



DETERMINISTIC HYBRID POWER RATIOS CONSIDERING VARIOUS FAILURE CASES FOR QUAD TILTROTOR AIRCRAFT

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Abstract

This paper study presents the deterministic hybrid power ratios, aimed at devising of the most lightweight series hybrid electric propulsion system for a generic quad tiltrotor aircraft. The research is guided by five proposed sizing elements, which inform the configuration proposals for the hybrid propulsion system. A key aspect of this study is the comparative analysis of four failure cases—One Engine Inoperative (OEI), One Battery pack Inoperative (OBI), One Proprotor Inoperative (OPI), and OPI+OBI—against three failure cases (OEI, OBI, OPI). This analysis focuses specifically on reducing the aircraft's gross weight. The research thoroughly investigates various parameters that influence the hybrid power sources, including the number of turbo-generators, battery packs, and lift rotors (or tiltrotors). Furthermore, the paper proposes the best TG configuration of the hybrid electric propulsion system with the deterministic hybrid power ratios, tailored to the current level of battery pack technology. The findings of this study aim to significantly improve the safety, reliability, and efficiency of hybrid eVTOL aircraft, contributing substantially to the advancement of modern aviation propulsion technology.

Keywords: Hybrid power ratio, Failure cases, Series hybrid-electric propulsion, eVTOL aircraft

1. Introduction

The trend towards electrification in aviation has seen a rise in the use of electric propulsion systems, especially for shorter flights in urban settings [1-3]. This movement supports global environmental sustainability goals and meets the demands for more efficient urban transportation methods [4-5]. In particular, Electric Vertical Takeoff and Landing (eVTOL) vehicles, including types like the generic quad tiltrotor aircraft [6], are becoming increasingly important due to their operational efficiency in urban air mobility [7,8].

However, the use of purely electric propulsion in Regional Air Mobility (RAM) encounters challenges, mainly the limited flight range and endurance, constrained by current battery technology [9-11]. To counter these limitations, hybrid electric propulsion systems, combining electric elements like batteries with conventional power sources such as gas turbines, have become more prominent [12-14]. These hybrid systems are known for their enhanced efficiency and lower emissions, offering a more adaptable alternative to conventional propulsion methods [15-18].

This research delves into the realm of hybrid electric power sources for eVTOLs, specifically exploring the synergy between batteries and gas turbines. The focus is on utilizing the strengths of each power source to achieve an overall more efficient propulsion system. The study examines three primary types of hybrid systems: Series Hybrid, Parallel Hybrid, and Series-Parallel Hybrid, with a particular emphasis on the series hybrid electric propulsion system [19, 20]. This system is recognized for its fuel efficiency and adaptability to different operational modes, making it a promising choice for future aircraft designs [12,21,22]. An important aspect of these propulsion systems is the hybrid power ratio, which determines the balance between electric power from the battery and the total power needed [23].

This paper sets out to propose a deterministic hybrid power ratio, targeting the development of the

lightest possible series hybrid electric propulsion system for generic quad tiltrotor aircraft. Central to these systems is the hybrid power ratio, which is pivotal in balancing electric and total required power. Prior studies have examined this ratio across different configurations, scrutinizing its effects on flight range and battery weight. Importantly, sizing hybrid power sources for aircraft, unlike ground vehicles, necessitates factoring in failure cases of each power source, including One Engine Inoperative (OEI), One Proprotor Inoperative (OPI), and One Battery Pack Inoperative (OBI).

This paper proposes a deterministic hybrid power ratio, targeting the development of the lightest possible series hybrid electric propulsion system for quad tiltrotor aircraft. The research focuses on the configuration of the propulsion system, structured around five proposed sizing elements. These sizing elements facilitate straightforward calculations of the required energy and power based on the mission profile, employing simplified models for key components like a battery and Turbo-Generator(TG). In this study, the deterministic hybrid power source is mathematically examined by considering the number of TGs, battery packs, and lift rotors (or tiltrotors). A comprehensive comparative analysis is conducted, contrasting cases with four failure modes (OEI, OBI, OPI, OPI+OBI) against those with three (OEI, OBI, OPI). This analysis highlights the importance of reducing the aircraft's gross weight while ensuring operational efficiency and safety. Furthermore, the paper introduces an innovative approach for configuring the TGs, designed to align with the latest developments and state of battery technology.

2. Vehicle Requirements and Information for Hybrid Power Sources

2.1 Mission requirement and performance estimation model

In the realm of hybrid power source sizing for aircraft, our methodology begins with defining a mission profile, modeled on NASA's 2-hop concept [24] but with an extended range of 60nmi per hop, aggregating to 120nmi, as depicted in Fig.1. The profile encompasses three distinct operational modes: Ground mode including 'Taxi' for terrestrial locomotion, VTOL phases including 'Hover', 'Hover Climb', 'Transition', and 'Descend' for vertical dynamics, and Airplane mode covering 'Acceleration + Climb' and 'Cruise' for longitudinal flight. This tripartite categorization facilitates an exhaustive analysis of the aircraft's capabilities across diverse flight conditions. The transition from VTOL to airplane mode poses significant predictive challenges in initial sizing [25], thus we approximated it with the hover phase. Additionally, we adopted a conservative stance in the fixed-wing descent phase, opting for a no-credit descent [24], which is a standard in aircraft design philosophy. Also, in our research, we have ensured that the takeoff and cruise altitude conditions, as well as the reserve mission requirements, are all congruent with the findings from NASA's studies. By aligning these aspects, as detailed in Table 1, with a payload of 1100lb and a cruise speed of 140knots, our vehicle requirements faithfully reflect the UAM mission profile as proposed by NASA [24], thereby solidifying our research's alignment with established studies in the sector. The hover climb rates, complying with 14 CFR Part 27 & 29, Category A, are set at 500fpm normally and 150fpm under failure conditions. The performance prediction model in Table 2, rooted in momentum theory, correlates with the three flight modes defined in our mission profile: Ground, VTOL, and Airplane mode, providing a comprehensive approach to evaluating aircraft performance in these modes [26, 27]. For aircraft performance calculations, the essential input variables are listed in Table 3. This study assumes the retrofit of a generic quad tiltrotor aircraft from a pure battery-powered system to a hybrid electric power source. This retrofit is intended to enable longer flight ranges while providing improved performance without requiring modifications to the airframe or payload.

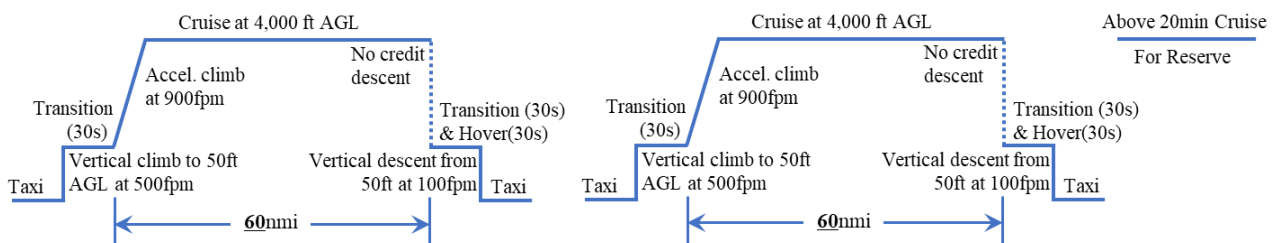


Figure 1 – Sizing mission profile

Table 1. Vehicle requirement

Category	Requirement
Payload	1,100 lb
Mission Range	120 nmi (2 hops, 60 nmi + 60 nmi)
Cruise Speed	140 knot
Takeoff Altitude	6,000 ft mean sea level (MSL)
Cruise Altitude	4,000 ft above ground level (AGL)
Hover Climb Rate	500 fpm for normal operating conditions 150 fpm for failure cases
Climb Rate at Airplane Mode	900 fpm
Reserve	20 min

Table 2. Simplified performance estimation model

Flight mode	Required power
Ground (Taxi)	10% of cruise power
VTOL (Hover Climb / Transition (=Hover) / Descend)	$P_{VTOL, req} = \frac{k_{download} mg \left(\frac{V_{Hover.climb}}{2} + \sqrt{\left(\frac{V_{Hover.climb}}{2} \right)^2 + \frac{DL}{2\rho}} \right)}{\eta_{electric} FM}$
Airplane (Cruise)	$P_{cruise, req} = \frac{GW V_{cruise}}{\eta_{electric} \eta_{prop} L/D}$

Table 3. Assumed parameters related to aircraft characteristics

Aircraft Characteristics Parameter	Input value
The number of tilt rotor	4 EA
Figure of Merit	0.75 ~ 0.78
Download factor	1.1
Prop. efficiency	0.8
Lift to Drag ratio	15
Control margin	1.05 ~1.10
Electric efficiency	0.85~0.90

2.2 Hybrid electric propulsion system for generic quad tiltrotor aircraft

In the design of hybrid electric VTOL aircraft, using a series hybrid electric propulsion system is seen as the best way to achieve high efficiency. In the series hybrid power system of a generic quad tiltrotor aircraft, all four proprotors are individually powered by their own set of dual redundant electric motors, as shown in Fig. 1. This hybrid power system is designed with four battery packs and either single or twin TG configurations to supply the necessary power for specific mission segments. The power is then efficiently distributed and managed via a Power Management and Distribution (PMAD)

unit, which channels electricity to each inverter, while also enabling the recharging of some of the energy. This system necessitates the calculation of the hybrid power ratio between the TG and the battery, a crucial parameter for delivering power to each electric motor and charging batteries. The hybrid power ratio is mathematically defined by Eq. (1), which illustrates the proportion of electrical power drawn from the battery relative to the total useful power [22]. The hybrid power ratio (H_p) is determined as 0 when the aircraft operates solely on TG power, and 1 when it relies entirely on battery power. An H_p between these values reflects a combined use of TG and battery. Additionally, a negative H_p value indicates that the TG is charging the battery. This variability in H_p , contingent on various flight segments and operational conditions, guides the sizing of hybrid power sources. This paper investigates the determining of hybrid power ratios to establish the least required capacity of the hybrid power source. With this objective in mind, we assume constant TG specific power and SFC, despite actual variations due to factors such as temperature, altitude, and operational conditions. Table 4 presents a detailed summary of key parameters for both the TG and the batteries in the hybrid power source. A simplified battery cell model [28] has been employed to address its voltage drop influenced by residual capacity. The formula presented in Eq. (2) rigorously establishes an effectiveness factor that is dependent on the battery's State of Charge (SoC), incorporating a standard constant representative of the battery model.

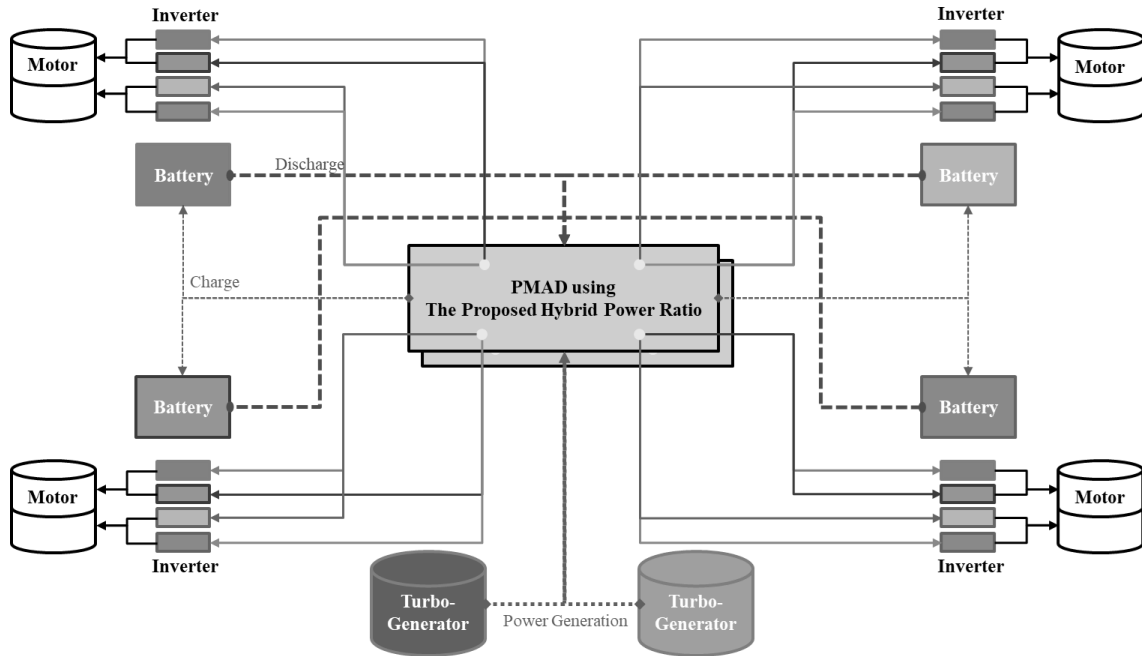


Figure 2 – Series hybrid electric propulsion system for quad tilt rotor aircraft

$$H_p = \frac{P_{bat}}{P_{bat} + P_{TG}} \quad (1)$$

- (a) TG only: $H_p = 0$
- (b) Battery discharge only: $H_p = 1$
- (c) TG + Battery discharge: $0 < H_p < 1$
- (d) TG + Battery charge: $H_p < 0; P_{bat} < 0$

$$e_{soc} = \frac{SoC}{1 - \varepsilon(1 - SoC)} \quad (2)$$

Table 4. key parameters of the hybrid power source

	Key parameter	Input value
Battery	The number of battery packs	4 EA
	State of Health(SoH) at End of Life(EoL)	90%
	Depth of Discharge(DoD) after reserve	50%
	Initial battery State of Charge(SoC)	85%
	Constant of voltage drop model by battery SoC	0.95
	Maximum discharge rate	9 C
	Proportion of continuous power to maximum power	56% (5 C)
TG	Maximum specific power (incl. installation weight)	1.64 kW/kg
	Proportion of continuous power to maximum power	93%
	Specific Fuel Consumption (SFC)	0.37 kg/kWh

3. Deterministic Initial Sizing Methodology

3.1 Five sizing elements for hybrid power systems

This chapter introduces five sizing elements that are designed to effectively allocate each available power in hybrid power systems. These sizing elements aim to achieve the minimum gross weight of the aircraft while ensuring safe flight, even under various failure conditions. These five sizing elements for hybrid power sources can be categorized into two power sizing elements (#1 and #2) and three energy sizing elements (#3 - #5). The power sizing elements #1 and #2 guide the determination of the capacity of key propulsion components to ensure safe and efficient flight under both normal and failure conditions. The energy sizing elements #3 - #5 provide guidance on the utilization of aviation jet fuel and battery energy for each mission profile, taking into account the characteristics of propulsion components.

Five sizing elements for hybrid power sources

- # 1. VTOL capability in any failure cases.
- # 2. Safe battery operation in normal flight condition
- # 3. Primary use of more efficient energy source (higher specific energy) in cruise flight
- # 4. Charge battery energy in nominal cruise flight
- # 5. Use all remaining energy in the reserve flight

The first element focuses on the requirements for hybrid power sources to maintain robust VTOL functionality in any failure cases. This sizing element ensures the aircraft's safety by guaranteeing reliable VTOL capabilities even in critical failure situations. This should allow safe VTOL flight, including when the battery has the lowest SOC after reserve flight. Second element specifies safe battery power use when operating VTOL under normal conditions. This guides battery operation below the maximum continuous discharge rate. This approach ensures both the longevity of the batteries and the consistent operational efficiency of the aircraft. Third element details the strategy for operations in the cruise flight. It gives precedence to utilizing a power source (TG) with higher specific energy for cruise flights with the longest flight time, aiming to reduce the weight of energy payloads. The fourth sizing element guides the battery to charge during nominal cruise flight, facilitating efficient power management for VTOL function. It includes maintaining a consistent SoC in the battery before and after nominal mission, aiding in straightforward energy consumption calculations. The last sizing element guides the aircraft to use up all of its remaining energy. This helps set the hybrid power ratio during a reserve cruise flight, which only uses up to the SoC of the VTOL-enabled battery and the rest uses fuel. Consequently, they contribute to the calculation of hybrid power ratios, each tailored to specific operational conditions, as presented in Table 5. Hybrid power calculation formulas of VTOL

and cruise mode calculated based on the available battery and TG power has been proposed. Since the reserve cruise flight uses battery energy, the hybrid power of the reserve cruise is calculated using the available battery power and the minimum SoC to enable VTOL. Hybrid power ratios for various failure cases guided by sizing element #1 is described in the following sections.

Table 5. Hybrid power ratio for normal flight

Flight mode	Hybrid Power Ratio		Sizing Element
	Based on battery power	Based on TG power	
VTOL	$\frac{P_{bat.avail} C_{bat.cont}}{P_{VTOL,req} C_{bat.max}}$	$1 - \frac{P_{TG.avail}/R_{TG.cont of Max}}{P_{VTOL,req}}$	#2
Cruise	$-\frac{P_{charge}}{P_{cruise.req}}$	$-\frac{E_{charge}}{E_{cruise.req}}$	#3 and #4
Reserve Cruise	$\frac{P_{bat.avail}}{C_{bat.max} e_{SoC}} (SoC_{ini} - SoC_{VTOL})/E_{reserve} \leq 1$		#5

3.2 Hybrid power ratios considering various failure cases

It is important to define the potential failures for an eVTOL aircraft before adhering to sizing element #1. Typically, for conventional aircraft with engines, a single engine failure is characterized as a One Engine Inoperative (OEI). This could be analogous to a failure in one TG in eVTOL aircraft. Additionally, a malfunction in one battery pack is categorized as a One Battery pack Inoperative (OBI). A failure involving the propeller or its associated motors constitutes a One Proprotor Inoperative (OPI). These are the three generally potential failure cases. However, in the case of a generic quad tiltrotor aircraft, where motors, propellers, and batteries are collocated within a single nacelle, there exists a possibility for a more complex failure case. This unique design could lead to a combined situation of One Proprotor Inoperative and One Battery Inoperative (OPI+OBI), particularly in events such as a battery fire. Therefore, it might also be necessary to consider this four failure cases. By separately analyzing both the three and four failure cases, this paper conducted comparative analysis of the sizing results for two types of potential failure cases depending on the battery position.

Potential failure cases are

- (1) One Engine Inoperative (OEI)
- (2) One Battery pack Inoperative (OBI)
- (3) One Proprotor Inoperative (OPI)
- (4) One Proprotor Inoperative + One Battery Inoperative (OPI+OBI)

The capacity of each power source in an eVTOL aircraft is primarily influenced by the hover climb segment of the mission profile, which requires the highest power. To compare the total minimal available power consistently across different failure cases, the available power capacities are non-dimensionalized by normalizing them against the required power at the hover climb segment specified for the failures cases. Since the minimal total power available may be expressed as the sum of the available power of the battery and TG, the non-dimensionalized total power can be expressed as Eq. (3). The non-dimensionalized battery power can also be normalized to the required power, as shown in Eq. (4). Table 6 summarizes the formulas for calculating minimum non-dimensional total power and battery power based on two critical failure cases among the various potential failure cases. By comparing the minimum dimensionless total power capacity available in various potential failure cases, two critical failure cases can be found, and the minimal battery capacity available can be calculated using the dimensionless battery power calculation formula under that failure condition. The calculation of maximum required power in both the OPI and OPI+OBI cases utilizes an additional overhead factor(k_{OPI}), which is determined by the ratio of the total number of rotors to the operational rotors during the OPI. The quantity of batteries(N_{bat}) and TGs(N_{TG}) determines the power available in the

case of failure. Table 7 summarizes the hybrid power ratio calculation formula based on the battery and TG power available under each failure condition.

$$\Pi_{total.min} = \frac{P_{bat.avail} + P_{TG.avail}}{P_{VTOL,req}} \quad (3)$$

$$\Pi_{bat.min} = \frac{P_{bat.avail}}{P_{VTOL,req}} \quad (4)$$

Table 6. Non-dimensional power available (total and battery) based on two critical failure cases among various potential failure cases

Two critical failure cases	Minimum total power available ($\Pi_{total.min}$)	Minimum battery power available ($\Pi_{bat.min}$)
OEI & OBI	$\frac{N_{TG} + N_{bat}}{N_{bat} + N_{TG} - 1}$	$\frac{N_{bat}}{N_{bat} + N_{TG} - 1}$
OEI & OPI	k_{OPI}	$k_{OPI} + N_{TG} - k_{OPI}N_{TG}$
OBI & OPI		$N_{bat}(k_{OPI} - 1)$
OEI & OPI+OBI	$\frac{N_{TG} + k_{OPI}N_{bat}}{N_{bat} + N_{TG} - 1}$	$\frac{N_{bat}[k_{OPI} + N_{TG} - k_{OPI}N_{TG}]}{N_{bat} + N_{TG} - 1}$

Table 7. Hybrid power ratio for each failure case

Failure Cases	Hybrid power ratio	
	Based on available battery power	Based on available TG power
OEI	$\Pi_{bat.min}$	$\frac{P_{VTOL,req} - P_{TG.avail} \left(\frac{N_{TG} - 1}{N_{TG}} \right)}{P_{VTOL,req}}$
OBI	$\Pi_{bat.min} \left(\frac{N_{bat} - 1}{N_{bat}} \right)$	$\frac{P_{APO,req} - P_{TG.avail}}{P_{VTOL,req}}$
OPI	$\frac{\Pi_{bat.min}}{k_{OPI}}$	$\frac{k_{OPI}P_{VTOL,req} - P_{TG.avail}}{k_{OPI}P_{VTOL,req}}$
OPI + OBI	$\frac{\Pi_{bat.min}}{k_{OPI}} \left(\frac{N_{bat} - 1}{N_{bat}} \right)$	$\frac{k_{OPI}P_{VTOL,req} - P_{TG.avail}}{k_{OPI}P_{VTOL,req}}$

3.3 Initial sizing process of optimal hybrid power system

Figure 3 focuses on the sizing method of the hybrid power system during the initial sizing flowchart of the eVTOL aircraft. Initial sizing is an iterative computational process for aircraft prediction performance and predicted weight, and this study mainly deals with initial sizing of an optimal hybrid power system. The optimal hybrid power system for an aircraft means a power supply system with minimum weight capable of safely flight. Since hybrid power systems are composed of different types of power sources, the optimal hybrid power system may be configured by applying different initial sizing methods depending on the technology of each power source. When the TG technology is better than the battery, the sizing method with the minimum battery is applied, and when the battery technology is better than the TG, the sizing method with the minimum TG is applied. The minimum battery sizing method is a method of performing maximum TG power sizing using Eq. (5) by

calculating the hybrid power ratio of each operation condition through the battery power calculation formula derived from the critical failure cases in the previous section. The minimum TG sizing method first sizes the TG power available in a normal cruise flight, as shown in Eq. (6). The sum of the power required for cruise flight and the power capable of charging battery energy is the minimum TG power. The TG-based cruise hybrid ratio for cruise flights mentioned in Table 5 of Section 3.1 can be calculated as the amount of battery charged energy of the total energy required for cruise flights. The minimum TG power can be calculated using the maximum continuous power ratio to maximum rated power for the TG, $R_{TG.cont of Max}$. The maximum battery capacity can be calculated using Eq. (7) by calculating the hybrid power ratio of each normal and failure cases based on the minimum TG power. The weight estimation of hybrid power source is presented through a series of equations that correlate the weights of the TG, battery, and fuel, as illustrated in Eq. (8). Each key input parameter is detailed in Table 4 of Section 2.2.

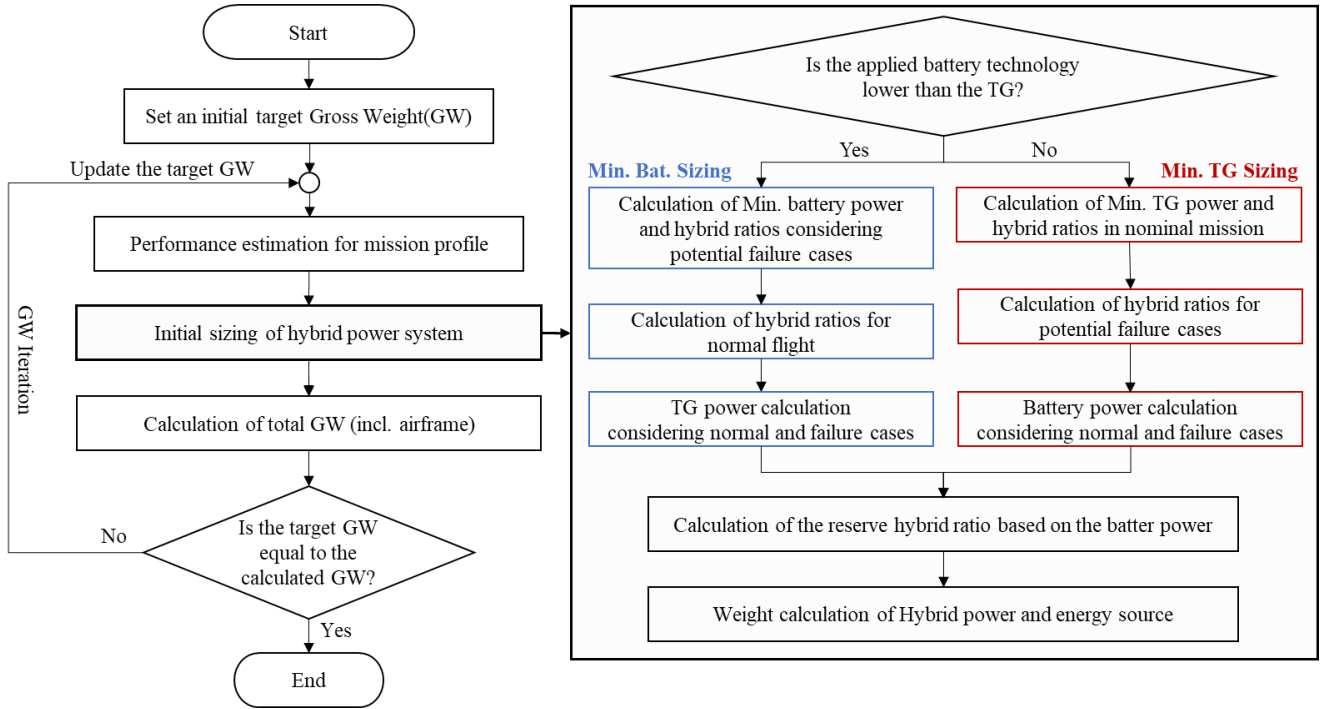


Figure 3 – Flow chart of initial sizing

$$P_{TG.avail} = \text{Max} \left[\begin{array}{l} \left(\frac{P_{cruise.req}(1 - H_{p,cruise})}{R_{TG.cont of Max}} \right)_{Cruise @Normal}, \left(\frac{P_{VTOL.req}(1 - H_{p,VTOL})}{R_{TG.cont of Max}} \right)_{VTOL @Normal}, \\ \left((1 - H_{p,OEI}) P_{VTOL.req} \frac{N_{TG}}{N_{TG} - 1} \right)_{VTOL @OEI}, \left((1 - H_{p,OBI}) P_{VTOL.req} \right)_{VTOL @OBI}, \\ \left((1 - H_{p,OPI}) k_{OPI} P_{VTOL.req} \right)_{VTOL @OPI}, \left((1 - H_{p,OPI+OBI}) k_{OPI} P_{VTOL.req} \right)_{VTOL @OPI+OBI} \end{array} \right] \quad (5)$$

$$P_{TG.avail} = (1 - H_{p,cruise}) \frac{P_{cruise.req}}{R_{TG.cont of Max}} \quad (6)$$

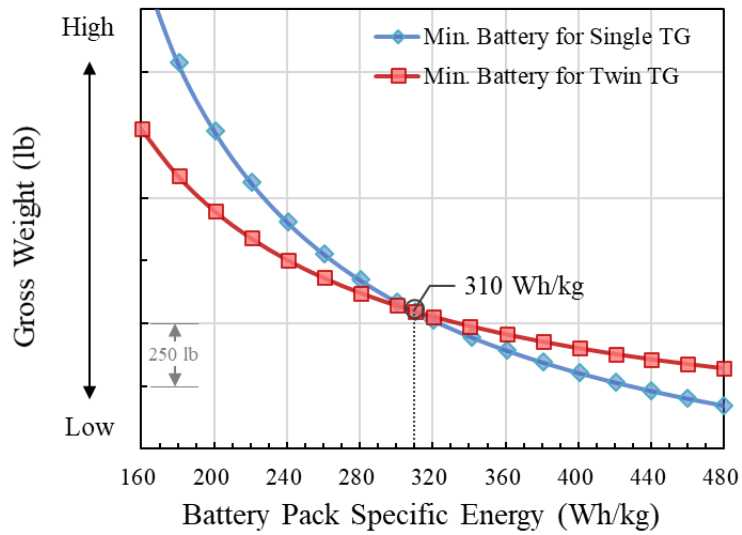
$$P_{bat.avail} = \text{Max} \left[\begin{array}{l} \left(H_{p,VTOL} P_{VTOL.req} \frac{C_{bat.max}}{C_{bat.cont}} \right)_{@Normal}^{VTOL}, \\ \left(H_{p,OEI} P_{VTOL.req} \right)_{@OEI}^{VTOL}, \left(H_{p,OBI} P_{VTOL.req} \frac{N_{bat}}{N_{bat} - 1} \right)_{@OBI}^{VTOL}, \\ \left(H_{p,OPI} k_{OPI} P_{VTOL.req} \right)_{@OPI}^{VTOL}, \left(H_{p,OPI+OBI} k_{OPI} P_{VTOL.req} \frac{N_{bat}}{N_{bat} - 1} \right)_{@OPI+OBI}^{VTOL} \end{array} \right] \quad (7)$$

$$\frac{P_{TG.avail}}{SP_{TG.max}} + \frac{P_{bat.avail}}{SP_{bat.max} e_{SoC} SoH_{EoL}} + SFC(E_{nominal} + (1 - H_{p.reserve}) E_{reserve}) = W_{HPS} \quad (8)$$

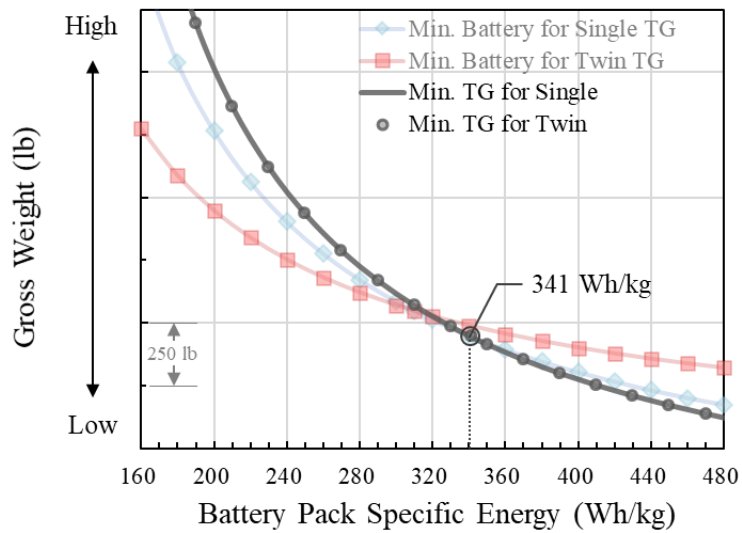
4. Results

4.1 Deterministic hybrid power source considering three failure cases

This is the initial sizing results, considering three failure cases (OEI, OBI, OPI), when the battery is not located in the nacelle. The study maintains constant values for the airframe and payload to concentrate on analyzing the hybrid power system. As a component of hybrid power systems, TGs have already reached a sufficient level of technological maturity. In contrast, battery technology is in a state of ongoing development. As such, this analysis includes a detailed exploration of various technological levels of battery packs. Fig. 4 depicts the gross weight comparison based on technological maturity of battery pack specific energy for hybrid electric propulsion systems with Single and Twin TG. The number of battery packs is fixed and single and twin TG configurations are compared. The initial sizing result for the minimum battery sizing method applied when TG technology is better, as shown in Fig. 4 (a). It can be seen that the better the battery technology, the lighter the total weight of the aircraft. Depending on the Single and Twin TG, the slope is different, and the intersection point where the weight of Single and Twin are equal can be found. When the battery pack's specific energy is below the threshold of 310 Wh/kg at the intersection point, Twin TG can design a lighter aircraft. Conversely, if the specific energy is higher than this threshold, Single TG can design a lighter aircraft. The initial sizing result for the minimum TG sizing method applied when battery technology is better, as shown in Fig. 4 (b). The minimum TG sizing method has the same sizing result for Single and Twin TG. The minimum TG sizing method enables the design of lighter aircraft compared to the minimum battery sizing method as battery technology improves. The intersection point (341 Wh/kg) where the same gross weight can be designed using both sizing methods can be identified. This intersection point serves as the criterion for selecting between the two deterministic initial sizing approaches. Fig. 5 illustrates only optimal sizing results considering three failure cases. When battery technology exceeds 341 Wh/kg (i.e. intersection point), the minimum TG sizing method should be applied for the hybrid propulsion system. Conversely, for battery technology below the intersection point, the minimum battery sizing method should be used. Specifically, if the specific energy is below 310 Wh/kg, the Twin TG configuration should be applied, and if it is above 310 Wh/kg and below 341 Wh/kg, the Single TG configuration should be used.



(a)



(b)

Figure 4 – Gross weight comparison based on technological maturity of battery pack specific energy; (a) single and twin TG hybrid electric propulsion system for min. battery sizing method, (b) single and twin TG hybrid electric propulsion system for min. TG sizing method

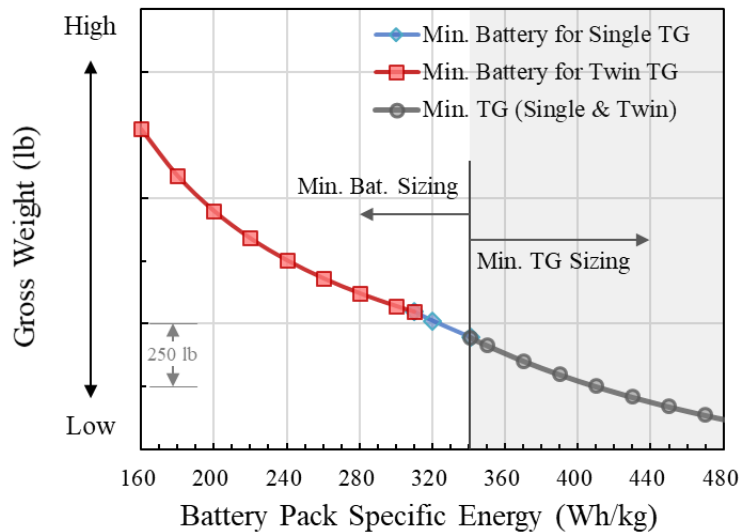


Figure 5 – Optimal gross weight based on technological maturity of battery pack specific energy

Hybrid power usage for each critical flight mode to determine initial sizing was analyzed considering three failure cases at each hybrid power system, as shown in Fig. 6. Twin TG hybrid power system of the minimum battery sizing method determines the available power capacity based on Hover Climb flight at the OEI and OPI cases. Single TG hybrid power system of the minimum battery sizing method determines the available power capacity based on Hover Climb flight at the OEI and normal conditions. Hybrid power system of the minimum TG sizing method determines the available power capacity based on the Cruise and Hover Climb flight at normal condition. The minimum TG sizing method determines the hybrid power system under normal flight states based on the max. continuous power, and the minimum battery sizing method determines the hybrid power system under failure cases based on the max. rated power. If the sizing results for Single and Twin TG configurations are identical, it would be advisable to choose the Twin TG configuration with power margin during normal operations for development. At battery specific energy 310 Wh/kg and 341 Wh/kg, the same sizing results (i.e. gross weight) are obtained for hybrid power systems with different deterministic hybrid power ratios. Depending on the sizing conditions, it would be preferable to select a hybrid power system with a favorable power margin.

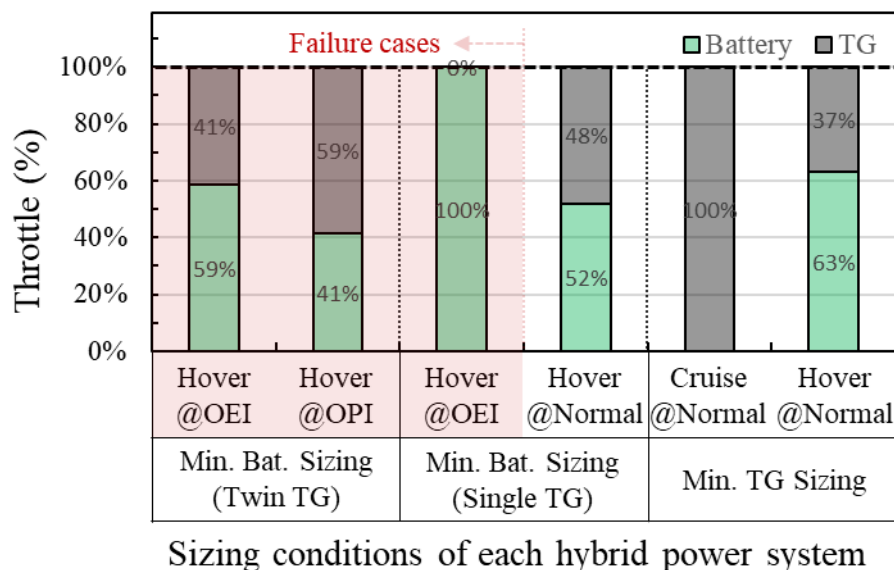


Figure 6 – Hybrid power usage in each critical flight mode to determine initial sizing considering three failure cases

4.2 Comparison between 3 failure cases and 4 failure cases

This chapter extends the analysis to include and compare sizing results under four failure cases adding the condition where both OPI and OBI occur simultaneously. Fig. 7 presents a continuation of the analysis from Fig. 5, detailed in the prior chapter. This analysis focusing on four failure cases, is represented using a dotted line, following the same symbolic representation consistently for each sizing method. Depending on the applied battery technology, considering OPI + OBI case in initial sizing results in an increase in the aircraft's gross weight by approximately 50 to 300 lb. This increase can be attributed to the need for additional power capacity, as two failure conditions occur simultaneously. It can be seen that the selection criteria for the sizing methodology to derive the optimal aircraft gross weight depends on the type of failure cases. The weight of a hybrid power system designed with a battery specific energy of 274 Wh/kg is the same regardless of the minimum battery and TG sizing method, TG configuration. Considering four failure cases, the minimal Battery sizing method applied when battery technology is low shows that twin TGs are more optimal than single TGs for designing hybrid power systems. When the battery technology increases, the minimum TG sizing technique can design the optimal hybrid power system. As shown in Fig. 8, the operating conditions for which the initial sizing of the minimum battery sizing method is determined are Single and Twin TG, and the hybrid power capacity is determined for OEI and OPI+OBI, i.e., the failure case. The minimum TG sizing method will be the TG power required for cruise flight and the hybrid power of OPI+OBI will be the sizing condition for the hybrid power system. Accordingly, a battery specific energy (274 Wh/kg) exists that can render the initial sizing outcome of the three hybrid power system types identical. Table 8 summarizes the deterministic hybrid power ratios for the on-board hybrid power system. The minimum battery sizing method allocates the remaining required power to TG based on the minimum battery power needed considering normal and failure conditions, so it decrease the hybrid power ratio in the results of the four failure cases. The minimum TG sizing method determines the maximum battery power based on the minimum TG power needed considering normal cruise condition. The deterministic hybrid ratio for the four failure cases versus the three failure cases is such that if the battery technology is worse than the TG, the hybrid power ratio is lower, and if the battery technology is better than the TG, the hybrid ratio is higher. Had the batteries been placed somewhere other than the nacelle, it would have been possible to size the aircraft based on the three failure cases without considering the OPI+OBI. This study reinforces the importance of accounting for potential failure cases from the beginning of aircraft design including battery location.

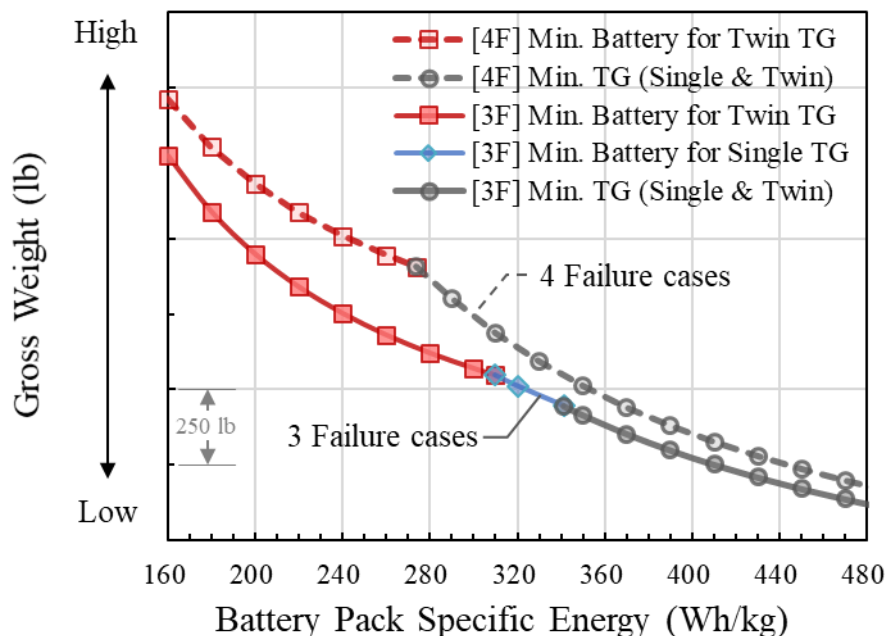
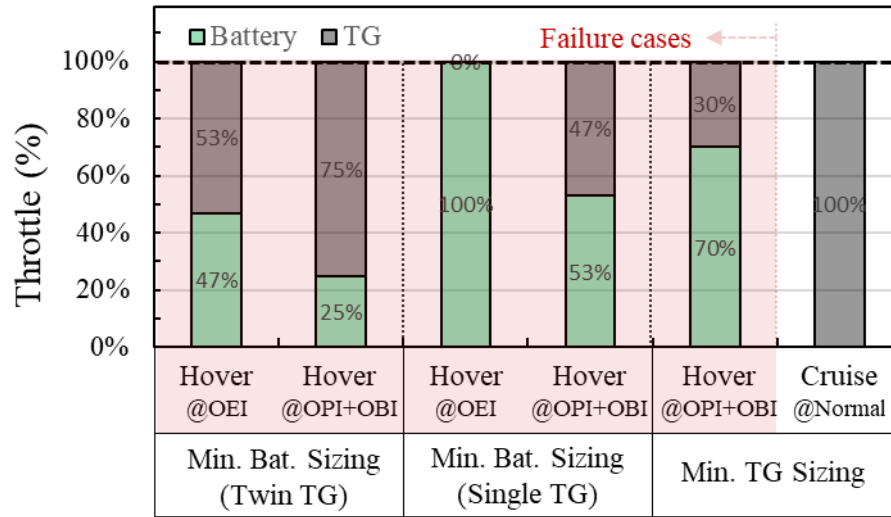


Figure 7 – Gross weight comparison based on technological maturity of battery pack specific energy considering four and three different failure cases; In the figure's legend, the dotted line represents four failure cases, and the solid line represents three failure cases.



Sizing conditions of each hybrid power system.

Figure 8 – Hybrid power usage in each critical flight mode to determine initial sizing considering four failure cases

Table 8. Deterministic hybrid power ratio of inboard hybrid power system

	Minimum Bat. Sizing (Twin)	Minimum Bat. Sizing (Single)	Minimum TG Sizing
3 Failure cases	0.43	0.65	0.75
4 Failure cases	0.32	0.61	0.77

5. Discussion (Uncertainties and limitations)

This section discusses the inherent uncertainties and limitations of the hybrid power source model used for eVTOL aircraft and some of the assumptions made in the study.

Firstly, this research relied heavily on simplified performance models and static efficiency values. These models, while facilitating a streamlined approach, lack the complexity to fully simulate actual hybrid eVTOL propulsion systems. Basic technical parameters, such as the specific energies of battery packs and fuel, along with the specific power of TG, were chosen for simplicity. However, this approach may not cover the entire spectrum of variables that exist in the real operational range of the hybrid power source.

Furthermore, the simplified battery model for SoC was conducted in this study. Although effective for the scope of our study and developed to mitigate the impact of battery SoC on available power, this model introduces inherent uncertainty. The simplified nature of our battery SoC model, while aiding in reducing the complexity of the analysis, fails to fully capture the nuanced effects of SoC variations on the battery's available power in real environment. The necessity to balance model complexity with computational feasibility led to a certain level of uncertainty. As such, our study has made strides in minimizing the impact of battery SoC on power availability, but the uncertainties arising from the simplified SoC model cannot be completely eliminated. This limitation underscores the need for future research into more sophisticated battery models that can accurately reflect the dynamic nature of battery SoC and its impact on the hybrid power system in eVTOL aircraft.

Additionally, the fixed specific power of TG, including the weights of accessories installed on the aircraft, was addressed. While practical for simplifying the initial analysis, this approach introduces a notable degree of uncertainty. This uncertainty is primarily due to variations in TG configurations

(Single vs. Twin), each with different accessory weights, and the influence of various operating environments such as altitude, temperature, humidity, and power throttle settings. Simplifying these aspects was deemed necessary in the initial design phases to concentrate on the critical parameters of interest. However, in future studies, specific power values for TGs that change under different operating conditions and environmental factors will be used to increase the fidelity of the model. This progression will enable a more detailed and accurate representation of TG performance under various operation conditions. By integrating variable specific power values, this subsequent research is expected to significantly reduce initial uncertainties and provide a more comprehensive understanding of TG dynamics in eVTOL aircraft.

To conduct an in-depth exploration of the initial sizing methodologies for hybrid power system, the critical assumption that the airframe weight is constant was made. This assumption was illustrated in the retrofit where the propulsion system of an existing battery-powered aircraft was replaced with a hybrid propulsion system. The key constraint in this retrofit was to design the hybrid power source such that its weight, combined with the airframe and payload weight, did not exceed the airframe's maximum gross weight capacity. This assumption allowed us to focus on the hybrid power source sizing exclusively, without the complexities of varying airframe weights. However, in the actual hybrid electric airplane design, the fuselage weight will change with the change of gross weight, so the slope of the fuselage gross weight will change significantly with the development of battery technology. Therefore, this study can be used to accurately calculate the requirements of the hybrid power system, which will be useful for the actual aircraft design.

6. Conclusion

A deterministic initial sizing methodology of hybrid power system on eVTOL aircraft was proposed, including the number of TGs, battery packs, and lift rotors (or tiltrotors). The operating conditions and various failure conditions were considered to determine the hybrid power ratio. The best TG configuration and deterministic hybrid ratio of the hybrid power system depend on the battery technology used. Thus, the sizing strategy is changed according to the difference in technology of batteries and TGs. As the battery technology advances, the configuration of TG (Single or Twin) and deterministic hybrid ratio have been proposed for the optimal hybrid power system design. In this study, three and four failure cases were carefully analyzed depending on the battery pack layout, and the deterministic hybrid ratio was calculated to ensure safe flight and landing under all circumstances. These insights are valuable for developing safe and efficient eVTOL aircraft. However, the simplified system model was used in this study. Future research will involve applying a more sophisticated model for hybrid power sources to achieve more refined sizing results.

References

- [1] Holden J, Goel N. *Fast-forwarding to a future of on-demand urban air transportation*. Uber White paper, 2016. [Online]. Available: <https://uberpubpolicy.medium.com/fast-forwarding-to-a-future-of-on-demand-urban-air-transportation-f6ad36950ffa>. Accessed 27 October 2016.
- [2] Garrow LA, German BJ, Leonard CE. *Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research*. Transp. Res. Part C Emerg. Technol., Vol. 132, 103377, 2021. [Online]. Available: <https://doi.org/10.1016/j.trc.2021.103377>.
- [3] Geržinič N, van Oort N, Hoogendoorn-Lanser S, Cats O, Hoogendoorn S. *Potential of on-demand services for urban travel*. Transportation, Vol. 50, No. 4, pp. 1289-1321, 2023. [Online]. Available: <https://doi.org/10.1007/s11116-022-10278-9>. Smith J, Jones B and Brown J. *The title of the book*. 1st edition, Publisher, 2001.
- [4] Lah O, Fulton L, Arioli M. *Decarbonization scenarios for transport and the role of urban mobility*. In Sustainable Urban Mobility Pathways, 2019, pp. 65-80. [Online]. Available: <https://doi.org/10.1016/B978-0-12-814897-6.00003-X>.
- [5] Miskolczi M, Földes D, Munkácsy A, Jászberényi M. *Urban mobility scenarios until the 2030s*. Sustain. Cities Soc., Vol. 72, 103029, 2021. [Online]. Available: <https://doi.org/10.1016/j.scs.2021.103029>
- [6] Park M, Choi JYJ, Park SH. *Battery Sensitivity Analysis on Initial Sizing of eVTOL Aircraft*. J. Korean Soc. Aeronaut. Space Sci., Vol. 50, No. 12, pp. 819-828, 2022. [Online]. Available: <https://doi.org/10.5139/JKSAS.2022.50.12.819>.

- [7] Moore M. *Aviation frontiers-on demand aircraft*. 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 9343, 2010. [Online]. Available: <https://doi.org/10.2514/6.2010-9343>
- [8] Johnson W, Silva C. *NASA concept vehicles and the engineering of advanced air mobility aircraft*. Aeronaut. J., Vol. 126, No. 1295, pp. 59-91, 2022. [Online]. Available: <https://doi.org/10.1017/aer.2021.92>.
- [9] Warren M, Garbo A, Kotwicz Herniczek MT, Hamilton T, German B. *Effects of range requirements and battery technology on electric VTOL sizing and operational performance*. In AIAA SciTech 2019 Forum, 0527, 2019. [Online]. Available: <https://doi.org/10.2514/6.2019-0527>.
- [10] Maheshwari A, Mudumba S, Sells BE, DeLaurentis DA, Crossley WA. *Identifying and analyzing operations limits for passenger-carrying urban air mobility missions*. In AIAA Aviation 2020 Forum, 2913, 2020. [Online]. Available: <https://doi.org/10.2514/6.2020-2913>.
- [11] Viswanathan V, Epstein AH, Chiang YM, Takeuchi E, Bradley M, Langford J, Winter M. *The challenges and opportunities of battery-powered flight*. Nature, Vol. 601, No. 7894, pp. 519-525, 2022. [Online]. Available: <https://doi.org/10.1038/s41586-021-04139-1>.
- [12] Salem KA, Palaia G, Quarta AA. *Review of hybrid-electric aircraft technologies and designs: Critical analysis and novel solutions*. Prog. Aerosp. Sci., Vol. 141, 100924, 2023. [Online]. Available: <https://doi.org/10.1016/j.paerosci.2023.100924>.
- [13] Kuśmierk A, Galiński C, Stalewski W. *Review of the hybrid gas-electric aircraft propulsion systems versus alternative systems*. Prog. Aerosp. Sci., Vol. 141, 100925, 2023. [Online]. Available: <https://doi.org/10.1016/j.paerosci.2023.100925>.
- [14] Ye XIE, Savvarisal A, Tsourdos A, Zhang D, Jason GU. *Review of hybrid electric powered aircraft, its conceptual design and energy management methodologies*. Chinese J. Aeronaut., Vol. 34, No. 4, pp. 432-450, 2021. [Online]. Available: <https://doi.org/10.1016/j.cja.2020.07.017>.
- [15] Zhang H, Saudemont C, Robyns B, Petit M. *Comparison of technical features between a more electric aircraft and a hybrid electric vehicle*. In 2008 IEEE Vehicle Power and Propulsion Conference, 2008. [Online]. Available: <https://doi.org/10.1109/VPPC.2008.4677663>.
- [16] Gladin JC, Perullo C, Tai JC, Mavris DN. *A parametric study of hybrid electric gas turbine propulsion as a function of aircraft size class and technology level*. 55th AIAA Aerospace Sciences Meeting, AIAA Paper 2017, 0338. [Online]. Available: <https://doi.org/10.2514/6.2017-0338>.
- [17] Wroblewski GE, Ansell PJ. *Mission analysis and emissions for conventional and hybrid-electric commercial transport aircraft*. J. Aircr., Vol. 56, No. 3, pp. 1200–1213, 2019. [Online]. Available: <https://doi.org/10.2514/1.C035070>.
- [18] Mangold J, Brenner F, Moebs N, Strohmayer A. *Aircraft Design Implications of Alternative Fuels for Future Hybrid-Electric Regional Aircraft Configurations*. In 9th European Conference for Aeronautics and Space Sciences 27, 2022. [Online]. Available: <https://doi.org/10.13009/EUCASS2022-7294>.
- [19] Rendón MA, Sánchez R CD, Gallo M J, Anzai AH. *Aircraft hybrid-electric propulsion: Development trends, challenges and opportunities*. J. Control. Autom. Electr. Syst, Vol. 32, No. 5, pp. 1244-1268, 2021. [Online]. Available: <https://doi.org/10.1007/s40313-021-00740-x>.
- [20] Nakka SKS, Alexander-Ramos MJ. *Simultaneous combined optimal design and control formulation for aircraft hybrid-electric propulsion systems*. J. Aircr., Vol. 58, No. 1, pp. 53-62, 2021. [Online]. Available: <https://doi.org/10.2514/1.C035678>.
- [21] Finger DF, Braun C, Bil C. *An initial sizing methodology for hybrid-electric light aircraft*. 2018 Aviation Technology, Integration, and Operations Conference, 2018. [Online]. Available: <https://doi.org/10.2514/6.2018-4229>.
- [22] Zong J, Zhu B, Hou Z, Yang X, Zhai J. *Evaluation and comparison of hybrid wing VTOL UAV with four different electric propulsion systems*. Aerospace, Vol. 8, No. 9, 256, 2021. [Online]. Available: <https://doi.org/10.3390/aerospace8090256>.
- [23] Isikveren AT, Kaiser S, Pornet C, Vratny PC. *Pre-design strategies and sizing techniques for dual-energy aircraft*. Aircr. Eng. Aerosp. Technol., Vol. 86, No. 6, pp. 525-542, 2014. [Online]. Available: <https://doi.org/10.1080/00036817.2014.944444>.
- [24] Patterson MD, Antcliff KR, Kohlman LW. *A proposed approach to studying urban air mobility missions including an initial exploration of mission requirements*. Proc. AHS Int. 74th Annu. Forum Technol. Display, 2018.
- [25] Yu X, Chen R, Wang L, Yan X, Yuan Y. *An optimization for alleviating pilot workload during tilt rotor aircraft conversion and reconversion maneuvers*. Aerosp. Sci. Technol., Vol. 129, 107854, 2022. [Online]. Available: <https://doi.org/10.1016/j.ast.2022.107854>.
- [26] Raymer DP. *Aircraft design: a conceptual approach*. 5th ed., AIAA Education Series, 2012. [Online]. Available: <https://doi.org/10.2514/4.869112>.
- [27] Leishman JG. *Principles of helicopter aerodynamics*. 2nd ed., Cambridge University Press, Cambridge, 2006.
- [28] Wang M, Diepolder J, Zhang S, Söpper M, Holzapfel F. *Trajectory Optimization-based Maneuverability*

Assessment of eVTOL Aircraft. *Aerosp. Sci. Technol.*, Vol. 117, 106903, 2021. [Online]. Available: <https://doi.org/10.1016/j.ast.2021.106903>.

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