding hybrid aircraft types, multiple manufacturers have been designing their own specific model. However, this mainly concerns smaller aircraft not meant for the commercial market. Collaborative research in this field is especially noteworthy from the MAHEPA project by hybridization of a Velis Panthera [104]. Larger commuter aircraft are also being designed, however almost all of them are still in a very conceptual stage and are not foreseen to fly before a fully electric counterpart. For instance, a hybrid version of the Twin-Otter with projected cost savings of up to 30% and maintenance cost savings of 10% to 25% [12] is very unlikely to be certified before the to be discussed ES-19 given the preliminary design phase.

Given the longer purpose range, later expected introduction and possible lower cost savings, hybrid electric aircraft will be discarded for the very short distance flights between Bonaire and Curaçao/Aruba. Additionally, as a conservative approach is adhered to, hybrid-electric aircraft do not fit within the goal of demonstrating the maximum energy needs for BIA.

Hydrogen

Next to electric energy storage, alternative fuels may also be considered. As Sustainable Aviation Fuel (SAF) still results in CO2 emissions and is at this moment in time very difficult to produce in bulk, especially on a small island, this option is discarded for now. Hydrogen will likely also be difficult and energy intensive to produce, however, this option is a lot more likely in the further future. The main advantage of hydrogen is the energy density of 33 kWh/kg. Almost three times as high as the energy density of kerosene [35, 106]. However, the main drawback is that the volumetric energy density is very low. In other words, for a reasonable size tank, hydrogen must be kept under enormous pressure of up to 700 bar. This thus induces extra weight with regards to cryogenic tanks. Furthermore, also explosion and fire safety hazards are way higher than for conventional kerosene designs [48]. Lastly, although no hydrocarbons are emitted, water vapour is, which is also linked to climate effects [72, 94].

Fitted in the aircraft, hydrogen could be used as fuel cell, closely related to the serial hybrid architecture discussed earlier or could be burnt directly [35]. The efficiency of hydrogen propulsion lies around 10% higher than that of kerosene, making it a very attractive alternative for future aircraft. However, this would only be a feasible and realistic option in the longer term future as concluded by Dahal et al. [48]. On the shorter term, hybrid-hydrogen aircraft are found to be a very plausible option. They also noted that medium and long haul flights would be feasible for hydrogen powered planes.

Because of the lower technology readiness level that needs to be overcome before being introduced in aircraft and the fact that hydrogen will purpose longer range flights, it is discarded for this research.

5.2. Electric Aircraft Design

This introduces an overview of several main factors in the design process of electric aircraft. First, the energy density and weight restrictions are addressed after which the range and sizing, and operating costs are discussed. Next, details will be given onto the potential of replacing conventional aircraft to all-electric planes. Lastly, the main disadvantages and advantages are summarised.

5.2.1. Energy Density

The translation from conventional fuel powered aircraft to electric aircraft is not as easily done as with electric vehicles. Mainly this originates from one aspect: weight. As the main and only power source of electric transport is currently primarily designed using batteries, a huge difference arises. In literature the widely used number for the energy density of kerosene is 12 kWh/kg, while for batteries a maximum achievable energy density of 0.25 kWh/kg and average of 0.18 kWh/kg is generally used [34, 88, 92, 106] (also see section 4.1). For the same energy capacity, batteries will thus take more than 50 times more weight than conventional kerosene.

To cover the full picture, also the energy conversion must be taken into account. The heavily used turbofan and turboprop engines rely on the coherence of many moving parts. At every mechanical transfer, some energy is lost and together with other factors result in an efficiency of a jet engine of about 30 to 40% [34, 106]. However, when looking at electrical motor driven propulsion systems, the efficiency that is adhered to is 85% [84, 88, 132, 134], as less moving parts are present in the engine architecture. However, this mainly is found for hybrid electric aircraft. It could thus be that the efficiency of full electric propulsion lies a bit higher [141]. Therefore, electric propulsion will show a major benefit over conventional turbofan engines and from this point of view, less energy and thus weight would be needed.

In literature, the target battery energy density of 0.5 kWh/kg is sometimes referred to as the energy density at which electrical propulsion will show similar energy/weight performance as conventional turbofan/turboprop propulsion [92]. With the data provided above, this assumption seems plausible. But since other factors such as high power output must also be taken into account, it is envisioned that jet fuel will still outperform batteries with an energy density of 0.5 kWh/kg [134]. Schäfer et al. reckons that only if a specific energy of 0.8 kWh/kg is reached, will electric aircraft the size of an A320 or B737 be feasible on short range flight [141].

5.2.2. Range and Sizing

While extra weight for electric vehicles is not that much of an issue, in aircraft design, it is one of the most important factors. The added weight needed for batteries mainly has implications on the range of an aircraft. The more mass should be lifted, the more power is needed and thus the power runs down quicker such that a shorter range is reached. Gnadt et al. showed that with current battery technology, an electric equivalent of an A320neo would need a four times higher energy density for only a 900 kilometers range [77]. Preliminary estimations by the German Aerospace Center DLR show that the range would drop down from 1200 kilometres to only 200 when completely electrifying a Dornier 328 [134]. Another estimation by Finger et al. showed a deduction of more than half of the range, 1100 km to less than 450 km, for a 19-seater [69]. In order to gain some of the lost range, unrealistic design assumptions should then be made (50% wing span increase, 20% drag coefficient decrease) to only gain 100 kilometers.

Although the earlier mentioned example is based on the conversion of an existing aircraft into an electric aircraft, it clearly shows how critical the mass is in terms of range, also for new to be designed aircraft. Brdnik et al. have made a high-level weight sizing model which showed that even for larger (70 seats) all electric aircraft, the range would be very limited even given an energy density of 0.25 kWh/kg [34]. Also Sahoo, Zhao and Kyprianidis projected that range would be rather limited given an improved battery specific energy, see Table 5.1. This is also seen by Le Bris et al. which came to similar results [93]. Although the focus of research in this field focuses more on hybrid-electric aircraft weight estimations at the moment, even with an already made baseline validation model [69], Riboldi, Gualdoni and Trainelli [132] as well as Riboldi and Gualdoni [131] have published a preliminary sizing specifically for small all electric aircraft. Unfortunately, a proper all including estimation model for fully electric regional aircraft still lacks in literature.

What is also important to note is that a full battery does not mean that it can be used in its entirety for flight range. Where reserve fuel regulations are clearly set for conventional aircraft, for electric aircraft, it remains a best estimate guess on what guidelines to follow. For their Velis Electro, Pipistrel indicates that VFR reserves have been taken into account [124] and also Heart Aerospace and Eviation are designing their aircraft with reserves in mind [63, 80]. The FAA specifies a VFR reserve of 30 minutes extra flight time [65]. Also EASA states this VFR reserve, however later in 2022, regulations will see some more flexibility in the light of sustainability [58]. In terms of electric aircraft, it will likely result in a certain minimum SOC or reserve battery capacity. Commonly, it is believed that around 20% to 30% SOC should be reserved for unforeseen conditions of future electric aircraft [78, 79, 112].

Table 5.1: Payload-range projection for future fully electric aircraft by Sahoo, Zhao and Kyprianidis [137]

Battery specific energy (Wh/kg)	Segment, Range
250	6-10 PAX, 300-600 nm
400	19 PAX, 400 nm; 50-70 PAX, 300 nm
500	30 PAX, 500 nm; 50-70 PAX, 400 nm

5.2.3. Operating Costs

Besides the factors concerning the design of the aircraft, also side effects of the design must be considered to cover the full picture of electric aircraft operations. Directly linked to the investments and the question if it will be beneficial to fly fully electric aircraft are the costs. The FAA has published averages regarding expected costs very extensively, however, these are all based on conventional aircraft, see Table 5.2 [64]. Research into hybrid electric aircraft operating costs is again abundant, such as the very recent paper of Scholz, Trifonov and Hornung [142]. They concluded that for a hybridisation ratio of 0.3 (thus 30% being electrically powered), operating costs would not be lower than for a conventional aircraft. Environmental costs and emissions would lie slightly lower. However, a lot of factors are involved and these hybrid-electric aircraft operating costs are thus highly dependent on the chosen research outline.

For instance Vercella, Fioriti and Viola proposed an adapted cost determination framework for both hybrid and all electric aircaft [156]. With the design of a new regional 90-seater propeller aircraft in conventional, hybrid and fully electric form, they mainly found an increase in maintenance cost savings due to electrification of the propulsion system. Total fuel cost savings were found to be 6% to 14.5% per hour of block time, while overall direct operating costs only saw a 1.8% to 2.5% saving per hour of block time. The presented methodology has been validated with data originating from the ATR-72 and assumptions that are made in this research are deemed realistic specifically for the regional missions. However, for the Bonaire case study, several factors must be changed.

Although outdated, Ploetner et al. in 2013 already touched upon the potential cost savings of electric aircraft [125]. They did not look at small regional aircraft, but focused on the design of the Boeing Ce-Liner aimed to enter into service 2035, comparing it to the never built Boeing 787-3. Therefore, the research is far from realistic anymore, however, due to the scarceness of other research, it is nevertheless presented here. Concluding, the researchers found a significant increase in cost of ownership (including battery acquisition, depreciation and insurance costs) of 23%. However, this could be compensated by a 34% reduction in direct maintenance costs for the electric aircraft under the unrealistic assumption that the battery would last 3000 cycles.

Lastly, it is worth mentioning the results of a master thesis of the Linköping University in Sweden [143]. Albeit it only uses simple calculation models, it gives an excellent overview and insight into a Swedish case study of an all-electric regional aircraft network. Comparing the Beechcraft 1900, Jetstream JS31 and the future ES-19 aircraft (see section 5.4), it was concluded that for every considered domestic route, the total operating costs would be lower for the ES-19 in the range of 15% to 22%. This research has split the operating costs into non (system) operating costs, direct (flight) operating costs and indirect (ground) operating costs.

Table 5.2: Average operating and fixed costs per block hour for general aviation and air taxi aircraft [64]

Aircraft Category	Crew	Fuel and Oil	Maintenance	Annual Fixed Costs Other	Annual Depreciation
Piston engine, one-engine	$63	$84	$90	$19788	$18840
Piston engine, multi-engine	$63	$200	$216	$27867	$23238
Turboprop, one-engine	$132	$290	$333	$86895	$153303
Turboprop, multi-engine	$268	$561	$731	$102687	$155238
Turbojet/turbofan	$911	$1297	$1411	$237395	$721790

5.2.4. Electric Replacement Potential

The first fully electric or hybrid regional aircraft is yet to fly, however, it would also be good to get an idea of what market potential it could serve. Given the electric propulsion technology, it is especially turboprop aircraft that will see high potential of replacement by a an electric counterpart. Brdnik et al. mainly concludes this as current electric aircraft in design all have propeller aircraft and that electric jet propulsion is still to be developed [34]. They further conclude that around 40% of new regional aircraft has the potential to be replaced by a hybrid-electric counterpart given a range of around 500 kilometers. Especially for the smaller size aircraft, scheduled and non-scheduled flights, they foresee high potential for full electric aircraft. Marksel et al. share this vision given their research into the European market of 19 seater aircraft [107]. They furthermore conclude that secondary, underutilized and noise-restricted airports will benefit from hybrid-electric flights in case they are not served by a high-speed railway.

A case study by Baumeister, Leung and Ryley on the national network of Finland goes further into detail with regards to alternative modes of transport and the potential for electric flights [18]. By taking into account conventional modes of transport (car, train, aircraft) and the electric counterparts of cars and aircraft, they modeled the equivalent CO2 emissions for 47 routes out of the capital of Helsinki. The three researchers found that electric flights would outperform electric vehicles on routes beyond 170 kilometers and (electric) trains would almost always show less CO2 emissions than electric flights. However, travel times could be decreased significantly.

5.2.5. Advantages and Disadvantages

Within this section, already some advantages and disadvantages have been mentioned. For completeness and overview, this subsection will briefly mention all significant (dis)advantages. Of course the main advantage of full electric flying is the lack of emitted green house gasses by the aircraft. However, this does not mean that the flight is fully ’green’. Especially the energy with which the aircraft is provided plays an important role in the sustainability aspects of an electric flight. Ideally, this energy would originate in renewable energy sources. As mentioned in subsection 5.2.1, the electric power train will see a relatively high efficiency, but there is another potential advantage to using electric propulsion. The produced noise lies lower than conventional aircraft [19, 124]. It is even found that the noise contour area could potentially decrease with 36% [141]. Pereda Albarrán et al. however found that for a single engine electric aircraft, the engine and propeller cause slightly more annoyance. In contrast, they also see potential in reducing noise when multiple electric engines are used which causes the propeller tip speed to be reduced [120]. The last main advantage of electric aircraft to be discussed here is was already touched upon in subsection 5.2.3. Due to the simplicity of the electrical power train, maintenance costs may be reduced. Moreover, once purchased, fuel costs will be interchanged for lower energy costs. This thus also means lower operational costs [18, 141].

In the end, the costs may equate to a lower number, however, certain new maintenance costs will also be introduced regarding the battery system. This battery system cannot last the entire aircraft lifetime just as fuel tanks. Given the degradation of batteries, at some point in time, they must be replaced with new ones. And recycling of batteries is unfortunately not a mature industry, what is more, recycling processes of new batteries gives rise to different challenges [56]. What goes hand in hand with the battery system is the need to charge the batteries or replace the battery packs with fully charged ones. This could significantly reduce the availability of aircraft which is not desired from an airline perspective. Another drawback for airlines is the limited range already discussed in subsection 5.2.2. Furthermore, extra safety issues related to the all electrical propulsion system may be guaranteed provided the guidelines from the regulator.

5.3. Current Electric Aircraft

Fully electric aircraft have been flying around for many years now. However, this also includes all sorts of experimental designs and missions including a solar powered plane that flew around the world in 2015/2016 [147]. As it pertained experimental aircraft, most general aviation pilots did not have the chance yet to fly fully electric. With the roll-over to the 2010 decade, this slowly changed as more and more manufacturers developed electric ultralight aircraft. This section will address several models together with available specifications, summarised in Table 5.3.

Pipistrel Velis Elektro

What started with the WATTsUP in 2014, Pipistrel soon redeveloped this prototype into the ALPHA Electro and the Velis Electro [123]. This last aircraft now even is the only EASA certified fully electric aircraft. Designed for pilot training purposes, it is able to fly up to 50 minutes while also taking into account VFR reserves. The 24.8 kWh batteries (± 140 kg) inside the Velis Electro can only be charged through a ’plug-in’ charging station [124]. Pipistrel offers a compatible 20 kW charging station with a three phase operating voltage of 400 Volt [122]. For a charging cycle from 35% to 95% SOC, it is stated that it would take up 1 hour and 20 minutes. Initially, the limitation imposed on the batteries is set to 500 hours, but is expected to increase as research develops and technology advances.

Elektra Trainer

Being certified under the German ultralight class, this electric trainer aircraft promotes itself with a maximum flight time of 2.5 hours using 30 kWh out of the 35 kWh battery capacity (5 kWh reserve). Although not visible on company graphics, this endurance can only be reached when the aircraft is equipped with solar cells. They furthermore state that only 35 minutes of charging is required with a 18 kW charging power for 50 minute flights [76]. Financially, the manufacturer states that over 50% of the operational costs could be saved up to only 50 per flight hour.

Flight Design F2e

Another German plane comes from the Flight Design team which promotes its F2e trainer aircraft. With the CS-23 and FAA Part23/F44 certification in mind, the aircraft includes 75 kWh batteries for a typical mission usage of 66 minutes (32 kWh). According to their published charging schedule, a 45 kW charger would be needed for 40 minutes to ensure a battery capacity sufficient for a one hour flight [70].

RX1E & RX4E

In 2012 the first flight of the RX1E, a Chinese designed, US manufactured fully electric two-seater aircraft targeted for pilot training [10] took place. The RX1E can fly up to one hour with its six battery packs, which must be replaced with fully charged ones after every flight [146]. The Liaoning General Aviation Research Institute has further developed this two-seater into the RX4E, a four-seater. With a range of 300 km or endurance of 1.5 hours, this aircraft already comes closer to a general aviation aircraft [71].

Bye Aerospace eFlyer2

The eFlyer 2 is the first in series for Bye Aerospace. Carrying two passengers, the manufacturer projects a 220 nm or three hour endurance. With more than 300 orders for its series production, it is also building further with a four seater [37].

Hamilton Aero Electric

Also in the segment of aerobatics aircraft, an electric model has been produced. The Hamilton Aero Electric was not found to be in series production, however, certain specifications were published. A battery weight of 160 kg lets the aircraft fly over a maximum range of 160 kilometres. Its MTOW is designed to be 420 kg [102].

Table 5.3: Overview of existing electric aircraft [37, 70, 76, 102, 124]
([1] When equipped with solar cells, [2] Without reserves, [3] Using 0.25 kWh/kg)

Aircraft model	Battery capacity	Range	MTOW	Price
Elektra Trainer	35 kWh	2.5h[1]/300km	600 kg	-
Flight Design F2e	75 kWh	144 min[2]	1000 kg	245,000
Velis Elektro	24.8 kWh	50 min	600 kg	-
eFlyer 2	-	405 km	-	$489,000
RX1E	-	1 h	-	-
RX4E	-	1.5h/300km	-	-
Ham. Aero Electric	40 kWh[3]	160 km	420 kg	-

5.4. Future Electric Aircraft

Aforementioned aircraft have been specifically designed for flight training and general aviation purposes. This makes them far from suitable for commercial flights due to their limited passenger capacity and range. Fortunately, start-ups as well as established manufacturers have dedicated themselves to the design of such a fully electric commercial aircraft. Given the minimum passenger capacity of nine seats of current flights on inter-island flights to and from Bonaire, the following overview only contains electric aircraft in development with at least nine passenger seats up to larger regional aircraft. Also note that only fully electric aircraft will be discussed thoroughly and hybrid electric and hydrogen aircraft will be addressed briefly in the next section. Table 5.4 is provided at the end of the section to summarise all relevant specifications.

Eviation Alice

Probably the first commercial electric aircraft to enter into service is the Eviation Alice. Although the company has not yet published an official expected entry into service period, the most promising estimation sees the aircraft commercially fly late 2024 [51]. With nine passengers, it will be targeted to fly 815 km (no payload, IFR reserves) using its 820 kWh lithium-ion battery [82]. Half an hour of charging would already permit one hour of flight time. The design Maximum Take-Off Weight (MTOW) has been set to 7484 kg (16,500 lbs) with a useful payload of 1134 kg (2,500 lbs) and a maximum cruise speed of 250 knots using two 640 kW propeller engines [63].

Even though Alice has not yet flown a mile, two costumers have already shown interest in the new commuter aircraft. Parcel delivery by DHL Express along the US east and west coast will, after delivery, take advantage of Alice as twelve aircraft have been officially ordered [130]. Also commuter airline Cape Air has shown dedication to the project by signing a letter of intend for the purchase of 75 planes [74].

Tecnam P-Volt

Another 9-seater is scheduled for commercial service in 2026. The Italian manufacturer Tecnam is collaborating with Rolls-Royce to develop their P-Volt. Besides the electric aircraft being based on the existing Tecnam P2021, only unofficially some specifications have been published. With a 1100 kg battery pack, it is stated that a 85 nautical mile range could be reached with a maximum speed of 180 knots (120 knots typical cruise speed) and even a 145 nm range is projected for 2030 due to technology advancements [126]. A Maximum Ramp Weight of 4086 kg and useful payload of just 806 kg are furthermore goals set for the design. The aircraft is foreseen to be equipped with two 320 kW (take-off thrust) engines. It is also highlighted that use will be made of swappable batteries which are located in the bottom of the airframe [46, 135].

Just like Alice, the P-Volt sees commitment from two airlines. Norwegian regional carrier Widerøe together with Cape Air have joined the two manufacturers in their mission. It is unknown what the specific role of the airlines are, but it is indirectly stated that the two airlines have committed by purchasing the aircraft when ready for operation [45, 47].

Heart Aerospace ES-19

Slightly more seat capacity is offered on the Swedish Heart Aerospace ES-19. With an expected EASA CS-25 certification and first commercial delivery in 2026, it will likely be the first 19-seater aircraft without any operational emissions [80, 121]. In terms of weight this thus means that the CS-23 value of 8618 kg of MTOW will be exceeded. Furthermore, this slightly larger aircraft model is stated to save up to 75% of fuel costs and 50% of maintenance costs while flying around 180 knots cruise speed due to four 400 kW engines [9, 118]. However, in an interview, a company engineer states only a 15% reduction of maintenance and fuel costs [4]. Routes of up to 400 km will be within range of this aircraft with current technology levels while being charged for 40 minutes according to a manufacturer recommended 1 MW charger [81]. The manufacturer assumes 1000 battery cycles before replacement for a 720 kWh battery pack [118], although they envision that up to three times more would be achievable in the future. The ES-19 is up to this moment most popular under airlines in terms of orders. Albeit it concerns conditional orders, United Airlines as well as regional partner Mesa Airlines both ordered 100 [16].

Aura Aero ERA

In the same segment, Aura Aero is developing their ERA aircraft. It has an all electric range of 400 kilometres while carrying nineteen passengers onboard. However, also another range of 1000 nm is provided when a hybrid configuration is chosen. The French manufacturer expects its first flight in 2024 and the aircraft to have entered into service by 2027 [15]. Only one potential costumer (leasing company Amedeo) has dedicated itself to the project by an agreement and letter of intent for 200 planes [11].

Maeve 01

Moving up on the passenger capacity ladder, Maeve, formerly known as Venturi Echelon, is developing their Maeve 01. Close to the size of an ATR42, it can carry 44 passengers to a destination 550 kilometers away. For lifting the 45 tons MTOW, it uses eight electric propellers. Comparing these features with the lower capacity aircraft it is significantly heavier and might thus rely on future energy density advancements. The foreseen batteries are expected to last 1.5 years (given 5 daily operations) and are envisioned to be replaced within regular C-checks [103]. Batteries are estimated to be loaded within 35 minutes with their Maeve ReCharge of up to 9 MW.

Wright Spirit

Even larger capacity is offered by the future Wright Spirit. They take advantage of retrofitting the existing airframe of a British Aerospace 146 to an all electric configuration. From 2023 onwards, every year one conventional engine is expected to be replaced by an electric counterpart to finally enter into service in 2026. With a flight range of one hour, typical high capacity routes such as London-Paris or Sydney-Melbourne are targeted. Partnered up with amongst others easyJet, Viva Aerobus and Honeywell, this 100 passenger aircraft could make a significant impact on future electric short haul aircraft [168].

Table 5.4: Overview of future regional electric aircraft [15, 46, 51, 63, 80, 81, 82, 103, 118, 126, 135, 168]
([1] Using 0.25 kWh/kg; [2] 2030 manufacturer projection)

E-Aircraft	PAX	Battery	Range	MTOW	EIS	Comment
Alice	9	820 kWh	815 km	7484 kg	2024	First flight scheduled in 2022Q3
P-Volt	9	275 kWh[1]	155/265[2] km	4082 kg	2026	Battery swapping
ES-19	19	720 kWh	400 km	>8618 kg	2026	
ERA	19	-	400 km	8100 kg	2027	
Maeve 01	44	-	550 km	45000 kg	-	
Spirit	100	-	1 h flight	-	2026	BAe 146 retrofit

5.5. Certification

Where multiple electric aircraft types are able to fly due to certificates or exemptions under local authorities, the Velis Electro remains the only country-wide (Europe) certified aircraft by EASA. As there were no certification requirements set out for electric or hybrid aircraft, things needed to change. In close collaboration with Pipistrel, EASA worked on a full set of requirements. After slightly less than three years, the Velis Electro could be certified in 2020 [57] and now future electric aircraft will need to follow the 'Special Condition E-19'. This document has been set up due to the lack of fully or hybrid electric propulsion system requirements. Amongst others fire protection, strength and icing/snow conditions are discussed from a design perspective as well as numerous system and equipment requirements. The document furthermore states that for CS-25 aircraft certificates, the 'SC E19' shall be complemented by to be defined emission requirements [59]. This is of importance as CS-23 aircraft can only certify commuter aircraft up to 19 passengers.

In the US, a similar process was followed, however, in that case it did not result in an FAR Part 23 or Part 25 aircraft certification but the certification of engine models under Part 33. As done by the European counterpart, the Federal Aviation Administration (FAA) published special conditions specifically for two mangiX engines. This may then serve as guidelines for future electric engines on for instance containment, engine cooling and vibration demonstration [66].

5.6. Battery Swapping vs. Plug-in

As becomes clear from section 5.3 and section 5.4, two different options are currently designed for recharging: plug-in and battery swapping. Plug-in charging is relatively simple and is very much like one would do with electric vehicles these days. Although swapping (partially) empty batteries for charged ones is not a new concept, in the aviation industry it does come with certain design and operational characteristics to take into account which will now be discussed with respect to plug-in charging.

The most convenient aspect of battery swapping is that within a relatively short time frame, the electric aircraft is fully charged again. Just simply by replacing the batteries as part of the turnaround process this could be achieved. Although this sounds very easy, from an aircraft design perspective, it might show some drawbacks. As the battery or batteries must be able to be replaced easily, the structure surrounding the battery compartment will most likely need to be adapted. For a free passage of the battery, some acting loads need to be diverted which likely induces a reinforcement elsewhere resulting in a slightly higher weight. Please note that in literature this particular drawback is not explicitly mentioned.

Furthermore, the weight of the battery itself will likely also not be low. In other words, battery packs will not be able to be replaced by (wo)manpower. It is not completely sure what exactly will be the 'go-to' solution, but at least some sort of specialised equipment is bound to be made for proper battery swapping [42, 54]. This could be a completely new ground service equipment vehicle or just an attachment to an existing vehicle. Nevertheless, different aircraft types might also need different equipment in case no mutual solution is discussed [105]. Because of all this specialized equipment and also potential safety issues [106], in literature, it could be stated that battery swapping will induce new specialised maintenance procedures and personnel [79].

Once the batteries are swapped, the (partially) empty battery will be taken to a dedicated battery swapping station. There, it may be charged until it is needed again. The main advantage of this is that the time limits for charging are not bounded as strict by the flight schedule. In other words, more efficient charging could take place in this swapping station (discussed earlier in chapter 4). Optimisation models have already been proposed to limit the maximum peak power as well as the number of batteries in the swapping pool (for instance by Sarker, Pandzic and Ortega-Vazquez (vehicles) [139] or Justin et al. [89] (e-aircraft)). Furthermore, proper cooling of batteries could be achieved while charging [89]. With respect to plug-in charging, batteries will thus also last longer and a more efficient way of using renewable energy sources could be utilised. Although batteries will last longer, you would also need extra spare batteries which of course will induce extra investment costs. These investment costs are also reflected by building a complete new swapping station and its infrastructure [42]. Differently from plug-in charging, no adaptations close to or on the airport stands are needed.

Besides discussed in literature, also two manufacturers have shared their opinion on the battery swapping-plug-in debate. Pipistrel states that due to their implemented battery cooling system the decision has been made to exclude battery swapping. Furthermore, they mention the excessive weight of the batteries as potential safety hazard. Lastly, they inform that the battery will be a Line Replaceable Unit and can only be replaced after certification of a special training course specifically designed for their Velis Electro [124].

Also Heart Aerospace does not foresee battery swapping technology during day-to-day operations. According to them, the process adds too much complexity and costs with respect to their projected short charging times during the turnaround process. In case batteries are swapped, it is believed that at this time, it would even take longer than just charging the batteries due to the maintenance actions needed [81]. Furthermore, they mention that battery swapping will be a dedicated maintenance task which would need trained mechanics and thus induce extra costs and complexity [4].

Given the above mentioned factors, at this moment in time, it is still unknown to what extent especially battery swapping will be introduced at or around airports. For plug-in battery chargers, it is however commonly envisioned by the industry that this would be introduced onto the airport apron. Additionally, international standards and certification must be introduced and followed to make both types of charging a success. Lastly, by choosing plug-in charging, the most demanding option will be evaluated in terms of needed energy infrastructure.

6

Feasibility Analysis

Provided the described future aircraft developments in chapter 5, this chapter will analyse the feasibility of these aircraft taking into account the presented battery theory in chapter 4. The focus will especially lie on the practicality and feasibility on the Bonaire use-case and the technical development feasibility with respect to battery capacity and range. In section 6.1, a general analysis is performed by means of three ratios that will be compared. An estimation of the cruise power setting is evaluated in section 6.2 after which the charging proposed by certain manufactures is rationalised in section 6.3.

6.1. Ratio Analysis

To get a general idea of the trends in electric aircraft design characteristics as published by the manufacturers, three different ratios will now be calculated and designed. First of all, a range ratio is calculated simply by dividing either the maximum flight time or maximum range by the total battery capacity (thus excluding reserves). In the end, two different ratios will thus be evaluated depending on the data available. Looking at the results in Table 6.1, a decreasing trend is seen with increased aircraft size. Although the Elektra Trainer shows more than twice the value of the F2e and Velis Electro, it is not that odd given that the former aircraft is more designed as a glider and the 2.5 hours of flight time includes solar cell charging during flight. In design, the F2e and Velis Electro are very similar, which is also reflected in the ratios.

Somewhat more information was available to calculate the range ratio in terms of kilometres per battery capacity. Also here, a decreasing trend is seen. As the Hamilton Aero Electric was designed as aerobatics aircraft, it is very logical that it shows a lower ratio than the Elektra Trainer which is more focused on endurance given its training design purpose. It is furthermore remarkable that the Tecnam P-volt shows such a low ratio, closer to a 19-seater, for current technology levels. Also taking into account the future 2030 projection, this either means that the Eviation Alice and ES-19 show too optimistic data, or that the estimations of Tecnam are off. Furthermore, at first sight, it makes sense that the ratio is decreasing. As the aircraft size is increased, more weight and thus power is needed. This could of course be solved by adding extra batteries, however, they also add weight. In other words, the snowball effect kicks in and it is up to the manufacturer to trade-off these design features up to the desired level.

In the last column of Table 6.1, the MTOW is divided by the battery capacity. The higher the ratio, the more weight the aircraft can transport per kWh of battery capacity. One could thus say that a higher number means a higher efficiency in terms of lifting capacity. However, it does not indicate anything about the range. What is noticeable from the results is that almost all values lie not that far apart. This could indicate that weight estimations are more advanced and more aligned with each other for electric aircraft. Again, when looking at the future commercial commuter aircraft, the P-Volt shows a slightly different design ratio than the Alice and ES-19. The same optimistic/pessimistic scenario conclusion as with range could be made.

Table 6.1: Battery capacity ratios with respect to range and MTOW for described electric aircraft
[1] 2030 manufacturer projection

Aircraft	Range Ratio (h/kWh)	Range Ratio (km/kWh)	MTOW Ratio (kg/kWh)
Elektra Trainer	0.071	8.57	17.14
Flight Design F2e	0.032	-	13.33
Velis Electro	0.034	-	24.19
Ham. Aero Electric	-	4.0	10.5
Eviation Alice	-	0.99	9.13
Tecnam P-Volt	-	0.56 (0.96[1])	>14.84
ES-19	-	0.56	>11.97

6.2. Cruise Power Setting

To even get a better insight into the range-energy relation, now, the assumed cruise power setting is calculated based on the cruise speed, battery capacity, maximum range and maximum engine power. This is done for three aircraft expected to enter into service relatively soon (Eviation Alice, Tecnam P-Volt and Heart Aerospace ES-19) and as these flight missions also align best with the Bonaire inter-island flight case-study. The percentage of cruise power is roughly estimated by Equation 6.1. Note that the nominal battery capacity has been set to 70% of the total battery capacity as per subsection 5.2.2 to account for fuel reserves and that 70% of the maximum cruise speed is taken as typical cruise speed for the Eviation Alice.

$$Cruise\ Power\ Setting = \frac{Nominal\ Battery\ Capacity \cdot Cruise\ Speed}{Max.\ Range \cdot Max.\ Engine\ Power} \tag{6.1}$$

For the Eviation Alice, data all originates from their official website and eventually results in a cruise power setting of 17.8% of the maximum available power. The data for the Tecnam P-Volt is deemed less reliable and originates from multiple (unofficial) sources and the estimation of 0.25 kWh/kg is still used for the stated 1100 kg battery weight. This resulted in a 43.1% cruise power setting with respect to the indicated take-off power. For the ES-19, data also came from multiple sources, however, all directly related to Heart Aerospace or a collaborator. The estimated cruise power setting is 26.3% of the maximum power. Note that this is a very rough estimation and that the number likely lies lower as take-off is very demanding in terms of energy and only covers a short range in a short period of time.

Even without further consultation of other sources, the values of the Eviation Alice and ES-19, are very low and deemed unrealistic. The Tecnam P-Volt seems more plausible, however, with a lower battery energy density, the value decreases and becomes more unrealistic. These thoughts are confirmed by the ICAO power settings for a standard mission [86]. According to Doc 9889, the power settings of 30%, 85% and 100% are associated with approach, climb-out and take-off respectively.

Although the author of this review only has basic knowledge of aircraft design, also a more experienced aerospace engineer has dedicated himself to the feasibility of the Eviation Alice proposed aircraft design in particular. In his manifest, Russo concluded using simple lift, drag and thrust calculations that according to the data published by Eviation, very optimistic and unrealistic assumptions and values must have been used [136]. In an attempt to estimate a more realistic design, he found that for different mission profiles, the maximum range would never exceed 100 nm (185 km) with a newly estimated battery capacity of 561 kWh. All calculations are based on well known aerospace engineering calculations, however it is unknown to what extent Russo's function as head of R&D of competitor Tecnam is involved.

6.3. Manufacturer Proposed Charging

Next to the technical design features of the aircraft, also the charging strategies proposed by the manufacturers may be reviewed and evaluated. Starting with the already flying Velis Electro, the charging cycle from 35% to 95% in a bit more than an hour of a 24.8 kWh battery is very realistic as an average of 14.88 kW is used for charging. This is lower than a 1C charging rate and thus seems to take into account fast charging and slower charging above 80%. It may not be the best strategy as the depth of charge is rather high, however, this is unavoidable with such a small battery capacity and the training mission purpose.

The Elektra Trainer indicated a 35 minute charging time with a 18 kW charger to fly almost an hour. Charging is perfectly possible using these values, however, an hour of flight time with only 10.5 kWh capacity charged is not really deemed realistic when compared to the Velis Electro.

Continuing to the Eviation Alice, given the data in section 5.4, a charger of around 500 kW is proposed to reach the 1 hour flight time in 30 minutes charging time. Current chargers are not yet capable of reaching this amount of power, however, it is deemed realistic that within a few years such larger chargers are developed. In case only 1 hour missions are flown, it is also considerably better in terms of battery life time than operating up to the full capabilities of the aircraft range.

Lastly, the Heart Aerospace ES-19 recommends a 1 MegaWatt charger that would only be needed for 40 minutes to charge the battery almost fully. Although in terms of C-rating this might still be in the feasible region, in terms of technology readiness, it is absolutely not. Such high power chargers are not foreseen in the coming few years, which also holds for the excessive high charging number of 9 MW proposed by Maeve.

7

Optimisation Models

Just as with battery charging technology and infrastructure, the aerospace sector has been keeping a close eye on the developments of electric vehicles when it comes to optimization models. In general, the well known linear scheduling problem lies at the basis of both these sectors optimization models. However, certain 'electrification' constraints must be added for fully electric transport operations of for instance parcel delivery, but also for electric flights. Therefore, first a brief outlook will be provided of existing e-vehicle models. Afterwards, three unique models specifically designed for electric aircraft will be highlighted. These models might not align perfectly with the presented theory as discussed in earlier chapters, however it are the only three available aircraft models which will thus serve as the basis for a future model potentially together with E-vehicle models. The aircraft models and its specifications are summarised in Table 7.1.

7.1. E-Vehicle Models

Probably the most relevant optimisation models to be used in this research coming from electric vehicles are those regarding public transport or bus operations given a fixed timetable. In general, the model then assigns an available vehicle to a scheduled route by minimising the costs, total distance or deadheading distance. This last term is defined as the extra distance a vehicle must drive to the starting point of a new trip and also includes the extra distance to and from a recharging station. These specific models have already been covered extensively in literature of which several specifications will now be addressed.

First of all, also for bus operations, a difference is seen in swapping stations and plug-in charging. While most papers are using plug-in charging as their main and only way of increasing the battery SOC, Chao and Xiaohong only allow battery swapping conducted in one single vehicle depot [41]. Specifically for a battery swapping station itself, optimisation is proposed by Sarker, Pandzic and Ortega-Vazquez [139]. Also combined plug-in and swapping are modelled by Li [96]. For plug-in charging only, also multiple variants can be found. From a mix of a fully and hybrid electric fleet by Rinaldi et al. [133] to different available recharging stations by Wen et al. [166] and Adler and Mirchandani [8].

All of these presented models are MILPs, however some of these models use a somewhat different solving approach. Emde, Abedinnia and Glock provide besides an MILP formulation also several heuristics which show faster running times for a near optimal solution [60]. The column generation algorithm together with branch-and-bound, named as branch-and-price was used by Adler and Mirchandani [8] as well as by Li [96]. Lastly, also an adaptive large neighborhood search heuristic was proposed by Wen et al. [166].

7.2. Aircraft Model 1: Hybrid-Electric Aircraft Milan & Athens

The first real optimization study regarding electric aircraft was initiated in 2018 by Bigoni et al. [29]. This study investigated the airport infrastructure needs for hybrid-electric aircraft with both plug-in charging and battery swapping. Based on the specifications of the hybrid-electric Pipistrel Panthera, a case-study was performed on a local flight club in outer Milan comprising of 21 smaller aircraft. With a Mixed Integer Linear Programming (MILP) model adapted from an electric vehicle schedule problem, their goal was to minimise the electricity costs as well as investments of (60 kW) chargers, (spare) batteries (20 kWh; 13kWh nominal) and new aircraft. Based on a fixed peak period weekly flight schedule, the number of hybrid-electric aircraft and spare batteries was found.

Although the model indicated an optimised operation with only 10 aircraft, after inducing repair constraints the final number of aircraft was found to be 14 alongside a total of 16 batteries. The batteries were estimated to last 2.5 years (one charger strategy), while this decreased to 1.72 when only 11 batteries (two charger strategy) were to be used. After 12 and 15 years, the costs for hybrid operations compared to conventional operations was found to be lower for the one and two charger strategies respectively. In other words, on the long term, replacing conventional AVGAS aircraft with a hybrid-electric equivalent is more cost-effective. However, it must be stated that several battery constraints are not referenced and could be up to further discussion.

Two authors of the previous research took it a step further which resulted in an adaptation of the same model for the regional network of Athens International Airport. As in that moment no concrete specifications were available for larger 40-70 seat hybrid-electric aircraft, Salucci et al. [140] used a dedicated tool created by the university 'Politecnico di Milano' to come to the electric design features of such regional aircraft in their hybrid forms. Preliminary price estimations and battery capacity sizing were executed for a Dash-8 Q400 (M21.9, 1400 kWh), ATR42 (M12.2, 1000 kWh) and ATR72 (M15.4, 1300 kWh). They considered 200, 400 and 800 kW chargers with two charging strategies (night focused or day focused) where only in Athens, charging could take place.

This research did not focus so much on the costs, but more on the charging schedule with differences in day and night. It was found that although at night the electricity price is lower, charging all batteries at night was not the cheapest option as more batteries needed to be purchased. Also the battery replacement period is addressed in this research resulting in 1.78 years for the daytime focused and 2.12 for the night time focused charging strategies for 200 kW chargers. By using 400 kW or 800 kW chargers, this was reduced to 1.51 years. Unfortunately, it is not discussed how they came to this estimation. In the end, they concluded that battery swapping was the only reasonable way of operating the hybrid-electric aircraft given the research framework.

With the knowledge of these two 'pre-studies', the authors finally came to an overall combined published article. Here, Trainelli et al. [154] introduced their complete MILP model called 'Airport Recharging Equipment Sizing' (ARES) with extensive presentation of their constraints and results. For the Bresso case study, slightly different results were presented as only 12 batteries were found by the optimisation model together with the earlier found 10 aircraft. Battery life time would be 1.35 years provided an average weekly schedule. Interestingly, the model only uses battery swapping while no plug-in charging is to take place. Moreover, the focus of the results lies on the charging schedule instead of the earlier presented financial aspects.

For the regional network of Athens, also some differences are present. In the former paper, the option of 800 kW chargers was still present, however this was now discarded. Furthermore, no day or night focused strategies is adhered to any more. Where no evident distinction is made in the previous research regarding the different charger types (200 kW and 400 kW), here the differences in results are presented. For both, it yields that a mix of battery swapping and plug-in charging is to be executed according to the model, however three less spare batteries are needed for the total of 14 aircraft (different per aircraft type).

7.3. Aircraft Model 2: Battery Swapping only

A second group of researchers from the US has independently conducted similar research to their Italian counterparts. With a slightly different focus, Justin et al. [89] included battery swapping only into a two step algorithm for fully electric aircraft based on the ’machine scheduling’ problem. First, the number of batteries and charges is optimised after which a charging schedule is modelled. Two different strategies were proposed: a power optimized and a power-investment optimized strategy. Important assumptions include the presence of a swap and recharge station at every airport, only minimum charging per mission is adhered to, upon arrival the battery is always swapped and no individual specific battery State of Charge is used. Especially this last assumption is very debatable just as the low value of 125 kW for a charger.

The algorithm was executed on the regional networks of Cape Air (New England operations) and Mokulele Airlines (Hawaii). For the power optimised model, it was shown that a decrease of up to 85% in peak power could be achieved with an average of about 60%, leading to an average decrease in electricity prices of around 25%. The power-investment optimised strategy shows slightly lower decreases of around 50% on peak demand and 20% on electricity prices. In both solutions battery swapping was used for an electric aircraft with specifications inspired by NASA’s X-57.

7.4. Aircraft Model 3: Battery Swapping & Plug-in

The most recent paper concerning the charging problem with electric aircraft is written by Mitici, Pereira and Oliviero [112]. Again a MILP model split into two phases was used wherein the first phase aircraft are assigned to a certain mission and if plug-in or swap charging takes place. The actual charging time is optimized in the second phase. The battery charge, plug-in or battery swap, is performed after a return flight under the assumption that only the hub airports own the needed electric infrastructure. As fuel reserves must be taken into account, the SOC cannot go below 20% and when 90% is reached while charging, a switch from fast charging to slow charging is made to preserve battery life time. Furthermore, the SOC decrease is assumed to be linear with range. With these main parameters, the fleet size was determined for 49 flights spanning a maximum range of 350 kilometers (one way) out of the full flight schedule from Amsterdam Airport Schiphol. The specifications of a fully electric aircraft, based on the Embraer 175, have been estimated using a modified class I estimation. As this estimation is only based on existing non-electric aircraft, this method may be questioned.

In conclusion, seven charging stations would be needed to cater for the 15 e-aircraft and 8 spare batteries. Moreover, it was found that during the busy part of the day, battery swapping was preferred over plug-in charging, while the opposite is true for the more quiet part of the day. Although the model seems very well implemented, it is however unknown which Amsterdam flights and routes were considered and what flight schedule is adhered to. This makes it very difficult to compare the found result with a baseline scenario. Moreover, it is a purely hypothetical study which does not consider airport infrastructure complexity such as stand demand and allocation problems at Schiphol.

Table 7.1: Concise overview of the three available electric aircraft charging models

Model	Charging	Framework
Trainelli et al. [154]	Plug-in/Swapping	Hybrid e-aircraft for GA (Bresso) & 40-70 seat (Athens Int.)
Justin et al. [89]	Swapping only	Based on NASA X-57 specs
Mitici et al. [112]	Plug-in/Swapping	Schiphol <350km network, electric E175 Class I estimation

8

Conclusions

The goal of this literature review was to dive deeper into the user case of electric flights in the Dutch Caribbean and the identification of a research gap which may serve a future master thesis project. Provided the earlier published high-level road map onto the introduction of electric aircraft in the Dutch Caribbean and the existing charging optimisation models, several research gaps might be identified to be filled in a future master thesis. First of all, battery theory was not used in all models. Therefore, it would be very useful to include certain constraints into an optimisation model that at the same time optimises or at least improves battery life time. Moreover, battery swapping was not found to be preferable over plug-in charging, however, all available aircraft models include battery swapping. In the future model, it is thus proposed to only allow plug-in charging. Next, also the fixed flight schedule restricts the model to optimise the peak power demand which will likely result in higher investment costs. It is envisioned to at least include some flexibility in flight schedule to ease this restriction and potentially lower investment costs. Furthermore, the focus of the future model will not be to optimise the number of aircraft. What is also not included in current models or only partially are airline cost of ownership costs. Lastly, the energy provision of the islands itself was not considered in any model. By including this, the investments could be optimised as well for a maximisation of renewable energy sources.

Taking into account the research gaps related to airport, airline and energy network infrastructure costs and investments, a more complete overview of investments and operations would be provided. The following research question could be formulated which serves as the start of the master thesis:

> ”What are the preferred implementation strategies for the introduction and upscaling of electric aircraft at Bonaire Airport for an optimistic, realistic and pessimistic scenario, taking into account energy supply infrastructure, energy supply costs and the airline cost of ownership over a time period of 15 years?”

III

Supporting work

1

Route Energy Estimation

Information about electric aircraft has already been provided in the literature review and research paper. However, there, also it is discussed that the ES-19 design has been discontinued in favour of the larger ES-30. Unfortunately, specifications of the larger aircraft are too scarce and insufficient for implementation in this research at the moment of writing. On the other hand, before the announcement of the ES-30, ample data was available for the ES-19. Together with the fact that the ES-19 nicely aligns with the used 19 seaters in 2019, it is decided still to continue with the design features of the ES-19 and exclude the ES-30 until more data becomes available.

As the to be electrified aircraft depend on battery capacity as energy carrier to fly to their next destination, their battery SOC need to be estimated. The estimations in this research are based on the Breguet E-Range equation and a simplified performance model.

For conventional aircraft, the Breguet Range Equation is a very famous and well known first order estimation of the feasible range per trip given fuel fractions. However, this equation is based on the fact that the aircraft loses mass by burning fuel which is not the case for battery electric aircraft. Therefore, a simple modification could be made to come to the Breguet E-Range Equation as per Equation 1.1 [83].

$$R_E = \frac{c_b}{g}\frac{C_L}{C_D}\frac{W_{batt}}{W_{TO}}\eta \tag{1.1}$$

In this original form, the range is first estimated using a battery density c_b of 0.25 kWh/kg, a C_L/C_D of 16 and an efficiency η of 0.82 next to known parameters discussed earlier. Combined with the (estimated) cruise speeds, this then first translates into a 30 min reserve battery capacity.

Rewriting Equation 1.1 to calculate the battery mass and using the battery density will provide an indication to how much energy is required per route. The used distance between Bonaire and Curaçao equals 80 kilometers, for Bonaire and Aruba, a distance of 200 kilometers is used.

The performance model is based on the performance model outlined by [17]. Given mission profiles extracted from `Flightradar24.com` for all reference routes, the energy required for the ground acceleration, acceleration in the air and cruise phase has been estimated. Note that all easterly flight legs are flown over a somewhat shorter distance than all westerly bound flight legs given the dominant easterly winds and local restricted ATC areas. For the sake of simplicity, these parameters are averaged out. Also the reserve battery capacity could be estimated using the performance model. This is simply the calculated cruise power required times the 30 minutes reserves.

Given the two estimations, Table 1.1 shows the results for the reserve energy required. Table 1.2 shows the energy estimation per route. Both tables also include the values that were used in the final electrification algorithm. Please note that a conservative approach is again adopted.

Table 1.1: Overview of parameters and results of Breguet E-Range and final reserves

E-Aircraft	*E-Breguet*					*Perf. Model*	
	W_{batt}	W_{TO}	**E-range**	**Cruise**	**Reserves**	**Reserves**	**Used Values**
Alice	3280 kg	8346 kg	473 km	220 kts	353 kWh/43%	232 kWh/28%	328 kWh/40%
ES-19	2880 kg	8600 kg	403 km	180 kts	298 kWh/41%	195 kWh/27%	288 kWh/40%

Table 1.2: Results and used values for required energy per route per aircraft type

E-Aircraft	**E-Breguet (kWh)**		**Model (kWh)**		**Used Value (kWh)**		**Used Value (SOC)**	
	CUR	AUA	CUR	AUA	CUR	AUA	CUR	AUA
Alice	139	347	156	269	164	328	20%	40%
ES-19	143	357	137	238	180	324	25%	45%

The final values as specified in Table 1.1 and Table 1.2 will be used for the different routing options that could be present in the E-flight schedule. Table 1.3 summarizes all different combinations and the required battery SOC per aircraft type and route. These values were chosen aligned with the battery charging theory discussed in the research paper and the literature review. All departing only E-Flights will be given a departing SOC of 100%. For arrival only E-flights, the required end SOC is set to at least 98%.

Another distinction in terms of charging requirement is made if an early morning flight is electrified. As it is expected that electric aircraft will be fully charged at the beginning of each day, this aircraft may thus arrive on Bonaire with more battery capacity than a flight later that day. Therefore, all flights that arrive before 07:30 local time will see these adapted energy requirements. Do note that for a round trip from/to Curaçao in essence, charging is not needed, however given battery degradation and operational habits, it is foreseen that the charging cable is plugged in in any case.

Table 1.3: Final used battery SOC values for different flights per aircraft type

Flight	**Alice**		**ES-19**	
	to CUR	to AUA	to CUR	to AUA
Regular	40% → 60%	40% → 80%	40% → 65%	40% → 85%
Early flight out of AUA	50% → 65%	50% → 80%	45% → 65%	45% → 85%
Early flight out of CUR	60% → 65%	60% → 80%	55% → 65%	55% → 85%
Arrival only	40% → ≥ 98%		40% → ≥ 98%	

2

Parking and Infrastructure Assumptions

Given the use case of electric inter-island flights on Bonaire, certain (operational) data and assumptions regarding BIA will be presented here. First of all, as the introduced detailed daily optimization model is based on a gate assignment model, aircraft may only be parked at positions fit for its aircraft size. Out of the BIA masterplan [116], it becomes clear that parking positions 5 and 6 (see again Figure 2.1 of the literature study) are able to handle (ICAO) code E aircraft. In theory, parking positions 1 through 4 are all capable of handling code D aircraft. However, this would then restrict the aircraft sizes of the neighbouring stands. In practice, almost all inter-island flights are handled on the 1-4 apron and in the event of multiple code C aircraft, only one can be parked on either 5 or 6 due to the requirement of power-in power-out at the stand. In the model as described in the research paper, such a level of detail is not implemented. However, to cover possible code D aircraft, only two parking positions on the 1-4 apron will be made available in the model. No restrictions on neighbouring stands have been implemented. Furthermore, two code C aircraft may still be parked at P5 and P6. Table 2.1 Shows the ICAO code adhered to in the detailed daily model.

Table 2.1: Overview of the parking positions and their ability to handle different aircraft ICAO codes

Parking Position	**ICAO Code Capability**
P1	D
P2	C
P3	D
P4	C
P5	E
P6	E

Inter-island flights will thus mainly be handled at the P1-P4 apron, therefore it is these parking positions that were investigated to be electrified. Figure 2.1 indicates the roughly estimated locations of the main charging station, cable ducts and apron power connections. Note that the location of the main station was estimated given an indication of BIA during a site visit and the proximity to an existing incoming grid power connection. The power connections on the apron were located on the right side of the aircraft as passengers will always disembark on the left. Furthermore, they were located on the edge of the parking position to cause the least hindrance. However, the exact location on the apron remains unknown as standards are still to be made.

Figure 2.1: Estimation of locations of main charging station (yellow), underground cable ducting (green) and apron connection points (red) [based on Google Earth Image]

3

Additional Results

Besides the presented results in the research paper, more data could be retrieved from the optimisation models. Therefore, this appendix will address some more results that were generated to provide even more insights regarding the model and the case-study. section 3.1 addresses the daily operational model while section 3.2 will outline additional results of the yearly energy model.

3.1. Daily Operational Optimization

In the research paper, the base scenarios includes maximum time shifts of 30 minutes. However, the most demanding scenario (2;3) was also run for a various range of other minimum and maximum possible time shifts. The results for all time shifts from 0 up to one hour are presented in Table 3.1.

Looking at the results, it first of all is clear that with increasing possible time shifts, costs would decrease. Although the three most flexible scenarios possibly did not reach the full optimum, its costs still show the same decreasing trend. With respect to the energy provision types, flexibility allows for a shift from a wind turbine to a decreasing number of solar panels as peak powers could be lowered more with a more flexible schedule. The decreasing required solar panel surface area could be explained as the morning flights could be shifted later in the morning such that more energy could be generated per surface unit. Energy storage is only required to be minimal in combination with a wind turbine while in a system with solar panels it all ranges around and slightly above a capacity of 1 MWh. Another converging trend is seen with the number of chargers required. When time shifts are increased, one charger could be spared. However, given an afternoon flight that remains overnight, the minimum number of chargers (without capability of repositioning) is two. Now also becomes clear why the base scenario in the research paper included half an hour of time shifts as this lies just on the side of the tipping point where only two chargers are required instead of three. However, on the other hand, it could be argued that a total time window of 1 hour of time shift might be too large and that especially airlines would try to limit the time shifts as much as possible. However, given the newity of electric aircraft and the accompanying charging time requirements, it is believed that new flights schedules are eventually bound to be made. Within this framework, a maximum shift of half an hour is believed to be reasonable.

Table 3.1: Results for the most demanding scenario (2;3) on the representative peak day for different time shift allowances with 10 minute time intervals

Min/max Time Shifts	**{0,0}**	**{-10,10}**	**{-20,20}**	**{-30,30}**	**{-40,40}**	**{-50,-50}**	**{-60,60}**
Charger types (kW)	1100 500 300	600 300 100	600 200 200	600 200	600 200	600 200	600 400
Wind turbine(s)	1	1	-	-	-	-	-
m^2 Solar panels	-	-	18706	13143	8471	6236	6392
ESU capacity (kWh)	108	65	997	1056	1106	1202	1192
Costs w.r.t. D={0,0}	-	-10.3%	-21.4%	-34.7%	-41.7%	-45.5%	-46.3%
Gap	-	-	-	-	2.9%	4.2%	21.2%

Narrowing down to the more detailed results of the (2;3) base scenario, it is also good to review where time shifts have occurred and what might form the basis of these time shifts. To visualize this, Figure 3.1 has been made. In this figure, the difference between the turnaround times of the case where no time shifts (blue) and where half an hour of time shift is allowed (green) have been plotted for the electrified flights only. Furthermore, the time shift of the arrival and the departure are indicated next to the number of passengers of both the incoming and outgoing flight leg.

Already in the first three flights something peculiar occurs. Between 7 and 8 in the early morning, originally three flights were scheduled that would use the apron simultaneously. However, to limit the number of chargers and thus reduce costs, time shifts were called by the model. Flight 1 is not shifted, Flight 2 is shifted half an hour later and Flight 3 is shifted twenty minutes later. In terms of energy, all three flights adhere to the early morning flight SOC's. But where Flight 1 and Flight 3 were carried out by 9-seater aircraft, Flight 2 was a 19-seater and thus Flights 1 and 3 require less charging energy. It therefore makes sense that Flight 1 is not shifted as also twenty minutes was already available for charging inducing lower peak power demand. However, this also induced that Flights 2 and 3 should be shifted if only one charging station is to be used. Looking at the number of affected passengers by both flights, one would argue that the flight with the most passengers would be shifted less than the other flight as it would induce higher costs. In this specific case, this was not true. The most likely reason for this counter intuitive swap lies with the required charging energy. As Flight 2 requires more energy before its next flight leg could be operated safely, it also requires higher peak power. Because later in the morning, the sun intensity also increases, this higher peak power demand could be achieved by the solar panels.

The rest of the day sees a similar pattern: flight times were shifted just to adhere to the minimal required charging stations. Besides, turnaround times were also always extended to the minimum of twenty minutes to lower the peak power. At Flights 7, 8 and 9, another assumption of the model is clearly visible. As turnarounds of more than one hour could be decreased to the minimum of one hour given allowed by the time shifts, Flight 7 could not be decreased more. Given the assumption, two chargers would be needed regardless for these three flights. Although the turnaround time of Flight 8 was decreased, it was apparently less costly to shift Flight 9, with more passengers, than Flight 8 with far less affected passengers. Also here, the peak power comes at play as only a maximum of 200 kW is available for Flight 8. The turnaround time of this flight could be decreased by another ten minutes, but apparently, this is not beneficial enough for the overall system.

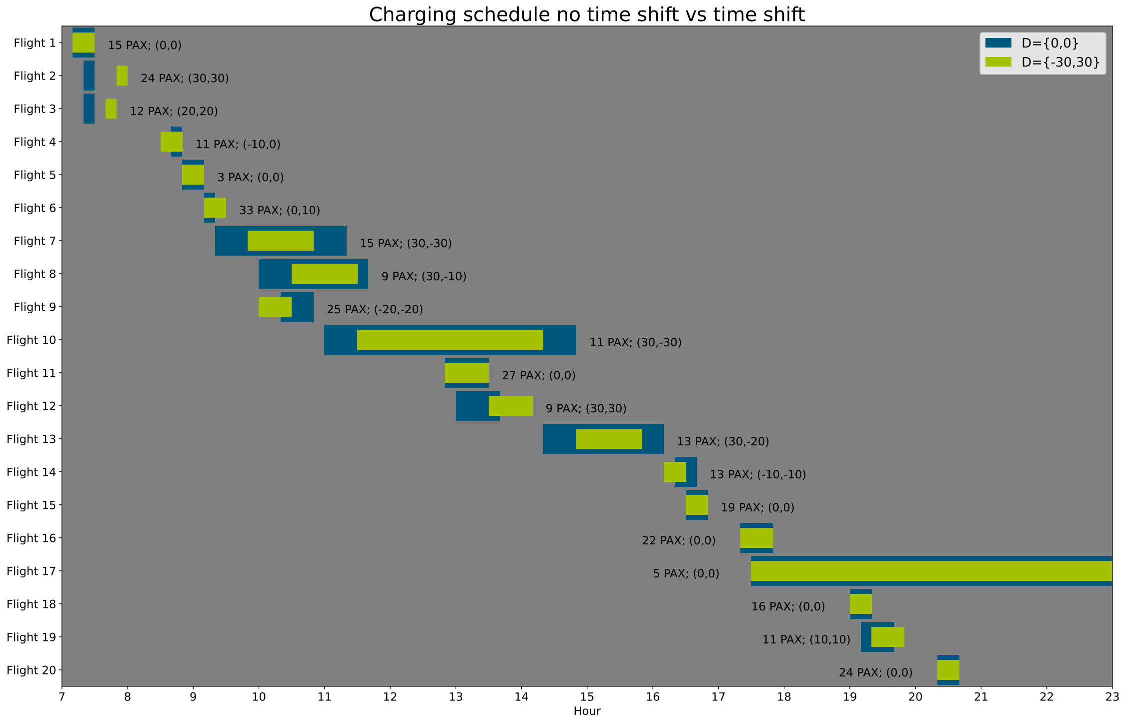

Figure 3.1: Visual representation of the output flight schedule without time shift allowance (D={0,0}) and with time shift allowance (D={-30,30})

3.2. Yearly Energy Optimization

A lot of extra results have been generated in order to provide more insights into the yearly energy requirements. First in subsection 3.2.1 the solar panel area and battery capacity will be fixed to model the yearly grid and surplus ratio. While this optimization is then compared to the monthly optimizations, subsection 3.2.2 presents the results of two-monthly optimizations. subsection 3.2.3 presents the results of the representative peak day by means of the yearly energy model. Lastly, the results of a simplified energy model will be discussed in subsection 3.2.4.

3.2.1. Fixed Energy Infrastructure

The presented results per month in the research paper provide the cost minimized energy infrastructure needs in terms of battery capacity and solar panel area. However, variations are seen and if the worst case month is chosen as design point, all other months show very sub-optimal results and thus indirectly also extra investment costs that may not have been needed. Running the entire year would solve these design issues, however, as mentioned, the system would then be too complex to solve in proper time requirements. Therefore, now efforts will be made to estimate the yearly optimum by fixing the battery capacity and solar panel area. This resulted in converged results of the entire optimized year and thus not in separate months, as seen in Table 3.2 and Table 3.3 where the grid and surplus ratio are given.

Two trends may be identified in the tables. First of all, with an increasing battery capacity, the grid and surplus ratio decreases. This is logical as it is still only allowed to feed back energy to the grid when the full battery capacity is reached. With increasing battery capacity, less energy will thus be available to return to the grid. However, as more energy could be stored, less grid energy is required. An increase in solar panel area will lower the grid ratio, however it will increase the surplus ratio. Again, a logical explanation is available as more solar energy could be generated and thus less grid energy is required and more energy may be available to return to the grid.

Looking back at the monthly results, it may be calculated that the grid ratio would be 4.7% for the complete year of 2019. The surplus ratio came down to 18.3%. Although originating from twelve separate optimizations, these numbers could be seen as the optimized values for the entire year. In the introduced tables, the values closest to the 12-monthly deduced average(s) have been highlighted. Clearly, the two lower solar panel areas show the most resemblance with these yearly average ratios. This would then most likely be in combination with a minimum of 1300 kWh battery capacity. Depending on the desired focus on more or less energy return to the grid and vice versa drawing energy from the grid, a more precise decision could be made.

Table 3.2: Grid ratio for complete year optimization (60-minute time intervals) with fixed combinations of solar panel area and battery capacity

Battery Capacity / Solar Panel Area	**1100 kWh**	**1200 kWh**	**1300 kWh**	**1400 kWh**	**1500 kWh**
2900 m^2	9.7%	8.3%	7.1%	6.1%	5.3%
3200 m^2	7.6%	6.1%	4.9%	4.0%	3.4%
3500 m^2	6.0%	4.7%	3.6%	2.8%	2.1%
3800 m^2	4.8%	3.6%	2.6%	1.9%	1.4%
4000 m^2	4.2%	3.1%	2.2%	1.5%	1.1%
4200 m^2	3.7%	2.7%	1.9%	1.3%	0.9%

Table 3.3: Surplus ratio for complete year optimization (60-minute time intervals) with fixed combinations of solar panel area and battery capacity

Battery Capacity / Solar Panel Area	**1100 kWh**	**1200 kWh**	**1300 kWh**	**1400 kWh**	**1500 kWh**
2900 m^2	16.8%	15.5%	14.4%	13.4%	12.8 %
3200 m^2	22.8%	21.6%	20.6%	19.9%	19.3%
3500 m^2	28.2%	27.2%	26.4%	25.8%	25.3%
3800 m^2	33.1%	32.2%	31.5%	31.0%	30.6%
4000 m^2	36.0%	35.3%	34.7%	34.2%	33.9%
4200 m^2	38.7%	38.1%	37.6%	37.2%	36.9%

3.2.2. Two-monthly Optimization

Now that all results have been outlined for consecutive monthly optimizations, it might also be worthwhile to investigate the option of running two months in one optimization. This will likely average out the solar panel area and battery capacity as a larger time scope is chosen. However on the other side, it will introduce extra complexity to the model. For these six optimizations a maximum time limit of four hours was adhered to. Please note that the overnight constraint between two consecutive runs remains valid.

The results in Table 3.4 show that for four periods, a very low solution gap was seen after the optimization time limit was reached. Only for May-June and Nov-Dec, this was not the case. For all other months, it is seen that slightly less solar panel area is outputted with respect to the monthly optimizations. The results show also less variation. Comparing the battery capacity, comparable numbers are given. Looking at the grid and surplus ratios, it can be seen that a lower solution gap, sees a higher surplus ratio and a lower grid ratio. The solar panel area and battery capacity are then only expected to vary slightly. Although in the Nov-Dec period shows a relatively large solution gap, it is remarkable that its required solar panel area lies significantly lower than the monthly outcomes.

From these results, it may be concluded that with running the optimization over a longer time period, it is thus true that results are averaged out as also less extreme variation is seen over the time periods. What is more, even slightly lower values of solar panel areas are seen, indirectly implying cost savings with respect to the monthly optimizations.

Table 3.4: Solar panel area and battery capacity for two-month optimization for 2019 including solution gap (60-minute time intervals)

Parameter	**Jan-Feb**	**Mar-Apr**	**May-Jun**	**Jul-Aug**	**Sep-Oct**	**Nov-Dec**
Solar Panels (m^2)	2721	2938	2072	2556	2601	2929
Battery Capacity (kWh)	1311	1134	1244	1275	1335	1459
Grid Ratio	6.8%	5.7%	17.5%	6.3%	11.8%	15.7%
Surplus Ratio	6.3%	21.4%	1.8%	12.3%	6.8%	2.3%
Solution Gap	2.1%	-	16.9%	1.7%	4.2%	11.6%

3.2.3. Yearly Model on Representative Peak Day

Although the research paper addresses the worst-case scenario for the representative peak day, the yearly model introduces some other practical constraints in terms of energy provision (mainly grid). If the representative peak day, according to the fixed flight schedule, is run in the yearly model for that day only, results can also be generated. In this way, it is thus a representation of the worst-case scenario, but then including a grid connection and the allowance of surplus energy only when the battery is at its full capacity. The infrastructural needs of both situations have been summarised Table 3.5. Figure 3.2 shows the 10 minute intervals of all variables.

Clearly, introducing the new energy constraints lets the cost minimized solution shift from a wind turbine to a solar panel-battery system. However, as this is done, slightly less than 10% of energy is drawn from the grid without returning any significant part. Furthermore, the investment costs for a single wind turbine are now to be traded-off against drawing some (extra) energy from the grid in combination with solar energy. Another aspect that is now visible is that the battery capacity compared to the flexible flight schedule is relatively large. This may be understood by the addition of the extra surplus constraint. In this case, surplus energy is not seen anywhere. This also indicates that all solar energy generated during this day, is not sufficient for the energy demand of all electric flights. What is more, extra energy is to be received from the local energy grid. All solar energy may thus not be wasted and must be stored, hence the large(r) battery capacity. The battery capacity is now still constrained by the late-afternoon/evening flights. However, the solar panel area is now less sensitive to the early morning flights as grid energy could be used.

Table 3.5: Energy infrastructure needs for the representative peak day only without overnight energy available for a fixed flight schedule in 10-minute intervals

Parameter	Daily Operational Model	Yearly Energy Model
Wind turbine(s)	1	-
Solar panels (m^2)	-	3952
ESU capacity (kWh)	108	1356
Grid ratio	-	9.5%
Surplus ratio	24.5%	-

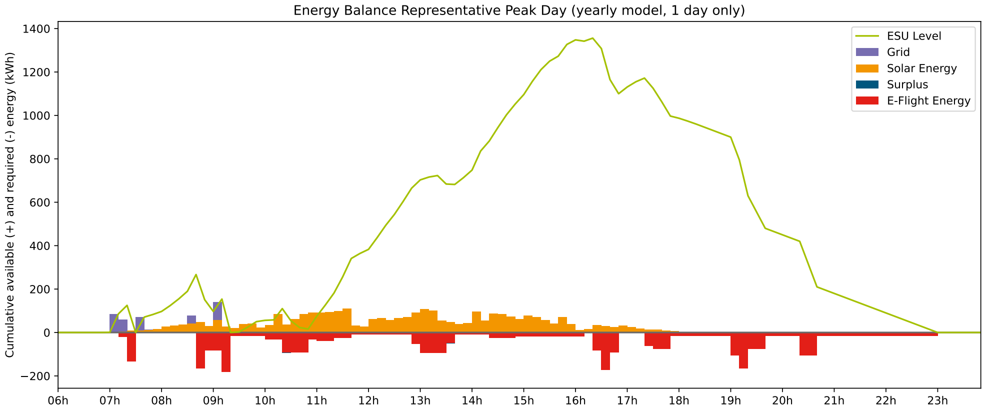

Figure 3.2: Energy balance of the representative peak day as output from the yearly energy model, run for 1 day only

3.2.4. Simplified Energy Model

Before the yearly energy model included a connection to the local grid or included the assumption to only allow surplus energy when the energy storage was full, results were already generated. And although this simple energy balance might not be the most representable or practical, it does provide another insight into the minimum energy infrastructural needs of the problem in its simplest form. Table 3.6 shows the solar panel surface area and Li-ion battery capacity for the full year for five different time intervals. Note that this model was not as complex as the presented yearly energy model of the research paper and it was thus not necessary to run only 1 month at a time.

These results may be compared directly with the presented sensitivity results of the research paper where no grid connection was available. Looking at the 60 minute interval results, October shows the largest solar panel area (7279 m^2) while the simple model only outputs 6443 m^2. In terms of required battery capacity, the sensitivity results show a minimum of 2478 kWh required in November while for the simple model this is slightly less at 2428 kWh. Interestingly, the most constraining day for the battery in the simple model is October 12th, but for the presented yearly model, the most constraining month is November. In general, the assumption of only allowing surplus energy thus induces a larger solar panel area and battery capacity, be it on possible other identified peak/most demanding periods.

Table 3.6: Cost minimized energy provision infrastructure needs for 1 year optimization in different time intervals

Parameter	**T={10}**	**T={20}**	**T={30}**	**T={40}**	**T={60}**
Solar panels (m^2)	6000	6120	6135	6165	6443
ESU capacity (kWh)	2659	2614	2595	2563	2428

As already discussed in the research paper, just like the daily operational model, the simple yearly energy model may 'dump' energy whenever desired. Figure 3.3 again shows this phenomenon, but now for the representative peak day of the simplified energy model. As it felt wrong not to store the energy in the middle of the day by being able to look into the future, eventually, the already addressed surplus assumption was introduced. Although that the presented model in the research paper was also able to look into the future, it is however now limited to a trade-off of extra battery capacity versus drawing more energy from the local electricity grid..

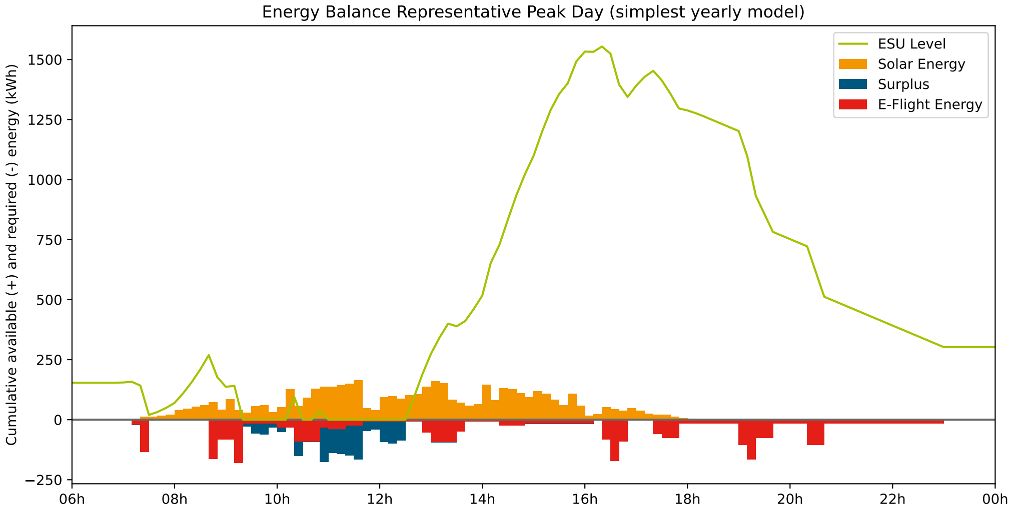

Figure 3.3: Energy balance of the representative peak day as output from the simple yearly energy model

4

Model Verification

In terms of operational and charging constraints, three different flight schedules have been run to check if the proper expected outcome was reached by the daily operational model. All indicated flights in this chapter are flights requiring charging according to the same parameters as discussed in the research paper.

Firstly, a very simple schedule consisted of three individual non-overlapping flights as seen in Table 4.1. As all flights do not show overlap, only one charging station is expected on P1. In the flight schedule, two 'special' flights are present. Flight 01 is a flight that arrives earlier than 07:30 and is thus regarded as an 'early flight' with less charging energy required. Flight 12 is scheduled for a departure to Aruba and thus requires 36 kWh charging above 80% which may only be done by charging below the set threshold of 100 kW. Although Flight 02 is not deemed particularly 'special' it does only have a turnaround time of ten minutes. From the energy requirements this would translate into 984 kW charging. But this is not possible as the maximum charger capacity is set at 600 kW. Therefore, at least 20 minutes turnaround time is expected.

Table 4.1: Verification parameters for showing only 1 parking position needed and slow charging

Verification Set 1								
Input					*Model Output*			
Flights	**A/C type**	**Routes**	**Arr**	**Dep**	**Arr**	**Dep**	**Parking**	**Time Shift**
Flight 01	9-seater	CUR;CUR	07:10	07:20	07:40	07:50	P1	{30,30}
Flight 12	19-seater	CUR;AUA	08:50	9:10	08:40	09:40	P1	{-10,30}
Flight 02	9-seater	CUR;CUR	10:30	10:40	10:20	10:40	P1	{-10,0}

Looking at the results, it can be seen that all flights will be parked at position 1 which is the only parking position equipped with a charger. Although Flight 01 requires less charging energy, the model shifts this flight to the maximum boundary while the original turnaround time of ten minutes is remained. This shift is likely done to be able to lower the number of solar panels as these will not be able to generate much energy earlier in the morning. Flight 12 is desired to be on the ground for a longer time than originally planned. This is mainly due to the slow charging constraint above 80%. As the minimum time needed for 36 kWh at 99 kW (just below threshold) is 21.8 minutes, the model rounds this up to 30 minutes, please see Table 4.2. Before, 30 minutes of fast charging was already outputted by the model. Flight 02 indeed requires more time and its arrival time is therefore shifted to ten minutes earlier.

Table 4.2: Charging results for verification set 1

Flight 01		**Flight 12**		**Flight 02**	
Time	*Power* (kW)	*Time*	*Power* (kW)	*Time*	*Power* (kW)
07:40	492	08:40	600	10:20	384
		08:50	447	10:30	600
		09:00	600		
		09:10	99		
		09:20	99		
		09:30	99		

In the second verification set, the time shift will be tested. Table 4.3 shows two flights that are identical except for the number of passengers onboard both the incoming and outgoing legs. As the time shift cost C_{d1} is the cost per passenger per minute time shift, it is expected that the flight times of the flight with the most passengers onboard (Flight 38) will be shifted less than the flight with less passengers onboard (Flight 22). Looking at the results in Table 4.3, indeed the model shows that Flight 22 is rescheduled just after Flight 38 on parking position 1.

Table 4.3: Verification parameters for showing flight time shifts dependency on passengers

Verification Set 2									
Input						*Model Output*			
Flights	**A/C type**	**Routes**	**PAX**	**Arr**	**Dep**	**Arr**	**Dep**	**Parking**	**Time Shift**
Flight 22	19-seater	CUR;CUR	2;3	14:00	14:20	14:20	14:40	P1	{20,20}
Flight 38	19-seater	CUR;CUR	14;15	14:00	14:20	14:00	14:20	P1	{0,0}

Lastly, also a verification set is used to check the functioning of the aircraft repositions. Table 4.4 shows one arriving flight leg in between two return trips. It is expected that two charging stations would be needed on P1 and P2 respectively in case the reposition input parameter is set to 0. However, if this parameter is set to allow one reposition per eligible flight, it is expected that Flight 51 is repositioned to P1 somewhere after Flight 45 has left. Before this reposition, any other parking position would suffice for this flight.

The top part of Table 4.4 indicates the model without any possible repositions. As expected, two charging stations would be needed on P1 and P2. However, the charger at P2 is not required when indeed Flight 51 is repositioned exactly after the departure of Flight 45.

Table 4.4: Verification parameters for showing aircraft repositioning

Verification Set 3									
Input						*Model Output*			
	Flights	**A/C type**	**Routes**	**Arr**	**Dep**	**Arr**	**Dep**	**Parking**	**Time Shift**
Repos = 0	Flight 44	19-seater	CUR;CUR	17:20	17:40	17:20	17:40	P2	{0,0}
	Flight 51	9-seater	CUR;CUR	18:50	-	18:50	-	P1	{0}
	Flight 45	19-seater	CUR;CUR	19:40	19:50	19:30	19:50	P2	{-10,0}
Repos = 1	Flight 44	19-seater	CUR;CUR	17:20	17:40	17:20	17:40	P1	{0,0}
	Flight 51	9-seater	CUR;-	18:50	-	18:50	19:50	P2	{0}
						19:50	-	P1	
	Flight 45	19-seater	CUR;CUR	19:40	19:50	19:30	19:50	P1	{-10,0}

5

Energy Storage Types

Within the recommendations of the research paper, further research into different types of energy storage is mentioned. This extra chapter will therefore provide some basic information on four different energy storage types while also presenting an initial back-of-the-envelop calculation on costs and required storage per type. This all is focused on the purpose of electric flights and may therefore be seen as a very brief start of further research. In the coming four sections, Li-ion battery, flow battery, hydrogen and pumped hydro storage will be addressed. Lastly, a sample calculation is presented. Note that all specific costs and parameters mentioned are based on the Energy Storage Grand Challenge 2020 report [113].

5.1. Li-ion Battery

Where the research paper only implemented the overall costs per kWh of Lithium-ion battery storage, a further distinction could be made in terms of capacity costs ($/kWh) and power costs ($/kW). Here, the capacity is mainly the physical battery and project costs while the power costs mainly concerns inverters and integration into for instance the grid. Table 5.1 shows the costs per capacity and power for two different Li-ion types in a researched system closest to the found results in the research paper. As is very clear from the table, the decrease foreseen up to 2030 is quite significant. But what is also seen is that the investigated systems only had a limited time to deliver the desired power. In other words, Li-ion batteries should mainly be purposed for shorter (<24 hr) periods of bulk energy storage provision. This could then be done with expected round trip efficiencies of 88%.

Table 5.1: Unit and system costs per capacity and power for a 1 MW / 4h storage system for Li-ion batteries and flow battery [113]

	Li-ion LFP		Li-ion NMC		Flow Battery	
Cost	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
Unit ($/kWh)	408	285	420	297	545	434
Unit ($/kW)	156	126	156	126	226	186
System ($/kWh)	448	317	459	272	601	480
System ($/kW)	1793	1266	1838	1089	2404	1922

5.2. Flow Battery

Besides well known battery types, technology has also advanced in different less conventional battery storage types. The flow battery is one of them of which the Vanadium Redox flow batteries are now seen as the most advanced technology. It requires much more surface area than a conventional Li-ion battery as the liquids storing the energy should be there in abundance. Costs lie higher than for Li-ion batteries, especially for power requirements as is also presented in Table 5.1. Larger power requirements are therefore not the main target of this storage system. Projected costs in 2030 are nearing 2020 levels of Li-ion batteries, but remain rather high if compared to 2030 Li-ion battery costs. The round trip efficiency that could be reached with flow batteries lies at around 70%.

5.3. Pumped Hydro

Already a developed technique that uses gravity to store energy comes in the form of pumped hydro. Surplus energy is then used to pump water into a higher elevated reservoir while the difference in height in combination with gravity are utilized to produce energy when needed and water is available in the upper reservoir. However, this does mean that height differences are essential and ample of reservoir space should be present. In terms of costs this is also reflected as a 100 MW / 10 h system was researched (see Table 5.2) with a 80% round trip efficiency. Meaning: only very large systems are the way to go at the moment and smaller systems are probably not worth the investment costs.

Table 5.2: Unit and system costs per capacity and power for a 100 MW / 10h storage system of pumped hydro and hydrogen [113]

	Pumped Hydro	Hydrogen	
Cost	**2020/2030**	**2020**	**2030**
Unit ($/kWh)	76	4	3
Unit ($/kW)	1209	3081	1581
System ($/kWh)	262	312	161
System ($/kW)	2623	3117	1612

5.4. Hydrogen

Perhaps the most promising technology that is widely researched now is the production and storage of hydrogen. If electrolysis is used to produce hydrogen and storage is done in underground (salt) caverns, the costs in 2030 are expected to be more than half of Li-ion batteries as seen in Table 5.2. In contrast, only a 35% efficiency is expected during these energy cycles. Furthermore, the costs mainly originate from power related components and thus originate from the conversion processes to and from hydrogen. What is more, energy is required for the electrolysis which in this case is not taken along in the published report. Ideally, this energy should then of course come from a renewable source. Lastly, in the research, use is made of underground caverns. However, major bulk storage above ground might be more likely, depending on the local situation. The advantage of hydrogen is that it may be stored over a longer period of time than the Li-ion is purposed for.

5.5. Sample Calculation

Using the data provided in Table 5.1, Table 5.2 and the mentioned efficiencies, a simple sample calculation could be made for a system very similar to the results of the research paper (2 MWh, 600 kW). Please see the results in Table 5.3, linearized for 2025 costs. Clearly, a pumped hydro system would be the most cost efficient option. However, given the local situation on Bonaire with little height difference and nature reserve parks, this option is deemed infeasible. The runner up is the flow battery with significantly less costs than the Li-ion battery and hydrogen systems. The technology is still to advance even more and therefore it might thus be a feasible option when a larger area is to be developed in the future.

Interestingly, the Li-ion battery and hydrogen do not lie very far apart with the set parameters. For Li-ion batteries, this value is rather fixed, however for hydrogen two remarks could be made. First of all, Bonaire unlikely has the opportunity to utilize underground caverns as storage. In other words, bulk storage on land should be developed to store the produced hydrogen, inducing more costs. This could of course be done in parallel with other industries requiring hydrogen in the future. Automatically this then translates into the second remark. In case hydrogen industry is already present in the vicinity, it could very well be that storage of surplus hydrogen should only be developed. Therefore, costs may be far lower than constructing the complete process up until the energy conversion to a grid.

In conclusion, with the use of the described values, a clear decision is not unambiguous if local factors are taken into account. Given these caveats, further research in especially hydrogen and flow battery technology show the most perspective and may in the future prove a better business case than the Li-ion batteries.

Table 5.3: Estimation of yearly costs for a 2 MWh/600 kW system in the year 2025

	Li-ion (LFP)	**Flow Battery**	**Pumped Hydro**	**Hydrogen**
Yearly cost estimation (k$)	166	112	33	163

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