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RESEARCH ARTICLE

Model-Based Analysis of Lithium-Ion Battery Technology Predictions in Light-Sport Aircraft

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ABSTRACT A flight performance model was used to analyze the range capability of fully electric and hybrid-electric aircraft powertrains to determine their implementation feasibility compared to a similarly sized traditionally powered reference aircraft. Range was calculated for a given mission using future Lithium-Ion battery technology predictions from the year 2030. To the authors' knowledge, there are no known studies which attempt to predict future range capabilities of electrified aircraft using future battery technology predictions in this manner. Results showed that fully electric powertrains could achieve ranges of up to 30% of the selected reference aircraft range, while hybrid electric cases could achieve ranges of between 30% and 73% depending on the fuel volume and the energy distribution strategy. Fuel volume was found to be a major contributor to the overall range, due to its high energy density, which tends to dominate the battery capacities used in this study. Thus, hybrid electric results were also analyzed at one selected fuel volume to identify trends in other parameters. It was found that the range of hybrid electric powertrains could be improved by up to 3.3% utilizing the optimal degree of hybridization, and up to 37% utilizing the optimal energy distribution strategy, compared to the range of the baseline hybrid energy distribution method. These results suggest that battery capacity improvement and optimal energy distribution strategy development are key to improving the feasibility of implementing electrified light-sport aircraft into the aviation industry over the next ten years.

INDEX TERMS Degree of hybridization, electric propulsion, electrification, flight performance, hybrid, powertrain, simulation.

I. INTRODUCTION

Aircraft electrification is a rapidly emerging research area and a promising solution to the ever-growing impact of aviation pollutants on the environment. However, the current level of battery technology is often insufficient to meet the range and power demands of many aircraft types, solidifying the fact that electrified aircraft propulsion will not be widely adopted until the battery technology improves significantly [1], [2], [3], [4], [5]. The required technological improvement is in battery energy density, meaning the amount of energy that a battery can hold per unit mass. At present, the energy density value is still not sufficient and is the most important limiting factor of the implementation of electrified aircraft technologies. For comparison, the liquid hydrocarbon fuels typically used to power aircraft have a larger energy density than present-day batteries by a factor of 50 [3]. Therefore, utilizing these batteries on aircraft has a hefty mass penalty, which makes flight nearly impossible when scaled up to larger airliners. If a large airliner were to use present-day batteries in a fully electric powertrain configuration, 540 tonnes of batteries would be required to generate the power of the jet engine and fuel it would be replacing [4]. Therefore, it is predicted that the implementation of a fully electric airliner on the scale of a Boeing 777 is still decades away [4].

On a smaller scale, short-range, electrified general aviation or light-sport aircraft (LSA) are beginning to make their debut into the industry and are predicted to be well-implemented by

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2030 with the current level of research and public interest [4]. There have been some instances of small-scale fully electric success thus far, including the Pipistrel Alpha Electro (2017), which achieved a range of approximately 140 km [5], and the Harbour Air eBeaver (2019) with a range of approximately 160 km [6]. However, these ranges are severely lacking in comparison to traditionally powered light-sport aircraft such as the Pipistrel Virus 912, which has a maximum range of 1650 km [7].

An alternative to the systems presented above is a hybrid-electric propulsion system for aircraft. Such aircraft utilize both batteries and a fuel-based energy source in their powertrain, which is advantageous in terms of range and flight time capabilities compared to a fully electric option. Although battery energy densities continue to limit range, the second energy source provides a fraction of the power required, thus complementing the battery energy. With an improvement in battery energy density, these ranges will also be improved. To date, there has also been some examples of real world successes in the hybrid electric regime; including Ampaire's Electric EEL, a general aviation aircraft which flew 550 km (2020), which at the time held the record for the longest commercial flight of an electrified aircraft [11], [12]. Additionally, the Zuri 2.0, a hybrid electric vertical takeoff and landing (VTOL) aircraft achieved a 700 km range (2022), the longest in its class [13], [14]. However, hybrid electric propulsion research is lacking in the area of LSAs. A recent review paper [12] suggests that the need for hybrid research is urgent for aircraft in this class. The methodology described in this paper is based on both a fully electric configuration and a serial hybrid electric configuration, providing the urgently needed insights.

The energy densities of Lithium-Ion batteries are expected to improve from their current levels, which will facilitate the implementation of all types of electrified propulsion systems [13]. Contrary to popular belief, Lithium-Ion batteries are not approaching their maximum energy density, as new improvement strategies are being applied to form the next generation of cells [13]. One technique involves operating cell materials outside of their thermodynamic stability windows, surviving by forming a solid-electrolyte interphase to prevent degradation [13]. It is predicted that electrified aircraft similar in size to those that have flown successfully thus far can see an improved range due to improved battery technology by 2030. Therefore, this study allows for comparison of electrified propulsion systems powered with present-day Lithium-Ion technologies from [1], and the future Lithium-Ion technologies that are predicted to make electrified powertrains more feasible by 2030.

It was found in [1] that present-day Lithium-Ion technologies of approximately 100 Wh/kg are insufficient to power fully electric and hybrid-electric LSAs in a meaningful manner. In [2], it is predicted that battery energy densities of batteries to power a fully electric 19-seat commuter aircraft would have to be between 1200 and 1800 Wh/kg to complete an acceptable range. However, it was predicted in [14] that the required energy densities of lithium-based batteries are 600, 820, and 1280 Wh/kg to generate acceptable ranges of regional, narrow body, and wide body aircraft, respectively. Finally, it was reported in [15] that the mass of batteries with the energy densities possible today increases logarithmically with a general aviation aircraft's range capability. This is predicted to impact the effective range of such aircraft [15].

Noting all of these critical findings, improving the battery energy densities (larger than 100 Wh/kg) in smaller-scale aircraft such as LSAs may increase the range to an acceptable level. This paper will present the results obtained when testing these predictions using the aircraft flight performance model described in [1] with modified battery specifications and energy distribution algorithms. By implementing higher capacity batteries, the range of LSAs may be found to be comparable to a traditionally powered LSA, thus making it feasible for implementation into the industry.

II. METHODOLOGY

A. AIRCRAFT FLIGHT PERFORMANCE MODEL

The basis of the methodology of this study stems from a previously developed and tested aircraft performance model described in detail in [1]. This model, developed in the MATLAB/Simulink environment, simulates LSAs powered with either a fully electric or hybrid-electric propulsion system with an overall goal of analyzing the feasibility of their implementation into the industry in the near future. MATLAB/Simulink was chosen to build the model as it is commonly used in other studies involving aircraft flight performance models and it has the benefits of modularity, visualization, and shorter computational times [16].

Other aircraft flight performance models in the literature were referenced in the development of this model to draw on previous findings while ensuring novelty. Power management of an unmanned aerial vehicle (UAV) hybrid electric system is described in [17]. Three electric propulsion systems with different power sources, such as solar cells, fuel cells, and batteries, are considered. A comparison between different power distribution strategies is given. This study also determines the optimal power distribution method but expands further to optimize the parameters which also have an effect on range and performance such as degree of hybridization (DOH) and fuel mass.

In [18], the goal of the project is to determine the feasibility of hybrid electric propulsion over a wide range of aircraft scales. This was accomplished using several linked software packages including X-Plane, MATLAB, and JavaProp. However, the simulator is not easily applicable to other powertrain architectures. Therefore, the model used in this study is advantageous due to its ability to simulate aircraft flights with hybrid electric and fully electric powertrains.

In addition to the above, the model and its usage in this study provides novelty to the field because, to the authors' knowledge, there are no known studies which attempt to predict range capabilities using future battery technology predictions. Therefore, this study is advantageous in the implementation of electrified aircraft into the aviation industry over the next 10 years.

The aircraft geometry used in model development [1] is based on the Pipistrel Virus 912 [7] and is used to obtain the power requirements and other aerodynamic-related values. The powertrain components and their limitations were modelled after those implemented in a ground-based test stand located at the National Research Council of Canada.

This study is limited to LSAs which are categorized based on their maximum takeoff mass (MTOM). Independently of the propulsion system, the MTOM of the aircraft was limited to 600 kg to adhere to the reference aircraft limit [7]. The empty weight of the reference aircraft was fixed, and a payload of two passengers was added. Based on these assumptions, the allowable masses of additional components required for the given electrified propulsion systems such as the electric motor, batteries, engine, fuel, and wires were determined via a mass analysis [1]. The mass analysis allowed for the maximum allowable battery mass to be found (using a given fuel mass for the hybrid cases) in an attempt to maximize the range that the aircraft can achieve. Thermal effects of components were not considered in this study.

The aircraft model's main task is to continually analyze the motor's power draw. This analysis is done by updating the aerodynamic and powertrain parameters throughout each segment of the selected mission. In a fully electric configuration, the motor's power draw assists in determining the remaining state of charge (SOC) at a given time. The SOC is defined as the ratio of the available capacity of the battery pack to its maximum capacity at a given time, which is critical to the model's functionality to predict the remaining flight time. In a hybrid configuration, the power draw value determines how it is distributed between the two sources of energy to complete the mission effectively. Subsequently, the selected power distribution is used to determine the SOC and the fuel usage at a given time.

There are five controllers used in the aircraft model, each of which follows a basic proportional integral derivative (PID) closed-loop feedback control structure and has a corresponding equation of motion in its plant block. The same method was previously detailed in [1]. PID control loops may be used in a cascaded control structure, meaning that the output of the plant of the outside loop is used as reference data to the inside loop, as seen in Fig. 1. The first three control loops, which control motor torque, propeller angular speed, and aircraft thrust, respectively, are cascaded and control the aircraft's motion in the body reference frame. The fourth and fifth loops, which control the aircraft climb/descend angle and vertical velocity, respectively, are also cascaded control loops (but are separate from the first three) and are responsible for controlling the aircraft's motion using the ground reference frame. In addition to the five controllers, there are two separate algorithms, energy distribution and variable cruise, which provide inputs to the main control structure. The functions of these algorithms are described below. A full account of the model methodology including detailed descriptions can be found in [1].

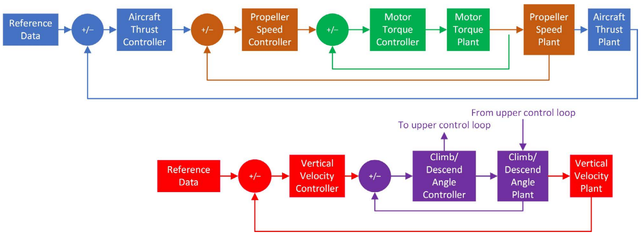

FIGURE 1. Aircraft model cascading control loop structure overview [1].

The fully electric powertrain calculates the instantaneous SOC using the power demand of the motor at a given time. The hybrid electric powertrains continuously determine the instantaneous power draw of the motor and decides the best way to split the demand between the two power sources based on a set of pre-determined conditions. After the instantaneous power condition of each energy source is determined based on the described algorithm, individual calculations are completed to determine the SOC of the battery using the following equation [19]:

$$SOC = \int_0^t \frac{I_{\text{pack}}}{C_{\text{pack}}} \mathrm{d}t \tag{1}$$

where I_{pack} is the current through the battery pack and C_{pack} is the total capacity of the battery pack. The SOC is then used to calculate the open-circuit voltage and resistance via reference data of battery properties [20]. For the hybrid models, the fuel consumption is found by using reference data of the selected internal combustion engine (ICE), the Rotax 912 [21], describing the fuel consumption at a given power setting and rotational speed.

The energy distribution conditions of the hybrid electric powertrains described in [1], are maximum power, hybrid, ICE-only, and safety. The condition selections during a given section of the mission are slightly different for the two energy distribution methods presented in [1], ICE-only cruise and total mission hybridization. The ICE-only cruise algorithm utilizes the hybrid condition during the beginning and end of the mission, but most of the mission (cruise) is accomplished using the ICE-only condition. The total mission hybridization algorithm accomplishes the mission using the hybrid condition throughout the entire mission. Both algorithms also use the other two conditions, maximum power, and safety, as needed. It should be noted that safety here refers to a margin of safety in battery power management, which is different from the storage and operational safety considerations of aviation batteries. Although the latter is an important issue for electric propulsion feasibility, it is not considered in this study.

A flight mission profile consisting of five segments, i.e., takeoff, climb, cruise, descent, and landing, is used throughout the simulations. A variable cruise algorithm is utilized to maximize range by fixing the mission's climb and descent times but keeping the cruise time variable. There is a "trigger point" at which the powertrain has just enough remaining energy to complete the fixed descent segment. This trigger point depends only on SOC for the fully electric configuration and depends on both SOC and the percentage of fuel volume remaining for the hybrid configuration, as output by the powertrain energy distribution algorithm. The trigger point can be changed as needed based on the mission and overall powertrain energy but is always set such that a safe descent can be completed.

B. FUTURE BATTERY TECHNOLOGY

A study [22] from NASA researchers investigated battery energy density improvement predictions for three types of Lithium-based batteries: Lithium-Ion, Lithium-Sulfur, and Lithium-Oxygen. Lithium-Ion batteries are commercially available, while the other two are continually being studied and developed. Table 1 shows the results of this study [22], highlighting improvements in battery energy densities of the various battery compositions over a 30-year span, beginning with the state-of-the-art values as of 2015. Lithium-Sulfur and Lithium-Oxygen batteries were not studied in this paper, but energy density improvement predictions showcase the promising future of electrified flight through their continued development.

TABLE 1. Battery energy density predictions over a 30-year span [22].

Battery Composition	2015	2030	2045
Lithium-Ion	80–200 Wh/kg	400 Wh/kg	450 Wh/kg
Lithium-Sulfur	200–300 Wh/kg	500–650 Wh/kg	800–950 Wh/kg
Lithium-Oxygen	300–350 Wh/kg	600–750 Wh/kg	1200–1400 Wh/kg

As hybrid-electric propulsion in aviation is still an emerging technology, analyzing the performance using predicted future battery chemistries and energy densities is critical to highlight the prospects of the technology over the coming years. By using the prediction of Lithium-Ion cells for 2030 as seen in [22] (400 Wh/kg), applying them to the aircraft performance models reported in [1], and studying the range increase achieved through their usage, one can study the feasibility of fully electric and hybrid electric propulsion systems in approximately ten years.

Numerical predictions of the range of the electrified aircraft using the "new" cells can be made by extrapolating from the results of [1]. For a fully electric powertrain, the range is expected to increase by a factor of four since it is expected that the battery pack, which is the sole provider of power to the system, will have a capacity increase of the same factor. Based on the previous results from studying present-day battery technology, this prediction suggested a maximum range of 368.8 km will be possible by 2030 using the fully electric powertrain. For a hybrid electric powertrain, however, the "new" battery will likely continue to not have the same effect that the fuel mass has. Despite all advances in battery technology, hydrocarbon fuel will continue to have the superior energy density.

Since current batteries have approximately 50 times lower energy density than liquid hydrocarbon fuels [6], even with an energy density increase of a factor of four, it is unlikely that the ranges of traditionally-powered aircraft will be matched. Using the previous range results of the hybrid powertrain in [1], a potential maximum range for a light sport hybrid electric aircraft can be 872.6 km by 2030. This value was calculated by using the maximum hybrid range result from [1], which was 728 km, as a baseline. Then, the result of a mission completed using the same amount of fuel and no battery was calculated to have a range of 679.8 km. Thus, the difference between these two values, 48.2 km, is what the current battery achieves. Assessing that the "new" battery could potentially increase the battery-produced range by a factor of 4, giving 192.8 km, plus the range achieved using fuel only, gives a potential maximum range of 872.6 km, 16.6% more range than the maximum range simulation result in [1].

The fully electric and both hybrid electric aircraft flight performance models will utilize the "new" battery specifications to verify or disprove the previous predictions by utilizing the model's adaptability and implementing the "new" cell specifications.

C. SIMULATION PARAMETERS

Throughout the simulations there are three variable parameters to test the model in various ways, while the overall mission profile remains the same. The variable parameters include flight mission (cruising altitude), battery properties, and DOH.

The flight mission profile consists of five segments where the velocity and intermediate altitudes are constant for each simulation run, but the cruising altitude is variable, as mentioned. These segments were defined in the model as two variable MATLAB codes that were inputs to the main control structure. They are defined as follows:

1) Takeoff and initial climb to 152.4 m (500 ft) at 100% power.
2) Continued climb at the best rate of climb until the desired cruising altitude is reached.
3) Cruise at the selected altitude and a constant true airspeed of 246 km/h.
4) Descending flight (maintaining cruise speed) to 152.4 m (500 ft) at a constant descending rate.
5) Approach and landing at 94.8 km/h.

The cruising altitudes tested are 2500 ft, 5000 ft, and a battery pack's maximum altitude. As discussed in [1], the battery packs with current battery technology that were used were subject to a maximum altitude because of the motor's torque-speed curve limitations, these limitations also stemmed from the fact that the packs had a non-optimized design. With the mass limitations, the packs were only able to have one module which causes a relatively high resistance because the pack resistance increases with a decreasing number of modules in parallel. This high resistance, increases the voltage drop of the pack, thus decreasing the voltage used to power the electric motor. By using four modules in parallel, an improved pack design with a much lower resistance is seen. Thus, it is possible for higher cruising altitudes to be achieved for missions using the "new" battery pack. However, for this study, the same maximum altitudes discussed in [1], which range from 5000 ft to 8500 ft, will be used for to keep a consistent results comparison.

The Reynolds number of the airflow at cruise is calculated using the following [24]:

$$Re = \frac{\rho v L}{\mu} \tag{2}$$

where ρ is the air density, v is the aircraft speed, L is the wing chord, and μ is the dynamic viscosity. It is found to be 4.72×10^7, 4.44×10^7, and 4.07×10^7 for 2500 ft, 5000 ft, and 8500 ft, respectively.

The same selected cell from [1], the LG Chem pouch-type cell [21], is used in this study to obtain the most accurate results comparison. Each cell has a nominal voltage of 3.7 V, an energy density of 111 Wh/kg, a mass of 703 g, and a capacity of 21 Ah [20]. Other cell information such as anode, cathode, and electrolyte material, was not provided. For this study, analyzing the effects of future battery technology, some changes need to be made. An improved battery energy density can be conceptualized in two ways; either each cell has the same mass as before, but the internal capacity is larger, or each cell has the same internal capacity as before, but the mass has been reduced. Both options will ultimately yield the same results, but this paper realizes the capacity increase as the latter. Thus, four times more cells are utilized in the aircraft because their mass has been quartered.

The pack design is unable to take any more cells in series or the nominal voltage will be too high for the electric motor limitations, so the number of cells in series will remain the same as those presented in [1], but there will be four parallel cells. This change has no effect on the reference aircraft mass analysis which was presented in [1], but it gives the opportunity to add cells in parallel while keeping the desired nominal voltages. This was not previously an option using current battery technology due to the MTOM of 600 kg. The addition of cells in parallel reduces the resistance of the pack significantly and will be an overall better pack design, because higher resistance depletes the battery faster. The capacities of all battery packs in this study are 84.2 Ah. Thus, voltage/number of cells is the primary differentiating property that will affect range since the energy storage capability will be equivalent. A summary of the packs that are used in simulations in this paper is presented in Table 2.

TABLE 2. Selected battery pack configurations.

Pack Number	Powertrain Type	Series Cells	Parallel Cells	Nominal Voltage
1	Fully Electric	214	4	800
2	Fully Electric	190	4	700
3	Fully Electric	163	4	600
4	Hybrid Electric	130	4	480
5	Hybrid Electric	119	4	440

The degree of hybridization is critical to the development of a hybrid electric propulsion system. The degree of hybridization for power is defined as the ratio of power produced by the electric motor to the total power of the entire propulsion system. An increased DOH is desirable from an environmental perspective, but it is often limited by the current battery energy densities. In [1], the degrees of hybridization for energy selected for the present-day ICE-only cruise simulations were 0.5 and 0.3, where 0.5 is 50/50 split of the power demand between the energy sources, and 0.3 is a case using 30% battery power and 70% ICE power. Due to the relatively low capacity of the present-day batteries, analyzing a higher DOH was not beneficial as the SOC would diminish very quickly.

The DOHs selected for the ICE-only hybrid powertrain cases powered with future battery capacities in this study are 0.75 and 0.85. The higher capacities of future batteries make it possible to employ higher DOH values and keep a sufficient range. In fact, employing a DOH of 0.3 or 0.5 will never reach the ICE-only activation point because it has enough battery power to stay in hybrid mode for the entire mission.

D. REFERENCE AIRCRAFT RANGE

The performance measure of this study is overall range, which is compared to the range of the baseline that is powered using a traditional ICE powerplant. The maximum range of selected reference aircraft used to develop the aircraft models, the Pipistrel Virus 912, is 1650 km [7], which occurs at its maximum range speed (157–162 km/h depending on the altitude). However, the range that the Virus can achieve at the constant true cruising airspeed analyzed in this study, 264 km/h, is significantly less than its maximum range. The range of the ICE-powered aircraft, r_{ICE}, is calculated to be 1288 km using the following [24]:

$$r_{\mathrm{ICE}} = \frac{\eta_{\mathrm{prop}}}{SFC}\left(\frac{L}{D}\right)\ln\left(\frac{W_1}{W_2}\right) \tag{3}$$

where η_{prop} is propeller efficiency, SFC is the ICE's specific fuel consumption, L/D is the lift-to-drag ratio, and W is weight. The subscript 1 on the weight represents the condition at takeoff, and the subscript 2 represents the landing condition. The weight distribution of the aircraft model was assumed to be a point mass for simplicity.

III. RESULTS

A. FULLY ELECTRIC RESULTS

Utilizing future battery capacity in the fully electric model showed a significant improvement in range for all voltage and altitude combinations. The average range increase was found to be 305.6%, with the largest and smallest ranges being 390.5 km and 262.5 km for the selected parameter combinations. The largest range is only 30.3% of the traditionally powered aircraft model's range (1288 km) at the selected cruise true airspeed, even with the capacity increase. Nevertheless, this is a vast range improvement compared to the present-day fully electric maximum of 92.2 km [1], thus showing that with the projected increase in battery capacity, electrified aircraft powertrains will become significantly more feasible by 2030.

Figure 2 shows a depiction of the results and the effect that altitude and voltage have on range. The results show that an increase in nominal voltage gives an increase in range because, in this case, a higher voltage means a larger number of cells and a larger overall energy storage capability of the pack since each pack used has four modules in parallel. Additionally, range increases with increased altitude due to the lower air density and thus lower drag that occurs at higher altitudes. One of the differences between the results of the present-day battery pack and the high capacity one is that reducing aircraft mass by the margin which was previously possible no longer has a significant effect. In the fully electric results in [1], it was shown the lower nominal voltage battery configurations had the option to take no payload and decrease the MOTM or to take a payload up to a MTOM of 600 kg. These results showed that a reduction in mass of up to 50 kg could provide a range of up to 10% longer [1]. This range increase percentage was not seen to the same degree using future capacities because the effect of the four times capacity increase contributes much more to the overall range than the small mass decrease.

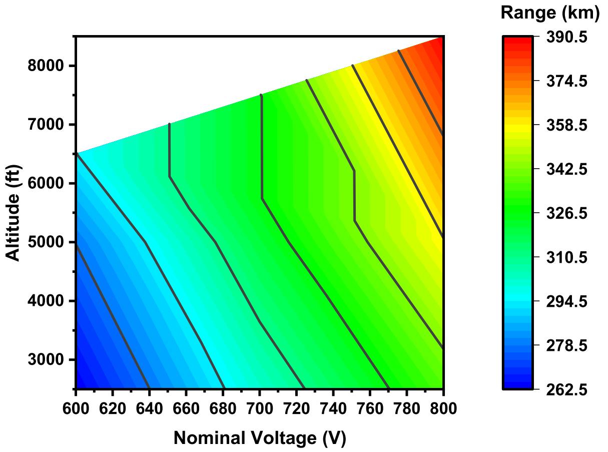

FIGURE 2. High-capacity fully electric altitude vs voltage range comparison.

A numerical comparison of the results of the high capacity fully electric simulation results to the present-day capacity results from [1] is seen below in Table 3. One of the most interesting columns is the factor increase which shows by what multiple range was increased when increasing battery capacity by a factor of four. It was predicted that increasing the battery capacity by a factor of four would increase range by a factor of four in the fully electric configuration. Most results confirm that this prediction was very accurate, but some results show values are slightly above or below four. This is because the capacity increase is not the only factor influencing the range, it is also influenced by pack design and discharge limitations. As previously mentioned, the increased capacity allows for adding modules in parallel, which reduces the resistance of the pack. A lower resistance gives a lower discharge rate, thus allowing for even more range than there would have been without a better pack design. The discharge limitations refer to the safety condition in the energy distribution algorithm which states that the battery will never be discharged below 20%. When capacity is increased by a factor of four, 20% of the new capacity must remain untouched. This 20% of the higher capacity battery does not equal the 20% of the lower capacity battery meaning that a larger amount of capacity will be unusable for the higher capacity batteries. Therefore, there can be some discrepancies in the range.

TABLE 3. High-capacity fully electric results compared to low capacity fully electric results from [1].

Altitude (ft)	Nominal Voltage (V)	Range (km)	Range in [1] (km)	Range Increase (%)	Factor Increase
5000	800	357.91	89.15	301.48	4.01
2500	800	336.75	85.66	293.13	3.93
8500	800	390.21	92.16	323.39	4.23
5000	700	320.64	80.44	298.63	3.99
2500	700	301.92	75.86	297.98	3.98
7500	700	326.16	81.95	298.00	3.98
5000	600	278.72	66.79	317.31	4.17
2500	600	262.73	64.89	304.92	4.05
6500	600	294.30	70.89	315.12	4.15

B. HYBRID ELECTRIC RESULTS (ICE-ONLY CRUISE)

Utilizing future battery technology predictions in the ICE-only cruise hybrid electric model showed minimal improvement in overall range and is still not comparable to a traditionally powered aircraft's range. The average range using the ICE-only cruise distribution method was found to be 10.3% higher than the previous ICE-only cruise results using current battery technology. Two cases of varying fuel masses were studied, one using 20 kg of fuel and one using 10 kg of fuel (i.e., 3.33% and 1.67% of the MTOM, respectively). This was done to account for the influence of fuel mass which could overpower other parameters which are to be studied. The largest ranges calculated were 819.4 km and 397.3 km using 20 kg and 10 kg of fuel, respectively, with the parameter combinations selected. These values are 63.6% and 30.8% of the traditionally powered aircraft model's range at the selected cruise true airspeed, and the 20 kg result is 6.5% less than the calculated range prediction made in the previous section of 872.6 km.

Despite the name ICE-only cruise, the corresponding energy distribution algorithm does not set the ICE-only setting based on the mission segment, but rather based on the battery's SOC. Once the battery reaches a previously defined value, the ICE-only condition is activated. Using current battery technology and the DOHs of 0.5 and 0.3 selected for testing in [1], the battery reached this value almost immediately after the start of cruise, due to the lower energy density levels. However, when using a DOH of 0.5 and 0.3 using the future battery technology, the battery never reaches the SOC value needed to activate the ICE-only condition because the battery capacity is increased and thus depletes at a lower rate. Thus, for the ICE-only cruise future capacity simulations, the DOHs tested are 0.85 and 0.75, which give a more accurate comparison between the present-day and future batteries since the length of operation using the ICE-only condition are similar. The results of the various parameter combinations are visually presented in Figs. 3–6.

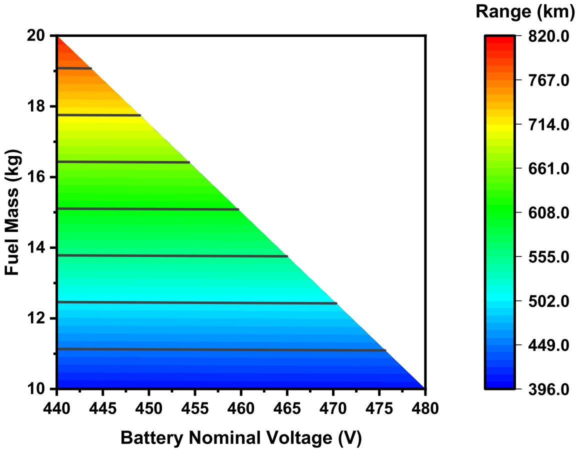

FIGURE 3. Hybrid electric fuel mass vs. voltage vs. range (ICE-only cruise).

Figures 3 and 4 once again solidify fuel mass' significant influence on range. Despite the increased capacity of the battery pack, the battery related parameters such as nominal voltage (i.e., energy storage) and DOH still have a near-negligible impact. Additionally, even the previously discussed effect of increased cruising altitude on range is insignificant compared to the fuel mass. The trendlines of both plots are nearly horizontal, depicting these claims. Thus, the 10 kg of fuel cases are plotted separately in Figs. 5 and 6 to better visualize if there has been any change in the less-impactful parameters' influence on range when using the future battery technology.

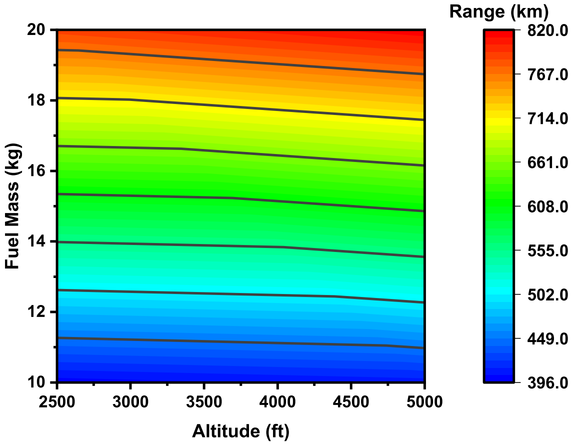

FIGURE 4. Hybrid electric fuel mass vs. altitude vs. range (ICE-only cruise).

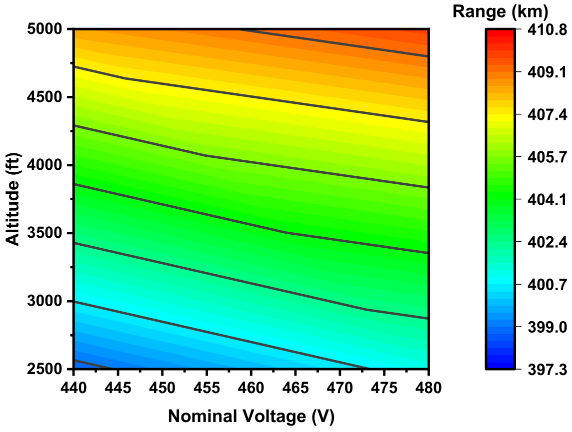

FIGURE 5. Hybrid electric altitude vs. voltage vs. range: 10 kg cases only (ICE-only cruise).

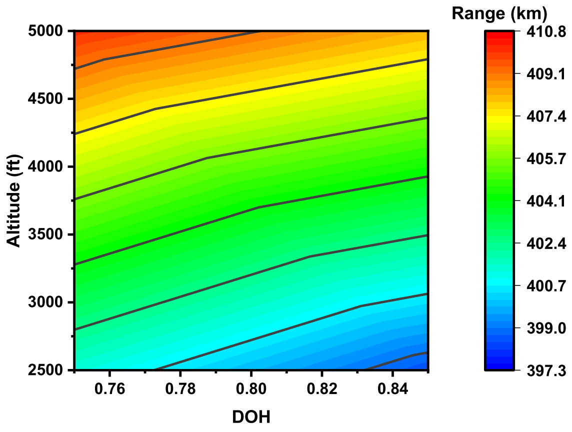

FIGURE 6. Hybrid electric altitude vs. DOH vs. range: 10 kg cases only (ICE-only cruise).

Figures 5 and 6 are nearly identical to their present-day technology counterparts in [1] in terms of overall trends. The only difference is that the range values have been scaled up. To summarize the results, an increase in nominal voltage gives an increase in range. A higher voltage means a larger number of cells and a larger overall energy storage capability of the pack since each pack has four modules in parallel. Secondly, range increases with increased altitude due to the lower air density and thus reduced power demand. Finally, a DOH of 0.75 provides a more extended range than a DOH of 0.85. Since the selected battery pack has little influence compared to the ICE, distributing the battery energy over more of the mission is found to be more beneficial. However, a lower DOH does not always mean a longer range. There is a critical point in which a lower DOH is no longer beneficial, as discussed in the next section investigating the total mission hybridization method.

A numerical comparison of the high-capacity hybrid electric ICE-only cruise simulation results to the present-day capacity results from [1] is seen below in Table 4. As previously mentioned, the simulation cases using 20 kg of fuel have a significantly higher range than those using only 10 kg of fuel. However, it is interesting to note that these cases also have a more significant range percentage increase than their 10 kg counterparts. The 20 kg of fuel cases have an average range increase of 12.6%, whereas the 10 kg of fuel cases only see an average increase of 9.1%. The reasoning behind this discrepancy is described below.

TABLE 4. **High-capacity hybrid electric results compared to low-capacity hybrid electric results from [1] (ICE-only cruise).**

Altitude (ft)	Nominal Voltage (V)	Fuel Mass (kg)	DOH	Range (km)	Range in [1] (km)	Range Increase (%)
5000	480	10	0.85	408.85	376.85	8.49
5000	480	10	0.75	410.79	376.85	9.01
2500	480	10	0.85	399.63	365.98	9.19
2500	480	10	0.75	402.49	365.98	9.98
2500	440	20	0.75	790.62	699.86	12.97
2500	440	20	0.85	787.79	699.86	12.56
5000	440	20	0.85	817.58	727.97	12.31
5000	440	20	0.75	819.36	727.97	12.55
5000	440	10	0.85	407.62	375.99	8.41
5000	440	10	0.75	409.39	375.99	8.88
2500	440	10	0.85	397.32	364.63	8.96
2500	440	10	0.75	400.14	364.63	9.74

It can be noted that the average range increases of 12.6% and 9.1% are nearly insignificant compared to the range increase of more than 300% that was seen in the fully electric results of Section III. A. Although the increase of battery capacity is the same for both cases, there are three reasons why the range increase is less substantial for the hybrid powertrain. Firstly, the impact of fuel on the overall range still overpowers that of the battery pack, as was seen in Figs. 3–4. Secondly, the allowable battery pack of the hybrid powertrain has less energy storage capability, due to fewer cells, to accommodate the required fuel as calculated in the mass analysis of [1]. Finally, and likely the main cause of the less-than-expected range increase, is the ICE selection. The reference data of the selected ICE [21] shows that the minimum power output of the ICE is approximately 30 kW. Therefore, the minimum fuel consumption also occurs at this point. However, the total power requirement is approximately 40 kW during cruise, meaning that all simulation cases using a DOH of 0.25 or more will have the ICE operating at the same fuel consumption value, its minimum. When using higher capacity batteries, the DOH is also increased to enable the ICE-only cruise condition, as previously discussed. In an ideal scenario, increasing the DOH makes the hybrid electric system more and more like a fully electric one, with less fuel being burned overall. However, since fuel continues to be consumed at the same rate with DOHs greater than 0.25, the range benefit of the capacity increase is not as prominent as expected. These results suggest that with future battery technologies, there is significant potential to achieve higher ranges by selecting a powerplant which has more suitable operational characteristics at low power demands and implementing an adaptive energy distribution method.

The explanation of the less-than-expected range increase due to the increased DOH and no benefit on the fuel consumption is the main cause of the larger range increase for the 20 kg of fuel cases. In the simulations with 10 kg of fuel, the ICE-only cruise condition was very short-lived due to the increased battery capacity allowing for a longer hybrid period. However, this actually had a negative effect on the overall range because it meant that there was a longer period in the hybrid condition which, as explained, had no benefit in fuel consumption despite an increase in DOH. Therefore, when utilizing 20 kg of fuel, more time is able to be spent in the ICE-only condition, which saves overall powertrain energy. The results presented in Table 4 also show that the future capacity ICE-only cruise cases with 10 kg of fuel provide ranges that are only about 2% longer than the future capacity fully electric results. This small difference is likely also due to the same finding. If the fuel consumption continued to decrease with increasing DOH, the difference in the fully electric and hybrid electric results would be larger, but this is not realized given the selected ICE.

To help curb the undesirable constant fuel consumption condition that is seen in the hybrid models with DOHs greater than 0.25 and to realize the full range potential of a hybrid powertrain, a new energy distribution method is proposed, known as "battery-only cruise". The algorithm operates in a similar manner to the ICE-only cruise, except the ICE-only condition is replaced by a battery-only condition. This condition states that when the fuel mass remaining reaches a previously defined value, and the mission is in its cruise phase, the battery pack will generate all power required (i.e., fully electric). The powertrain will operate using a DOH less than 0.25 during the beginning and ending of the mission in order to maximize the powertrain energy without any waste. This algorithm will be investigated in Section III. D. to study how much of an effect on range it will have compared to the results of the ICE-only cruise algorithm previously presented.

C. HYBRID ELECTRIC RESULTS (TOTAL MISSION HYBRIDIZATION)

The results of the hybrid simulations using the total mission hybridization method and future battery technology are compared with the results of the future capacity ICE-only simulations presented in the previous section. This comparison will determine whether energy distribution method continues to impact range, as was proven for hybrid simulations with present-day battery technology in [1]. This section will also determine the critical value of DOH at which the total mission hybridization method becomes more beneficial over the ICE-only cruise method.

The range results of 20 simulations with varying DOH and altitude/battery combinations are shown in Tables 5 and 6, where altitude 1 is 5000 ft, altitude 2 is 2500 ft, and the battery data was previously listed in Table 2. The fuel mass is kept constant at 10 kg for all simulations to be able to study the trends without the overwhelming range impact using 20 kg of fuel. Table 5's change in range value is compared to the same simulation run for the ICE-only cruise case with an 0.85 DOH, while Table 6's is compared to the ICE-only cruise case with a 0.75 DOH. The highlighted cells represent the maximum range case.

TABLE 5. **Total mission hybridization simulation results compared to 85% DOH future capacity ICE-only cruise simulations (highlighted values correspond the maximum range cases).**

Battery 4, Altitude 1			Battery 5, Altitude 1		
DOH	Range (km)	ΔRange (km)	DOH	Range (km)	ΔRange (km)
0.48	411.46	2.61	0.46	411.45	3.83
0.50	411.48	2.63	0.48	411.46	3.84
0.52	411.49	2.64	0.50	411.47	3.85
0.54	411.49	2.64	0.52	407.51	-0.11
0.56	407.55	-1.30	0.54	404.32	-3.30
Battery 4, Altitude 2			**Battery 5, Altitude 2**		
DOH	Range (km)	ΔRange (km)	DOH	Range (km)	ΔRange (km)
0.48	410.47	10.84	0.44	410.46	13.14
0.50	410.48	10.85	0.46	410.47	13.15
0.52	404.79	5.16	0.48	410.44	13.12
0.54	390.83	-8.80	0.50	386.67	-10.65
0.56	377.88	-21.75	0.52	372.88	-24.44

TABLE 6. **Total mission hybridization simulation results compared to 75% DOH future capacity ICE-only cruise simulations (highlighted values correspond the maximum range cases).**

Battery 4, Altitude 1			Battery 5, Altitude 1		
DOH	Range (km)	ΔRange (km)	DOH	Range (km)	ΔRange (km)
0.48	411.46	0.67	0.46	411.45	2.06
0.50	411.48	0.69	0.48	411.46	2.07
0.52	411.49	0.70	0.50	411.47	2.08
0.54	411.49	0.70	0.52	407.51	-1.88
0.56	407.55	-3.24	0.54	404.32	-5.07
Battery 4, Altitude 2			**Battery 5, Altitude 2**		
DOH	Range (km)	ΔRange (km)	DOH	Range (km)	ΔRange (km)
0.48	410.47	7.98	0.44	410.46	10.32
0.50	410.48	7.99	0.46	410.47	10.33
0.52	404.79	2.30	0.48	410.44	10.30
0.54	390.83	-11.66	0.50	386.67	-13.47
0.56	377.88	-24.61	0.52	372.88	-27.26

It was found that the optimal DOHs ranged from 0.46–0.54, depending on the battery and altitude combination. The simulation results with a less than optimal DOH value still show an increased range compared to the ICE-only cruise missions. In this case, the fuel reserve has been depleted upon landing, but some battery energy remains. The range values of these cases are not significantly smaller than the optimal range value because the battery's specific energy is much less than that of fuel (even with the future capacity), therefore the remaining battery energy upon landing does not show much of an impact. A DOH value greater than the optimal shows a near-zero or negative change in range compared to the ICE-only cruise missions, meaning that when the battery has been depleted up to the 20% SOC limit upon landing, some fuel mass remains. Thus, the optimal DOH cases involve both the fuel reserve and the battery pack depleted to their minimum levels upon landing.

One notable result seen in Tables 5 and 6 is that the change in range values is more significant for altitude 2 cases. This difference is because all hybrid missions are triggered to begin their descent at the same point, and since the altitude 2 cases are already closer to the ground, they will have a shorter descent overall and thus use less energy during descent. This means that for ICE-only missions, an altitude 2 case will land with more energy remaining than an altitude 1 case. In the total mission hybridization results, both altitude cases have completely used both fuel sources because their DOHs are optimized. Therefore, since the ICE-only altitude 2 case had more overall energy remaining than the ICE-only altitude 1 case, the change in range is more significant for altitude 2 energy distribution method comparisons.

A difference between these results and those presented in [1] is that when using present-day battery technology, the optimal value of DOH was found to be only dependent on the battery configuration and does not seem to be related to the altitude. In [1], both cases using battery 4 have an optimal of 0.13 and both cases using battery 5 have an optimal of 0.12. In the results presented in Tables 5 and 6, it is seen that each combination of altitude and battery configuration shows a different optimal DOH. It is known from previous results sections that battery configuration (total energy storage) and cruising altitude are both key parameters in increasing range and would thus both impact the optimal DOH case. Therefore, the perceived relationship from the present-day total mission hybridization cases that suggested optimal DOH only depends on battery configuration is not valid for all cases.

D. HYBRID ELECTRIC RESULTS (BATTERY-ONLY CRUISE)

As mentioned at the end of Section III. B., battery-only cruise is an energy distribution method introduced in this study to help curb the undesirable constant fuel consumption condition that is seen in the hybrid models with DOHs greater than 0.25 and to realize the full range potential of a hybrid powertrain. This section will highlight the results of this method using the same simulation parameter combinations as the previous sections and prove whether or not this method is useful in maximizing range.

The hybrid electric model with the battery-only cruise energy distribution method calculated maximum ranges of 938.0 km and 563.7 km using 20 kg and 10 kg of fuel, respectively, with the parameter combinations selected. These values are 72.8% and 43.8% of the traditionally powered aircraft model's range at the selected cruise true airspeed, the largest recorded values of any energy distribution strategy in this study or in the results of [1].

To achieve the battery-only cruise conditions, the DOH had to be reduced significantly below the critical DOHs found in Section III. C. using the total mission hybridization method. This is because, as previously mentioned, a less than optimal DOH value means that the fuel reserve has been depleted upon landing, but some battery energy remains. However, implementing the battery-only cruise algorithm will fully utilize all battery energy in an attempt to maximize range. Therefore, for these simulations, DOHs of 0.2 and 0.1 are selected to showcase the algorithm's capabilities with a long battery-only cruise period.

A numerical comparison of the hybrid electric battery-only cruise results to the hybrid electric ICE-only cruise simulation results presented in Section III. B. is seen below in Table 7. This comparison shows that the prediction previously made, which stated that battery-only cruise energy distribution method is more beneficial for future battery technology, is proven correct. It was found that the range is significantly increased compared to the previously presented ICE-only cruise results, a maximum range increase of 37% is found. The main trends observed in the results are nearly identical to those seen in the ICE-only cruise results seen in Figs. 3–6. To summarize, results showed that range is proportional to altitude, nominal voltage, and most significantly, fuel mass.

TABLE 7. **Hybrid electric battery-only cruise results with a comparison to the hybrid electric ICE-only cruise.**

Altitude (ft)	Nominal Voltage (V)	Fuel Mass (kg)	DOH	Range (km)	Range Increase (%)
5000	480	10	0.2	546.81	33.74
5000	480	10	0.1	563.66	37.21
2500	480	10	0.2	522.31	30.70
2500	480	10	0.1	540.10	34.19
2500	440	20	0.1	906.24	14.62
2500	440	20	0.2	865.04	9.81
5000	440	20	0.2	890.58	8.93
5000	440	20	0.1	937.95	14.47
5000	440	10	0.2	538.86	32.20
5000	440	10	0.1	557.87	36.27
2500	440	10	0.2	515.62	29.78
2500	440	10	0.1	533.74	33.39

Table 7 also shows that the changes in range values are significantly less for the cases which used 20 kg of fuel. This discrepancy is due to the previously described relationship in Section III. B. where the 10 kg of fuel cases using ICE-only cruise were more impacted by increased DOHs providing no benefit on the fuel consumption than the 20 kg cases (because of the ICE-only condition). Therefore, using this improved energy distribution algorithm, the 10 kg of fuel cases show a significant range improvement as the problem has been solved and the full range potential of the powertrain is realized.

E. RESULTS SUMMARY

The fully electric aircraft model using 2030-batteries achieved four times the range of the present-day battery results that were predicted in a previous study [1]. With the future battery technology, the difference between the fully electric range and hybrid electric range (using ICE-only cruise and 10 kg of fuel) is nearly zero. This is a significant improvement as hybrid range results were previously found to be up to three times larger using currently available technology [1]. This major change in the results shows that battery technology improvement significantly increases the feasibility of electrified aircraft. However, the influence of fuel mass on range is still dominant with an energy density of approximately 12 times the 2030 battery predictions.

The parameter-related trends showed that an increased battery voltage (i.e., energy storage capability), higher altitudes, and lower DOHs assisted in providing longer ranges. Of these parameters, battery voltage had the most impact on the fully electric range results, while altitude and nominal voltage had a significant impact on the hybrid electric range results, for all energy distribution types. However, it was found that most of the hybrid electric range capability actually came from the superior energy density of fuel, even when future battery technologies were tested.

Varying the energy distribution method was found to yield a range benefit in [1], and was found to be even more beneficial in this study. Using the total mission hybridization method, a maximum range increase of 13.15 km (i.e., 3.5%) was accomplished compared to the ICE-only cruise results. It was also found that limitations related to the selected ICE mean that fuel consumption is constant when the DOH is 0.25 or more, significantly slowing the range improvements with increased DOHs. This issue prompted the development of a new energy distribution type, battery-only cruise.

A maximum range increase of 37% was found compared to the ICE-only cruise method when using the battery-only cruise method, which yielded the longest and most feasible range yet. Compared to the calculated range of the traditionally powered aircraft at the selected cruising speed, 1288 km, the battery-only cruise method achieved up to 72.8% using 20 kg of fuel and up to 43.8% using 10 kg of fuel. Although the battery-only cruise results continue to highlight the significant influence of fuel mass on the range, it also begins to properly showcase the capability of future battery technology in hybrid configurations.

Table 8 below highlights the combination of parameters that produced the largest range for each of the powertrain, energy distribution, battery technology, and fuel mass combinations. The trends which were described in this section can be clearly seen in this table.

TABLE 8. Maximum range parameters and results for each simulation type.

Powertrain Type	Nominal Voltage (V)	DOH	Range (km)	Comparison to Traditional Range (%)
Fully Electric	800	N/A	390.21	30.30%
Hybrid ICE-only cruise: 10 kg fuel	480	0.75	410.79	31.89%
Hybrid ICE-only cruise: 20 kg fuel	440	0.75	819.36	63.61%
Total Mission Hybridization	480	0.54	411.49	31.95%
Hybrid Battery-only cruise: 10 kg fuel	480	0.10	563.66	43.76%
Hybrid Battery-only cruise: 10 kg fuel	440	0.10	937.95	72.82%

IV. CONCLUSION

This study explored the potential of using electrified propulsion with a battery energy density that is predicted to be available by 2030. Compared to the present-day technology, a major improvement in the overall feasibility of such propulsion systems appears to be possible, which manifests itself in an increase in overall range. However, even the best range results did not yet achieve the same range as the conventionally powered aircraft model at the selected cruise true airspeed. Nevertheless, this highlights well the impact that future battery technologies will have on possible flight ranges.

The predicted future battery advancements of the year 2030 hold the opportunity for being more widely implemented in LSA aircraft. The range capabilities are still slightly lacking compared to a traditionally powered aircraft, but the improvements seen may catalyze the progressive adoption of electrified powertrains if the potential ranges are close to the values achieved by the models in this study. For example, a range of approximately 73% of a traditionally powered aircraft was achieved using battery-only cruise and 20 kg of fuel. It was also shown in this study that the energy distribution method and the properties of the selected ICE have a major impact on the range and thus overall feasibility, so there is still potential for more efficient distribution strategies that will increase range capabilities even further.

To conclude, implementing electrified propulsion systems powered with future battery technology predictions presents a much more feasible option in terms of range capability than using present-day battery technology. However, the calculated future ranges are still below those of traditionally powered LSAs. The predictions of the range made for the future of light-sport aircraft using the various aircraft models have highlighted the fact that improving battery technology over time is key to electrified aircraft feasibility. These results will hopefully demonstrate the need for further research in battery energy density improvement to make aircraft electrification a reality in the not-so-distant future. The simulation models described in this study can be adapted to future research needs to continue studying and improving the aircraft electrification field to reduce major pollutant sources in the aviation industry.

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