OFF-GRID CHARGING OF ELECTRIC AIRCRAFT FACILITATED BY RENEWABLES COUPLED WITH ENERGY STORAGE

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Keywords: ELECTRIC AIRCRAFT, OFF GRID, CHARGING INFRASTRUCTURE, ENERGY STORAGE

Abstract

This paper presents a methodology for optimising the sizing of a flight school electric aircraft off-grid charging system powered by renewable energy sources and including energy storage to meet the Jet Zero strategy target for a greener ground-based infrastructure to achieve net zero aviation in the United Kingdom by 2050. The analysis uses solar and wind data measured at an airfield in the south east of England. Annual charging load profiles were created using the specification of a battery electric aircraft used for pilot training. The results show that continuous usage of one electric aircraft throughout the year for three training sessions per day requires an off-grid system with a minimum solar and wind capacity of 22 kW and 2.5 kW, respectively, coupled with 133 kWh battery storage. Using two electric aircrafts to allow a quick turnaround at the flying school increases the size of the system to 43 kW for solar, 5 kW for wind and a battery of 264 kWh. The payback period for both scenarios is 8.4 years, assuming the price per kWh is £0.51/kWh similar to the current rate of public fast/slow charging station and decrease to 5.5 years when the charging price is set at Rapid/Ultra-rapid station level of £0.75/kWh.

1 Introduction

The need to reduce greenhouse gas emissions globally is now accepted globally. The International Energy Agency (IEA) estimates that to limit global warming to 1.5 °C above pre-industrial levels in 2100 the global energy related emissions need to be reduced from the 37 Gt in 2021 to 23 Gt by 2030 and then net zero by 2050 [1]. Increased penetration of renewable generation and other low carbon technologies paired with growing electrification of areas such as space heating and road transport have led to good progress in the reduction of emissions in these sectors. Progress in other areas, such as aviation is slower, but there is still a commitment to reaching net zero by 2050 [2].

Decreasing aviation emissions is a significant challenge with alternative fuels likely to be needed for most commercial air travel due to the higher weight of alternatives such as batteries and fuel cells. For short distances, however, battery powered electric aircrafts provide a promising solution. In the United Kingdom (UK), for example, following a Climate Change Committee (CCC) recommendation, the Jet Zero strategy aims to achieve net zero for all domestic flights and airport operations by 2040 [3]. Norway takes this strategy a step further and sets a target that all domestic and short haul flights will be operated by electrified aircraft by 2040 [4].

However, there remain substantial challenges, even for short flights, with decarbonising air travel. A case study of Brighton City Airport in a report commissioned for the Department for Transport in the UK found that sustainable aviation fuel was not feasible due to the low demand at an airport of that size, and that supply was unreliable and expensive compared to standard aviation fuel [5]. Electric aircraft are promising for short distance flights. However, many airfields and airports that facilitate short flights do not have a suitable grid connection to charge electric aircraft. Increasing the size of the grid connections is often time consuming, expensive, and approval of applications is not guaranteed.

One possible solution to address this challenge is to facilitate charging electric aircraft using an off-grid system that makes use of renewable energy, such as solar and wind and an off-vehicle energy store (OVES). Such a system is currently the subject of research as part of Future Electric Vehicle Energy networks supporting Renewables (FEVER) programme grant [6]. The FEVER system provides a local off-grid energy network with the primary aim of charging electric vehicles, aircrafts in this case. As a further benefit, this system can support auxiliary services, e.g., supporting the electrification of ground vehicles, which in 2019 released 5.8 ktCO2e [5].

In this paper we consider the feasibility of using a FEVER systems for present charging electric aircraft used for training pilots comprising a solar array, a wind turbine, an OVES, and a charger. The following sections present the methodology used for the optimal sizing of the system. Section 3 presents the results and Section 4 concludes the paper.

2 Methodology

This study utilised the specifications of Pipistrel Velis Electro, the first Type Certificate electric aircraft, to create a charging load demand profile. The electric 2-seater aircraft is tailored for pilot training and has been commonly used by flight schools in several European countries. According to Pipistrel, the electric aircraft can cover the flight endurance for typical training of 50 minutes plus reserve, and the normal charging cycle of the 24.8 kWh battery from 35% to 95% state of charge (SOC) takes around 1 hour and 20 minutes to complete [7]. The aircraft can be charged by a SKYCHARGER charger designed for electric aircraft capable of up to 22 kW charging power and an efficiency of 96% [8].

A recent UK government response for consultation on consumer experience at charging points suggests that operators must meet a minimum of 99% availability as an average across all charging stations. Based on this target, the optimisation model in this work sizes the solar panels, wind turbine and battery energy storage system (BESS) for an off-grid charging system able to meet the load demand of charging an electric aircraft with less than 1% of the load unserved.

Blackbushe Airport is located near Camberley in the south east of England and is the base for several flying schools, each offering packages for different types of training [9]. One of the airport's flying schools operates engine-powered aircrafts of a similar segment to Velis Electro, making it an ideal case study. The flying school opens for flight training from 7 am until 8 pm [10], set in this study as the time window for when the electric aircraft operates and charges. Table 1 summarises the FEVER model input data to generate electric aircraft charging load profile.

Table 1: Summary of the main input parameters.

Parameter	Value
Electric aircraft battery capacity	24.8 kWh
Charging cycle	35% to 95% SOC
Charger efficiency	96%
Charging duration	1.5 hours
Time period	7 am to 8 pm

A scenario is modelled based on using the electric aircraft daily for three training sessions separated evenly throughout the day, and charges from 35% to 95% after each session. Pipistrel recommends using more than one electric aircraft for quick turn arounds in a flying school instead of swapping the battery, which requires additional ground handling equipment and imposes safety hazards concerning the possibility of dropping an accidently unsecured battery. An additional scenario is considered where one charger alternately charges the two electric aircrafts with a continuous charging event, leading to a total of three hours for each of the three charging sessions during the day. Figure 1 illustrates the two scenarios considered in this study during the day. The in-operation time refers to the period when the electric aircraft is being used for the training session, parked time covers the total time the aircraft is on the ground and charging time is when the aircraft is plugged in and charging from the off-grid system.

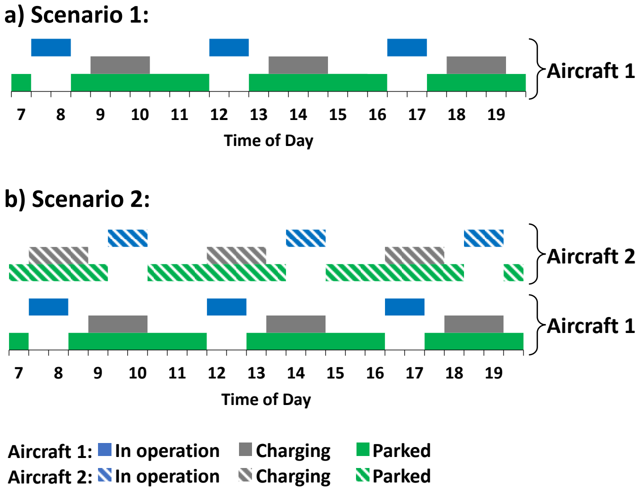

Figure 1: General presentation for the two scenarios, a) one electric aircraft and one charger, b) two electric aircrafts and one charger.

The location of Blackbushe Airport was used to obtain the solar and wind generation profiles using wind speed and irradiance data from Open Meteo for 2022 [11]. The wind profile was built based on the power generation curve of Aventa AV-7 [12], and the solar panel module was assumed to have 20% efficiency [13].

The cost of the BESS was calculated based on the current trend of battery price at a pack level with an additional 20% added as VAT, making the price for the battery £146/kWh [14]. The BESS's fixed operation and maintenance (O&M) cost is assumed to be £8/kW, and variable O&M equals £0.24/MWh/year based on [15]. Additionally, the model assumes a usable battery capacity of 90% with 97.5% efficiency. The cost of the converter is set to £90/kW with 95% efficiency, and the wind turbine cost of £5000/kW with fixed O&M of £10/MWh and variable O&M of £6/MWh [16, 17]. The solar system cost is assumed to be £1605/kW with an O&M cost of £8/MWh [17, 18].

The optimisation model method to minimise total system cost, is based on mixed integer linear programming (MILP) formulation [19]. The objective function for the optimisation, using capital expenditure (CAPEX) and operating expense (OPEX), is based on a similar approach to [20] and is defined as follows:?

$$OF = U_{PV}S_{PV} + U_W S_W + U_{conv}S_{conv} + W_{BESS}B_{BESS} + OPEX_{PV} + OPEX_W + OPEX_{BESS} \tag{1}$$

where U_{PV} is the cost of solar, in £/kW; S_{PV} is the size of solar panel, in kW; U_w is the cost of the wind turbine, in £/kW; S_W

is the size of the wind turbine, in kW; U_{conv} is the cost of the converter, in £/kW; S_{conv} is the size of the converter, in kW; W_{BESS} is the battery cost, in £/kWh; and B_{BESS} is the BESS capacity, in kWh. The OPEX for solar, wind and BESS are calculated using the following equations:

$$OPEX_{PV} = \sum_{y=1}^{N_Y}\sum_{t=1}^{N_D} M_{PV}S_{PV}P_{PV}(y,t)\Delta t \tag{2}$$

$$OPEX_{W} = \sum_{y=1}^{N_Y}\sum_{t=1}^{N_D} M_{W,F}S_{W} + M_{w,V}S_{w}P_{w}(y,t)\Delta t \tag{3}$$

$$OPEX_{BESS} = \sum_{y=1}^{N_Y}\sum_{t=1}^{N_D} M_{BESS,F}S_{BESS} + M_{BESS,V}S_{BESS}P_{BESS}(y,t)\Delta t \tag{4}$$

where y is operation time, in years; N_Y is the total number of years when the system is in operation; t is the time index, in days; N_D is the total number of days; M_{PV} is the O&M for solar, in £/kWh; P_{PV} is solar power, in kW; $M_{W,F}$ is the wind fixed O&M, in £/kWh; $M_{W,V}$ is the wind variable O&M, in £/kWh; P_W is wind power, in kW; $M_{BESS,F}$ is the BESS fixed O&M, in £/kWh; $M_{BESS,V}$ is the BESS variable O&M in, £/kWh, and P_{BESS} is BESS power, in kW. The energy balance of the system is defined using the following equation

$$P_{PV}(y,t)\Delta t + P_W(y,t)\Delta t + P_{dis}(y,t)\Delta t + UL(y,t) = P_{ch}(y,t)\Delta t + L(y,t) + ER(y,t) \tag{5}$$

where P_{dis} is the discharging power of the BESS, in kW; UL is the unmet load, in kWh; P_{ch} is the charging power of the BESS, in kWh; L is the load energy, in kWh; and ER is the excess renewable energy, in kWh.

3 Results

In the first scenario, where one electric aircraft operates at the flight school with three flying sessions per day for one hour each, the total energy demand is estimated to be 46.5 kWh per day. Assuming continuous operation throughout the year, the annual demand for charging the electric aircraft will be 17 MWh. For the second scenario, where two electric aircraft alternate charging with the same charger, the daily energy demand will be 93 kWh and 34 MWh per year, assuming similar operations for both electric aircraft.

The optimisation model to minimise the cost of the system for the first scenario results in sizing a BESS capacity of 133 kWh coupled with PV and Wind capacity of size 22 kW and 2.5 kW, respectively, with an associated total capital cost of installing such system of £68k. To meet the load demand in the second scenario, a 43 kW solar and 5 kW Wind capacity are needed; the required BESS capacity is 264 kWh with a total cost of £133k. Table 2 summarises the load energy demand and the optimisation model results for both scenarios.

Table 2: Load demand and optimisation model results.

Output	Scenario 1	Scenario 2
Yearly demand (kWh)	16973	33945
Capital cost (£)	68020	133311
PV size (kW)	22	43
Wind size (kW)	2.5	5
BESS capacity (kWh)	133	264

Figure 2 shows the off-grid system component capital costs and O&M cost per year for both scenarios, excluding the cost of the SKYCHARGER unit. The solar system in both scenarios accounts for more than 50% of the total cost, as the optimisation model oversizes the solar capacity being the cheapest option while keeping the overall system cost to the minimum and aiming to achieve an overall reliability of 99%. In both scenarios, the battery and the wind account for nearly 29% and 18% of the total cost, respectively. While the yearly operation and maintenance cost for the off-grid system is less than 1% of the total cost.

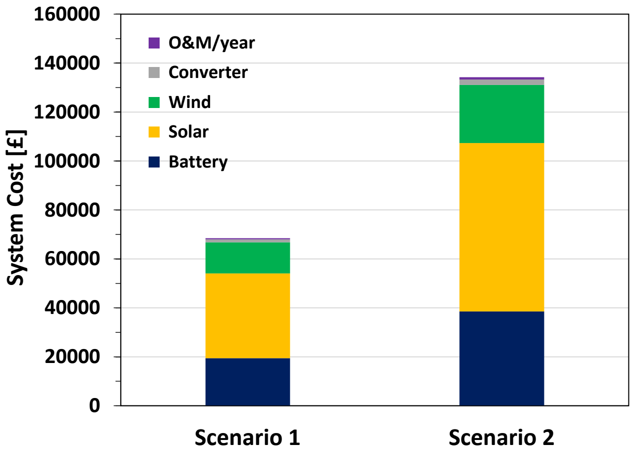

Figure 2: Cost of the off-grid charging system.

In the first scenario, the average sufficiency for renewables, defined as the portion of the load demand met by renewable energy during the specific period, is 55% for a year. In June, the sufficiency reaches the maximum value of 80% but drops to the lowest value of 30% in January. In the second scenario, the average sufficiency of renewables throughout the year is 71%, where the maximum of 92% occurs in June and the minimum of 41% in January. The reason for the higher renewables sufficiency in the second scenario is the longer charging periods during the day, allowing further renewables utilisation to directly charge the electric aircrafts, particularly midday when solar generation is typically at its peak value.

Figure 3 illustrates the relationship between the price to charge an electric aircraft and the payback period of the off-grid charging system. The payback period is estimated to be 8.4 years if the price of charging the electric aircraft matches the average price to charge an electric car with a Slow/Fast public charging network of £0.51/kWh. Setting the charging price at a similar level to the public Rapid/Ultra-Rapid charging station of £0.75/kWh for electric cars reduces the payback period to 5.5 years. The payback period can be further reduced by using the excess renewable generation to charge any other electric vehicles at the airport.

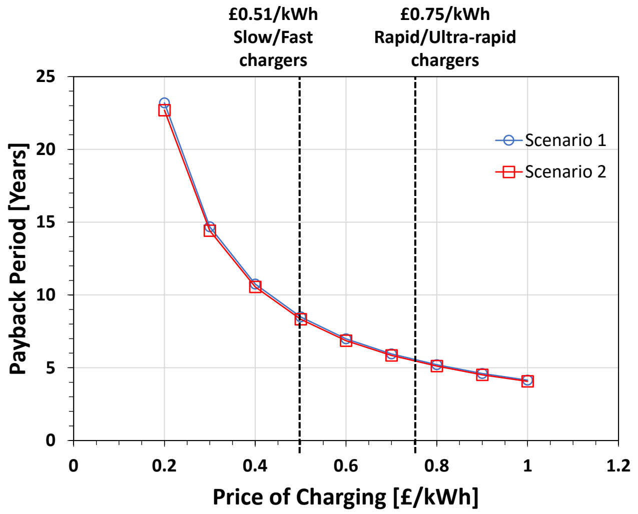

Figure 3: Payback period versus price of aircraft battery charging.

4 Conclusion

A mathematical model was developed to create the load profile for charging flight school electric aircraft and to optimise the sizing of an off-grid charging system powered by renewable energy using a mixed integer linear programming formulation. Two scenarios were considered in this work of using one or two electric aircrafts for quick turnaround at a flying school in the south east of England. To achieve a charging system availability of a minimum of 99%, the optimisation model oversizes renewable capacity to directly cover the charging load resulting in the solar system accounting for more than 50% of the total cost. At the simulated conditions with one electric aircraft, the off-grid system need to consist of 22 kW solar and 2.5 kW wind capacity connected to a 133 kWh battery. Using an additional electric aircraft increases the required capacity for solar to 43 kW, wind to 5 kW and battery to 264 kWh for the off-grid charging system. The payback period for the off-grid charging system is 8.4 years, assuming a £0.51/kWh charging price and drops to 5.5 years when the charging price is set to £0.75/kWh. These results suggest that the FEVER system could be a promising solution for battery power electric aircraft charging, which will help meet the Jet Zero target.

5 Acknowledgements

The authors acknowledge the financial support received from the Engineering and Physical Sciences Research Council (EPSRC) through Future Electric Vehicle Energy Networks supporting Renewables (FEVER) grant EP/W005883/1.

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