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Electric Aircraft Operations: An Interisland Mobility Case Study

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Abstract: This study focuses on the feasibility of electric aircraft operations between the Caribbean islands of Aruba, Bonaire, and Curaçao. It explores the technical characteristics of two different future electric aircraft types (i.e., Alice and ES-19) and compares their operational requirements with those of three conventional types currently in operation in the region. Flight operations are investigated from the standpoint of battery performance, capacity, and consumption, while their operational viability is verified. In addition, the CO_2 emissions of electric operations are calculated based on the present energy mix, revealing moderate improvements. The payload and capacity are also studied, revealing a feasible transition to the new types. The impact of the local climate is discussed for several critical components, while the required legislation for safe operations is explored. Moreover, the maintenance requirements and costs of electric aircraft are explored per component, while charging infrastructure in the hub airport of Aruba is proposed and discussed. Overall, this study offers a thorough overview of the opportunities and challenges that electric aircraft operations can offer within the context of this specific islandic topology.

Keywords: electric aircraft; electric flight operations; electric ground operations; aircraft charging; aircraft batteries; powertrain components; interisland mobility; aviation emissions; airport infrastructure; sustainable aviation

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1. Introduction

Motorized flying has been possible since 1903, and in the following century, aerospace innovations have occurred at a fast pace. Aviation has become an indispensable part of the transportation of humans and goods, but one thing has remained the same: the use of fossil fuels for propulsion. Even though engines nowadays are highly efficient, aircraft emissions have grown due to an overall increase in the volume of flights [1]. Using fossil fuels comes with a penalty, namely contribution to climate change, the depletion of raw materials, and the deterioration of air quality [2]. A large part of next-generation aircraft is currently being developed with the use of hydrogen, electricity, and Sustainable Aviation Fuel (SAF) as the primary energy sources or in hybrid configurations, combining electrification and some forms of fuel [3]. Several airports in the former Dutch Caribbean have the ambition of making interisland air transportation more sustainable and affordable with the introduction of electric aircraft operations. Similar studies have highlighted the benefits and challenges of electric aviation [4–6]. It is important to note that electric aircraft are sometimes referred to as zero-emission aircraft, which is untrue since emissions still exist in terms of the manufacturing, ground support, and non-renewable electricity production. However, the benefits include a reduction in CO_2 and non-CO_2 emissions indeed, as electrical grids increasingly rely on renewable energy sources. Major challenges include the specific energy of the batteries, the thermal management of propulsion systems, and the overall architecture of the electrical components. Various initiatives and studies have already shown that, in the short-term, flying electric between the islands of Aruba, Bonaire, and Curaçao (the ABC Islands) is feasible [7]. In fact, this area of the Caribbean would be particularly suitable due to its stable weather and the relatively short distance between the islands. Aruba International Airport is starting to explore the options for electric flight operations; however, the required knowledge, expertise, and infrastructure currently make such an endeavor challenging. Therefore, the present case study focusses on the characteristics and complexities of performing electric flight and ground operations, as well as the effects of the environmental conditions on the reliability and maintenance of distinct components of electrified aircraft.

In more detail, this study makes use of the conceptual designs of two electric aircraft, which are currently in the process of detailed design and are expected to become commercially available later this decade. The scope of this paper is to draw a realistic picture of the operational aspects of future commercial electric flights in the ABC Islands. This is a proposition that, to the best of the authors' knowledge, is novel and provides a holistic understanding of the venture of electric aviation, not only in the Dutch Caribbean but also in similar operational islandic environments. As a result, a comparison between the current and future landscapes is performed to reflect on the feasibility of the transition to electric aircraft. Even though the central point of this study is this specific region of the map, some of the outcomes can be generalized, and the same methodology can be used in other areas in order to draw conclusions about the local feasibility of electric aircraft operations. Consequently, the main contribution is expected to be a total overview of the application of electric aircraft operations in a context which is as realistic as possible given their early design phase. Additionally, a comparison to conventional aircraft operations is made. To perform this analysis, the hypothesis that battery-electric aircraft can act as a drop-in substitute for conventional aircraft is tested, and a mix of methods were used, such as analysis of the preliminary performance data and on-site investigation of the current operational landscape and power production, as well as a literature review of the regulatory, safety, and proposed sustenance and maintenance frameworks.

The first section of this paper identifies and discusses the technical characteristics and performance of the two electric aircraft concepts. This forms the basis of the study and explains what the general potential and limitations of electric aircraft operations are. Following this, the current operations are explored according to the following areas: the routes and schedule, local airlines and aircraft types, emissions, payload, and fuel costs. The results of these explorations are then used to determine the operational characteristics of the interisland routes for electric aircraft. More specifically, based on updated information on the local energy mix for these islands, the energy consumption, CO_2 emissions, and energy costs are calculated. Continuing from this, the local climate is explored, and the expected environmental effects on the main critical aircraft components are identified. The next section deals with the operational procedures and safety aspects of future electric operations in the ABC Islands, followed by an elaborate study of the maintenance aspects of electric aircraft from a regulatory standpoint, as well as in terms of climate-related challenges and costs. The following section discusses the charging infrastructure and airport master planning, in combination with the technical requirements for timely charging, which can support the ground operations. The power supply and energy at the Aruba airport are then discussed, followed by some main considerations on ground safety and emergency procedures.

2. Characteristics of Electric Aircraft

The main difference between conventional and electric aircraft is the mode of propulsion. This section looks at the various components in the electric propulsion system, their properties, and the general performance of electric aircraft.

2.1. Comparison of the Powertrain Architecture

As already mentioned, the major difference lies within the powertrain. The energy for propulsion is not obtained from fuel but from electrical charge, which is used to drive a motor. A major advantage of an electric powertrain is that it entails a clean process; therefore, there are no CO_2 emissions at the local level. Figure 1 illustrates the process in both cases, of a small conventional aircraft and of a battery-electric aircraft. It should be noted that one needs to take into consideration the electricity production for correct efficiency bookkeeping.

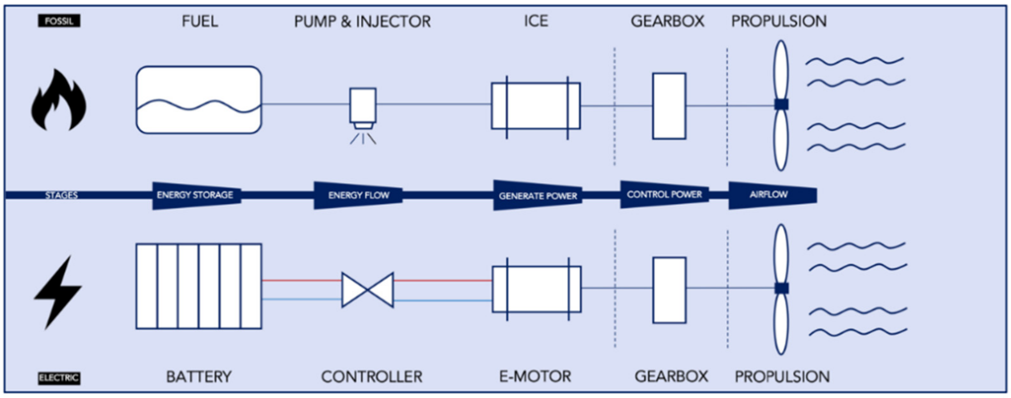

Figure 1. Powertrain in an electric and a conventional small aircraft (adapted from [8]).

2.2. Electric Motor Considerations

Electric motors use electrical energy, derived from a potential difference and current flow, and convert this into mechanical movement. Their construction is simple and consists of various components. Overall, the only moveable part in an electric motor is the rotor, compared to the often hundreds or thousands of moving parts in a combustion engine. This makes electric motors more reliable and less maintenance-sensitive. Cooling is provided by means of conduction, convection, and/or cooling liquid [9]. Furthermore, the electric motor has a high power-to-weight ratio, and where almost half of the potential energy is lost in the thermodynamic process of a combustion engine, the electric motor achieves an efficiency of around 98% [8].

2.3. Controller System

The controller manages all systems for the desired performance. Some functions that the controller can perform are starting/stopping the motor, selecting forward or reverse drive, and regulating the speed and torque. It ensures that the right amount of energy is delivered from the battery to the engine when prompted. Various environmental factors are present in aviation, so controllers are protected by several features, such as liquid cooling systems, useability in non-pressurized operations, redundant electronics, and protective casings [10].

3. Battery and Health Management

Batteries store the energy that provides power to engines. It is noteworthy that, during a flight, the weight of a battery does not decrease, in contrast with fuel consumption. The most common type of battery found in electric vehicles (EV) is lithium-ion (Li-ion) due to its high energy density. Li-ion batteries are sensitive to cold and warm environments. In a warm environment, the capacity of a Li-ion battery slightly increases, with the adverse effect of accelerating its lifecycle degradation. A cold environment increases the internal resistance of the battery, resulting in a lower efficiency [11]. The battery temperatures should therefore stay between the ideal operating temperatures. To achieve this, battery cooling is provided during its operation to achieve thermal stability. The biggest risk in current batteries is the chemical 'thermal runaway' reaction. To reduce this risk, thermal management is of significant importance, as well as precaution measures taken in the battery design. Batteries used for aerospace applications feature a battery management system (BMS). This system keeps track of all the important battery parameters. The State of Health (SoH) and State of Charge (SoC) are two important battery parameters; the first indicates how much of the initial capacity is available, while the latter indicates what percentage of the available capacity is charged. In general, battery-electric aircraft could make use of various data analytics concepts encountered in conventional aircraft [12–14].

3.1. Battery Density and Developments

As illustrated in Figure 2, Li-ion batteries have one of the highest energy densities within the family of batteries, namely 100–265 Wh/kg to date [15]. The performance of Li-ion batteries is determined by the design of cells and materials used. It is expected that in the near future, the development of Li-ion batteries, based on the current materials and designs, will reach its peak. In comparison, the energy density of kerosene lies at around 12,000 Wh/kg [16]. In terms of energy density, a major limitation becomes visible for the application of batteries in electric aircraft. For the same amount of kerosene and battery weight, 45.3 times more potential energy can be carried in kerosene. Even if the low efficiency of the fossil powertrain is considered, this is still much greater efficiency with fossil aircraft. However, two new battery types are expected: advanced Li-ion and solid-state batteries, of which the latter is the most promising technically [17,18].

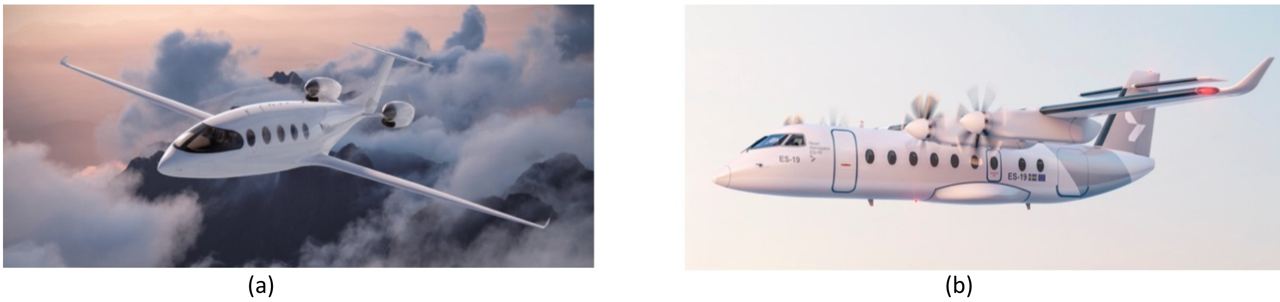

Figure 2. Overview of the electric aircraft. (**a**) Eviation Alice [19]; (**b**) Heart Aerospace ES-19 [20].

3.2. The Performance of Electric Aircraft

The only battery-electric aircraft currently certified to fly under the jurisdiction of the European Aviation Safety Agency (EASA) is the Pipistrel Velis Electro, a two-seater light aircraft. However, this study is focused on 9- and 19-seaters, the Eviation Alice (Figure 2a) and the Heart Aerospace ES-19 (Figure 2b). The Eviation Alice is in the phase of early flight testing, which means that no performance data are available outside its development team. The Heart ES-19, which was recently reconfigured into a new design called ES-30, is in the main design phase and has not performed any flights yet. As a result, the only option for this study was to make use of the announced specifications and performance characteristics of the two aircraft, which are provided only for cruising in both cases [19,20]. Unknown values were calculated or assumed. Lastly, it is important to clarify that even though the Heart has switched from model ES-19 to ES-30, the scope and conclusions of this investigation remain relevant, as they highlight the operational aspects of battery-electric aircraft, independent of their type.

Below is a concise overview presented of how the values in Table 1 have been approached; for the full calculations, please refer to the original case study in [21].

Table 1. Performance values of the aircraft intended for interisland flights.

Aircraft	**Battery Capacity [kWh]**	**Range [km]**	**Energy Consumption [kWh/km]**	**Payload [kg]**
Eviation Alice (nine passengers)	initial: 820 end-of-life: 656 standard reserve: 246	470	cruise: 1.75 climb: 5.74	total: 930 per seat: 103
Heart ES-19 (19 passengers)	initial: 900 end-of-life: 720 standard reserve: 270	448	cruise: 2.01 climb: 6.62	total: 1635 per seat: 86

3.2.1. Battery Capacity

The initial maximum battery capacity is derived from the NACO and NLR research and is 820 kWh for the Alice and 900 kWh for the ES-19 [7]. In order to determine the available capacity at an SoH of 80% (end-of-life), the initial capacity was multiplied by a factor of 0.8. As a result, the capacity of the Alice is reduced to 656 kWh and of the ES-19 to 720 kWh. According to the same sources, the reserve energy requirement is 30% of the original available capacity. Specific reserve energy requirements have not yet been established for electric aircraft; however, EASA recently published a proposal regarding this topic [22].

3.2.2. Technical Range

Since the mass of the battery does not change during the flight, the range equation of electric aircraft is simplified in comparison with conventional aircraft. Eviation claims a range of 440 nautical miles, which is equal to approximately 820 km; however, this is based on an empty aircraft, while commercial operations will always involve a payload. Therefore, in these range calculations, the Maximum Take-Off Weight (MTOW) has been assumed for both the Eviation Alice and Heart Aerospace ES-19. Under these circumstances, the Alice can fly 470 km and the ES-19 448 km.

3.2.3. Energy Consumption

It is important to understand the amount of consumed energy for a specific distance. To calculate this, the consumption per km traveled was determined for cruise, climb, and descent. This value only looks at the consumption for the propulsion of the aircraft itself in ideal conditions. There are also on-board systems that require additional energy, but since no relevant information is available, these have not been considered in this preliminary study. In addition, real operational conditions will produce differentiations in the consumption figures, but these will only be explored during flight testing.

- *Cruise:* The cruise speed represents the optimal balance between the energy consumed and distance traveled; in this scenario, the maximum range is achieved. As the initial battery capacity was known and the technical range has been calculated, the average consumption during cruise could be derived. This is achieved by dividing the initial capacity by the technical range. For cruise (with full payload), the Alice consumes 1.75 kWh/km and the ES-19 2.01 kWh/km.
- *Climb.* Currently, there are no flight performance charts available for either the Alice or the ES-19. In [8], a conceptual electric drop-in version of the Dornier 328 aircraft was investigated and simulated with regards to its performance. The total energy that the aircraft uses during climb and cruise was calculated, and this is the sole reliable source that provides such a figure. By considering the duration of each segment and the covered horizontal distance, it was possible to calculate the energy ratio between cruise and climb in the present study. This is the baseline for all of the following performance calculations. As a result, by analyzing the segment data, it could be derived that the energy consumption per km ground distance traveled is approximately 3.29 times higher during the climb phase. The fact that different aircraft have different behaviours and that this calculation applies to specific conditions is acknowledged, but, at the same time, it provides a reasonable order of magnitude of a figure which is not accessible otherwise. In order to assume the values for climb as close as possible to realistic scenarios, this factor has been applied to the cruise consumption. For climb, the Alice then consumes 5.74 kWh/km at a horizontal distance, while the ES-19 consumes 6.62 kWh/km. Eviation mentions a climb rate of 2000 ft/min for Alice. No data from Heart Aerospace are given on the ES-19, but the same value as for the Alice is determined to be realistic and therefore assumed.
- *Descent:* A minimum idle engine speed is not necessary during descent as in conventional engines since there is no possibility of a flame-out. In addition, as the engines in electric aircraft can also act as generators, it is possible that the propellers can

recover some of the energy during the descent phase. This recovery function will entail more drag as the propeller is rotated by the airflow. Due to the increase in aerodynamic resistance, the descent rate of the aircraft will also increase. Therefore, it is realistic to expect that the descent phase starts later and will be steeper than that of conventional aircraft. However, such operations can only be accommodated if Air Traffic Control (ATC) makes this possible with special approach procedures. Despite the ability to recover energy, the overall drag of the windmill propellors is high and the efficiency is low; only around five percent can be recovered per flight, depending on the propulsion system, flight distance, and altitude [8]. Because neither the exact numbers nor whether the proposed aircraft support this principle are known yet, an energy consumption of 0 kWh per km ground distance will be used for the calculations. As the descent speeds are also unknown, the same duration as in the climb phases is used for these calculations.

3.2.4. Payload

In order to determine the available payload, as stated in Table 1 above, the average weight of the flight crew needs to be subtracted from the nominal values. According to EASA, the standard flight crew weight is 85 kg per pilot. This means that when assuming two pilots behind the deck, the Alice can accommodate 930 kg and the ES-19 1635 kg.

4. Sustainable Interisland Flights

This section is focused on the question of how interisland flight operations are currently performed between the ABC Islands, what amount of electric energy is needed to fly these routes with electric aircraft, and how electric flight operations compare to conventional operations. A combination of interviews, on-site visits, and literature [21–25] has been used.

4.1. Air Transport between the ABC Islands

On the ABC Islands, there are three main international airports: Aruba Airport (AUA), Bonaire Airport (BON), and Curaçao Airport (CUR). In terms of the flight distances, CUR and BON are closest to each other, with a flight distance of 76 km, followed by the connection of AUA and CUR at 120 km, as illustrated in Figure 3. Currently, there is no scheduled service between AUA and BON, which are 194 km apart. Flights are operated using small aircraft that can accommodate up to a few dozen passengers.

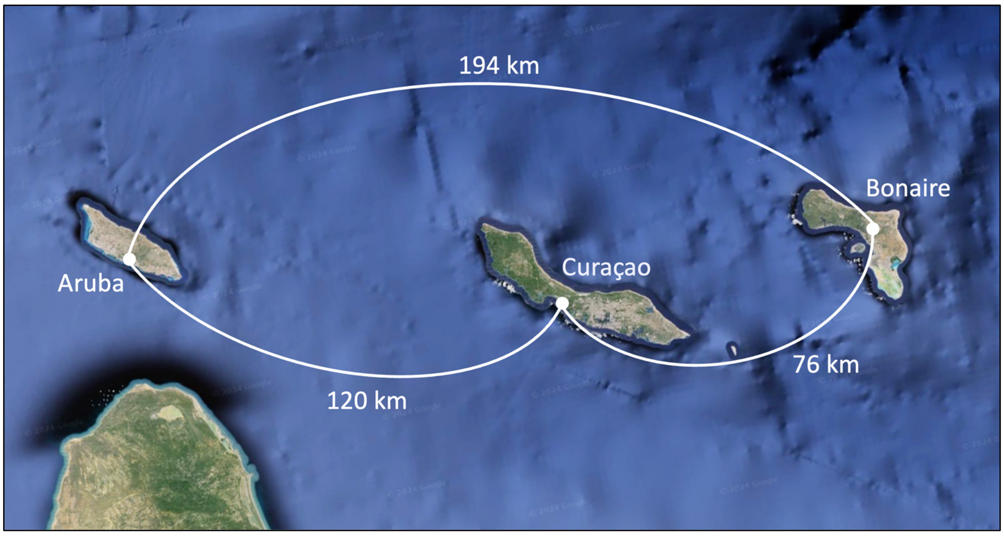

Figure 3. Flight routes between the ABC Islands.

4.2. Air Operators for Interisland Travel

As stated in Table 2, the airlines that operate flights between one or more of the ABC Islands are Divi Divi Air (DVR) and EZ Air (EZR). Flights between Aruba and Bonaire are operated through CUR, the hub for all interisland traffic. The flight schedule is fixed throughout the year, as there are no seasonality effects. The fleet of Divi Divi Air consists of three DHC-6 Twin Otters (19 passengers) and two BN-2 Islanders (8 passengers). The current fleet of EZ Air consists of three Saab 340B aircraft (34 passengers).

Table 2. Interisland operators, flight routes, their frequency, and the aircraft used.

Mission Route	Airline	Weekly Frequency	Aircraft
CUR–AUA	DVR and EZR	46 and 14	DHC-6 and Saab 340B
AUA–CUR	DVR and EZR	46 and 14	DHC-6 and Saab 340B
CUR–BON	DVR and EZR	41 and 17	DHC-6 (37), BN-2 (4), and Saab 340B
BON–CUR	DVR and EZR	41 and 17	DHC-6 (37), BN-2 (4), and Saab 340B

Red: Divi Divi Air, Green: EZ air.

4.3. Flight Routes in the Current ABC Islands Network

The aircraft used on the routes have a standard seating configuration; however, in practice, fewer seats are sold than there are available. This is related to the fact that travelers are heavily packed, and, as a result, the max payload is easily achieved. From interviews with the two airlines, the average fuel consumption, desired flight times, and assumptions on the payload values were derived. Also, using site visits, it became clear what their operations entailed in practice, such as the turnaround process. In Table 3, an overview of the most important operational parameters of the different aircraft is given.

Table 3. Conventional aircraft specifications.

Aircraft	Fuel Type	Fuel Consumption [kg/h]	Passengers	Luggage (kg)	Extra Payload (kg)	TAP (min)
DHC-6	Jet A-1	272.2	17	18	120	30
BN-2	AVGAS	73.1	7	18	120	30
Saab 340B	Jet A-1	450.0 [23]	25	23	-	30

5. Comparison of Energy Sources

Electric flying can be sustainable only if the used energy is also renewable. On the ABC Islands, electricity is generated using a mix of energy from fossil fuels and renewable sources. For this section, calculations were made on the fuel usage, price, and emissions of the current flights. The emissions per kg of Avgas or Jet A-1 were calculated using basic chemical reaction equations. The combustion of 1 kg Avgas results in 3088 kg of CO_2, and combusting 1 kg of Jet A-1 produces 3106 kg of CO_2. As almost all refueling takes place in Curaçao, the prices of the airport supplier CUROIL were consulted. The costs of both fuel types were equal at that moment, namely $1.56 per litre (price level: 1 May 2022). The average flight times for the routes per aircraft and airline were derived from Flightradar24 data. As all uncertain values were now known, the fuel usage, total price, and emissions could be calculated for the current operations. In Table 4, an overview is given of the calculated average values.

Table 4. Average fuel, emissions, and cost calculations for current flight operations.

Mission Route	Airline	Aircraft	Duration (min)	Fuel (kg)	CO_2 (kg)	CO_2/Seat (kg)	Cost (USD)
CUR–AUA	DVR	DHC-6	31	140.6	436.7	23.0	268.5
	EZR	Saab 340B	21	154.0	478.3	14.4	294.1
AUA–CUR	DVR	DHC-6	28	127.0	394.5	20.8	242.5
	EZR	Saab 340B	21	154.0	478.3	14.4	294.1
CUR–BON	DVR	DHC-6	21	95.3	296.0	15.6	182.0
		BN-2	24	29.2	90.2	11.3	60.7
	EZR	Saab 340B	16	117.3	364.3	11.0	224.0
BON–CUR	DVR	DHC-6	20	90.7	281.7	15.6	173.2
		BN-2	24	29.2	90.2	11.3	60.7
	EZR	Saab 340B	20	146.7	455.7	13.7	280.1

Each island uses a different mix to obtain its required amount of electrical energy (Figure 4). An interview with Aqualectra (Curaçao) revealed that fossil generators for production had an average consumption of 0.22 L of heavy fuel oil per kWh of electric energy. This oil has an emission factor of 3310 kg of CO_2 per litre [24]. The fuel consumption for Aruba and Bonaire was assumed to be equal. Because the energy mix and fossil production emissions were known, the average emissions per kWh of energy could be calculated. The prices for electrical energy were derived from the current published tariffs on its site (price level: 1 May 2022).

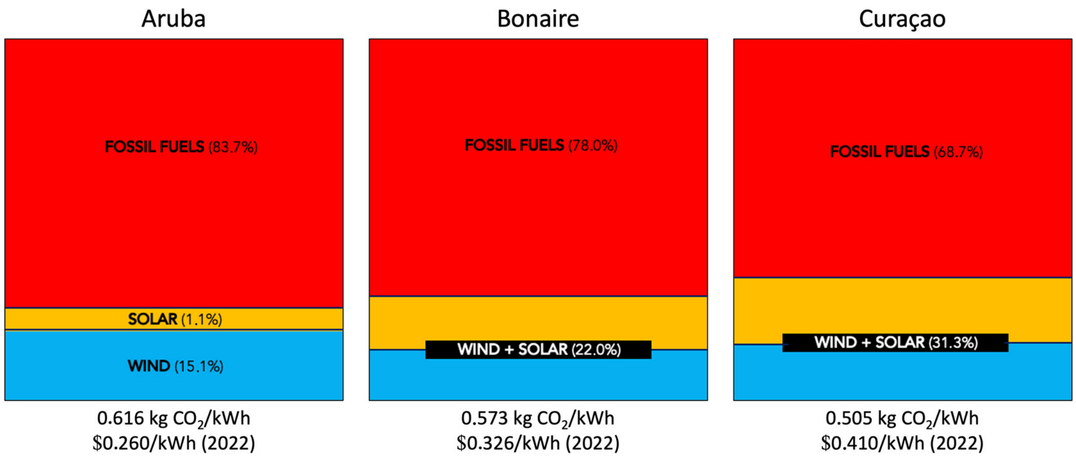

Figure 4. Energy mix of the ABC Islands.

5.1. Mission Profiles for Interisland Routes

One of the main research objectives was to identify the amount of energy needed to fly the interisland routes with the proposed electric aircraft. This is important to determine whether the routes are feasible in different conditions, as well as to examine whether charging is possible in the desired turnaround time. Comparison with the conventional operations can be made of the energy prices and emissions for performing the flights. To calculate the amount of electrical energy used, the flight time, and the emissions per flight segment for the Alice and ES-19, a model was developed [21], considering multiple preconditions.

This model makes use of the flight distance, taking into consideration the climb and approach angles and the expected flight level, in order to calculate the required energy of the flight leg, as suggested in Section 3.2.3. In addition, the most severe wind influence that could be realistically expected was applied to the cruise segment based on the local climate. Furthermore, two pilots behind the flight deck, the maximum payload configuration, and the current flight altitudes for the routes were used so the most energy-demanding scenario could be investigated. The calculated energy and times are stated in the mission profiles of Figure 5. In addition to the required energy, the reserve energy was always considered so there was the capability for a diversion. Lastly, based on the information above, the flight times per flight segment and in total were measured.

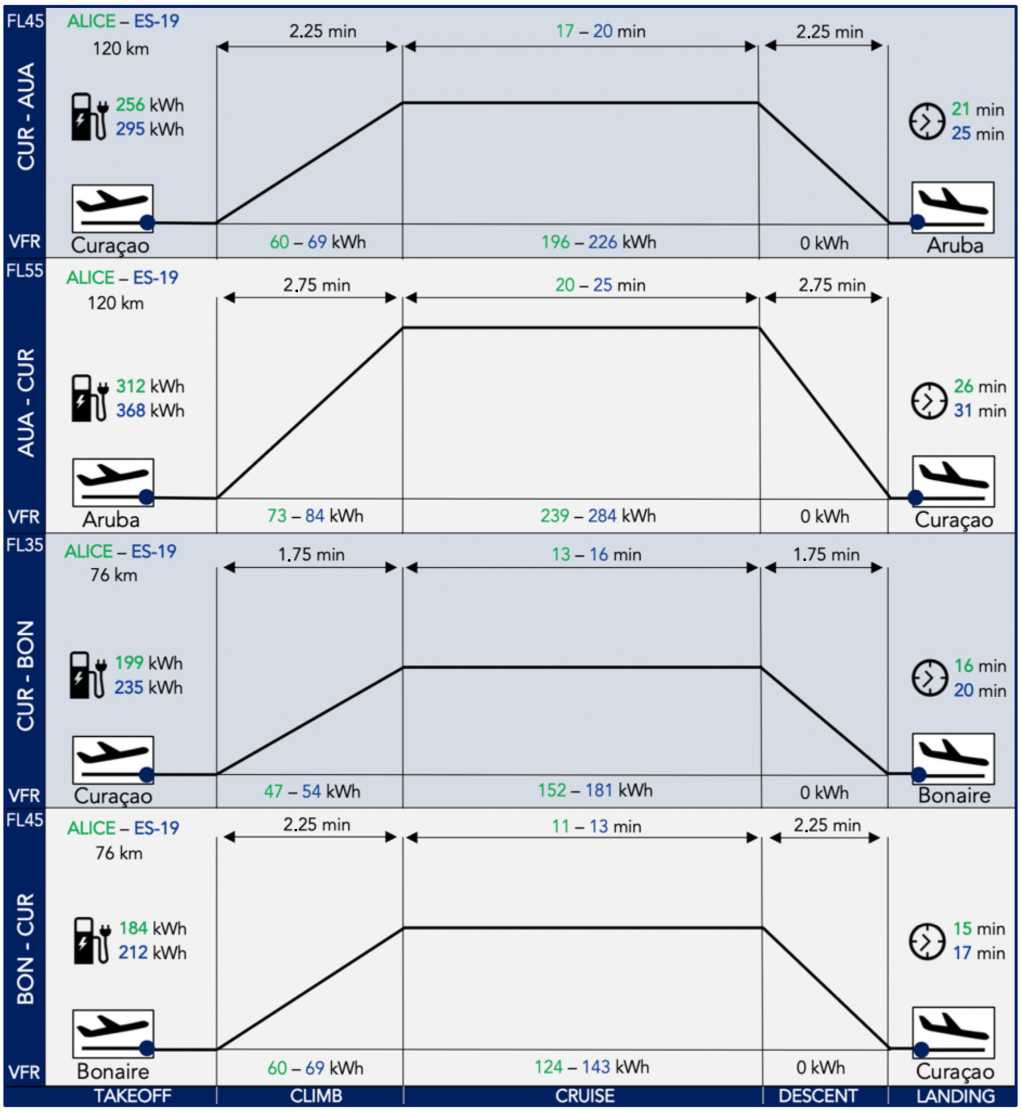

Figure 5. Interisland mission profiles for the four routes (green: Alice, blue: ES-19).

5.2. Costs and Emission Overview

The energy requirements per flight route and aircraft are determined, as well as the emissions and prices per kWh on the different islands. Currently, the efficiency of chargers for heavier applications is approximately 96% [24]. The energy costs and emissions are stated in Table 5 below. One noticeable point is that the emissions per flight are lower, especially when compared to the conventional flights in Table 4.

Table 5. Average fuel, emissions, and cost calculations for electric flight operations.

Mission Route	Aircraft	Mission Energy (kWh)	Energy Provider	CO_2 (kg)	CO_2/Seat (kg)	Cost (USD)
CUR–AUA	Alice	256	Aqualectra	134.7	15.0	109.4
	ES-19	295		155.1	8.2	125.9
AUA–CUR	Alice	312	WEB Aruba	200.2	22.2	84.5
	ES-19	368		236.2	8.2	99.7
CUR–BON	Alice	199	Aqualectra	104.5	11.6	84.8
	ES-19	235		123.4	6.5	100.2
BON–CUR	Alice	184	WEB Bonaire	109.9	12.2	62.5
	ES-19	212		126.6	6.7	72.0

5.3. Payload for the Desired Capacity

It is pivotal to estimate how electric aircraft can replace the current network capacity between the islands. During the discussions with the local operators, it became clear that their interest revolves around a direct comparison between the conventional and electric aircraft, so they can have a better understanding of the future challenges and opportunities. In principle, they wished to understand whether their operations could be performed in their current form using electric aircraft. This comparison could only be conducted by comparing the respective payloads within a constrained operational schedule, as, in any other case, there are additional variables that affect any conclusions regarding the feasibility of this scenario.

In Table 6, the payload capacities are compared to each other. The maximum payload values for the electric aircraft were already previously determined. Interpolating between the performance data [25] resulted in realistic assumptions of the payload values for the DCH-6 and BN-2. The payload values of the Saab 340B could be calculated based on airline information and have been used for EZ Air. The results in the table show that the payload per seat in the ES-19 is slightly higher than in the DHC-6. The BN-2 offers the highest available payload per seat, after which the Eviation Alice follows. The overall payload values of the electric and conventional aircraft are quite similar. Capacity-wise, the aircraft can therefore be simply interchanged based on seats.

Table 6. Payload comparison of different aircraft for interisland travel.

Aircraft	Pilots	Seats	Passengers	Available Payload (kg)	Payload/ Passenger (kg)	Payload/ Seat (kg)
Alice	2	9	9	930	103	103
ES-19	2	19	19	1635	86	86
DHC-6	2	19	17	1597 (21)	94	84
BN-2	1	8	7	849 (21)	121	106
Saab 340B	2	34	25	2725	109	80

6. Influence of Local Conditions on the Components

This section discusses the effects of the local environment conditions on electric aircraft. For the weather section, data from the Meteorological Department of Aruba (DMA) were used [26]. By consulting several sources, the sensitivity of the systems and components was identified.

6.1. Local Climate and Weather Conditions

In general, the climate on the islands is tropical with a dry and wet season. There is relatively little rain and a lot of sun, and there is an apparent wind component. The temperature is high and remains fairly constant throughout the year. The following provides more details:

- *Temperature:* The temperature in Aruba is relatively high and constant. The minimum temperature range over the latest published years (2018–2020) is on average 27.2 °C and the maximum is 29.8 °C.
- *Humidity:* Humidity has fluctuated significantly over the past few years. Overall, it is relatively high and therefore significant enough. The average relative humidity during the years 2018–2020 was measured between 73.5% and 78%.
- *Wind speed and direction:* The ABC Islands are relatively windy, which can influence the overall flight time and range. From the published data over the period 2018–2020, the average wind speed varies between 5.5 and 9.2 m/s, with a wind direction average ranging from 85.7° to 92.7°.
- *Salinity:* The combination of salt, humidity, and water is known to potentially cause corrosion. According to the European Space Agency (Figure 6), the salinity levels on the ABC Islands appear to be above average when compared to the rest of the world [27].

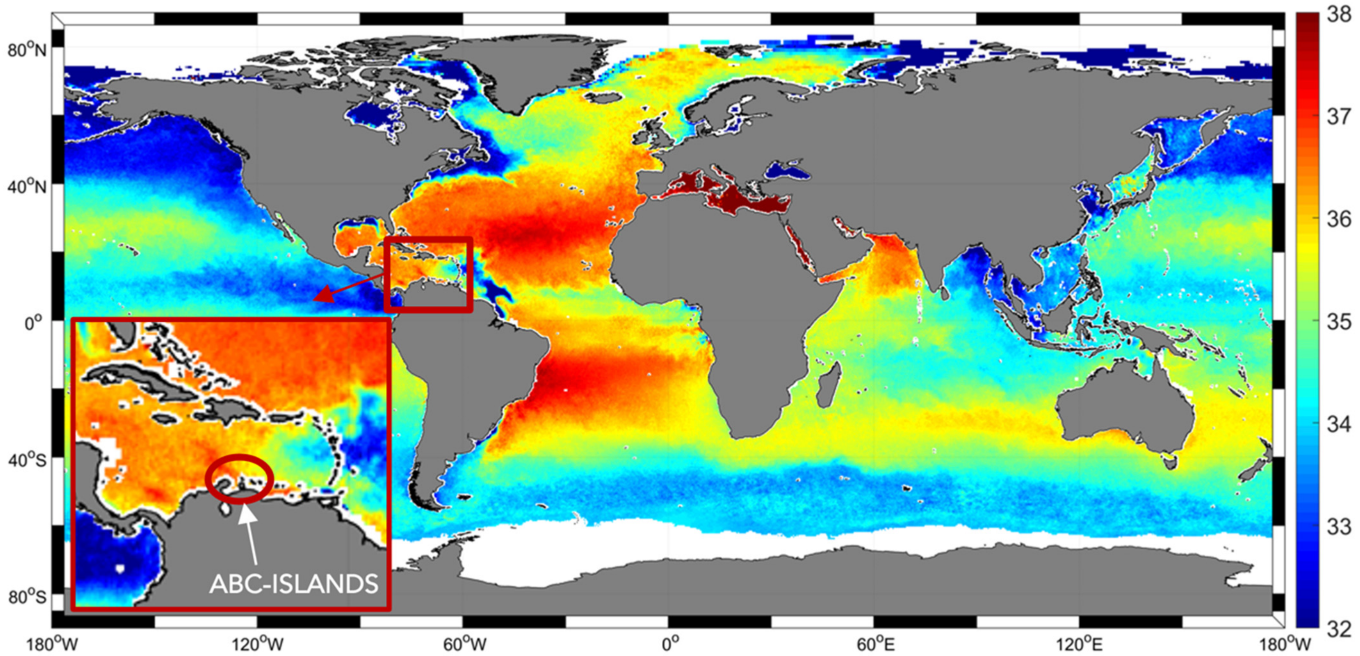

Figure 6. Ocean salinity levels across the world [27].

6.2. Effect on Systems and Components

The potential effect of the local climate on the systems and components of electric aircraft is discussed in this paragraph. At the moment, corrosion is the biggest culprit for the local airlines Divi Divi and EZ Air. Our interviews have shown that corrosion leads to additional maintenance for the airframe, powertrain, and movable parts. However, the effects of environmental conditions on the different systems of battery-electric aircraft are not entirely clear yet. It is true that the extent of many of these effects becomes evident only after a reasonable amount of time in service, even for conventional aircraft types. However, the presented points are based on assumptions which are generally valid for any kind of asset and not only for battery-electric aircraft and systems. Moreover, these assumptions are supported by some initial observations made by Pipistrel and magniX, with the support of additional relevant literature. This way, a general framework of the potential environmental effects and their risks is provided.

6.2.1. Electric Motor

Electric motors are sensitive to dirt ingestion. If engine cooling is performed by means of fans or air inlets, these parts can become clogged with dirt, gradually reducing their cooling effectiveness. Another important aspect is the construction of the electric motor, as the shaft, rotor, and bearings are sensitive to corrosion, which can be caused by moist salty air. During both storage and operation, a relative humidity level of over 80% should be avoided [28]. Since the humidity in Aruba and the other Caribbean islands is close to this level, this may lead to an increased risk of motor corrosion. However, in conceptual images of both the Alice and the ES-19, it is observed that the engines are fitted with a casing. magniX, the engine manufacturer of the Alice, claims that its casings are fully sealed. Heart has no information on this topic, but a similar layout could be expected. However, the casings must be checked periodically to ensure that their functioning is as expected.

6.2.2. Battery

Li-ion batteries are sensitive to environmental influences, such as heat. A distinction can be made between the influences during the operation and storage of the aircraft. During operation, the temperature-critical systems are cooled, including the batteries. However, electrical systems are not cooled when switched off. Overnight, the temperature drops only a few degrees but without the additional radiant heat from the sun. Experiments have shown that the ideal temperature for storage is between 5 °C and 10 °C, with a SoC between 40 and 50% [29]. The recommendations for storing aircraft at night, considering the batteries, indicate a dry place with as few corrosive components in the air as possible and a temperature of up to 35 °C. Deviating from these measures increases the chance that a battery can rust or leak more quickly in the longer term.

6.2.3. Airframe

Currently, corrosion has a major effect on the airframes of interisland aircraft. Both EZ and Divi Divi Air take preventive measures. These measures consist of applying a special coating to the sensitive parts of the aircraft and washing the aircraft regularly. Divi Divi Air performs the latter on a daily basis with sweet water. The ES-19 and Alice are not yet certified, so an environmental envelope is not available for them. What is known, however, is that the airframe structure of the ES-19 will be made of conventional aluminum alloys, and the structure of the Alice made of 95% composite materials. For metal-made aircraft like the ES-19, a coating should be used to protect the airframe from corrosion. However, a weakness of composites is that they may be negatively affected by environmental factors such as heat and UV radiation [30]. The composites used for the CS-23/25 class have high temperature standards; local temperatures should therefore not be a problem. Specific coatings to protect composite airframes from environmental influences are still required.

6.2.4. Controllers and Connectors

As the controller manages the electric propulsion system, any water damage or corrosion can influence the performance of the propulsion system. Therefore, it is of great importance to protect the system. For example, the controller of the Velis Electro has been rated according to the IP65 standard [31]. In the Eviation Alice, the magniDrive controller is used, which has been developed according to the DO-160 standard and ensures protection against environmental influences [32]. Heart has no information on its controller yet. As the controller systems feature internal cooling systems, heat should also not cause problems. Next to the controller, there are connectors used for the components of the powertrain. In reference [33], we can see the effect of corrosion on the performance of connectors. First of all, the contact resistance increases with corrosion, and in addition, the high-frequency and general performance decreases with the corrosion time. Ultimately, corrosion can render a connector unable to perform its primary functions and affect its power or signal transfer. It is therefore extremely important to apply a coating to the connector surface and periodically check for corrosion.

7. Flight Operation, Safety, and Legislation

To gain insight into the difference in flight operations between an electric aircraft and a conventional one, it was important to look at the operational, safety, and legislation aspects of electric flying. Research has been performed by conducting multiple interviews with the following parties: E-Flight Academy, which is a Dutch-based flight school for the Pipistrel Velis Electro; a university lecturer in aircraft performance; representatives from the aviation authority of Aruba; the air traffic management authority of Aruba; and the EASA.

7.1. Operational Differences and Aerodrome Procedures

This section aims to approximate the general differences in performing flight operations. The reasoning is largely derived from experiences with the Pipistrel Velis Electro and its Pilot Operating Handbook (POH) [31], as well as a site visit to derive insights from the current operations. Ultimately, the actual differences depend on the precise specifications and designs of the proposed electric aircraft. However, most of the principles will likely be similar.

7.1.1. Refueling/Charging

Currently, electric aircraft are technically not able to be recharged within minutes. The advantage of conventional aircraft lies in the fact that refueling is performed in a short time. The time in which electric aircraft can be ready for their next flight mission depends on the amount of energy required and the speed at which the battery can be charged. For interisland operations, fast charging will have to take place in between flights. Currently, the conventional aircraft that fly between the islands are refueled with passengers on board in order to save operational time, especially for transfer passengers. Refueling with passengers on board is allowed by means of a special exception released by the local aviation authorities. It is currently unknown whether charging electric aircraft with passengers on board will be allowed. According to an interview with EASA, it was stated that this will depend on proof from the manufacturers that safety is not compromised.

7.1.2. Aircraft Inspection

Aircraft are inspected every day and before every flight to ensure that all major systems and components are deemed safe for the flight operation. Checking the propulsion system of electric aircraft is expected to be less complex due to fewer components and parts. Cooling systems require special attention in electric aircraft, as batteries are very temperature-sensitive. The rotor blades mounted on the electric motors need to be able to turn freely.

7.1.3. Pre-Departure

Right before departure, checks are made to ensure the functioning of all the cockpit systems, motors, and flight controls. According to E-Flight Academy, a major difference is the number of systems in the cockpit. Since the powertrain is simpler, there are fewer actions required, resulting in additional clarity for the crew. A combustion engine needs to warm up, while an electric motor has no such requirement, as long as the battery remains within its operational temperatures. In addition, for an electric aircraft on the ground, setting its thrust lever in the IDLE position means that the motor and propeller will not rotate. For people on the ground, there is no visible difference between an engine that is switched off and one set in the IDLE position. Familiarization with this characteristic is important to ensure safety.

7.1.4. Take-Off

When performing the take-off roll, a pilot will notice that an electric aircraft is more responsive than a conventional aircraft due to its improved transient performance. An electric motor can also deliver the maximum power in a much shorter timeframe. In order to protect the engine and the controller from overheating, the maximum power settings can be used for a limited time. This time is, however, more than sufficient to become airborne.

7.1.5. Cruise

During flight, there are few differences between conventional and electric aircraft. As they are both designed for maximum endurance and efficiency, the changes in flight behaviour are not noteworthy. During flight, the available battery voltage drops slowly, so a higher current is needed to deliver the same amount of power. Energy management is an important aspect of electric flight operations.

7.1.6. Descent and Landing

An electric aircraft is able to regenerate a certain amount of energy back during descent. Because the aircraft drag force increases when a propeller regenerates energy, the rate of descent will also increase. It is therefore likely that this phase will entail a steeper approach when energy is regenerated. In addition, the maximum landing weight does not have to be considered if a flight is aborted earlier than planned. This is since the battery weight does not alter during flight.

7.1.7. Training of the Flight Crew

Currently, it is not exactly known what a future training program for commercial pilots of electric passenger aircraft will entail. According to an interview with EASA, and when looking at the current program for the Pipistrel Velis Electro, it is highly likely that pilots will need to obtain a special rating for electric operations. The conversion program for the Velis Electro consists of both flight and theory training. When the final requirements have been determined, local pilots can work toward their rating.

7.1.8. Air Traffic Management (ATM)

According to the local ATM authority, the procedures for departure and arrival will entirely depend on the performance of an electric aircraft. If it is comparable to that of current aircraft, none of the existing procedures have to be adjusted. From an operational standpoint, steeper arrival procedures could be developed to allow the electric aircraft to regenerate energy.

7.2. Safety Aspects of Electric Flight Operations

With this new form of flying, it is important to ensure similar levels of safety. As a result, the risks have to be mapped and emergency procedures need to be developed so that those directly involved can respond adequately. No type-specific safety concerns are yet known for the ES-19 and the Alice. This section is mainly derived from a study on the risk considerations with electric aircraft [34] and the set of emergency procedures related to the electric propulsion system of the Velis Electro [31].

7.2.1. Risk Considerations

In 2018, researchers from the MIT conducted a study into the safety and certification considerations for emerging electric aircraft architectures [34]. For the fixed-wing class (i.e., ES-19 and Alice), the following main risks were identified: thermal runaway, energy uncertainty, common mode power failure, and bird strike.

7.2.2. EASA SC E-19 Requirements

By means of a special condition, EASA gives aircraft manufacturers general requirements that must be included in the development of aircraft with an electric or hybrid propulsion system. To be certified by EASA, Heart Aerospace and Eviation will have to prove that their designs meet these safety requirements. By approaching the aircraft and propulsion system combined, EASA aims to achieve the best possible integration of all systems and ensure safety. The specific requirements for the propulsion system are stated in the means of compliance (MC) [35].

7.2.3. In-Flight Emergencies

A large part of the cross-training for the Velis Electro is spent on the emergency procedures stated in the POH. During flight operations, it is important that a pilot can recognize the origin of a problem and which concrete steps have to be taken.

- *Powertrain*: The main risks associated with the powertrain are a loss of power, the insulation of the electrical system, and failures of the converter, throttle lever, or electrical trim.
- *Battery*: In principle, there could be change in disconnection or a communication failure. The SoC shown on the display could be incorrect, or a drop in voltage could occur during flight operations. Batteries heat up during operation and could overheat, usually associated with a failure of the battery cooling system. It is also possible for there to be an overcurrent or for the current delivered by the different batteries to not be equal. The final and immediately most significant risk is a battery fire.
- *Electric motor:* Just like the battery, the engine can also overheat, sometimes associated with a cooling failure. Next to this, a communication failure can occur, in which the motor is not recognized by the powertrain anymore. Finally, in a worst-case scenario, the engine could ignite.

8. Maintenance Solutions for Electric Aircraft

8.1. Legal Requirements for Maintaining Electric Aircraft

The first component investigated in this paragraph is the regulatory framework that currently exists between the ABC Islands. Each island has a different aviation authority; the Department of Civil Aviation Aruba (DCA) and the Curaçao Civil Aviation Authority (CCAA) are both based primarily on FAA regulations. Bonaire is a special municipality of the Netherlands and therefore has adopted the EASA regulations. Due to a mutual bilateral agreement between the islands in the Dutch Caribbean, aircraft registered in one of these countries may be maintained there, and this must be accepted by all other countries within the Dutch Caribbean. Currently, there are hardly any regulations for electric flying. In continental Europe, this has been solved by issuing special conditions to the existing regulations so that aircraft can still be certified. In addition, each country must issue a permit for maintenance to be carried out on a new aircraft type [36]. According to this permit, a special addition to the licenses of the maintenance organization should be obtained. One of the requirements for maintenance organizations to achieve this is to let the engineers that will work on electric aircraft follow different training. On this course, the differences between a conventional aircraft and an electric aircraft will be discussed. The DCA has indicated that it will implement the ICAO standards and recommended practices in the local regulations as they become available.

8.2. Differences in Maintenance Considering the Environmental Conditions in the Caribbean

The next part of this research was the influence of the local weather conditions on electric aircraft. In the Caribbean region, corrosion is a major problem. Many extra measures are already being taken against this, according to talks with the local airlines Divi Divi Air and EZ Air. This research has shown that the batteries of electric aircraft are the most sensitive to environmental influences. This mainly concerns temperature [26]. In addition, batteries deteriorate after use. Normally, batteries are replaced after they have reached a state of health (SoH) of 80%. This means that a battery can only be used for 80% of its initial capacity. As battery technology improves, the number of flight hours that can be flown for before reaching a SoH of 80% will increase. An example of this is the newest battery type that is used in the Pipistrel Velis Electro. This battery has an operational limit of 1800 FH, while the old battery had a limitation of only 500 FH. Based on the current expectations of manufacturers and the current schedule of Divi Divi Air, it has been estimated that a battery replacement will be necessary approximately once a year. The charging range also influences the lifespan of a battery. Figure 7 shows that a Li-ion battery deteriorates quicker when the battery is charged from 0 to 100% every cycle instead of smaller charging ranges, such as from 40 to 60% and from 20 to 80%. The required energy reserves for electric aircraft mean that the batteries never have to be entirely drained, which is beneficial for their lifespan.

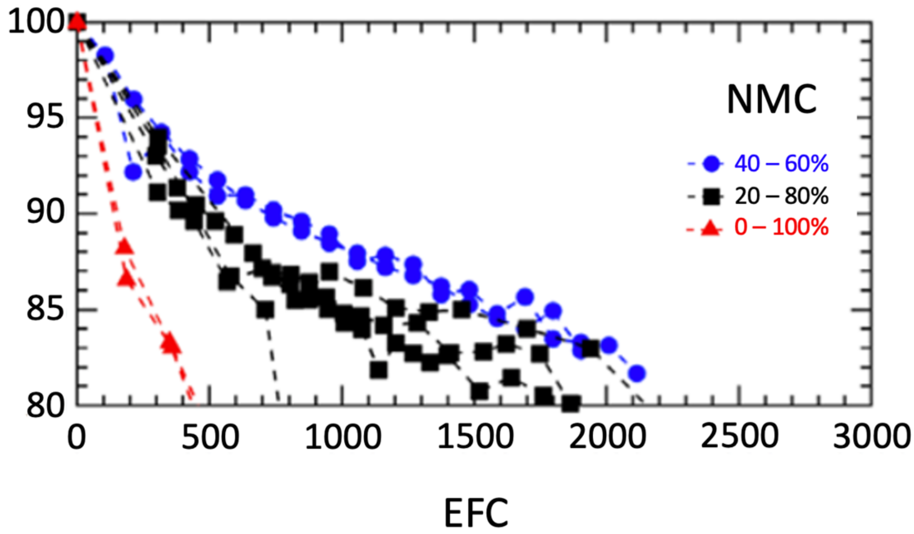

Figure 7. Degradation of NMC Li-ion batteries under different SoC ranges [37].

Electric motors may require less maintenance in general than a combustion engine, but they are not maintenance-free. The bearings inside of the motors need to be monitored regularly and replaced at pre-determined intervals. In addition to this, the windings in the motor can short out due to, for example, vibrations, contaminants, or voltage spikes, requiring the motor to be removed from the aircraft and be repaired. Thermal damage might be another issue, especially in hot climates, and this may lead to a loss of performance over time [38]. According to the maintenance manual of the Pipistrel Velis Electro, the electric motor does not have a fixed time limit for replacement. Before every flight and after every maintenance inspection, the motor should be tested. When the motor does not perform as expected, it should be inspected by Pipistrel [31]. magniX, an Australian-based manufacturer of electric aircraft motors, has stated that its motors will be easily maintainable [39]. The Eviation Alice makes use of magniX engines. Right now, electric motors are often podded as a single unit to increase the simplicity and reduce costs, but this means that in case of a sudden failure, the entire motor needs to be replaced.

Some newer aircraft types are equipped with a composite structure. The Pipistrel Velis Electro and the Eviation Alice are two examples of this. The Pipistrel is operationally limited to a surface temperature of 55° C [31]. However, the Pipistrel has been certified as a light sports aircraft, while the Eviation Alice will be certified under the FAA Part 23 regulations. In this category, the requirements are stricter, so heat will likely be less of an issue for the composite structure. The Boeing 787, for example, makes use of a high-solids epoxy primer to protect the composite and metal surfaces; an intermediate coating is applied to allow for topcoat removal; and, finally, a high-solids polyurethane topcoat is used [40].

For the other parts, such as the cooling systems, power controllers, and connectors, the greatest risk is corrosion or the ingestion of debris into the system, which can lead to performance degradation. It is therefore important that the condition of these systems is checked regularly to prevent damage. Overall, the maintenance of an electric aircraft is simpler because there are fewer moving parts.

8.3. Maintenance Costs

According to some scientific studies [41,42], it is expected that the maintenance costs of electric aircraft can ultimately be reduced significantly. A study from 2021 forecasts that the maintenance costs of such types of aircraft will be reduced to a degree between 20% and 50% compared to conventional aircraft [41]. However, the outcomes of an interview with E-Flight Academy have shown that maintenance is currently even more expensive of its electric aircraft than of its conventional aircraft due to the limited supply of parts, high battery depreciation costs, and technical start-up challenges of these new aircraft. Nevertheless, the expectation is still that electric flying will become eventually cheaper. For example, the increase in the lifespan of the Pipistrel Velis Electro batteries from 500 FH to 1800 FH means that the battery depreciation costs will drop. These costs currently represent a large portion of the operating costs of an electric aircraft, so when these can be reduced significantly, the operating costs will be decreased as well.

9. Number of Charging Stations and Location at the Aprons

As has already been mentioned, the NLR and NACO conducted a case study on electric flying on the ABC Islands [7]. They have included a timeline for the introduction of electric interisland flying in the Dutch Caribbean. This timeline consists of three phases. In the first phase, in 2026, the first three electric aircraft with nine seats will be introduced. In phase two, in 2030, three 19-seaters will be added, and 50% of the flights compared to in 2019 will be electric. Finally, in 2035, three 9-seaters and three 19-seaters will be added to fully replace the aircraft that are currently flying between the ABC Islands. Among two different charging scenarios, the second one assumes that the aircraft will be flown until an SoC of 30% is reached. This last scenario has been adopted in this research.

Our suggestion is to move interisland flights to the south side of the airport, which is currently used for general aviation. At the moment, passengers on interisland flights have to be at the Aruba airport at least 75 min before departure since they have to go through the same process as the rest of the international passengers. Interisland traffic should not be mixed with general aviation; thus, a separate terminal has to be built. Ideally, interisland air traveling should become as easy as taking a bus or train, which was also explained by the CEO of Aruba Airport during an interview. This simplified process also implies lower airports charges for passengers.

Two possible designs for the location of a new interisland terminal and the aprons for electric aircraft were developed. These concepts include the location of four charging stations, solar panels, and any extensions or adjustments to the current platform. Both concepts have their advantages and disadvantages. Concept 1 in Figure 8 makes use of the existing aprons, while concept 2 in Figure 9 consists of new aprons separated from the existing aprons. The first one will be more economical to implement, but it also means that the existing aprons will be used by interisland traffic instead of the current general aviation traffic, affecting its capacity. With the second concept, these two kinds of traffic are completely separated, but this will be more expensive because an entire new platform has to be built and the taxiway needs to be expanded.

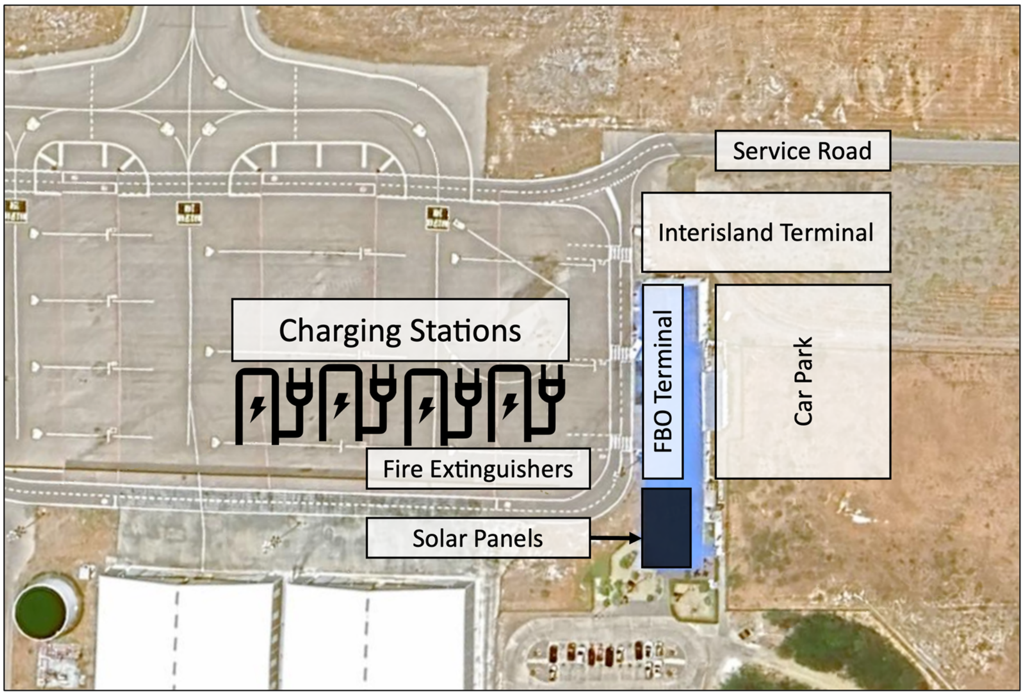

Figure 8. First conceptual design of the new terminal at the south side of Aruba Airport.

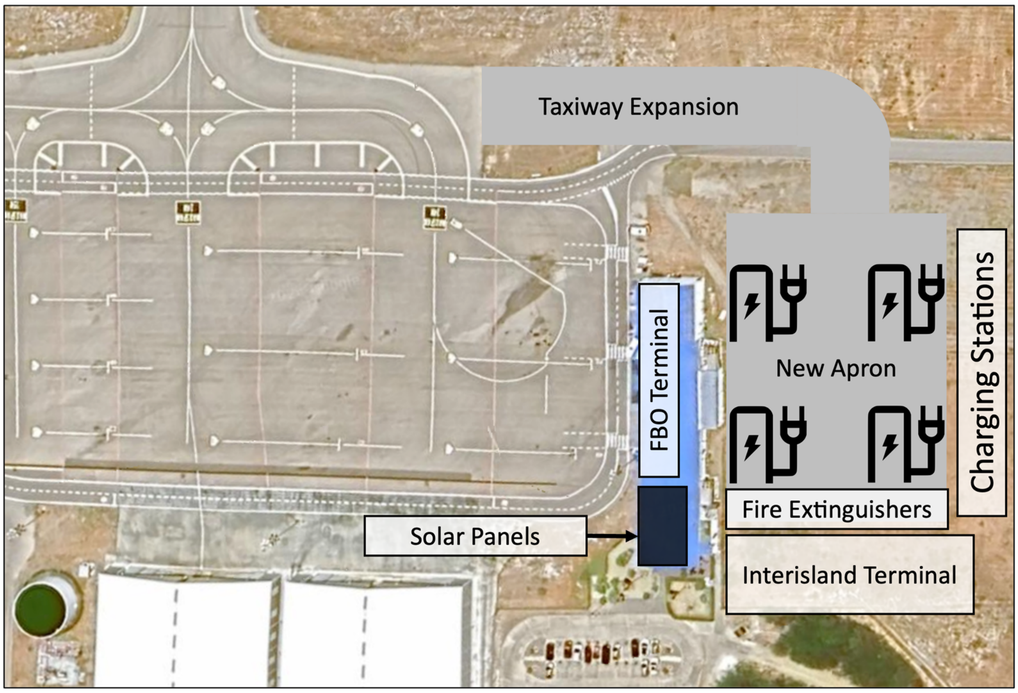

Figure 9. Second conceptual design of the new terminal at the south side of Aruba Airport.

10. Charging Station Standards and Power Requirements

SAE International is working on standards for charging electric aircraft within the AE-7D Aircraft Energy Storage and Charging Committee [43]. The Pipistrel charger has been designed according to the AS6968 standard. This standard includes the technical and minimal performance requirements for connection sets of the conductive charging systems that are used for charging light electric aircraft. This standard is not sufficient for charging larger aircraft in an acceptable turnaround time. Within the AE-7D committee, SAE is also working on the AIR7357 standard for charging moderately sized electric aircraft with a provided power between 500 kW and 1 MW.

According to Table 5, how much energy would be needed for flights between Aruba, Bonaire, and Curaçao was calculated for the two electric types under consideration. Table 7 shows the energy required to perform the flight itself and the total amount of energy required. The total amount of energy considers the losses in the charging process. According to a 2015 study into the efficiency of fast charging with DC power, the efficiency during charging is on average between 80 and 90 percent [44]. However, according to a more recent article, Siemens has now developed a charger that should achieve efficiencies of up to 96% [45]. This indicates that charging technology has developed significantly in recent years. To keep the calculation of the required energy as realistic as possible, a 96% efficiency of the charger has been included in the total energy required.

Table 7. Energy and power required for flights between the ABC Islands.

Mission Route	Aircraft	Energy Required for Mission [kWh]	Total Energy Required [kWh]	Power Required (25 Min Charging) [kW]
CUR–AUA	Alice	256	267	640
	ES-19	295	307	738
AUA–CUR	Alice	321	325	780
	ES-19	368	383	920
CUR–BON	Alice	199	207	498
	ES-19	235	245	588
BON–CUR	Alice	184	192	460
	ES-19	212	221	530

Equation (1) shows the calculation of the total energy required. This includes the efficiency of 96% of the charging station. The total energy required was then calculated by dividing the energy required for the mission by the efficiency of the charging station. In Equation (2), the power required for the charging station is calculated in kilowatts by dividing the total energy required by the desired charging time in hours.

$$E_{total\ required} = \frac{E_{mission}}{\eta_{charging\ station}} \quad (1)$$

$$P_{required} = \frac{E_{total\ required}}{\frac{t_{charging}}{60}} \quad (2)$$

This process has been repeated for all routes and aircraft types. From this table, it can be concluded that a power of 780 kW is required to charge the Eviation Alice within 25 min for a flight from Aruba to Curaçao. Since the power requirements for the ES-19 do not differ that much, a single type of charger is recommended. Another assumption is that the power provided for the charging process is constant, a fact that is highly affected by the battery type and external conditions.

A simplified overview of the electric infrastructure in the southern part of Aruba Airport is displayed in Figure 10. From this figure, it can be derived that 367.4 kVA of capacity is left in the current installation. In electrical systems, the power in kVA represents the total power within a system when, with the power in kW, system losses are taken into account. The difference between kVA and kW is wasted energy and can be calculated using the phase angle of the electricity grid, cosinus φ. However, this value was unknown in the case of Aruba Airport. In the calculations in the two concepts, kVA has been used, so these are the minimum power requirements, and the actual power consumption might be higher. This has to be further investigated by Aruba Airport together with ELMAR, the energy distributor in Aruba.

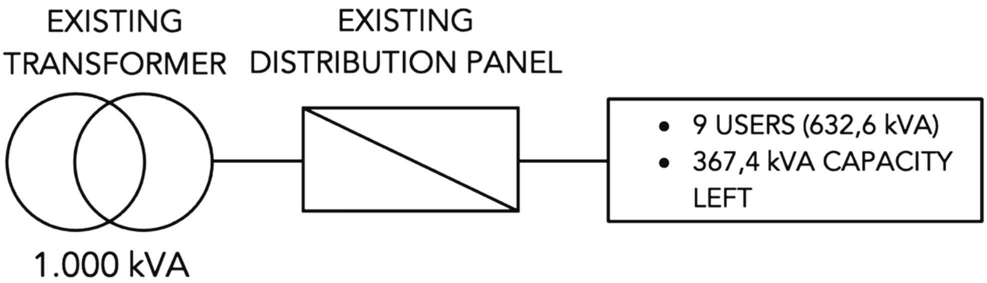

Figure 10. Simple drawing of the current electrical infrastructure on the south side of AUA.

Given that there is only 367.4 kVA capacity left in the current installation, it can be concluded that the current infrastructure at AUA is not capable of charging the electric aircraft that have been proposed within the turnaround frame of 25 min. The two concepts for new infrastructure that are proposed in this study also include to what extent solar energy can be used, although this is currently limited by the local regulations to 100 kW per installation. To put this into perspective, with the energy yield of a solar installation of 100 kW, approximately one or two aircraft can be charged using solar energy per day. This configuration requires the addition of a battery to the system to store the solar energy. The two concepts for new electric infrastructure are only based on the requirements of one charging station, but this design must be developed with modularity and expandability in mind. The first option is to replace the existing transformer with a new one with a higher power capacity. Then, electric aircraft could be charged directly from the grid. A drawing of this conceptual infrastructure is shown in Figure 11. This way, the aircraft can be charged directly from the electricity grid, from which energy is almost always available.

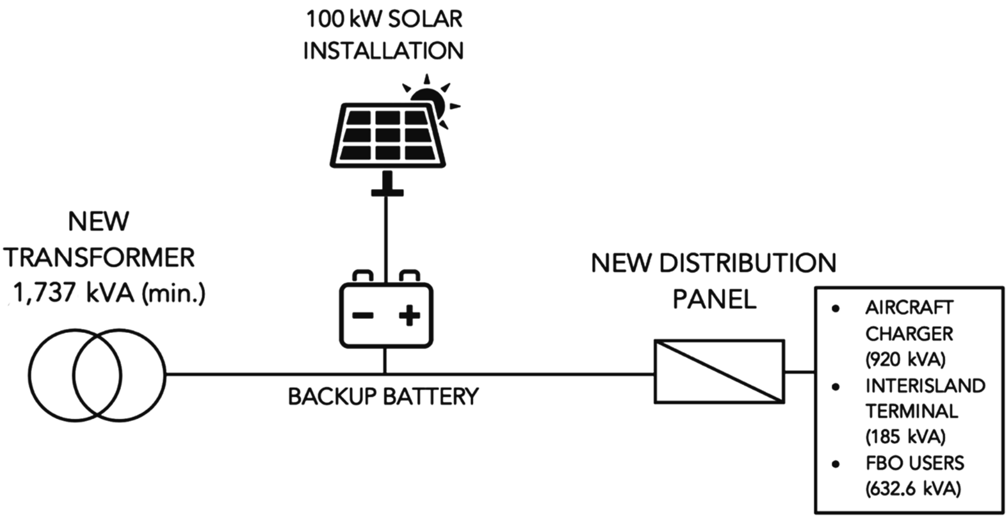

Figure 11. First concept drawing of a new electric infrastructure to install one charging station.

The second option, illustrated in Figure 12, is to install a separate transformer next to the existing one. This way, the aircraft can always be charged directly from the grid, just like with the first option. The benefit is that the infrastructure for the electric aircraft interisland operations is now completely separated from the other users on the southern side of the airport.

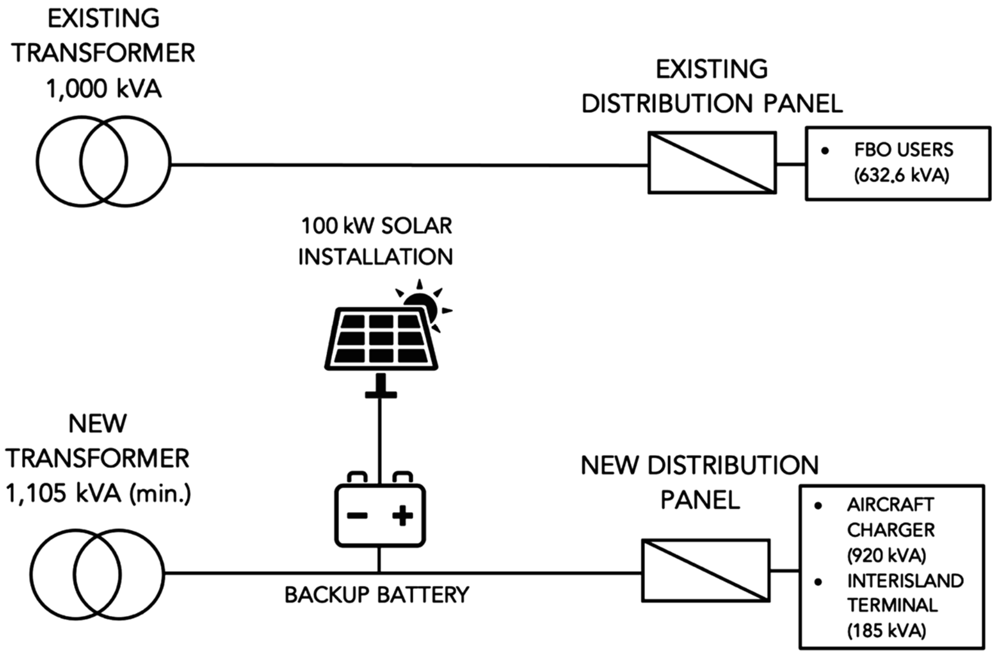

Figure 12. Second concept drawing of a new electric infrastructure to install one charging station.

11. Ground Safety and Emergency Procedures

Pipistrel have already defined the safety procedures for ground emergencies with its Pipistrel Velis Electro aircraft. Larger aircraft, such as the Eviation Alice and the Heart Aerospace ES-19, will possibly have more extensive emergency procedures, but since the technological principles of these aircraft are similar, the Pipistrel procedures give a good indication of what emergencies might occur on the ground. Figure 13 illustrates these ground emergency procedures for the Velis Electro, according to the Pilot Operating Handbook (POH). To make the types of emergencies clearer, they have been divided into emergencies related to battery problems and propulsion system problems.

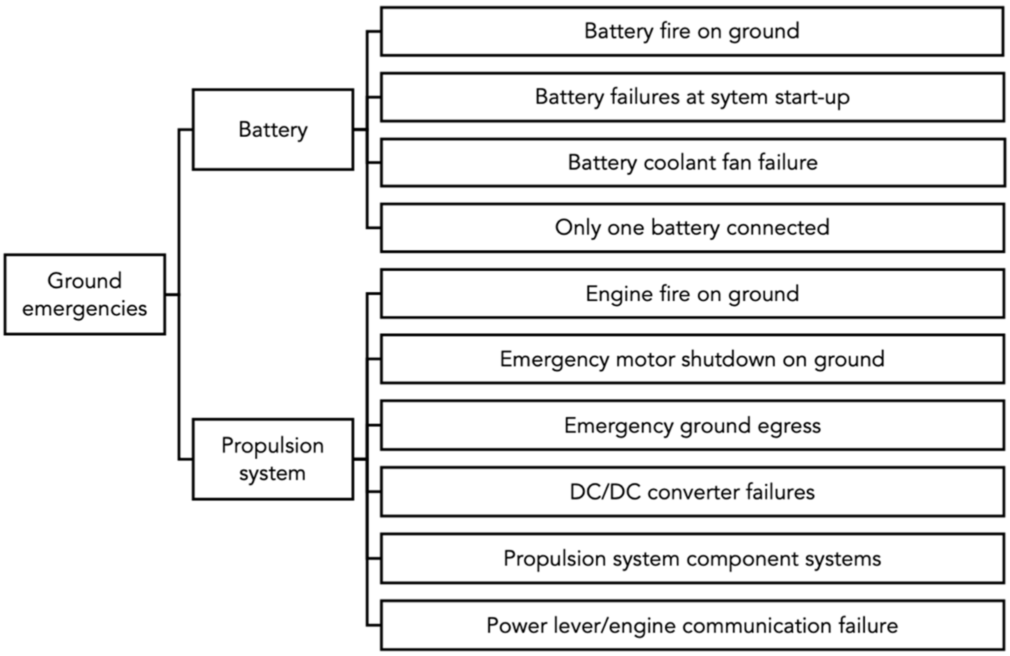

Figure 13. Ground emergencies that could occur with electric aircraft, based on the POH of the Pipistrel Velis Electro [31].

The most important emergency procedure in case of one of the emergencies under consideration is to shut down the related system or the aircraft as a whole and contact the maintenance organization to decide on the next steps. It is important to mention that electric aircraft require special fire extinguishing procedures depending on where the fire in the aircraft takes place [46]. In general, different extinguishing agents should be used in different cases. In case of a fire in the motor of the aircraft, only waterless extinguishing agents should be used. A battery fire is self-sustaining and thus not extinguishable; thus, the only solution is supplying lots of water to the fire to provide cooling and slow down the process. When a battery fire occurs, the aircraft should be left in isolation for at least 24 h to ensure that the fire is out.

In addition to the emergency considerations, there are also safety issues that must be considered with electric aircraft. A first point that is still uncertain now is whether passengers can remain on board during charging, in a similar way to the special procedures for refueling with passengers on board in conventional aircraft. However, there are currently no regulations on this process, so it remains to be seen what the regulators will decide. If charging with passengers on board will not be allowed, a waiting area near the apron is also necessary to build, where the passengers can wait for the aircraft to be charged again. This decision is important, as, during the charging of the aircraft, there are multiple risks with regards to the batteries and the charging station. In a recent study [47], the safety risks have been identified in the charging process of electric vehicles. According to this study, the risks for the battery are overcharging, overheating, and self-ignition.

The charging station should have protective measures as well. Many of these measures are covered by the global standards for charging stations. Failures that can occur in the charging station are mechanical failures, electrical failures, software failures, and communication failures. In principle, a charging station should be protected against each of these failures, but if something goes wrong nevertheless, there must be a mechanical override switch that can stop the charging process. In addition to this, it is important that sufficient electricity breakers are installed in the electrical infrastructure to which the charging stations are connected to prevent the electrical system from catching fire.

The last issue could be rainfall during charging. The Pipistrel Velis Electro is not allowed to be charged in the rain. However, it is likely that chargers for larger aircraft will be waterproof since electric vehicles in the automotive industry are most of the time protected against water ingress as well.

12. Discussion

This study examined the feasibility of electric aircraft operations in the ABC Islands of the Dutch Caribbean. In general, electric aircraft have a fundamentally different architecture in comparison with gas turbine or piston engine aircraft, which is translated into a series of dissimilar requirements with regards to their operation, ground service, storage, and maintenance, as well as their safety and certification procedures. Electric aircraft are significantly constrained by their batteries, which are one of the most critical components due to their sensitivity to environmental conditions and low energy density. The energy density dictates the regional nature of such aircraft types. However, as battery technology evolves at a fast pace, some promising developments (e.g., solid-state batteries) might be able to significantly improve the range and payload specifications of such aircraft in the future, even beyond their regional nature.

Two conceptual aircraft designs were considered, the Eviation Alice and the Heart Aerospace ES-19. They were both explored in terms of their battery capacity, consumption, and range for their main flight phases (i.e., climb, cruise, and descent), and it was concluded that they can operate in the explored region, even with the expected battery deterioration and energy reserves. Future electric operations had to be benchmarked against the existing operational landscape, which led us explore the current aircraft types in service and their respective operators. Based on the information obtained by these operators and the used fuel types, the current emissions and fuel costs were determined and compared against potential electric operations. The results revealed a moderate reduction in CO_2 emissions and a more drastic reduction in energy costs considering the current energy mix and fuel prices in the three islands. However, a planned expansion of wind farms in the area has the potential to significantly reduce the operational CO_2 emissions, as well as the electricity costs, of electric aircraft, and this is one aspect that makes investments in this area attractive. Moreover, a design payload comparison was made between the conventional and electric types, which did not show any significant differentiation in their capacity per passenger.

Following this, the local climate was investigated with regards to its influence on the mechanical components of electric aircraft. Temperature, humidity, wind, sunlight, UV radiation, and salinity were considered, which can have distinctive effects on the electric motors, batteries, metallic and composite airframes, and electronics. Some suitable mitigation actions were suggested, mostly related to the use of casings, the storage conditions, the recommended operating conditions, and coatings. Furthermore, the aircraft operations were also investigated, mostly in relation to the charging feasibility with passengers on board, taxiing and idling with electric motors, and take-off at maximum thrust. In general, there are some differentiations related to the behavior of electrical systems, which need special regulations and training. An interesting aspect is that steeper approach trajectories can be beneficial, as the motors can regenerate electricity as generators, but this will require a review of the existing ATM practices. In addition, potential risks were identified in relation to the main electrical components (i.e., the powertrain, battery, and electric motors) so that mitigation actions can be developed.

Continuing on, the maintenance was examined, initially with regards to the regulatory framework and how this can be implemented in the three islands. As Aruba and Curaçao have their own regulators, while Bonaire follows the EASA standards, the adoption of the same rules could be challenging. For the moment, there are no regulations in place for such aircraft, as they are still in early development, but this is a timely discussion nevertheless. The battery deterioration patterns were also examined, concluding that energy reserves are beneficial for the battery lifespan. Electric motors are much simpler in their number of moving parts compared to gas turbines and piston engines, which also leads to less maintenance, but mechanical deterioration of the rotating parts and thermal loads are always present. The above design features have the potential to reduce the maintenance costs to a degree of 20% to 50% compared to with conventional aircraft. However, all the unforeseeable events related to the introduction of an entirely new technology could led to higher initial costs due to the limited supply of parts, high battery depreciation costs, and technical start-up challenges.

Another aspect of this study was the topology of the charging stations at the airport of Aruba. Several options were considered, but ultimately the option of a new, regional terminal turned out to be the most convenient, as there is no mixing between long-haul passengers and the necessary charging infrastructure. The decision on whether the existing general aviation platform is sufficient or a new one is needed is inconclusive and dependent on the growth projections and certain practical considerations. Regarding the proposed charging stations, it was concluded that the existing power supply in the airport is not sufficient. Different architectures were proposed, which also include the installation of solar panels. However, due to regulatory restrictions on the maximum power output of the panels, new regulations are needed for greener charging electricity. A common or separate electrical transformer is also discussed, within the context of balancing costs and operational autonomy. Lastly, potential emergency procedures for the ground and charging process were identified and discussed, under the hypothetical scenarios of spontaneous ignition, charging station failure, and rain.

13. Conclusions

This study examines the feasibility of electric aircraft operations between the ABC Islands. A direct comparison with the conventional aircraft types currently in operation in the region revealed that the considered electric concepts have the range, payload capacity, and operational characteristics to complement and eventually replace conventional aircraft when they enter service in the next decade.

There were some obvious limitations in the calculations made, as such aircraft have only reached conceptual and preliminary design maturity, while their detailed design is still ongoing. However, with the available information, we were able to conclude that such aircraft types could be an ideal successor to the conventional types, with their continuously improving CO_2 emissions (electrical grid depending), lower energy costs, and minimal maintenance. In addition, the expected payload is on par with that of the conventional types operating in the area.

On the other side, such aircraft designs are asset-heavy in infrastructure, as they require high-power charging capabilities, specialized storage, and weather-related procedures. In addition, new regulations are being developed to cover such technologies and procedures, which are still unknown to a high extent, and they might affect the expected operational and maintenance standards. In all cases, the initial operations are expected to be challenging in terms of the technical support, supply chain, and battery limitations.

Overall, it is certain that electric aircraft will enter commercial operations in the future, and studies such as the present highlight the benefits and points of attention. As with any other disruptive technology, some time will be needed before operations are streamlined, but we can conclude that the expected benefits when the technology becomes mature will be significant in environmental, operational, and financial terms.

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