ANALYTICAL INITIAL SIZING OF A TURBOGENERATOR-BATTERY HYBRID POWERPLANT FOR eVTOL AIRCRAFT

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Abstract

The increasing demand for long-range electric vertical takeoff and landing (eVTOL) aircraft has underscored the need for efficient hybrid powerplant systems (HPPS) that integrate turbogenerators (TGs) and batteries. This study presents HYSIZE (Hybrid System Initial Sizing Method), an analytical approach for rapidly estimating HPPS weight fraction without iterative performance–weight coupling. By embedding OEI and OBI failure cases into the design logic, the method supports fail-safe architecture essential to eVTOL reliability. Two sizing strategies, targeting either vertical climb or cruise, are introduced, and a threshold is derived to determine whether TG- or battery-dominant configurations are more suitable based on specific power differences. Below the threshold, twin TGs alleviate battery burden under OEI conditions; above it, TG count has no effect on system weight. Sensitivity analyses and case studies for 5- and 9-seat aircraft demonstrate the method's scalability and practicality, offering a structured design tool for OEMs to explore viable TG–battery combinations.

1. NOTATION

Symbols

DL	Disk loading, kg/m^2
FM	Figure of merit
k_{WD}	Wing download factor
GW	Gross weight, kg
g	Gravitational acceleration, m/s^2
V_{vert}	Vertical flight velocity, m/s
ρ	Air density, kg/m^3
P	Power, kW
P^*	Normalized power
E^*	Normalized power, hours
L/D	Lift-to-drag ratio
η	Efficiency, %
H_p	hybrid power ratio
ε	battery model constant
λ	Ratio of continuous to rated power
PL	Power loading, kg/kW
γ	Margin factor, %
SP	Specific power, kW/kg
SE	Specific energy, kWh/kg
N	Componant quantity, EA
Φ	Power relaxation
WF	Weight fraction
t	Time, hours
θ_{SP}	Sizing point factor

Acronyms

eVTOL	electric Vertical Takeoff and Landing
HPPS	Hybrid Powerplant System
UAM	Urban Air Mobility
TG	Turbo-Generator
OEI	One Engine Inoperative
OBI	One Battery-pack Inoperative
VFM	VTOL Flight Mode
VCL	Vertical Climb
CRZ	Cruise
SoC	State of Charge
SoH	State of Health
EoL	End of Life
SFC	Specific Fuel Consumption
CBS	Cruise-based Sizing
VBS	VTOL-based Sizing
SAT	Sizing Approach Transition

2. INTRODUCTION

The development of eVTOL aircraft is accelerating the realization of UAM by offering a sustainable and efficient transportation solution. However, the feasibility of fully electric propulsion remains constrained by current battery technology limitations, particularly in energy density, charging time, and degradation over lifecycle (Ref. 1, 2). To overcome these limitations, hybrid powerplant systems (HPPS) combining TGs and batteries have been proposed as a promising alternative (Ref. 3, 4). A TG consists of a turboshaft engine and a generator that converts its mechanical output into electricity. In these systems, TGs provide continuous power for cruise flight, while batteries support peak loads during VTOL operations such as takeoff, hover, and transition (Ref. 5, 6). Recent research has incorporated redundancy criteria such as OEI into HPPS sizing frameworks. Finger et al. (Ref. 7- 9) showed that including OEI constraints significantly reduces the feasible design space. De Vries et al. (Ref. 10) extended this approach to account for failure cases involving all powertrain components. However, most previous studies have not considered the OBI condition, which should be jointly addressed with OEI in TG–battery hybrid HPPS architectures to ensure comprehensive redundancy coverage. Although Finger et al. (Ref. 11) demonstrated the influence of battery-specific power on initial sizing outcomes and emphasized the critical role of component-level performance in hybrid propulsion system design, the impact of technological maturity differences between TG and battery systems on sizing strategies remains largely unexplored and is not reflected in existing methodologies. Moreover, no prior work has proposed analytical initial sizing methods capable of rapidly estimating the HPPS weight fraction based on normalized power and energy requirements without iterative computation.

This study develops a rapid, analytical method for the initial sizing of TG and battery-based HPPS in eVTOL aircraft. The proposed method estimates the HPPS weight fraction without iterative coupling between weight and performance. The method supports a fail-safe architecture by explicitly incorporating two critical failure conditions, OEI and OBI, into the sizing logic. Two alternative sizing strategies are introduced: One focuses on the vertical climb segment, while the other focuses on the cruise segment. A transition threshold is analytically derived to determine the preferable strategy based on the specific power difference of the TG and battery systems. In addition, the influence of key aerodynamic parameters such as lift-to-drag ratio and disk loading is assessed. Finally, the method is applied to two representative aircraft with different payload capacities to demonstrate its applicability to early-stage eVTOL sizing.

3. INITIAL SIZING METHOD

3.1. eVTOL aircraft characteristics

For the effective design of a HPPS for eVTOL aircraft, a clear understanding of mission-specific flight characteristics is essential. Figure 1 illustrates a simplified power consumption profile across two primary flight modes: VTOL mode, enabling vertical operations through rotary-wing-like mechanisms, and cruise mode, providing efficient wing-borne forward flight. VTOL mode requires substantially higher instantaneous power to generate lift during takeoff, hover, and descent. Its performance is largely governed by disk loading, which determines the thrust and power needed. In contrast, cruise mode operates at a lower power level over a prolonged duration, making it the most energy-intensive segment overall. Here, lift-to-drag ratio is the dominant aerodynamic factor influencing efficiency.

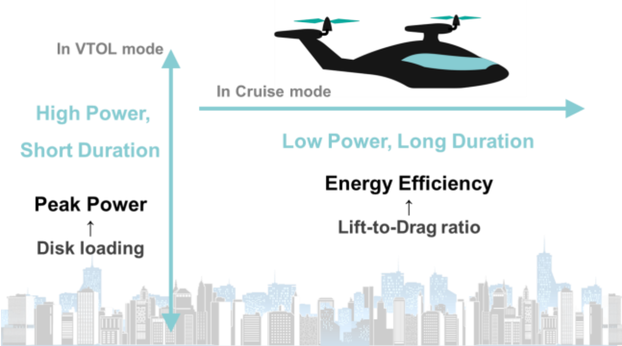


Figure 1: Simplified flight characteristics of eVTOL aircraft

Figure 2 presents the sizing mission profile used to perform the initial sizing of the HPPS for long-range eVTOL aircraft (Ref. 12). This profile includes both a nominal mission and a reserve cruise segment. In line with regulatory requirements applied to fixed-wing aircraft under instrument flight rules, a 45-minute reserve cruise is incorporated. This reserve is appropriate for eVTOL applications, as the aircraft operates in wing-borne cruise mode at its designated cruise speed during this segment. The cruise flight speed is defined by a speed of 300 km/h at an altitude of 1,500 feet above ground level (AGL). For simplification, the total mission range is assumed to consist solely of a 300 km cruise segment, excluding the effects of accelerated climb and decelerated descent. Transitions between vertical and cruise flight are replaced with a hover segment. Vertical climb and descent rates are set to 500 feet per minute (fpm) and 100 fpm, respectively. Based on this mission profile, aircraft performance is assessed to compute the required power and energy. Key performance parameters used in the analysis are summarized in Table 1.

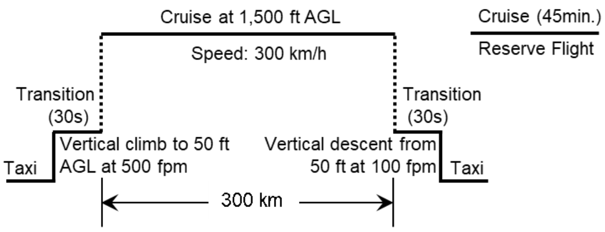


Figure 2: Sizing mission profile

Table 1: Performance parameters for eVTOL aircraft

Design parameters		Value
VTOL	Figure of merit, FM	0.75
	Disk loading, DL	608 N/m^2
	Electric efficiency including motor and invertor, $\eta_{electric@VFM}$	0.81
	Wing download factor, k_{WD}	1.1
Cruise	Propeller efficiency, η_{prop}	0.85
	Lift to drag ratio, L/D	11
	Electric efficiency including motor and invertor, $\eta_{electric@CRZ}$	0.86

These values represent typical assumptions but can be adjusted as needed. Required power during VFM is estimated using a momentum theory-based model (Ref. 13), as shown in Eq. (1).

$$P_{VFM} = \frac{k_{WD} GW g \left(\frac{V_{veti}}{2} + \sqrt{\left(\frac{V_{vert}}{2}\right)^2 + \frac{DL}{2\rho}} \right)}{\eta_{electric@VFM}\, FM} \quad (1)$$

This formulation is applicable to the hover, vertical climb, and vertical descent phases. Among these, the vertical climb phase is characterized by the highest power demand within the mission profile. Therefore, the required power during vertical climb under normal flight conditions is designated as the reference value, as expressed in Eq. (2), and is subsequently used to normalize all power and energy parameters throughout the analysis.

$$P_{VCL} = \frac{k_{WD} GW g \left(\frac{V_{VCL}}{2} + \sqrt{\left(\frac{V_{VCL}}{2}\right)^2 + \frac{DL}{2\rho}} \right)}{\eta_{electric@VFM}\, FM} \equiv P_{ref} \quad (2)$$

In contrast, the cruise phase operates at a lower power level but extends over a longer flight duration, making it the most energy-consuming flight of the mission. The required cruise power is calculated, as given in Eq. (3). For each operation mode, the motor and inverter efficiencies are collectively represented by a single electric efficiency parameter. Separate values are assigned to the VTOL and cruise segments due to differences in torque and RPM operating ranges.

$$P_{CRZ} = \frac{GW g\, V_{CRZ}}{\eta_{electric@CRZ}\, \eta_{prop}\, L/D} \quad (3)$$

To estimate aircraft performance (power and energy) without a predefined gross weight, power-based normalization is applied. Both the required power and energy are normalized with respect to the reference power, as described in Eqs. (4) and (5).

$$P^* = \frac{P}{P_{VCL}} \quad (4)$$

$$E^* = \frac{E}{P_{VCL}} \quad (5)$$

Table 2 presents the normalized power and energy values required for each segment for the sizing mission profile. The normalized energy reflects the number of flight hours the aircraft can sustain vertical climb segment. This approach allows the HPPS sizing to proceed independently of aircraft gross weight.

Table 2: Required P^* and E^* for the mission profile

Sizing Mission Profile	Nominal Mission					Reserve	unit
	Vertical Climb	Transition	Cruise	Transition	Vertical Descend	Cruise	
Vertical speed	2.5	-	-	-	-0.5	-	m/s
Horizontal speed	-	-	83.3	-	-	83.3	m/s
Flight Distance	-	-	300	-	-	225	km
Flight time	0.5	0.5	60.0	0.5	0.5	45.0	min
Required P^*	1.0	0.92	0.34	0.92	0.91	0.34	-
Required E^*	0.008	0.008	0.336	0.008	0.008	0.25	hour

3.2. TG-battery hybrid powerplant system

A TG-battery hybrid powerplant architecture employs a series hybrid electric powertrain that supplies electric power to a motor driving a propeller or rotor. The configuration considered in this study is illustrated in Figure 3, where the hybrid system comprises battery packs, TGs, and a fuel tank. While a twin TG configuration is used as the primary example, single-TG configurations are also considered. The term "twin TG" may refer either to two turboshaft engines each coupled with a separate generator, or to one turboshaft engine operating with two generator units. The selection between these options should be determined through safety analysis. However, in this study, the configuration is not explicitly specified; the twin TG is treated conceptually as a redundant configuration, and power allocation is analyzed at the system level under failure conditions.

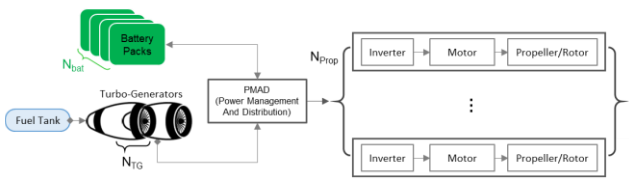


Figure 3: Schematic of serial TG-battery hybrid-electric powertrain

Power distribution is managed by a power management and distribution unit. A key design parameter is the hybrid power ratio, denoted as H_p, which represents the proportion of total power supplied by the battery. The total power is the sum of battery power, P_{bat}, and TG power P_{TG}, and H_p is mathematically defined in Eq. (6). When H_p is equal to 0, only TG power is used; when H_p is equal to 1, only battery power is used. Values between 0 and 1 indicate concurrent use of both sources, while a negative value indicates that the battery is being charged by excess TG power.

$$H_p = \frac{P_{bat}}{P_{required}} = \frac{P_{bat}}{P_{bat} + P_{TG}} \quad (6)$$

For battery sizing, a voltage drop model based on the SoC is employed. Eq. (7) presents a simplified battery cell model (Ref. 14) describing the voltage drop from initial voltage to the terminal voltage determined by the battery model constant. As SoC decreases, internal resistance increases, reducing power output and degrading energy performance.

$$e_{SoC} = \frac{SoC}{1 - \varepsilon(1 - SoC)} \quad (7)$$

Since battery degradation is associated with repeated charge-discharge cycles, capacity should be sized considering the SoH at EoL. A minimum SoC is also specified to prevent excessive sizing due to voltage drop. The battery model's characteristics vary with ε, which was calibrated using experimental data (Ref. 15), as shown in Figure 4.

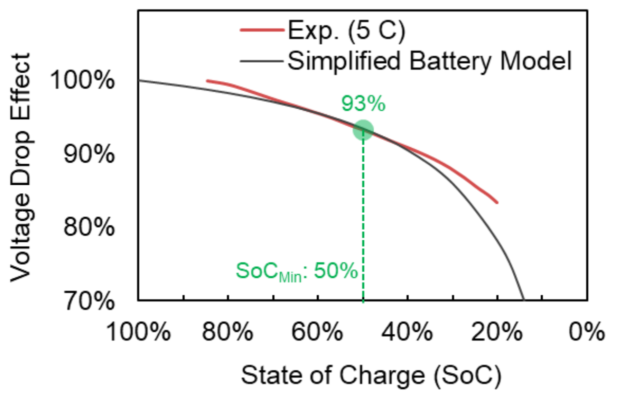


Figure 4: Comparison of experimental data and the simplified battery model

Calibration was based on a minimum SoC of 50%, with the resulting voltage drop effect evaluated at approximately 93%. The input parameters for each hybrid powerplant component are summarized in Table 3.

Table 3: Key parameters for each HPPS component

Parameters		Value
Battery	SoH at EoL, SoH_{EoL}	80%
	Minimum SoC, SoC_{min}	50%
	Initial SoC, SoC_{ini}	85%
	Model constant, ε	0.93
	Max. discharge rate, $C_{bat.max}$	9 C
	Ratio of continuous to maximum power, λ_{bat}	0.56
TG	Ratio of continuous to maximum power, λ_{TG}	0.93
	Specific power, SP_{TG}	1.65 kW/kg
	SFC	0.4 kg/kWh
Fuel	Ratio of fuel-to-tank mass	0.92
	Specific energy, SE_{fuel}	2.5 kWh/kg

Power demand is categorized into maximum continuous power for normal operation and maximum rated power under failure conditions. Their ratio is denoted by λ. Rather than constructing full engine performance maps, the study adopts system-level values from previous research or available datasets. The specific power and specific energy are interpreted under practical aircraft operation. TG-specific power reflects onboard cooling performance under high-power-demand phases such as VTOL phase, while cruise phase energy efficiency is represented by SFC, which dominates overall energy demand. System-level fuel specific energy is calculated from SFC and the fuel-to-tank mass ratio. As battery technologies continue to evolve, this study fixes TG technology level and explores various battery technology levels for comparison.

3.3. Sizing Guidelines

To guide the initial sizing of a HPPS, five key principles are introduced. These principles are based on three fundamental assumptions: the system must deliver sufficient power under both normal and failure conditions, store adequate energy to complete the entire flight mission including reserve segment, and minimize total system weight. These principles are grouped into two categories. The first two focus on sizing the hybrid power capacity for VTOL operations, while the remaining three address sizing the hybrid energy capacity for the cruise and reserve segments.

The five sizing principles are:

1) Safe operation of battery & TG in normal condition

2) Reliable VTOL flight in any failure cases

3) Primary use of efficient energy source in cruise

4) Charge battery energy in nominal cruise

5) Use the remaining energy in the reserve

First Principle: Under normal flight conditions, the battery must operate within its maximum continuous discharge rate to prevent thermal or chemical degradation. Among all flight phases, vertical climb during VTOL imposes the highest instantaneous power demand, making it the reference condition for evaluating battery discharge capability. Likewise, the TG must operate within its continuous power rating in the same condition. The hybrid power ratio for vertical climb segment is defined as the ratio of battery power to the total power required, as shown in Eq. (8)

$$H_{p.VCL} = P^*_{bat.avail}\lambda_{bat} = 1 - P^*_{TG.avail}\lambda_{TG} \quad (8)$$

Second Principle: The aircraft must maintain VTOL capability even when a single failure occurs. Two failure cases are considered in this study: OEI and OBI. The corresponding hybrid power ratios are presented in Eqs (9) and (10). A power relaxation between normal and failure conditions is used to account for the reduced vertical climb speed requirement under failure conditions, as shown in Eq. (11). In this study, the the degraded vertical climb speed under failure is assumed to be 100 fpm.

$$H_{p.OEI} = \frac{P^*_{bat.avail}}{\Phi_{fail}} = 1 - \frac{P^*_{TG.avail}}{\Phi_{fail}}\left(\frac{N_{TG}-1}{N_{TG}}\right) \quad (9)$$

$$H_{p.OBI} = \frac{P^*_{bat.avail}}{\Phi_{fail}}\left(\frac{N_{bat}-1}{N_{bat}}\right) = 1 - \frac{P^*_{TG.avail}}{\Phi_{fail}} \quad (10)$$

$$\Phi_{fail} = \frac{V_{VCL@fail} + \sqrt{V^2_{VCL@fail} + \frac{2DL}{\rho}}}{V_{VCL} + \sqrt{V^2_{VCL} + \frac{2DL}{\rho}}} \quad (11)$$

Third Principle: During cruise, the energy source with the higher specific energy, which is fuel, should be used as the primary source. Since the cruise segment is the longest flight of the mission, it contributes most significantly to overall energy consumption. Prioritizing the use of the TG, which uses fuel, reduces the total energy weight of the system.

Fourth Principle: During nominal cruise, surplus power from the TG should be used to recharge the battery, assuming no ground-based charging is available. The amount of energy charged must equal the battery energy consumed during VTOL flight operations, thereby restoring the SoC to its initial level by the end of the nominal mission. The hybrid power ratio during cruise is defined as the ratio of normalized battery charging power to the total normalized cruise power requirement, as shown in Eq. (12). If the battery charging duration is assumed to equal the cruise duration, this hybrid power ratio becomes equivalent to the energy ratio. Here, the normalized energy charged to the battery is calculated by multiplying the hybrid ratio of vertical climb by the total energy required for VTOL operations. The total VTOL energy is obtained by subtracting the normalized cruise energy from the total mission energy.

$$H_{p.CRZ} = -\frac{P^*_{charge}}{P^*_{CRZ}} = -\frac{E^*_{charge}}{E^*_{CRZ}} = -\frac{H_{p.VCL}E^*_{VFM}}{E^*_{CRZ}} \quad (12)$$

where, $E^*_{charge} = E^*_{VFM}H_{p.VCL} = (E^*_{NOM} - E^*_{CRZ})H_{p.VCL}$

Fifth Principle: This principle ensures that the aircraft utilizes all remaining energy while retaining the capability to perform a vertical landing after completing the reserve segment. The hybrid power ratio during cruise in the reserve segment is defined as the ratio of battery energy used during the reserve to the total energy required in that segment, as presented in Eq. (13). The usable battery energy is estimated based on the calculated available battery power capacity, which accounts for system-level sizing constraints, the maximum discharge rate and the voltage drop occurring at the minimum SoC required to ensure VTOL capability.

$$H_{p.RES} = \frac{E^*_{bat.avail}}{E^*_{RES}} = \frac{P^*_{bat.avail}(SoC_{ini} - SoC_{min})}{C_{bat.max}e_{SoC.min}E^*_{RES}} \quad (13)$$

3.4. Initial sizing process

To implement the proposed sizing principles in a systematic manner, an analytic initial sizing procedure for the hybrid powerplant system is developed in this section. Figure 5 illustrates the flow chart of the analytic initial sizing method. The process begins by entering the design parameters listed in Table 1 to estimate the normalized power and energy requirements of the eVTOL aircraft. These estimations are based on the mission profile provided in Figure 2, with results summarized in Table 2.

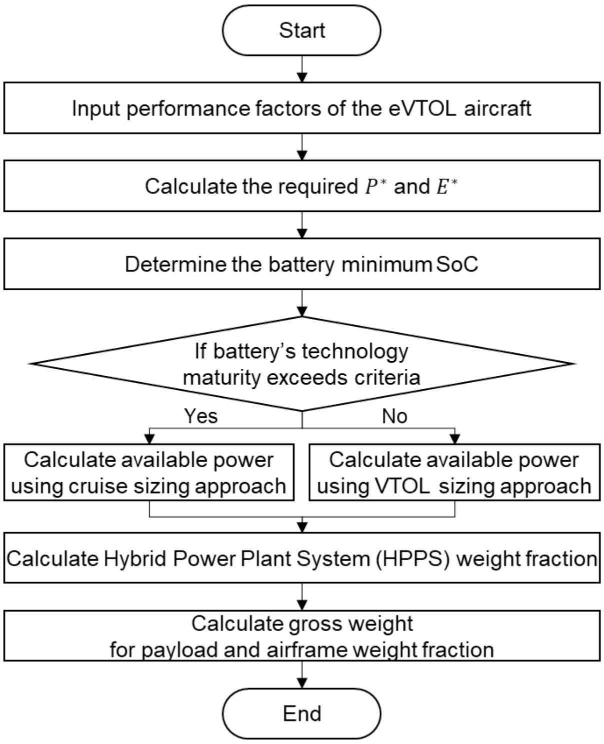


Figure 5: Initial sizing flow chart of HPPS

Subsequently, the minimum battery SoC must be defined to guarantee sufficient climb power following the reserve segment; in this study, the threshold is set at 50%, as shown in Table 3.

The total weight of the HPPS comprises the individual component weights of the battery, TG, and fuel. Each of these components can be expressed as a weight fraction by dividing its weight by the aircraft's gross weight, as indicated in Eq. (14).

$$\begin{aligned} WF_{HPPS} &= WF_{bat} + WF_{TG} + WF_{fuel} \\ &= \left[\frac{\gamma_P}{e_{SoC.min}\, SoH_{EoL} SP_{Bat}} P^*_{bat.avail} + \frac{\gamma_P}{SP_{TG}} P^*_{TG.avail} + \frac{\gamma_E}{SE_{fuel}} E^*_{fuel.avail} \right] PL^{-1} \end{aligned} \quad (14)$$

Here, the power loading factor, denoted as PL, is defined as the ratio of the gross weight to the reference power. This enables the initial sizing to be conducted independently of gross weight by calculating the HPPS weight fraction using PL in combination with normalized power and energy values. The last term in the sizing equation, the available fuel energy, which reflects the weight of the fuel system, can be reformulated as a function of the normalized available battery power, as defined in Eq. (15).

$$E^*_{fuel.avail} = E^*_{NOM} + (1 - H_{p.RES})E^*_{RES} = E^*_{NOM} + E^*_{RES} - P^*_{bat.avail}\frac{SoC_{ini} - SoC_{min}}{e_{SoC.min}C_{bat.max}} \quad (15)$$

Due to the differing levels of technological maturity between the battery and TG systems, the sizing process may follow different paths and produce different outcomes. However, there exists a convergence point at which the weight fractions calculated by the cruise-based sizing (CBS) and the VTOL-based sizing (VBS) methods are equal. This intersection is defined as the Sizing Approach Transition (SAT) threshold, represented by Eq. (16).

$$WF_{HPPS@VBS} + WF_{HPPS@CBS} = 0 \quad (16)$$

Eq. (17) is derived by substituting the normalized battery and TG power contributions into the hybrid power ratio expressions for vertical climb, given in Eq. (8) through (10).

$$(H_{P.sizingpoint@VBS} - H_{P.sizingpoint@CBS})PL^{-1}\left[\begin{array}{c}\dfrac{\gamma_P}{e_{SoC.min}\,SoH_{EoL}\,SP_{bat.crit}} \\ -\dfrac{\gamma_P}{SP_{TG}}\theta_{SP} - \dfrac{\gamma_E\,(SoC_{ini} - SoC_{min})}{SE_{fuel}C_{bat.max}e_{SoC.min}}\end{array}\right] = 0 \quad (17)$$

In this study, a sizing point is a flight condition which can potentially require the maximum power, specifically vertical climb in Normal, OEI, or OBI conditions. In this formulation, the sizing point factor varies depending on which sizing point determines the maximum battery capacity requirement. The sizing point is identified by comparing the highest battery power demand during vertical climb across all conditions, as shown in Eq. (18). Table 4 lists the sizing point factors for each sizing point.

$$Sizing\ Point = arg \max_{i\in\{Normal,\,OEI,\,OBI\}} P^*_{bat@i} \quad (18)$$

Table 4: Sizing point factors for each sizing point

Sizing Point	Normal	OEI	OBI
θ_{SP}	$\dfrac{\lambda_{bat}}{\lambda_{TG}}$	$\dfrac{N_{TG}}{N_{TG}-1}$	$\dfrac{N_{bat}-1}{N_{bat}}$

Since the sizing approaches differ, the resulting hybrid power ratios are naturally distinct. Therefore, to satisfy Eq. (17), the term within the square brackets must be zero. This condition leads to the determination of the battery system's specific power at the SAT threshold, calculated using Eq. (19). When the battery's specific power exceeds the SAT threshold, the CBS approach is adopted; otherwise, the VBS approach is applied.

$$SP_{bat.crit} = \frac{\gamma_P / (e_{SoC.min}\,SoH_{EoL})}{\left[\dfrac{\gamma_P}{SP_{TG}}\theta_{SP} + \dfrac{\gamma_E(SoC_{ini} - SoC_{min})}{SE_{fuel}C_{bat.max}e_{SoC.min}}\right]} \quad (19)$$

The CBS approach is grounded in sizing principles #3 and #4, which emphasize the use of energy-efficient TG during cruise. In this approach, the required TG capacity is computed first, followed by the determination of the remaining battery capacity necessary for vertical climb operations. The minimum available TG power required to meet cruise power demand while simultaneously charging the battery is derived by substituting the cruise hybrid power ratio, defined in Eq. (12), into Eq. (20).

$$P^*_{TG.avail} = (1 - H_{p.CRZ})\frac{P^*_{CRZ}}{\lambda_{TG}} = \left(1 - \frac{H_{p.VCL}E^*_{VFM}}{E^*_{CRZ}}\right)\frac{P^*_{CRZ}}{\lambda_{TG}} \quad (20)$$

The hybrid ratio for vertical climb is formulated and rearranged in Eq. (21) by applying sizing principle #4.

$$H_{p.VCL} = 1 - (1 - H_{p.CRZ})P^*_{CRZ} = \frac{1 - P^*_{CRZ}}{1 + \dfrac{E^*_{VFM}}{E^*_{CRZ}}P^*_{CRZ}} \quad (21)$$

This formulation links the hybrid power ratios between cruise and VTOL segments. Once the hybrid ratio for vertical climb is determined, it is inserted into Eq. (19) to calculate the minimum required TG capacity. The corresponding available battery power capacity is then obtained by evaluating the power demands during vertical climb under normal conditions, as well as under failure cases including OEI and OBI. The maximum value among these determines the final requirement, as shown in Eq. (22).

$$P^*_{bat.avail} = \max_{i\in\{Normal,\,OEI,\,OBI\}} P^*_{bat@i} \quad (22)$$

The VBS approach follows sizing principles #1 and #2, ensuring that the HPPS can safely operate within continuous power limits under normal vertical climb and within maximum power ratings under failure conditions.

Table 5 Available power formulation for each sizing case of VBS approach

No.	Sizing Points	$P^*_{bat.avail}$	$P^*_{TG.avail}$
1	Normal & OEI	$\frac{\Phi_{fail}\lambda_{TG}N_{TG} - N_{TG} + 1}{\lambda_{TG}N_{TG} - \lambda_{bat}N_{TG} + \lambda_{bat}}$	$\frac{(1 - \Phi_{fail}\lambda_{bat})N_{TG}}{\lambda_{TG}N_{TG} - \lambda_{bat}N_{TG} + \lambda_{bat}}$
2	Normal & OBI	$\frac{N_{bat}(\Phi_{fail}\lambda_{TG} - 1)}{\lambda_{TG}N_{bat} - \lambda_{TG} - \lambda_{bat}N_{bat}}$	$\frac{N_{bat} - 1 - \Phi_{fail}\lambda_{bat}N_{bat}}{\lambda_{TG}N_{bat} - \lambda_{TG} - \lambda_{bat}N_{bat}}$
3	OEI & OBI	$\frac{N_{bat}\Phi_{fail}}{N_{bat} + N_{TG} - 1}$	$\frac{N_{TG}\Phi_{fail}}{N_{bat} + N_{TG} - 1}$

In this study, a sizing case is defined as a pair of sizing points that together determine the capacities required for both TG and battery systems. For each case, full hybrid throttle is assumed at both sizing points. The hybrid throttle is defined as the ratio of the required power to the total available power. Sizing points are influenced by system configurations such as the number of battery packs and TGs as well as technical parameters including the ratio of continuous to maximum power and the power relaxation between normal and failure conditions. The possible combinations of sizing points are categorized into three sizing cases, as shown in Table 5.

For each sizing case, the normalized available powers of the battery and TG are derived using analytical formulas that assume full hybrid throttle at both sizing points. Table 6 presents the calculated hybrid throttle values for each condition.

Table 6 Hybrid throttle under each flight condition

Flight condition	Hybrid Power Throttle
Normal	$\frac{1}{\lambda_{bat}P^*_{bat.avail} + \lambda_{TG}P^*_{TG.avail}}$
OEI	$\frac{\Phi_{fail}}{P^*_{bat.avail} + P^*_{TG.avail}\left(\frac{N_{TG} - 1}{N_{TG}}\right)}$
OBI	$\frac{\Phi_{fail}}{P^*_{bat.avail}\left(\frac{N_{bat} - 1}{N_{bat}}\right) + P^*_{TG.avail}}$

Only physically feasible solutions are considered: the available battery power must be non-negative, the hybrid throttle must not exceed 1, and the available TG power must satisfy the cruise power requirement.

Among the feasible configurations, the one with the lowest total HPPS weight is selected as optimal, as determined by Eq. (23).

$$WF_{HPPS} = \min_{i\in\{feasible\ cases\}}\left[\left(\frac{\gamma_P}{e_{SoC.min}\,SoH_{EoL}SP_{Bat}}P^*_{bat.avail} + \frac{\gamma_P}{SP_{TG}}P^*_{TG.avail} + \frac{\gamma_E}{SE_{fuel}}E^*_{fuel.avail}\right)_i\right]PL^{-1} \quad (23)$$

The normalized available power of the battery and TG, obtained from either the CBS or VBS approach, is used to compute the HPPS weight fraction according to Eq. (14). Once this weight fraction is determined, it is combined with the payload and the airframe weight fraction, which includes the remaining aircraft mass, to calculate the gross weight using Eq. (24).

$$GW = \frac{Payload}{1 - WF_{airframe} - WF_{HPPS}} \quad (24)$$

This sizing methodology enables a one-pass estimation of aircraft gross weight that does not rely on any prior gross weight assumptions, making it suitable for early-phase conceptual design. However, the method assumes a constant disk loading. In cases where the rotor diameter remains fixed and the gross weight varies, the resulting change in disk loading requires iterative updates until convergence is achieved.

Dring the initial sizing process of the HPPS, the hybrid power ratio obtained from the vertical climb segment, which imposes the highest power demand, was consistently applied to all VTOL segments, including transition and vertical descent. This method enables sizing based on the most critical segment but causes variation in the TG power applied during each VTOL phase. From a practical standpoint, operating the TG with constant power output is preferable to maintaining a uniform hybrid ratio across all segments. To address this, Eq. (25) was developed. It represents the actual operational hybrid power ratio for each VTOL segment by combining their respective normalized power requirements with the hybrid ratio determined from the vertical climb segment, based on Eq. (8). Following Sizing Principle 4, the operational hybrid power ratio during cruise is updated in Eq. (26) to account for the battery energy consumed in each VTOL segment. Furthermore, substituting Eq. (25) into this formulation allows the hybrid power ratio to be expressed in a simplified, non-integral form.

$$H_{p.i.VFM.oper} = 1 - \frac{P^*_{TG.avail}\lambda_{TG}}{P^*_{i.VFM}} = 1 - \frac{1 - H_{p.VCL}}{P^*_{i.VFM}} \tag{25}$$

$$\begin{aligned} H_{p.CRZ.oper} &= -\sum_{i}^{VFM} \frac{E^*_i}{E^*_{CRZ}} H_{p.i.CRZ.oper} \\ &= -\sum_{i}^{VFM} \left(\frac{E^*_i - t_i(1 - H_{p.VCL})}{E^*_{CRZ}} \right) \\ &= \frac{t_{VFM}(1 - H_{p.VCL}) - E^*_{VFM}}{E^*_{CRZ}} \end{aligned} \tag{26}$$

4. RESULTS and DISCUSSION

4.1. Initial sizing of HPPS

The proposed method presents two distinct sizing approaches based on the relative maturity of battery and TG technologies. To analyze the impact of differences in technological maturity between the battery and TG, the TG specific power was fixed at 1.65 kW/kg, and the battery specific power was varied. The initial sizing results of the HPPS were analyzed to each approach. In this section, the HPPS configuration is assumed to consists of twin TG and 2+ battery packs. As shown in Figure 6, the HPPS weight fraction varies with battery specific power. Both sizing results from VBS and CBS approach are presented. The present method reveals that the optimal sizing approach, which minimizes the HPPS weight fraction, shifts at an TG specific power of 3.53 kW/kg. This transition point, referred to as the SAT threshold, is consistent with the analytically derived value from Eq. (19). If the battery specific power is below the SAT threshold, VBS approach yields better initial sizing results. Conversely, if the battery specific power exceeds the SAT threshold, the CBS approach is more suitable. Furthermore, when the battery specific power equals the SAT threshold, both sizing approaches yields the same HPPS weight fraction.

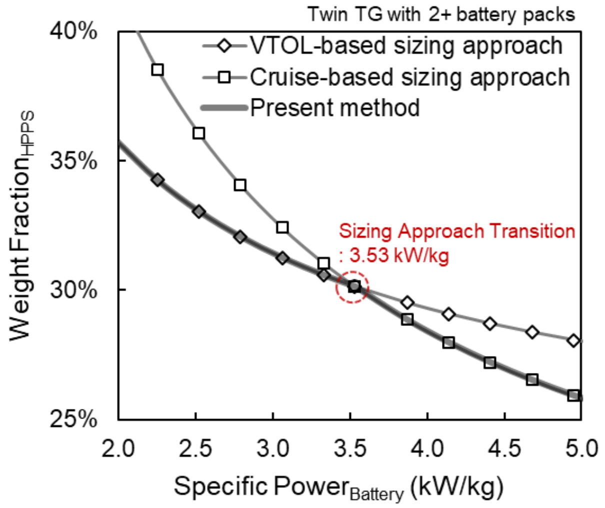


Figure 6: Initial sizing flow chart of HPPS

Even with the same HPPS weight fraction, different sizing approaches result in distinct component weight distribution. Figure 7 shows a comparison of the weight distributions from the two sizing approaches at an TG specific power of 1.65 kW/kg, corresponding to the SAT threshold.

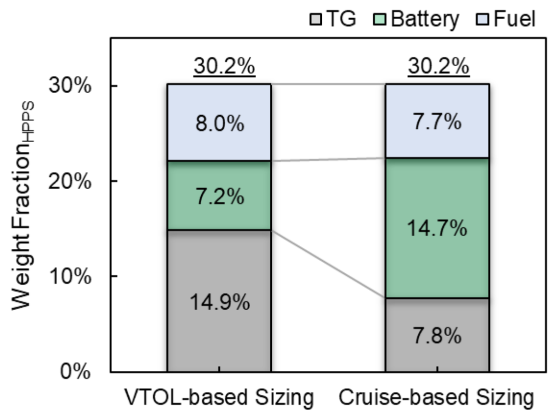
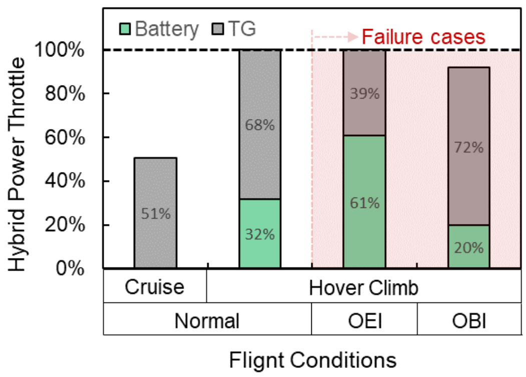


Figure 7: HPPS weight distribution comparison from two sizing approaches at the SAT threshold

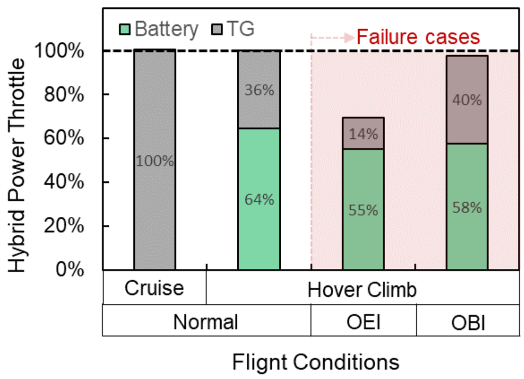
In the VBS approach, the weight distribution is highest for the TG (14.9%), followed by the battery (7.2%) and fuel system (8.0%). In contrast, the CBS approach shows the highest weight distribution for the battery (14.7%), followed by the TG (7.8%) and fuel system (7.7%). These result indicate the TG dominates in the VBS design, while the battery is the heaviest component in the CBS design. Notably, the higher battery weight fraction in the CBS results in increased stored battery energy, leading to a 0.3%

reduction in fuel weight fraction compared to the VBS design. To further understand the underlying reasons for the differences in component weight distribution between the two sizing approaches, it is essential to examine the operational throttle settings that drive the sizing of each power source during different flight phases.

The component sizing of the HPPS is essentially carried out by determining the maximum power demands across all phases of flight and verifying that each power source, or the combined system, is capable of meeting these demands. Accordingly, examining the flight segments in which the HPPS operates at full throttle helps to identify the specific flight conditions that govern the sizing of each power source. Figure 8 indicates the hybrid power throttle utilization across different flight conditions for both the CBS and VBS approaches, assuming a TG specific power of 1.65 kW/kg, which matches the SAT threshold.



(a) VTOL-based sizing approach

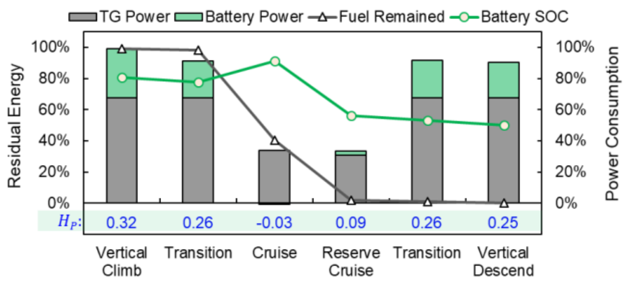


(b) Cruise-based sizing approach

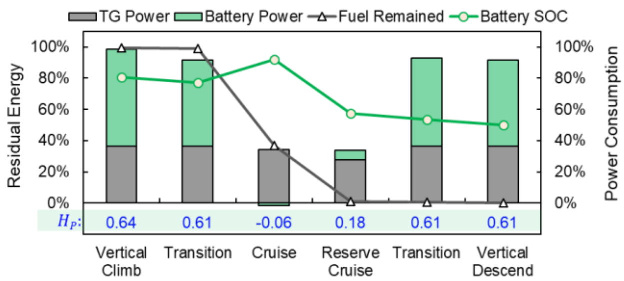
Figure 8: Analysis of sizing points requiring full throttle

The HPPS configuration employed in this evaluation includes twin TGs and 2+ battery packs, as described earlier. In the VBS case shown in Figure 8(a), the system is dimensioned to allow full throttle operation during both normal vertical climb and vertical climb under the OEI condition. Here, the normal vertical climb requires maximum continuous power, while the OEI condition demands maximum rated power. On the other hand, the CBS shown in Figure 8(b) sets the sizing point such that full throttle operation is available during both cruise and normal vertical climb. In this case, the TG is first sized to satisfy the cruise power requirement, followed by battery sizing to meet the vertical climb requirement. This approach justifies the designation of the method as cruise sizing. It demonstrates that the capacities of the TG and battery are simultaneously determined to fulfill the required power levels during both flight conditions.

Figure 9 presents the results of energy consumption, power usage, and hybrid power ratio throughout the sizing mission profile defined in Figure 2.



(a) VTOL-based sizing approach



(b) Cruise-based sizing approach

Figure 9: Energy and power consumed in executing the mission profile

The mission includes both nominal flight segments and a reserve segment. For this analysis, the reserve segment duration is included in the overall mission to evaluate energy allocation and power management over the entire flight envelope. In the figure, the remaining fuel and battery SoC are plotted as line graphs on the left axis, while the power output of each power source is displayed as bar graphs on the right axis. The hybrid power ratio values are indicated numerically in blue on the respective bars. Figures 9(a) and 9(b) show the results of the VBS and CBS approaches, respectively. Fuel is consumed from 100% to 0%, and the battery starts at an SoC of 85%, decreasing to a minimum of 50% by the end of the mission. For instance, the SoC drop to approximately 80% during the vertical climb indicates that 5% of the battery capacity is used during that phase. Notably, the battery is recharged during cruise, which aligns with the battery sizing objective of ensuring sufficient SoC for stable voltage in VTOL operations. During the reserve cruise segment, the battery is discharged to support the entire required duration while maintaining the 50% SoC threshold at landing. The CBS approach is intended to reduce TG usage, resulting in a peak hybrid power ratio of about 0.64, meaning the battery supplies more than half the power during vertical climb. Conversely, the VBS approach aims to limit battery use, yielding a lower hybrid power ratio of approximately 0.32. A comparison between the two approaches shows that the hybrid power ratio during vertical climb in the CBS case is nearly twice as high as that in the VBS case. However, this outcome is specific to the performance assumptions and HPPS configuration used in this study and may differ under alternative conditions.

4.2. Optimal combination analysis

For the TG-battery HPPS, various combinations of TG and battery units were analyzed to identify the optimal configuration that minimizes the total system weight while satisfying redundancy requirements. These combinations involve different counts of TGs and battery packs. To limit system complexity, the number of TGs was restricted to a maximum of two. Similarly, the configuration using only a single battery pack was excluded, as it was considered overly conservative in terms of redundancy. The input parameters for aircraft performance, system-level battery specific power, and hydrogen specific energy were kept consistent with those used in the previous section. Figure 10 illustrates the variation in HPPS weight fraction across several configurations, including a single TG with two or more battery packs, and twin TGs with two or more battery packs. In addition, the analysis revealed that increasing the number of battery packs beyond two had no effect on the initial sizing outcomes, indicating that system performance remains unchanged once the minimum redundancy requirement is met. The figure also presents the SAT threshold for each configuration, defined as the battery's specific power at which the sizing results from the CBS and VBS approaches intersect. This threshold varies depending on the number of TGs in the configuration. Consistent with the results of the previous section, for all configurations, the VBS approach results in a lower HPPS weight fraction when the battery specific power is below the SAT threshold. In contrast, once the battery specific power exceeds the threshold, the CBS approach becomes more favorable. In the low specific power region (i.e., below 3.53 kW/kg), configurations employing twin TGs yield a lower HPPS weight fraction than those using a single TG. This is primarily because, under OEI conditions, single TG configurations must rely entirely on the battery to meet power demands, leading to increased battery weight. Conversely, in the high specific power region (above 3.53 kW/kg), both configurations yield identical and optimal results, indicating that the number of TGs does not affect the battery-dominant sizing regime. Among all configurations investigated, the twin TG with 2+ battery pack consistently resulted in the lowest HPPS weight fraction across the full range of battery specific power conditions.

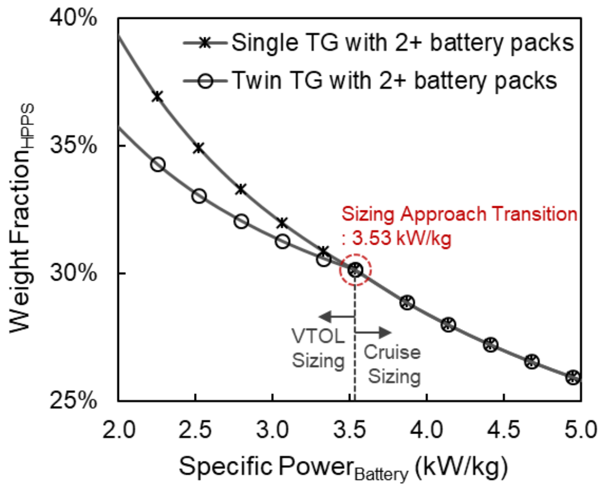


Figure 10: Comparison results for single and twin TG configurations across specific power of battery pack level

4.3. Effect of aerodynamic metric

This section presents a sensitivity analysis of HPPS sizing outcomes in relation to variations in key aerodynamic performance parameters. The analysis focuses on the initial sizing of the HPPS, where the outcomes are significantly influenced by the values of essential input variables. Among the various aerodynamic parameters, particular attention is given to the lift-to-drag ratio, which characterizes the energy demand during cruise, and the disk loading, which determines the power requirement during VTOL operation. These parameters are selected for detailed examination, with their effects on the HPPS weight fraction illustrated in Figure. 11.

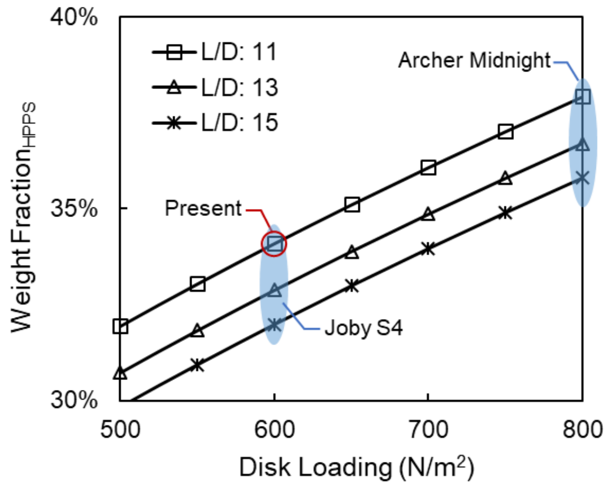


Figure 11: HPPS weight fraction variation across lift-to-drag ratio and disk loading

The analysis is performed based on the previously identified optimal configuration comprising twin TGs and two battery packs. A battery specific power of 2.25 kW/kg (corresponding to 250 Wh/kg of specific energy) is applied at the system level to ensure consistency. The analysis reveals that at a lift-to-drag ratio of 11 and a disk loading of 500 N/m², the HPPS weight fraction is approximately 32%. It increases by roughly 1% for every 50 N/m² increment in disk loading and decreases by about 1% for every 2-point increase in lift-to-drag ratio. The present study adopts a lift-to-drag ratio of 11 and a disk loading of 608 N/m². The selected parameter range closely aligns with estimates derived from current eVTOL aircraft. For instance, the disk loading values for the Joby S4 (Ref. 16, 17) and Archer Midnight (Ref. 18, 19) are approximately 600 N/m² and 800 N/m², respectively, based on their known gross weight and rotor area. Although no official lift-to-drag ratio data are available for these aircraft, it is generally estimated to fall within the range of 11 to 15 in typical eVTOL designs. These findings underscore the significant influence of lift-to-drag ratio and disk loading on HPPS sizing, highlighting the critical importance of accurately specifying these parameters in the conceptual design phase of HPPS.

4.4. Initial sizing of hybrid eVTOL aircraft

This section presents the initial aircraft sizing using the optimal HPPS configuration derived earlier, consisting of twin TGs and two battery packs. A system-level battery specific power of 2.25 kW/kg, corresponding to 250 Wh/kg of specific energy, is applied to ensure consistency with prior analyses. The resulting HPPS weight fraction is 34.3%, which provides the foundational input for the sizing calculations. The airframe weight fraction, reflecting the assumed aircraft geometry, is used as an input parameter. Due to uncertainty in the conceptual design stage, a range of 45% to 50% is assumed. The payload is defined as the total occupant mass, based on 200 lb (91 kg) per seat. Seating capacities ranging from 5 to 9 are examined, with the 5-seat case representing one pilot and four passengers. Gross weight is estimated using Eq. (24) as a function of HPPS weight fraction, airframe weight fraction, and payload. The resulting variations in gross weight across the specified ranges of airframe weight fraction and seating capacity are illustrated in Figure 12. Based on the derived gross weight, the maximum power capacities of the battery and TG can be estimated by multiplying the respective weight fractions by the gross weight and their specific power values. As shown in the Figure 13, the required power for vertical climb, indicated by the red line, is calculated by dividing the gross weight by the power loading (PL) defined in this study and multiplying the result by the power margin factor, γ_p. This figure highlights the 5-seat and 9-seat configurations, corresponding to airframe weight fractions ranging from 45% to 50%, with yellow shading. The 5-seat class represents the typical aircraft configuration currently under development by leading eVTOL manufacturers such as Joby and Archer. In contrast, the 9-seat configuration is under consideration as a candidate for replacing certain classes of conventional helicopters. Accordingly, these two configurations serve as representative cases for evaluating the scalability of the HPPS sizing approach, focusing on varying payloads within an airframe weight fraction range of 45% to 50%. As illustrated by the purple line, the total power capacity is calculated by summing the maximum power capacity of the battery and the TG. It consistently equals 1.5 times the required power during the vertical climb phase for all gross weight conditions. The sized TG power capacity corresponds to approximately 49% of the total power capacity and

73% of the required power. This consistent ratio results from the assumption that the HPPS input parameters and aircraft design variables remain unchanged regardless of variations in payload or gross weight. Consequently, under the configuration used in this study (the twin TG with 2+ battery packs) and with consistent input parameters, the TG and battery systems are sized to deliver 73% and 77% of the required vertical climb power, respectively, resulting in a total installed power capacity of 150%. The battery power capacity reflects the effects of voltage drop during operation at minimum SoC, as well as the SoH at the end of battery life. This condition enables the minimum-weight initial sizing of the HPPS.

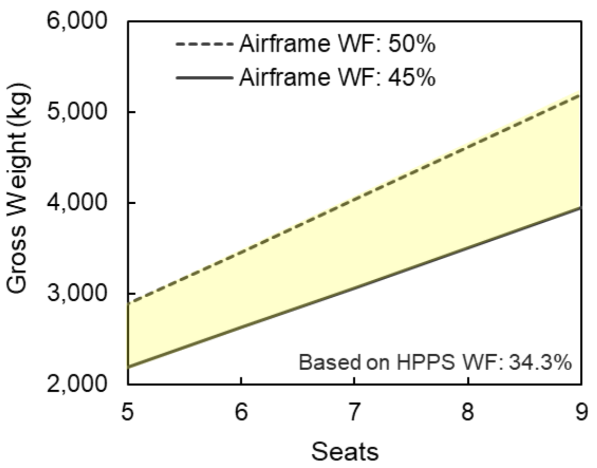


Figure 12: Gross weights for airframe weight fraction of 45% to 50% across seating capacities

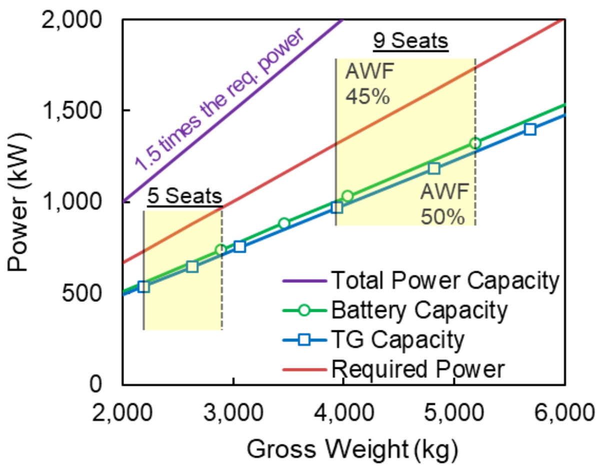


Figure 13: TG and battery power capacities across the gross weights

5. CONCLUSIONS

This study presented a rapid, analytical initial sizing methodology for TG and battery-based hybrid powerplant systems (HPPS) in eVTOL aircraft. The method, termed HYSIZE (Hybrid System Initial Sizing Method), enables single-pass estimation of HPPS weight fraction without iterative coupling between weight and performance, while explicitly addressing redundancy through One Engine Inoperative (OEI) and One Battery Inoperative (OBI) failure cases. The main objective of this research was to identify the optimal HPPS configuration by developing sizing strategies that reflect key component technology gaps, evaluating TG configurations, analyzing aerodynamic sensitivity, and demonstrating applicability across various aircraft classes.

1. Two sizing strategies were established: one based on the vertical climb phase and the other on cruise performance. Analytical derivation identified the Sizing Approach Transition (SAT) threshold at a battery specific power of 3.53 kW/kg. Below this threshold, the VTOL-based sizing strategy minimizes HPPS weight by leveraging TG power; above it, the cruise-based strategy becomes preferable due to improved battery performance. While both approaches yield identical total HPPS weight at the SAT point, they differ significantly in internal power distribution, with the cruise-based strategy exhibiting nearly twice the hybrid power ratio during vertical climb.

2. The influence of TG configuration on HPPS weight was assessed. Below the SAT threshold, a twin TG layout reduced battery sizing requirements under OEI conditions, resulting in a lower total system weight. However, above the threshold, TG quantity no longer influenced results, indicating battery dominance. Across all configurations, the combination of twin TGs and multiple battery packs yielded the lowest HPPS weight fraction.

3. Sensitivity analyses were performed to quantify the impact of aerodynamic parameters on HPPS sizing. Assuming a system-level battery specific power of 250 Wh/kg, the HPPS weight fraction increased by approximately 1% for every 50 N/m^2 increase in disk loading and decreased by 1% for every two-point increase in lift-to-drag ratio. These findings highlight the importance of selecting appropriate aerodynamic design parameters in early sizing stages.

4. The methodology was applied to two representative eVTOL configurations: a 5-seat and a 9-seat aircraft. For an assumed airframe weight fraction range of 45% to 50%, the optimized HPPS configuration ensured that TG and battery systems respectively delivered 73% and 77% of the vertical climb power, resulting in 150% installed capacity. This allows either power source alone to meet 100% of demand under OEI or OBI conditions, thereby satisfying redundancy requirements.

Limitations and Future Work:

To simplify the analysis of gross weight trends and payload scalability, this study assumed constant values for key aerodynamic parameters such as disk loading and lift-to-drag ratio. Future work will integrate an initial sizing platform that dynamically links aerodynamic, structural, and payload parameters. In the short term, the HPPS sizing framework will be extended to incorporate detailed models of motors, inverters, and rotors. The complete system will be implemented in an iron bird testbed to validate the sizing framework and assess system-level performance under representative operating conditions.

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