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Assessment of the Range of an Electric Aircraft

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ABSTRACT

Electrification of aircraft is a rapidly developing area of the aerospace industry. Thus, there are many electric aircrafts in development, testing, or production. Electric aircrafts are currently viable for short range and short time flight missions due to battery-specific energy limitations. Hence, training and commuter aircrafts are feasible targets for electrification. Pipistrel Velis Electro is the world's first certified crewed electric aircraft for pilot training. In this work, Pipistrel Velis Electro aircraft range is evaluated based on solution of longitudinal equations of motion. A simple flight mission that includes take-off, climb, cruise, descent and landing is considered. Electric propulsion components are modelled. The predicted range of the aircraft is 63 nm for a flight time of 43 minutes, which matches favourably with aircraft published data. The study showed that the Breguet range equation overestimates range, particularly at high altitudes. Hence, the proposed approach in this article is necessary for accurate prediction of range for short-range aircraft. Battery capacity-payload-range charts are developed for present and future battery technologies. Aircraft range can be extended to 150 nm if battery capacity is increased to 166 Ah and the payload is only the pilot. Doubling battery specific energy would extend the range to 193 nm with a flight time of 130 minutes.

1. Introduction

The shift towards electric propulsion is underway in air transportation sector. After the success in electrification of transportation using cars [1-4], trucks, buses and trains, the obvious target is aircrafts. Hydrocarbon fuels like JP-8 and Jet A-1 are currently used in aviation. Their average specific energy is 43 MJ/kg [5]. Lithium-ion batteries hold the highest position for transportation applications in terms of specific energy. It has a specific energy around 0.9 MJ/kg with maximum projected value of 1.7 MJ/kg [6]. Thus, jet fuels specific energy is nearly 24 to 50 times greater than specific energy for Lithium-ion batteries. Other types of batteries show promising specific energy values but they suffer from many problems including the capability to recharge, e.g., lithium carbon-fluoride batteries (2.3 MJ/kg) and lithium-sulphur batteries (9 MJ/kg) [7,8]. Electric propulsion offers many advantages compared to jet engine [9-11]. It is well known that electric propulsion has a higher energy conversion efficiency (from chemical energy in fuel or battery to mechanical energy) when

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compared with jet propulsion engines. Advantages of electric aircrafts are zero-emission decarbonization of air transportation, engine performance is independent of altitude, designer is free to split up and position the propulsion system as there is no weight change during flight, and consequently no change in the centre of gravity, excellent motor efficiency over wide operation ranges, simpler system architecture and reduced complexity (reduction of parts and especially reduction of rotating parts). The main challenges are the thermal control of all power electric components, the magnetic fields including the electromagnetic compatibility (EMC) and electromagnetic interference (EMI) issues, and insulation problems for higher voltage.

Based on present technology, electric aircrafts are limited to short range and short flight applications, such as training or commuter aircrafts engine [11-14]. Promising examples of these aircrafts are Pipistrel Velis Electro [15,16], Eviation Alice [17,18] and Heart ES-30 [19,20]. Pipistrel Velis Electro [15] is a two-seater aircraft for pilot training. It is the world's first and currently only in service, commercially available, type-certified electric aircraft, having achieved EASA type-certification in 2020 and UK CAA certification in 2022. It has a cruise speed of 90 kts (nautical miles per hour), a 50 minutes flight time with additional reserve time and a flight range of about 65 nm (nautical miles). Eviation Alice aircraft [17,18] is a commuter aircraft for 9 passengers with a range of 250 nm and a cruise speed of 260 kts. It is currently in testing phase with many purchase orders and a scheduled in-service date of 2027. Heart ES-30 [19,20] is a transport aircraft for 30 passengers with a range of 190 nm and a cruise speed of 190 kts. It is in testing phase with many purchase orders and a scheduled in-service date of 2028.

Electric aircraft range is usually predicted considering only cruise phase of flight [21-23]. Relative to other flight phases, cruise consumes most of the energy. For long-range aircraft, energy consumption during take-off and climb has a minor contribution to total energy consumption. Hence, neglecting these phases is acceptable. On the contrary, climb phase contributions should not be neglected for short-range aircraft. In this work, range is predicted by considering a flight mission that consists of take-off, climb, cruise, descent and landing [24]. The steady flight longitudinal equations of motion are solved for climb, cruise and descent phases while energy consumption during take-off and landing phases are estimated. Electric propulsion components are modelled. The modelling allows for battery voltage and current variation during flight mission. Range and flight time are predicted for Pipistrel Velis Electro aircraft. Different cruise altitudes are considered. Results are assessed against the values obtained utilizing Breguet range equation. Consequently, battery capacity-payload-range charts are explored for possible battery capacity options.

2. Methodology

This section describes the methodology for electric aircraft modelling and simulation. This includes flight mission description, the solution of longitudinal equation of motion for steady flight and propulsion system modelling. Figure 1 shows MATLAB Simulink model. Mission profile block is dedicated to the specification of the flight mission. Standard atmosphere properties are obtained in Environment block. Aircraft equation of motion is solved in Aircraft block. Power Subsystem block is allocated for propulsion system modelling. Modelling details are explained in the following subsections.

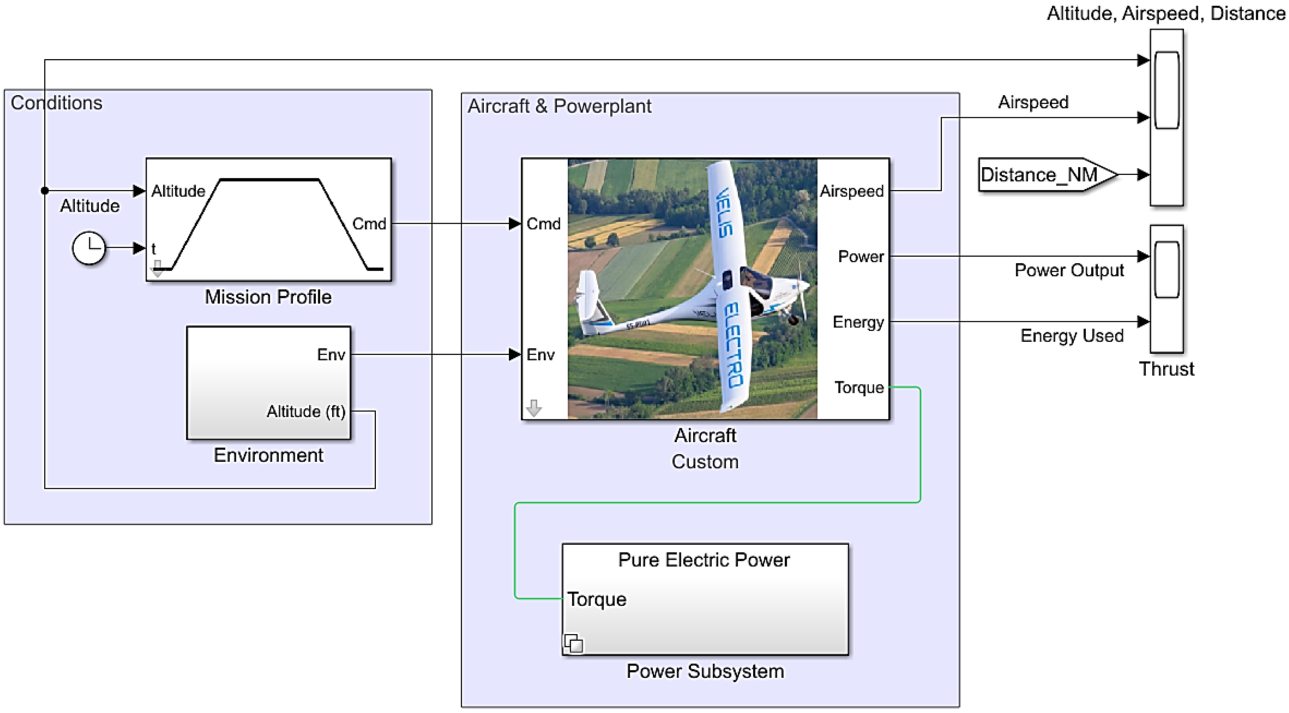

Fig. 1. Electric aircraft modelling in MATLAB [25]

2.1 Flight Mission

Aircraft is assumed to fly in a longitudinal plane. Simulation starts by assuming flight mission that consists of take-off, steady climb, cruise, steady descent and landing phases. Flight mission parameters are total travelled distance and flight phases parameters as shown in Table 1.

Table 1
Flight mission parameters

Phase	Parameters
Take-off	Take-off altitude and duration
Climb	Climb rate and velocity
Cruise	Cruise altitude and velocity
Descent	Descend rate and velocity
Landing	Landing altitude

2.2 Aircraft Equations of Motion

For a steady flight in a vertical plane without rolling, the longitudinal equations of motion are [24,26]:

$$L + T\sin\alpha - W\cos\gamma = 0 \tag{1}$$

$$T\ cos\ \alpha - D - W\ sin\ \gamma = 0 \tag{2}$$

where L is lift force, D is drag force, W is aircraft weight, T is thrust force, γ is flight path angle and α is angle of attack.

Aircraft aerodynamic forces are defined as

$$L = \frac{1}{2}\, \rho_\infty\, V_\infty^2\, S\, C_L \tag{3}$$

$$D = \frac{1}{2}\, \rho_\infty\, V_\infty^2\, S\, C_D \tag{4}$$

$$C_L = C_{L0} + \frac{dC_L}{d\alpha}\, \alpha \tag{5}$$

$$C_D = C_{D0} + \frac{C_L^2}{\pi\, AR\, e} \tag{6}$$

where ρ_∞ is density, V_∞ is flight velocity, S is wing area, C_D is drag coefficient, C_L is lift coefficient, C_{L0} is lift coefficient when $\alpha = 0$, C_{D0} is drag coefficient when C_L = 0, AR is wing aspect ratio, and e is Oswald efficiency factor.

Eq. (1) to Eq. (6) represent a nonlinear system of equations in nine variables. Since flight mission is specified, γ, ρ_∞ and V_∞ are known. Subsequently, the six equations can be solved to work out the six variables ($L, D, T, C_L, C_D, \alpha$) [27]. This procedure is applicable to steady flight phases, i.e., climb, cruise and descent. Since take-off and landing phases have minor contribution to total travel distance and total energy consumption, no attempt is made to solve unsteady equation of motion. Instead, estimates of energy consumption during these phases are used. Finally, flight trajectory is obtained by integrating aircraft velocity.

2.3 Propulsion System
2.3.1 Propeller

Propeller is modelled using propeller efficiency (η_p) which is given by

$$\eta_p = \frac{P_a}{P_s} \tag{7}$$

where P_a is available power or thrust power and P_s is shaft power delivered to propeller from motor. Typical values for η_p are assumed. Solving equation of motion, available power (P_a) is known and Eq. (7) is used to obtain P_s.

2.3.2 Electric motor

Electric motor is modelled as a brushless motor with closed-loop torque control based on a typical torque-speed envelope [28]. Knowing required shaft power (P_s), motor reference rpm is used to calculate required motor torque. Hence, motor rpm is obtained from torque-speed envelope.

2.3.3 Battery

Battery is modelled using equivalent circuit approach where Voltage (V) is a function of charge and has the following relationship:

$$V = V_0\, \left[\frac{SOC}{1-\beta(1-SOC)}\right] \tag{8}$$

where V_0 is nominal voltage, SOC is battery state of charge and β is a constant used to adjust battery model to satisfy a specified measured operation point (voltage, Ampere-Hours) [29].

3. Results

Pipistrel Velis Electro is used as a reference aircraft for this study. It is the first certified electric aircraft for pilot training purposes. In section 3.1, aircraft range and flight time are investigated for different cruise altitudes. Then, results are compared with the prediction using Breguet equation. In section 3.2, the aircraft is modified by changing battery capacity and maximum payload while maintaining maximum take-off weight (MTOW). Consequently, battery capacity-payload-range charts are explored.

3.1 Aircraft Range

Table 2 presents technical details of Pipistrel Velis Electro [15,16]. The aircraft has a MTOW of 1320 lbm and a maximum payload of 378 lbm. It can accommodate two persons. Cruise speed ranges from 90 kts (46 m/s) to 106 kts (55 m/s) . Endurance is up to 50 minutes and ceiling is 12000 feet (3660 m). It is equipped with one electric motor (maximum power = 57.6 kW), one propeller and two liquid-cooled lithium batteries with total battery power rating of 24.5 kWh. Using two batteries connected in parallel allows for better mass balance of the aircraft (one battery at front and another one at back) and improves reliability. Battery specific energy is 0.69 MJ/kg. Aerodynamic parameters (C_{D0}, C_{L0}, $\frac{dC_L}{d\alpha}$, e) and propeller efficiency are assumed using typical values for light propeller aircraft [30].

Table 2
Pipistrel Velis Electro Specifications

Parameter	Description
Empty weight with battery	942 lbm (427 kg)
Payload	378 lbm (172 kg)
Max take-off weight (MTOW)	1320 lbm (599 kg)
Electric motor	Pipistrel E-811, 57.6 kW MTOP at 2500 rpm
Battery	300 lbm (136 kg), 26 kWh (100 Ah), 348 V (max)
Propeller efficiency	0.85
Wing area	102 .4 ft^2 (9.51 m^2)
Wing span	35.1 ft (10.71 m)
Aspect ratio	12.04
Drag coefficient at zero lift (C_{D0})	0.02
Lift coefficient at zero angle of attack (C_{L0})	0.2
Wing lift slope ($\frac{dC_L}{d\alpha}$)	0.1 per degree
Oswald efficiency (e)	0.8
Cruising speed	90 kts (46 m/s)
Stall without flaps	51 kts (26 m/s)
Best climb speed	75 kts (39 m/s)
Max climb rate	647 ft/min (3.3 m/s)
Service ceiling	12000 ft (3660 m)
Endurance	up to 50 minutes plus Visual Flight Rule (VFR) reserve

3.1.1 Cruise altitude of 1500 ft

Flight mission is demonstrated in Table 3. For take-off, energy consumption is estimated to be equivalent of one minute of cruise energy consumption [24]. For landing, engine is assumed to be off after touch down. Both climb rate and descent rate are assumed to be 500 fpm. As stated in aircraft specifications, endurance is up to 50 minutes plus VFR reserve. To determine reserve fuel (reserve battery energy), we refer to EASA certification requirement [31]. EASA requires that the reserve fuel must be enough for the aircraft to fly at altitude 1500 ft (458 m) for 30 minutes with a cruise speed of 90 kts (46 m/s). Considering typical Lithium batteries efficiency, the final state of charge is limited to 0.1.

Table 3
Flight mission for cruise altitude of 1500 ft

Phase	Description
Take-off	Altitude = 0 ft, duration = 60 seconds
Steady climb	Climb rate = 500 ft/min, velocity 75 kts
Cruise	Altitude = 1500 ft, velocity = 90 kts
Steady descent	Descent rate = 500 ft/min, velocity 85 kts
Landing	Altitude = 0 ft, power off after touch down

Figure 2 shows battery status for a flight mission when the final SOC is 0.1. This corresponds to total delivered battery energy of 25 kWh (battery efficiency = 0.96) and a range of 109 nm. To maintain VFR reserve, 30 minutes are reserved as shown in Figure 2. This corresponds to a reserve SOC of 0.54, which is used as a stopping criterion for simulation to uphold VFR reserve policy.

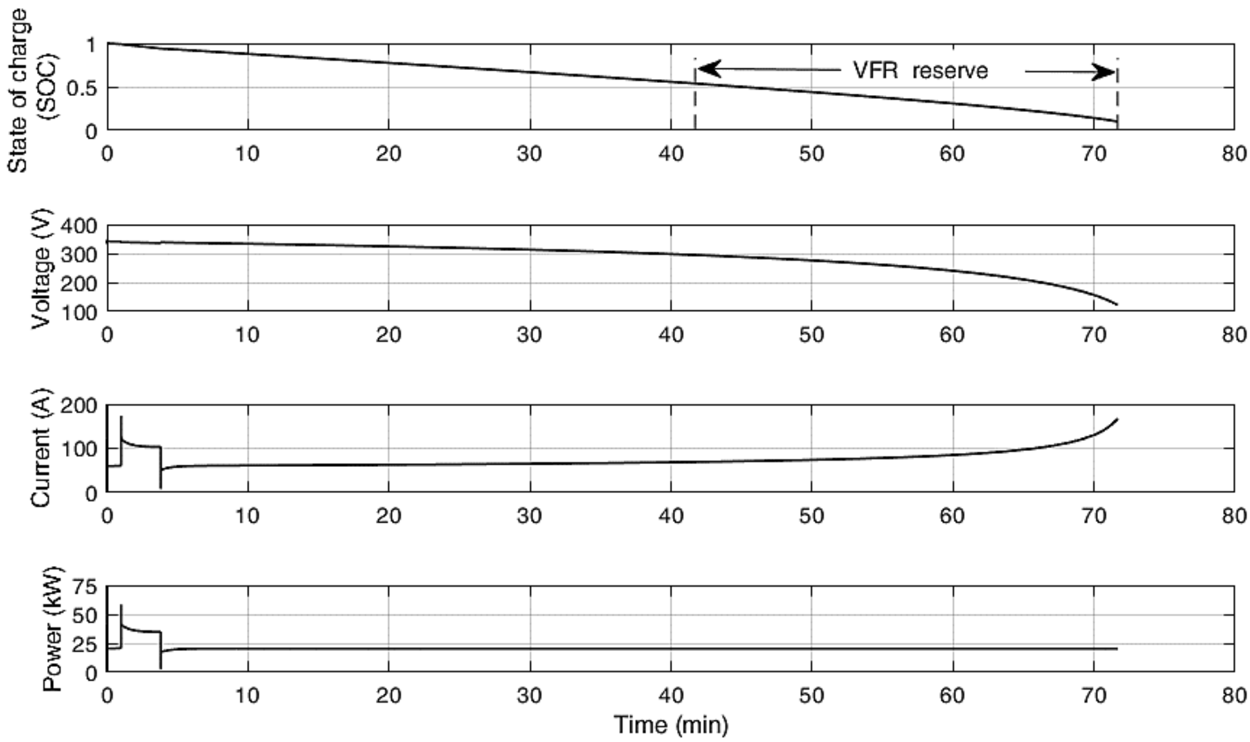

Fig. 2. Battery status during mission (cruise altitude = 1500 ft, cruise velocity = 90 kts, total distance = 109 nm)

Retaining VFR reserve policy, the range is predicted as 63 nm and flight time is 43 minutes as shown in Figure 3. Referring to

Table **2**, endurance up to 50 minutes is claimed. Although, no range data is given by manufacture, an estimate of maximum possible range is 90 kts x 50/60 = 75 nm. Both predicted range and flight time are consistent with aircraft published data. A propulsive power of 15.52 kW is required during cruise flight while climb requires 27.5 kW. The total consumed propulsive energy is 11.25 kWh.

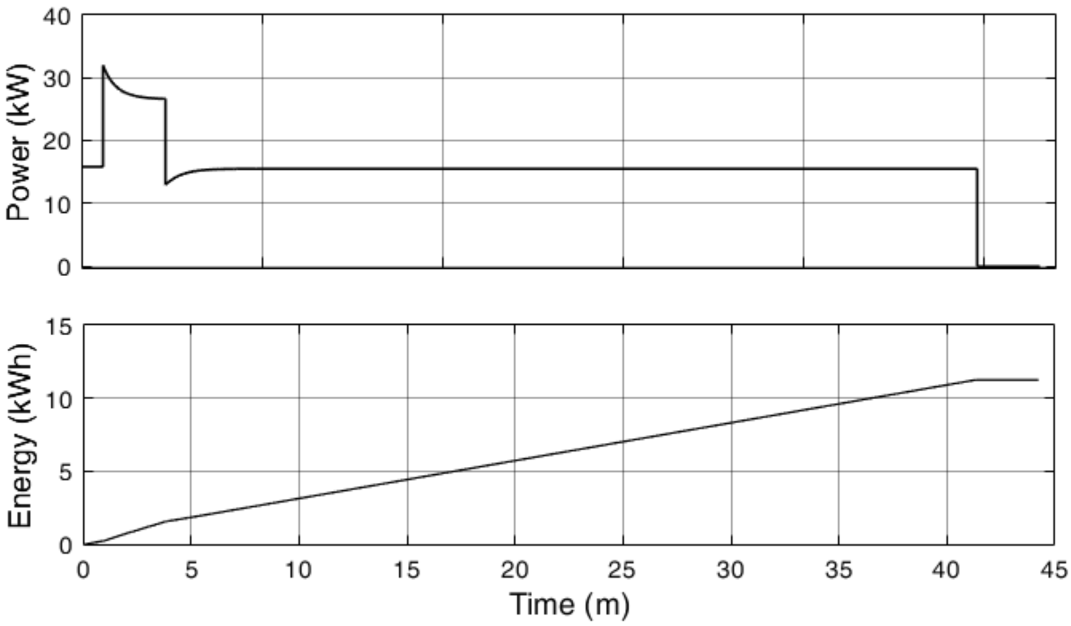

Fig. 3. Propulsive power and energy during flight mission (cruise altitude = 1500 ft, cruise velocity = 90 kts, total distance = 63 nm)

Battery status is presented in Figure 4. The final state of charge is 0.54 as required for VFR reserve. Higher current is demanded during climb indicating higher required power compared with cruise condition. Battery delivered power is 20 kW during cruise and approximately 34 kW during climb. Total battery supplied energy during mission is 14.58 kWh. Using average propulsive power and average battery supplied power, the overall efficiency of propulsion system is estimated as 0.77 (in agreement with typical values for electric propulsion systems [21,32]).

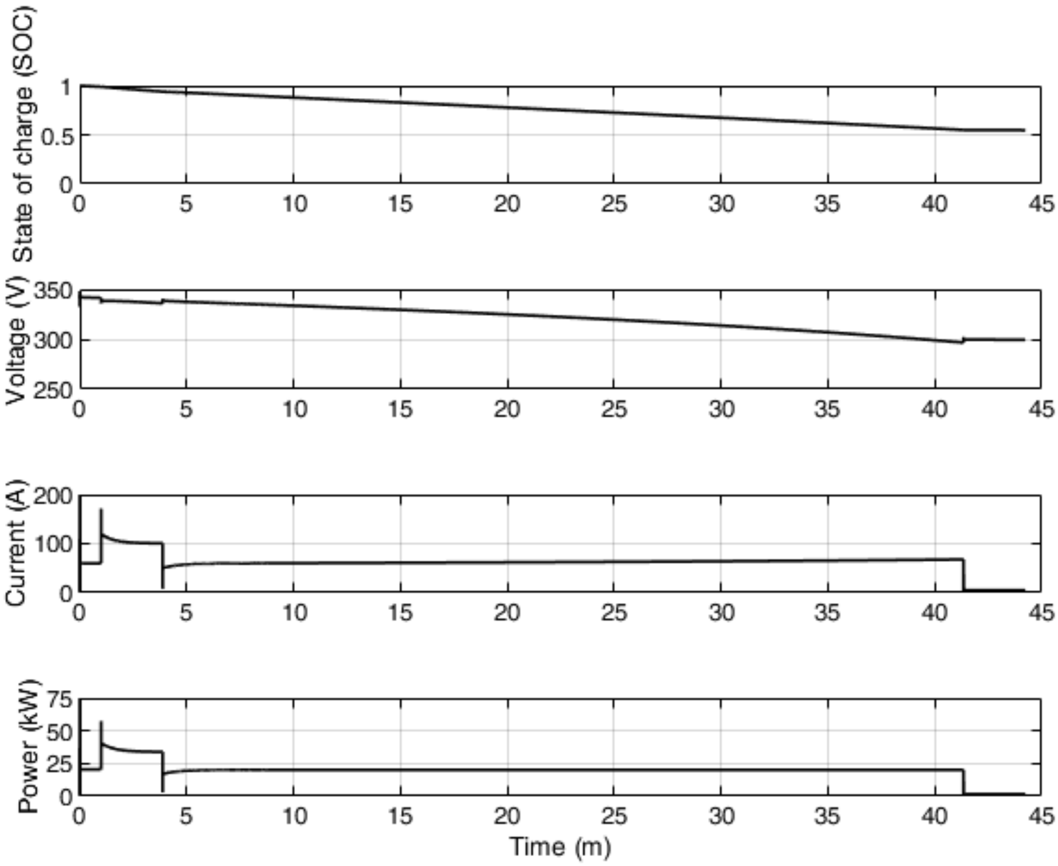

Fig. 4. Battery status during flight mission (cruise altitude = 1500 ft, cruise velocity = 90 kts, total distance = 63 nm)

3.1.2 Cruise altitude of 6000 ft

Cruise altitude is changed to 6000 ft (1830 m), while all other mission parameters are maintained (refer to Table 3). Propulsive power and energy are presented in Figure 5. Predicted range is 64 nm and flight time is 46 minutes. More time is needed compared with flight mission for cruise altitude of 1500 ft because of longer climb time. Compared with flight mission for cruise altitude of 1500 ft, aircraft consumes more power during climb and less power during cruise. Propulsive power is 14.74 kW for cruise and 26.65 kW for climb. Total consumed propulsive energy during mission is 10.83 kWh.

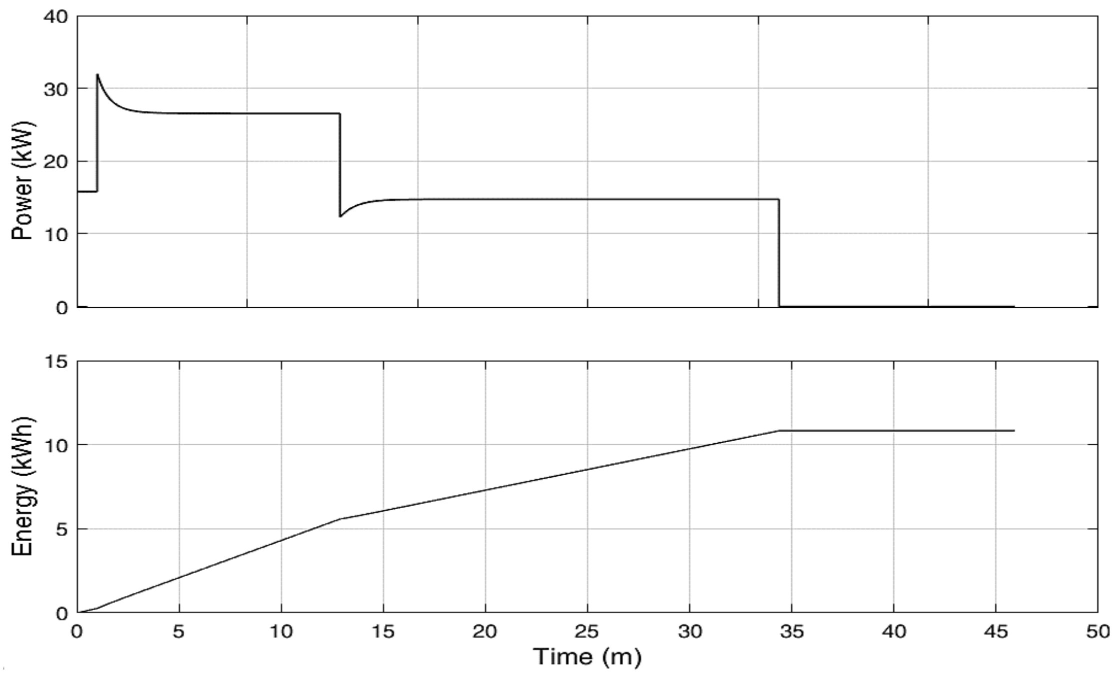

Fig. 5. Propulsive power and energy during flight mission (cruise altitude = 6000 ft, cruise velocity = 90 kts, total distance = 64 nm)

Battery status during mission is shown in Figure 6. Final SOC is 0.54 as required for reserve flight time. Battery supplied power is 19.76 kW during cruise and 33.77 kW during climb. Total energy withdrawn from battery is 14.3 kWh. Thus, range is slightly affected by changing cruise altitude. One important advantage of electric propulsion is that altitude has minimal effect on its performance. Conventional engine for propeller aircraft, such as internal combustion engine or jet engine, relies on air for combustion process. Consequently, engine shaft power delivered to propeller decreases as altitude increases. When altitude changes, optimum propeller efficiency can be maintained by adjusting cruise speed and propeller rotational speed (as long as tip speed does not reach supersonic speed). This results in lower propulsive efficiency as altitude increases. For electric propulsion, battery replaces combustion process as the source of energy. Theoretically, battery delivers the same amount of energy regardless of altitude. Hence, propulsive efficiency is relatively constant across a wide range of altitudes.

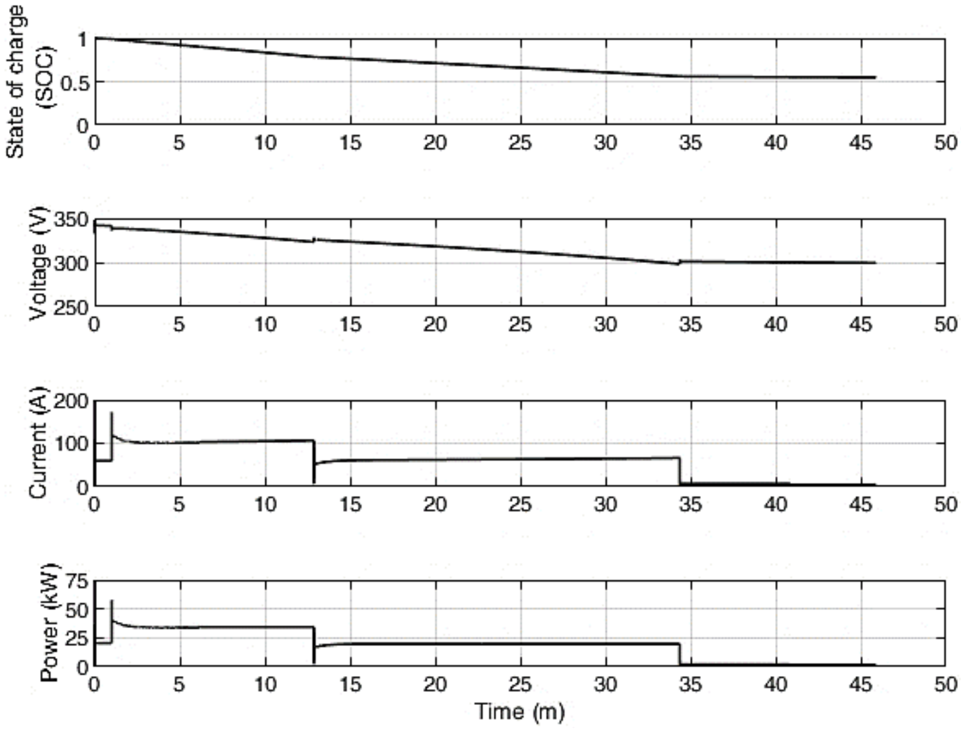

Fig. 6. Battery status during flight mission (cruise altitude = 1500 ft, cruise velocity = 90 kts, total distance = 64 nm)

3.1.3 Comparison with Breguet range equation

The range (R) for electric aircraft can be predicted using Breguet equation [21].

$$R = \frac{L/D}{MTOW} \; m_b \, e_b \; \eta_{overall} \quad (9)$$

where m_b is battery mass, e_b is battery specific energy, $\eta_{overall}$ is overall efficiency of electric propulsion system including battery efficiency.

To consider VFR reserve, a 45 nm (30-minute cruise flight at 90 kts) is subtracted from range calculated using Eq. (9). The comparison between present method and Breguet equation is depicted in Table 4. Difference increases as altitude increases. For higher cruise altitude missions, climb represents larger portion of the flight mission. When compared to cruise flight, climbing requires greater power and a longer period of time. Because the Breguet equation is based solely on cruise flight, it overestimates range as altitude increases.

Table 4
Comparison with Breguet equation

Cruise altitude (ft)	Range (nm)		Difference (%)
	Present method	Breguet equation	
1500	63	67	6.35
6000	64	72	12.5
12000	63	78	23.8

3.2 Battery Capacity-Payload-Range Charts

In this section, we explore the attainable range for different battery capacity-payload combinations. While battery and payload exchange masses, the aircraft's MTOW is maintained. Reserve battery energy of 54 Ah (10.5 kWh) is maintained for all flight simulations to ensure satisfaction of VFR reserve.

3.2.1 Present battery technology

Battery specific energy is 0.69 MJ/kg and battery mass is assumed to change linearly with the change in battery capacity. The total mass of the battery and payload is kept fixed in order to maintain the same MTOW. It is assumed that aircraft internal volume can accommodate mass exchange between battery and payload. Figure 7 presents battery capacity-payload-range (BC-P-R) chart for the modified aircraft at cruise altitude of 1500 ft. “Overweight” designates unfeasible area of the graph because take-off weight is higher than MTOW of the aircraft. Line ab represents payload-range variations using original battery (100 Ah). The airplane at a has a maximum range of 68.5 nm for only one occupant, the pilot. Point b corresponds to maximum payload (378 lbm) with range of 63 nm. Line cd represents payload-range combinations for MTOW using different battery capacities. Thus, line cd and area below represent the locus of possible (BC-P-R) combinations, if battery is changed and MTOW is maintained.

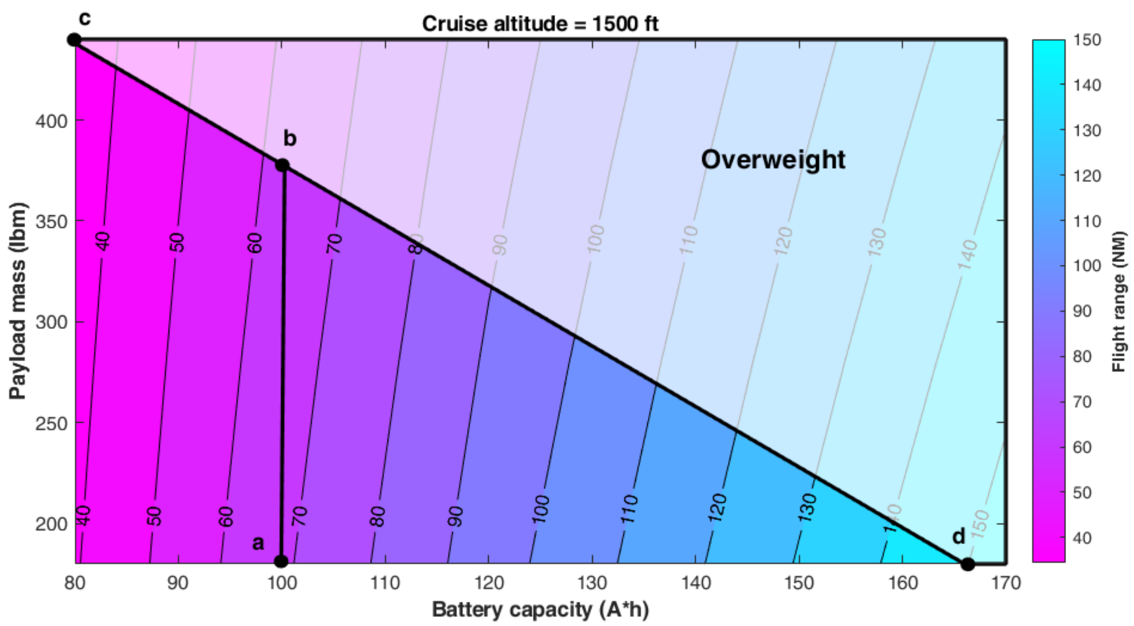

Fig. 7. Battery capacity-payload-range chart for Pipistrel Velis Electro aircraft (cruise altitude = 1500 ft, cruise velocity = 90 kts)

Payload-range diagram for selected battery capacities (100 Ah, 120 Ah and 140 Ah) is demonstrated in Figure 8. As battery capacity increases, range increases, and payload decreases since the total mass is maintained.

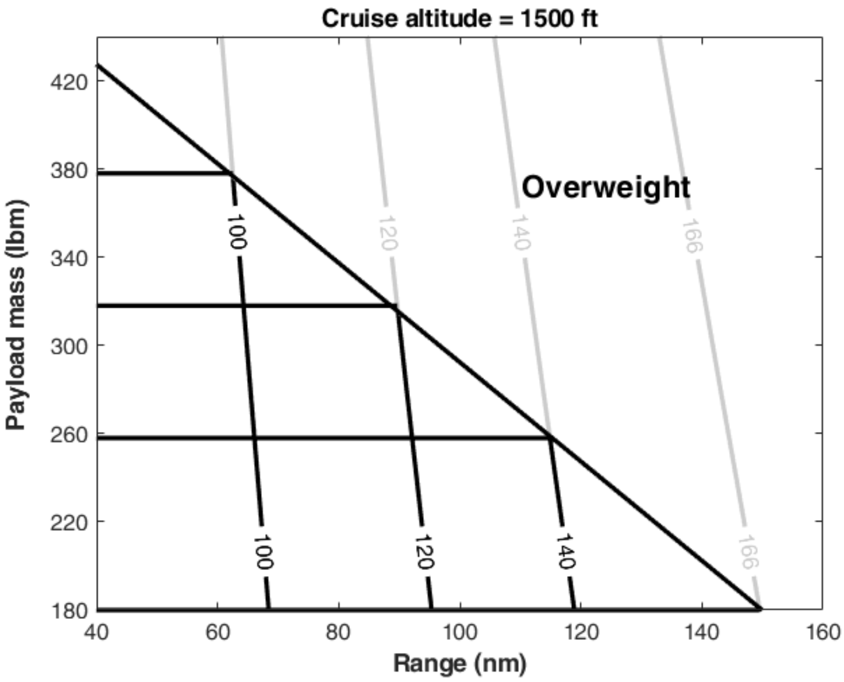

Fig. 8. Payload-range diagram for Pipistrel Velis Electro aircraft for selected battery capacities (current battery technology, cruise altitude = 1500 ft, cruise velocity = 90 kts)

Table 5 summarizes few possible BC-P-R combinations for the modified aircraft. With just the pilot aboard, the range may be extended to 150 nm by increasing the battery capacity to 166 Ah. A battery capacity of 80 Ah would increase maximum payload to be 438 lbm (not enough to fit a third person), while the range decreases to 35 nm. Ranges for battery capacity under 80 Ah are deemed impractical.

Table 5
Battery capacity-payload-range mapping for Pipistrel Velis Electro aircraft

Battery Capacity (Ah)	Maximum Payload (lbm)	Range (nm)	
		Minimum	Maximum
80	438	35	40
100	378	63	70
120	318	90	95
140	258	115	119
166	180	150	150

3.2.2 Future battery technology

To investigate the effect of expected advancement in battery technology, battery specific energy is doubled to be 1.38 MJ/kg (projected to be achievable by 2030's [21,33-35]). The flight mission is the same as in

Table **2**. The updated BC-P-R chart is presented in Figure 9. Maximum possible payload is 560 and maximum possible battery capacity is 332 Ah.

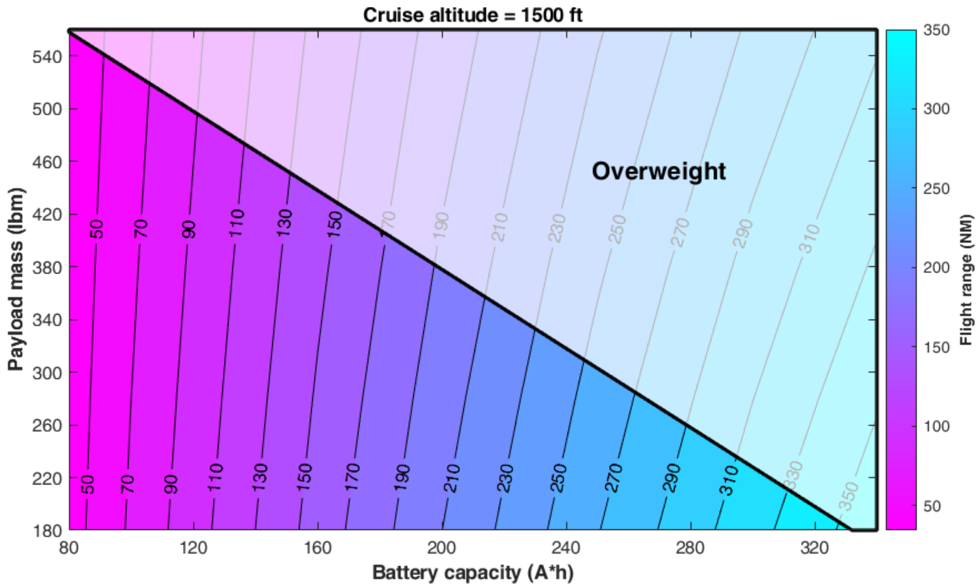

Fig. 9. Battery capacity-payload-range chart for Pipistrel Velis Electro aircraft future battery technology (future battery technology, cruise altitude = 1500 ft, cruise velocity = 90 kts)

Figure 10 shows payload-range diagram for selected battery capacities (100 Ah, 150 Ah, 200 Ah, 250 Ah).

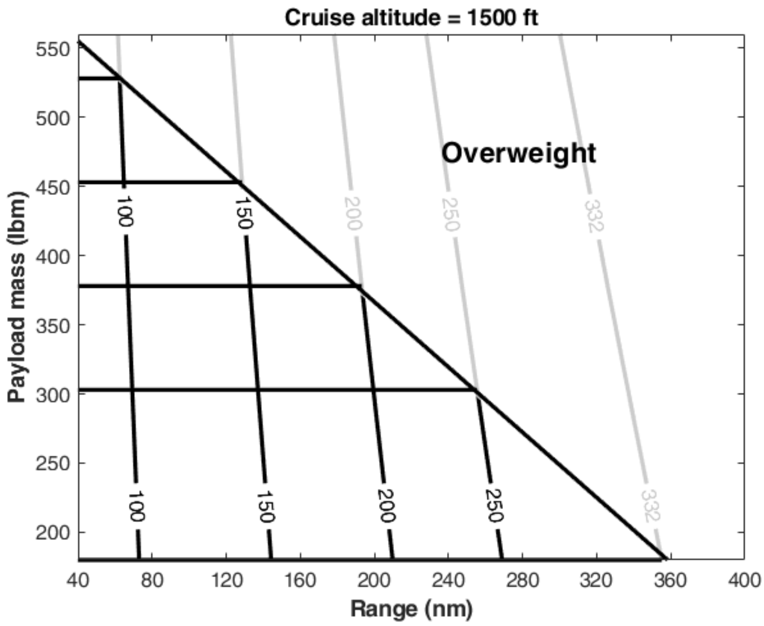

Fig. 10. Payload-range diagram for Pipistrel Velis Electro aircraft for selected battery capacities (future battery technology, cruise altitude = 1500 ft, cruise velocity = 90 kts)

Few possible BC-P-R combinations are listed in Table 6. Replacing the old battery (100 Ah) with a new one with double the capacity would increase range by 130 nm (87-minute extra flight time). A maximum payload of 560 lbm is now possible with a battery capacity of 80 Ah and a range of 35 nm. This design can accommodate three persons. Using a 332 Ah battery and a payload of one person, the maximum range increases to 363 nm. With advancements in battery technology, battery-powered aircraft will be able to fly longer distances, stay aloft for longer periods, and carry larger loads. BC-P-R charts can be used to explore possible battery options for electric aircraft.

Table 6
Battery capacity-payload-range mapping for Pipistrel Velis Electro aircraft employing future battery technology

Battery Capacity (Ah)	Maximum Payload (lbm)	Range (nm)	
		Minimum	Maximum
80	560	35	40
100	528	63	70
150	453	129	142
200	378	193	210
250	303	255	269
332	180	363	363

4. Conclusions

Electric aircraft range and flight time are assessed using longitudinal equations of motion. The method includes electric propulsion components modelling. Range and flight time are predicted for Pipistrel Velis Electro aircraft. Results are consistent with the aircraft's published data. Different battery capacities are investigated for plausible design modification. Battery capacity-payload-range charts are developed for the aircraft. With just the pilot aboard, the range may be extended to 150 nm by increasing the battery capacity to 166 Ah. BC-P-R charts are created for twice the original battery specific energy to examine how the expected evolution in battery technology will affect the aircraft range. Doubling battery specific energy would increase aircraft range to 193 nm (130-minute flight time). Other feasible options are a three-person payload and a 363 nm maximum range for one person.

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