

PRELIMINARY SIZING METHODOLOGY FOR HYBRID-ELECTRIC PROPULSION SYSTEM IN CARGO AIRSHIPS

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Abstract

Hybrid-electric propulsion (HEP) is emerging as a promising pathway for reducing emissions in airship-based cargo transport, yet systematic conceptual sizing methodologies remain limited. This study presents a conceptual sizing methodology for hybrid-electric propulsion systems in airships by adapting aircraft-based hybrid-electric range formulations to account for buoyancy effects through the concept of static heaviness. Existing hybrid-electric range models are evaluated, and a shaft-energy-based formulation is selected and modified for airship applications. The methodology further incorporates corrections derived from Zeppelin NT propulsion-system data, an improved battery-sizing approach that accounts for deep-discharge protection and pack-level energy density, and a component-wise propulsion-sizing framework. Validation using Zeppelin NT data demonstrated improved agreement with available propulsion-system and battery-sizing information. Parametric analysis showed that increasing electrification significantly increases vehicle weight at currently achievable battery energy densities. A MATLAB/Simulink-based time-step simulation framework was developed for independent assessment of the methodology, with analytical predictions showing close agreement with simulation results across a range of hybridisation levels. The proposed methodology provides a physically consistent and practically applicable framework for conceptual sizing of hybrid-electric propulsion systems in airships.

Keywords: Hybrid-electric Propulsion, Airships, Conceptual Sizing, Battery sizing, Sustainable aviation

1. Introduction and Background

Cargo airships are gaining renewed attention as platforms for sustainable heavy-lift transportation due to their inherent buoyant lift and comparatively low energy demand. In parallel, hybrid-electric propulsion (HEP) has emerged as a promising pathway for reducing aviation emissions. Recent cargo airship projects, including those by LTA Research [1] and Flying Whales [2], are incorporating HEP architectures in which gas-turbine-driven generators power electric motors, with batteries providing supplemental power during high-demand phases such as take-off and low-speed manoeuvring. As battery energy density improves, increasing levels of electrification and, ultimately, fully electric propulsion using fuel cells are being targeted in near-term designs by Flying Whales and Hybrid Air Vehicles [1–3].

Despite this potential, the development of systematic design and sizing methodologies for HEP systems in airships remains limited [4–6]. Existing studies on airship propulsion largely employ simplified relations to estimate battery or fuel cell requirements and do not account for the coupled behaviour of hybrid-electric systems. Furthermore, no study provides explicit formulations for comprehensive system-level modelling of HEP that includes all major components. Only limited work, such as that of Murugaiah et al. [7], attempts to formulate hybrid-electric range relations specifically for airships; however, such models lack validation and exhibit inconsistencies in their underlying assumptions.

In contrast, a substantial body of work exists for hybrid-electric aircraft. Modified Bréguet-type range equations proposed by Voskuijl et al. [8] and De Vries et al. [9], and later refined by Batra et al. [10], provide frameworks for analysing hybrid propulsion systems using constant power-split assumptions and efficiency-based formulations. However, these models are developed for aircraft and cannot be

directly applied to airships due to fundamental differences in lift generation and effective weight representation.

Consequently, there is no validated conceptual sizing framework for HEP systems in airships. This gap arises from two key challenges: the limited availability of airship-specific hybrid-electric models and the absence of operational hybrid-electric airships for validation.

To address this gap, the present study develops a conceptual sizing methodology for HEP in airships by adapting aircraft-based hybrid-electric range formulations to account for buoyancy-driven flight. The methodology incorporates a critical evaluation of existing hybrid-electric range formulations, modifications to conventional propulsion sizing through empirically derived correction factors, a refined battery sizing approach that accounts for deep-discharge protection and pack-level energy density, and an assessment of hybridisation effects on system mass and performance. Validation is performed using data from the Zeppelin NT airship and through comparison with published studies, complemented by parametric analysis and time-step simulation.

2. Hybrid-Electric Range Models

Several hybrid-electric range formulations have been proposed in the literature, primarily for fixed-wing aircraft, along with limited work for airships. Notable formulations include those by Voskuijl et al., De Vries et al., and Batra et al., as well as the airship-specific model proposed by Murugaiah et al. These models differ in their treatment of hybridisation, efficiency, and energy accounting, and are evaluated in the following subsections for applicability to airship propulsion sizing.

Additional studies provide insight into HEP characteristics and constraints. For instance, Hepperle highlights the dominant influence of battery-specific energy and system efficiency on achievable range. At the same time, Sahoo et al. and Brelje and Martins develop sizing methodologies based on performance metrics such as specific fuel consumption and energy-based range relations. These studies collectively emphasise the importance of consistent energy accounting and efficiency modelling in hybrid-electric systems.

2.1 Murugaiah et al. (2022)

Murugaiah et al. [7] adopted a hybrid-electric range equation originally proposed by Brelje [11], given by:

$$R_{tot} = \frac{C_L \eta_i \eta_m \eta_p}{g C_D} \left(\frac{\eta_g}{c_p} ln[A] + B \right) \tag{1}$$

where A and B are functions of degree of hybridisation, battery and fuel energy density, and weight fractions.

The formulation assumes constant aerodynamic efficiency and propulsion efficiencies during cruise. An attempt was made to reproduce the authors' published results for the Airlander 10 airship using the provided data. However, the computed range values were found to be an order of magnitude smaller than those reported. Further investigation revealed inconsistencies in the input parameters: key variables such as brake-specific fuel consumption (c_p) and engine efficiency (η_g) were not specified, and discrepancies were identified between the reported and implemented maximum take-off weight values. Additionally, the empty weight fraction used in the underlying code (~0.089) was unrealistically low.

2.2 Voskuijl et al. (2018)

Voskuijl et al. [8] derived a hybrid-electric range equation using an energy-balance approach, expressed as:

$$R_{hybrid} = \frac{\eta_{prop}}{\left(c_p \frac{H_{fuel}}{g}(1-S) + \frac{S}{\eta_{elec}} \right)} \frac{C_L}{C_D} \frac{H_{fuel}}{g} \frac{1}{(1-\psi)} ln \left(\frac{\left((1-\psi)\frac{g}{H_{fuel}} + \psi \frac{g}{H_{bat}} \right) E_{start} + W_{empty} + W_{payload}}{\psi \frac{g}{H_{bat}} E_{start} + W_{empty} + W_{payload}} \right) \tag{2}$$

The formulation explicitly distinguishes between shaft power-split (S) and degree of hybridisation (Ψ), defined as:

$$S = \frac{P_{br,electric}}{P_{br,total}} \tag{3}$$

$$\psi = \frac{E_{bat}}{E_{total}} \tag{4}$$

The model assumes steady, level cruise and continuous power-split. The model was tested by developing a hybrid variant of the ATR-72-600 aircraft, while keeping the design range unchanged. Their results were reproducible, but the equation was not selected for this study. For the present study, a formulation governed by a single hybridisation parameter was preferred because it simplifies the interpretation of hybridisation effects and facilitates integration with the proposed conceptual sizing methodology.

2.3 De Vries et al. (2020)

De Vries et al. [9] proposed a simplified hybrid-electric range equation assuming a constant power-split ratio throughout cruise:

$$R = \eta_3 \frac{e_f}{g}\left(\frac{L}{D}\right)\left(\eta_1 + \eta_2 \frac{\phi}{(1-\phi)}\right) ln\left(\frac{W_{OE} + W_{PL} + \left(\frac{g}{e_{bat}}\right)E_{0,tot}\left(\phi + \left(\frac{e_{bat}}{e_f}\right)(1-\phi)\right)}{W_{OE} + W_{PL} + \left(\frac{g}{e_{bat}}\right)\phi E_{0,tot}}\right) \tag{5}$$

The authors reported that aircraft range increases with increasing electrification beyond a threshold battery energy density, which depends on the aircraft and mission. However, the take-off weight will increase significantly due to the lower energy density of batteries.

Further analysis showed that this formulation is mathematically equivalent to the Voskuijl et al. [8] model if the shaft power-split is assumed constant in Eq. (2). The shaft power-split and degree of hybridisation are then related by:

$$S\ (or\ \phi) = \frac{\eta_2 \psi}{\eta_1(1-\psi) + \eta_2 \psi} \tag{6}$$

Thus, both formulations yield identical predictions under the assumption of constant power-split.

2.4 Adopted Hybrid-Electric Range Model

Based on the evaluation of existing hybrid-electric range formulations, the model proposed by Batra et al. [10] was selected for further development. This formulation provides a physically consistent framework for the conceptual sizing of HEP systems.

For a parallel hybrid-electric configuration, the range is expressed as:

$$R_{parallel} = \eta_{gt}\eta_{gb}\eta_p \frac{C_L}{C_D}\left(1 + \frac{\varphi}{(1-\varphi)}\right)\left(\frac{e_f}{g}\right) ln\left(\frac{W_{OE} + W_{PL} + \left(\frac{E_{0,tot}g}{e_{bat}}\right)\left(\frac{\varphi}{\eta_{em}} + \frac{e_{bat}(1-\varphi)}{e_f \eta_{gt}}\right)}{W_{OE} + W_{PL} + \frac{g}{e_{bat}}\frac{\varphi E_{0,tot}}{\eta_{em}}}\right) \tag{7}$$

This expression represents a modified Breguet-type relation that accounts for both fuel and battery energy contributions via an efficiency-based formulation. A parallel hybrid architecture is considered in this study because of its greater flexibility, reliability, and operational feasibility compared with series configurations.

In this formulation, the degree of hybridisation (φ) is defined based on the effective shaft power contribution as:

$$\varphi = \frac{P_{bat}\eta_2}{P_f \eta_1 + P_{bat}\eta_2} \tag{8}$$

$E_{0,tot}$ represents the total shaft energy delivered to the propeller over the duration of the mission, rather than the total stored onboard energy alone.

The model satisfies the expected limiting cases: for φ = 0, it reduces to the classical Breguet range equation, and for φ = 1, it reduces to the fully electric range formulation. These characteristics ensure

consistency with established propulsion theory.

The formulation is derived under the standard assumptions of Breguet-type range equations, namely steady, level cruise flight with zero flight-path angle, constant velocity during the cruise segment, constant aerodynamic efficiency $\frac{C_L}{C_D}$, constant propulsion system efficiencies, and negligible variation in atmospheric conditions. As a result, the model applies only to cruise segments and cannot directly capture transient phases such as take-off, climb, descent, or manoeuvring flight, which must be treated separately in a complete mission analysis.

The model by Batra et al. is particularly suitable for initial sizing applications. It demonstrates physical consistency by predicting a decrease in range with increasing battery energy density, consistent with the known limitations of current battery technology. Furthermore, reproducing the trends reported in the original study confirms that the model exhibits realistic sensitivity to battery energy density and hybridisation.

Thus, this formulation was selected as the basis for developing the proposed sizing methodology. Although it was found to be mathematically equivalent to the formulation of De Vries et al., Batra's formulation directly employs shaft energy as the primary sizing parameter, making it more convenient for propulsion system sizing and component-level energy estimation. The modifications required to adapt this aircraft-based formulation to airship configurations are presented in the following section.

3. Hybrid-Electric Propulsion Sizing Methodology

3.1 Adaptation of Hybrid-Electric Range Equation

Although the hybrid-electric range equation presented in the previous section is derived for fixed-wing aircraft, its direct application to airships is not appropriate due to fundamental differences in lift generation and weight characteristics. In aircraft, lift is entirely aerodynamic and directly coupled to weight, whereas airships derive a significant portion of lift from buoyancy. As a result, the effective weight that governs propulsion requirements in airships is not the total weight, but the static heaviness, defined as the difference between the vehicle's weight and buoyant lift. Therefore, the classical Breguet framework must be modified to account for buoyancy effects when applied to airships.

Carichner and Nicolai [12] derived a Breguet-type range equation for airships by expressing the range in terms of the variation of static heaviness, given by:

$$R = \frac{\eta_p}{c_p}\frac{C_{L,aero}}{C_D} ln\left(\frac{W_{H0}}{W_{H1}}\right) \tag{9}$$

where R is the range, η_p is the propeller efficiency, c_p is the brake-specific fuel consumption, $\frac{C_{L,aero}}{C_D}$ is the aerodynamic efficiency of the airship, W_{H0} and W_{H1} represent the initial and final static heaviness, respectively. Static heaviness is defined as:

$$SH = W_{TOW} - B \tag{10}$$

where W_{TOW} is the take-off weight, and B is the buoyant lift. The hybrid-electric aircraft range equation adopted in the previous section can therefore be extended to airships by replacing the total weight terms with static heaviness, consistent with Carichner and Nicolai's formulation. Applying this modification to the hybrid-electric range equation (for parallel hybridisation) yields:

$$R_{parallel} = \eta_{gt}\eta_{gb}\eta_p \frac{C_{L,aero}}{C_D}\left(1 + \frac{\varphi}{(1-\varphi)}\right)\left(\frac{e_f}{g}\right) ln\left(\frac{W_{H0}}{W_{H1}}\right) \tag{11}$$

where η_{gt} is the electric drivetrain efficiency, η_{gb} is the conventional drivetrain efficiency, g is acceleration due to gravity, and the initial and final static heaviness are given by:

$$W_{H0} = W_{OE} + W_{PL} + \left(\frac{E_{0,tot}g}{e_{bat}}\right)\left(\frac{\varphi(1+CCP)}{\eta_{em}} + \frac{e_{bat}(1-\varphi)}{e_f\eta_{gt}}\right) - B \tag{12}$$

$$W_{H1} = W_{OE} + W_{PL} + \frac{g}{e_{bat}}\frac{\varphi(1+CCP)E_{0,tot}}{\eta_{em}} - B \tag{13}$$

where W_{OE} is the operating empty weight, W_{PL} is the payload weight, η_{em} is electric motor efficiency, and e_{bat} and e_f are energy densities of the battery and fuel, respectively. This modification preserves the structure of the hybrid-electric range formulation while explicitly incorporating buoyancy effects through the static heaviness term.

For sizing purposes, the range equation is rearranged to express the total shaft energy required for a given mission range R and shaft power-split S as:

$$E_{0,tot} = \frac{(W_{OE} + W_{PL} - B)\left(exp\left(\frac{R}{K}\right) - 1\right)}{\left(\frac{g\varphi(1+CCP)}{e_{bat}\eta_{em}} + \frac{g(1-\varphi)}{e_f\eta_{gt}}\right) - \left(\frac{g\varphi(1+CCP)}{e_{bat}\eta_{em}}\right)exp\left(\frac{R}{K}\right)} \tag{14}$$

where,

$$K = \eta_{gt}\eta_{gb}\eta_p \frac{C_{L,aero}}{C_D}\frac{e_f}{g}\frac{1}{(1-\varphi)} \tag{15}$$

$$CCP = \frac{SoC_{off}}{(1 - SoC_{off})} \tag{16}$$

This expression provides the total shaft energy required to complete a mission of range R for a specified hybridisation level. By evaluating $E_{0,tot}$ as a function of S, the variation of energy requirement with degree of hybridisation can be obtained, enabling the selection of an appropriate hybridisation level for a given mission profile.

The formulation is derived under the assumption of steady, level cruise and is therefore applicable only to mission segments that satisfy this condition. Accordingly, the selected value of S must be consistent with the shaft power requirements for steady cruise. For other phases of flight, such as take-off, descent, and low-speed manoeuvring, the propulsion requirements may differ significantly, and the hybridisation strategy must be determined separately for each phase. In such phases, the battery's contribution is typically higher due to transient power demands. However, for initial sizing of conventional airships, the cruise energy requirement may be assumed to approximate the total mission energy, consistent with the approach of Carichner and Nicolai.

3.2 Conventional Propulsion Sizing Methodology and Corrections

To establish confidence in the proposed hybrid-electric sizing framework, the conventional propulsion system of an existing airship was first analysed. The Zeppelin NT (N07-101), developed by Zeppelin Luftschifftechnik GmbH & Co. KG, represents the only airship currently in active commercial operation and provides a suitable reference for validation. A detailed propulsion system breakdown is available from the HeRKoLus 2023 study conducted in collaboration with the University of Stuttgart [13,14], which serves as a reliable source of real-world data.

As a baseline, the conventional propulsion system of the Zeppelin NT was independently sized using the baseline methodology proposed by Carichner and Nicolai, which is widely used for conceptual airship design. The required system inputs, including mission and configuration data, were obtained from publicly available sources [15,16]. This allowed for a direct comparison between the estimated component weights and those reported in the HeRKoLus study.

The results of this comparison are summarised in Table 1, which presents a component-wise breakdown of propulsion system mass. The baseline methodology provides reasonable estimates for primary components such as the engine and propeller, while noticeable differences are observed in components associated with nacelles and transmission systems.

Table 1 Zeppelin NT conventional propulsion system component-wise weight comparison

Conventional system component (HeRKoLus 2023)	Component mass (in kg)	Conventional system component (Methodology)	Component mass (in kg)	*Zeppelin NT correction factor*
Engine (wet/fluids and Lubrication system included)	492.60	Engine Weight	447.70	1.10

Fairing/Cowling (including Cooling and Exhaust systems)	367.30	Engine Mount Mass	180.97	2.03
Engine Control Unit	13.50	Engine Controls Mass	36.67	0.37
Starter Battery	26.30	Engine Starting Component Mass	22.72	1.16
Gearbox/Transmission (wet)	194.80	Gearbox Mass (wet)*	62.76	3.10
Propeller	147.10	Propeller Mass	133.95	1.10
Fuel (Mission and Unusable)	51.50	Fuel Mass*	44.22	1.16
Fuel System	102.30	Fuel Tank Mass*	143.82	0.71
Total Mass	1,395.40	Total Mass	1,072.81	*1.30*

*Component not accounted for separately in baseline methodology; estimated via generic formulae.

To account for these differences, correction factors were introduced based on the ratio of actual component weights to those predicted by the baseline methodology. These factors, referred to as Zeppelin NT correction factors, are applied to the corresponding components in the sizing methodology to incorporate the contributions of unmodeled subsystems.

The inclusion of these correction factors enables the baseline methodology better to represent the propulsion system characteristics of the reference airship while retaining its suitability for initial design. The resulting framework forms the basis for HEP system sizing in the present study. The accuracy of the baseline methodology is further discussed in Section 4.1.

3.3 Battery Sizing Methodology

Accurate battery sizing is critical for HEP systems, yet commonly used formulations in aircraft sizing literature often omit key practical considerations. In particular, the effect of deep-discharge protection (DDP) and the distinction between cell-level and pack-level energy density are frequently neglected. Battery packs cannot be discharged below a minimum state of charge (SoC) without risking permanent damage. Additional subsystems such as the battery management system (BMS), thermal management system (TMS), casing, and interconnections can account for up to 40% of the total battery pack mass. As a result, using cell-level energy densities can lead to a substantial underestimation of battery weight.

To address these limitations, an updated battery sizing relation was adopted:

$$W_{0,bat} = \frac{g}{\eta_e}\frac{(1+DDP)E_{sh}}{e_{bat,p}} \tag{17}$$

where $W_{0,bat}$ is the total battery pack weight, η_e is the battery-to-shaft efficiency (taken as 86%), E_{sh} is the required shaft energy for the mission, and $e_{bat,p}$ is the battery pack energy density (taken as 200 Wh/kg). The deep-discharge protection factor is defined as:

$$DDP = \frac{SoC_{min}}{(1 - SoC_{min})} \tag{18}$$

For a minimum allowable state-of-charge of 20% for a Li-ion battery pack, this term accounts for the unusable fraction of stored energy.

The sizing procedure was applied to the Zeppelin NT sightseeing mission, using the mission parameters summarised in Table 2. The total shaft energy requirement, including both mission and reserve segments, was computed and used as input to the battery sizing equation. The resulting battery mass estimate is summarised in Table 3.

Table 2 Zeppelin NT sightseeing mission performance requirements [15,16]

Performance Parameter	Value
Cruise duration	45 min (0.75 hour)
Cruise speed	35 kts (64.81 km/h)
Cruise shaft power	75 kW
Reserve cruise duration	2 hours
Reserve cruise speed*	50.66 km/h
Reserve shaft power	44.7 kW (10% of Max. shaft power)

*Value estimated by using parasitic drag C_{D0} = 0.0362 (obtained from cruise mission segment) and static heaviness SH = 500 kg

Table 3 Battery weight sizing results

Parameter	Value
Estimated shaft energy required (mission + reserve)	145.65 kWh
Total battery mass (Zeppelin *NT* study)	1,167.11 kg
Total battery mass (our study)	1,061.74 kg
Error	9.03%

The battery sizing relation is subsequently integrated with the hybrid-electric range formulation to enable consistent estimation of propulsion system mass. The accuracy of this approach is discussed in Section 4.2.

3.4 Component-wise Sizing Methodology

A component-wise sizing methodology for the HEP system was developed based on an extensive review of available literature, with emphasis on both state-of-the-art and conservative estimates applicable to airship configurations. The primary components considered in this methodology are summarised below:

1) Battery pack (including state-of-charge constraints and packaging overheads)
2) Electric motor/generator
3) Power-electronic converters (PECs)
4) Switchgear and protection equipment
5) Power cables
6) Thermal and cooling systems
7) Mechanical transmission systems
8) Thrust-vectoring mechanisms

The sizing approach and governing parameters for each component are described in the following subsections.

1) Battery pack (including state-of-charge constraints and packaging overheads)

   Battery pack sizing is governed by two primary considerations: state-of-charge (SoC) constraints and packaging overheads.

   - State-of-charge constraints

     In hybrid-electric airship applications, batteries are subjected to rapid charge–discharge cycles, including fast charging and high-rate discharging. Under such operating conditions, it is necessary to limit both the minimum and maximum allowable SoC levels to ensure safe and efficient operation [17]. Charging at high SoC levels results in reduced efficiency, increased losses, and accelerated battery degradation [18]. Accordingly, the maximum SoC is typically limited to 80–95%, depending on cell

chemistry and charging requirements.

Similarly, deep discharge at very low SoC levels can result in irreversible damage to battery cells, including loss of recharge capability and accelerated ageing. To prevent this, the minimum SoC is typically set to 5–20%, depending on system requirements and operating conditions [19]. These constraints are incorporated into the total shaft energy sizing formulation through the charge constraint parameter (CCP), as defined in Eq. (16).

- Packaging overheads

  In addition to electrochemical storage, the total battery pack mass includes contributions from auxiliary subsystems such as the battery management system (BMS), thermal management system (TMS), interconnections, and structural casing. These packaging elements introduce a significant mass penalty, typically reflected in cell-to-pack mass ratios of 0.67–0.75, with long-term targets of 0.8–0.9 [19–24]. These overheads are accounted for in addition to the SoC-related constraints described above.

2) Power cables

   Power cables are sized based on their current-carrying capacity and installation length. Modern aviation-grade power cables exhibit typical performance characteristics of approximately 170 A/kg/m, which is used as the basis for estimating cable mass in the present methodology [25].

3) Electric Motor/Generator and Associated Electrical Components

   Electric Motors/Generators, power-electronic converters (PECs), switchgear & protection devices, and overall thermal/cooling systems are sized based on their power-handling requirements, using power density values. Known values of their densities are as follows [25–27]:

   - Motor/Generator: 9–13 kVA/kg
   - Power-electronic converters: 9–19 kW/kg
   - Switchgear and protection devices: ~200 kW/kg (DC systems) & up to ~350 kW/kg (AC systems)
   - Thermal and cooling systems: 0.38–0.68 kW/kg

4) Mechanical transmission systems

   Mechanical transmission systems are sized based on complexity and power distribution requirements [28]. For simple gearbox systems without accessory drives or shaft power-splitting, typical mass ranges from 0.14–0.20 kg/hp (0.18–0.28 kg/kW).

   In contrast, parallel hybrid-electric configurations require more complex transmission systems incorporating accessory drives and power-splitting mechanisms. These systems exhibit higher mass characteristics, typically in the range of 0.25–0.30 kg/hp (0.33–0.40 kg/kW).

5) Thrust-vectoring mechanisms

   Thrust-vectoring systems are essential for airships due to their low-speed flight characteristics and, in some configurations, vertical take-off and landing (VTOL) capability. In airship applications, thrust vectoring is typically achieved by tilting the propeller assembly.

   The mass of such systems is estimated based on the mass of the swivelled component, with typical sizing factors of 0.12–0.16 kg per kg of the actuated component [28].

4. Results and Analysis

To evaluate the proposed HEP sizing methodology, a combination of validation and parametric analysis is performed. The assessment includes (A) validation of conventional propulsion sizing against real airship data, (B) validation of battery sizing through mission-level comparisons, and (C) analysis of HEP behaviour across varying degrees of hybridisation.

In addition, validation of the hybrid-electric range formulation is addressed through comparison with higher-fidelity approaches reported in the literature and through the development of a time-step simulation framework. Due to the absence of operational hybrid-electric airships, validation relies on a combination of real airship data, cross-comparison with published studies, and analytical consistency of predicted trends.

4.1 Validation of Conventional Propulsion Sizing

The accuracy of the conventional propulsion sizing methodology in Section 3.2 was evaluated using the Zeppelin NT (N07-101) airship. A comparison of the estimated component weights with the reference data from the HeRKoLus 2023 study is presented in Table 1 (Section 3.2). The results show that the baseline methodology underestimates the total propulsion system mass by approximately 23%, with the largest discrepancies observed in nacelle-related components and transmission systems. For instance, the gearbox/transmission mass deviates by approximately 300%, while the fairing and associated subsystems exhibit similarly large differences.

These discrepancies indicate that Carichner and Nicolai's methodology does not fully capture several integral components of modern airship propulsion systems. In particular, elements such as propeller reduction gears, swivelling mechanisms for thrust-vectoring propellers, mechanical transmission systems, and auxiliary subsystems, including cooling, exhaust, and lubrication, are either simplified or not explicitly modelled. As a result, the baseline methodology underestimates the total mass of the propulsion system. The application of correction factors is essential for extending the methodology to HEP systems, as many of the omitted components, particularly transmission, cooling, and integration-related subsystems, are also present in hybrid and fully electric architectures. Furthermore, airships such as the Zeppelin NT employ complex gearing arrangements and non-uniform power distribution to accommodate different flight conditions.

Through this process, the baseline conventional propulsion sizing methodology is further augmented better to reflect the characteristics of modern airship propulsion systems. This corrected framework is subsequently used as the foundation for HEP sizing in the present study.

4.2 Validation of Battery Sizing

The proposed battery sizing formulation in Section 3.3 was validated against the Zeppelin NT sightseeing mission using data from the HeRKoLus study. Using the mission parameters summarised in Table 2 (Section 3.3), the total shaft energy requirement (including reserve) was computed as 145.65 kWh. The corresponding battery mass estimated using the proposed formulation was 1,061.74 kg, compared to 1,167.11 kg reported in the reference study, resulting in an error of 9.03%.

This level of agreement is considered acceptable given that the reference study employs a more detailed mission analysis, whereas the present formulation is intended for initial sizing. The discrepancy arises from differences in the underlying battery sizing formulations and the higher fidelity of the mission energy estimation in the reference study. Nevertheless, the results demonstrate that the proposed approach captures the dominant factors influencing battery mass estimation and is suitable for integration with the hybrid-electric range model.

4.3 Hybrid-Electric Sizing Analysis

Before validating the formulation against higher-fidelity models, its behaviour is first examined through parametric analysis. The adapted hybrid-electric range formulation was applied to the Zeppelin NT configuration to understand the effect of hybridisation on propulsion system sizing. The baseline parameters correspond to the sightseeing mission at an altitude of 300 m, an envelope volume of 8,425 m³, a payload of 1,038 kg, a maximum take-off weight of 7,086 kg, and an empty weight of 6,000 kg.

The total shaft energy $E_{0,tot}$ was computed using Eq. (14) by varying the φ, (shaft power-split) from 0 to 1. The corresponding take-off and empty weights were then evaluated by accounting for the required fuel and battery system masses. Fig. 1 shows the variation in take-off weight with φ for battery energy densities of 300 Wh/kg and 400 Wh/kg.

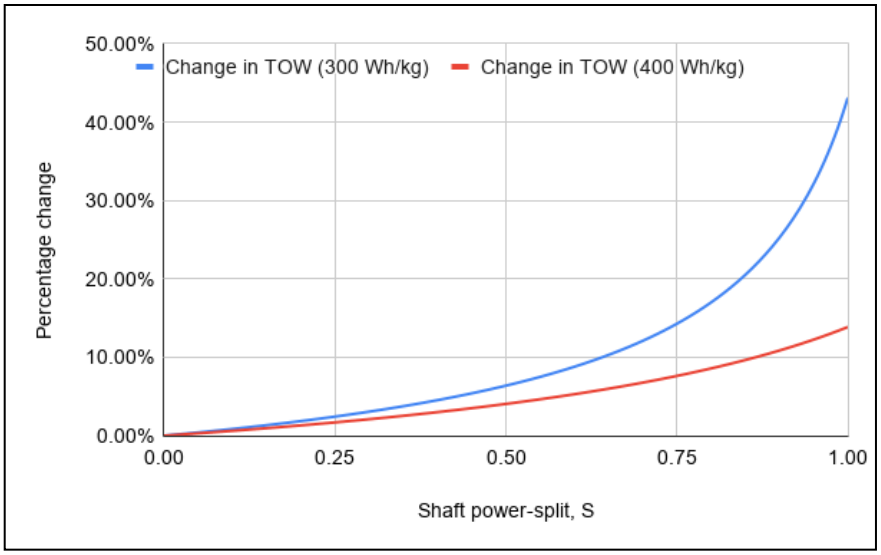


Figure 1 – Change in airship TOW with shaft power-split at e_{bat} = 300 Wh/kg, 400 Wh/kg.

The results indicate a significant increase in take-off weight with increasing electrification, particularly at lower battery energy densities. For a fully electric configuration, the take-off weight increases by approximately 43% at 300 Wh/kg and 14% at 400 Wh/kg relative to the conventional configuration. These trends are consistent with the expected impact of battery mass on overall vehicle weight and demonstrate the sensitivity of the proposed sizing methodology to battery energy density and hybridisation level.

4.4 Time-Step Simulation Validation

Due to the lack of operational hybrid-electric aircraft with significant hybridisation, direct validation of hybrid-electric range equations against flight data is currently not feasible. However, several studies have validated such formulations against high-fidelity simulations and independent sizing methods. Wroblewski et al. [29] validated a hybrid-electric Breguet range equation against a time-stepping simulation of an Embraer ERJ-175 regional jet, incorporating real engine performance data. The predicted ranges and endurance values matched simulation results within 2–5% across different flight conditions and hybridisation levels. Similarly, Finger et al. [30] performed cross-validation between two independent hybrid-electric sizing methodologies and reported agreement within 5% for key performance metrics.

These studies indicate that hybrid-electric range formulations can provide reliable predictions for conceptual design when validated against higher-fidelity models. However, the absence of real-world hybrid aircraft data remains a key limitation in the field.

To further assess the validity of the proposed HEP sizing methodology, a time-step simulation of a hybrid-electric airship was developed in MATLAB/Simulink (version R2024b). The simulation incorporates variation of airship weight, propulsion power requirements, and energy consumption over time. It provides an independent, higher-fidelity framework to evaluate the accuracy of the analytical hybrid-electric range formulation developed in Section 3.1. The model structure and its operation are described below.

4.4.1 Simulation Model

The overall Simulink model developed for the HEP system is shown in Fig. 2. It consists of three primary subsystems: (i) Mission Profile, (ii) Airship Model, and (iii) HEP system.

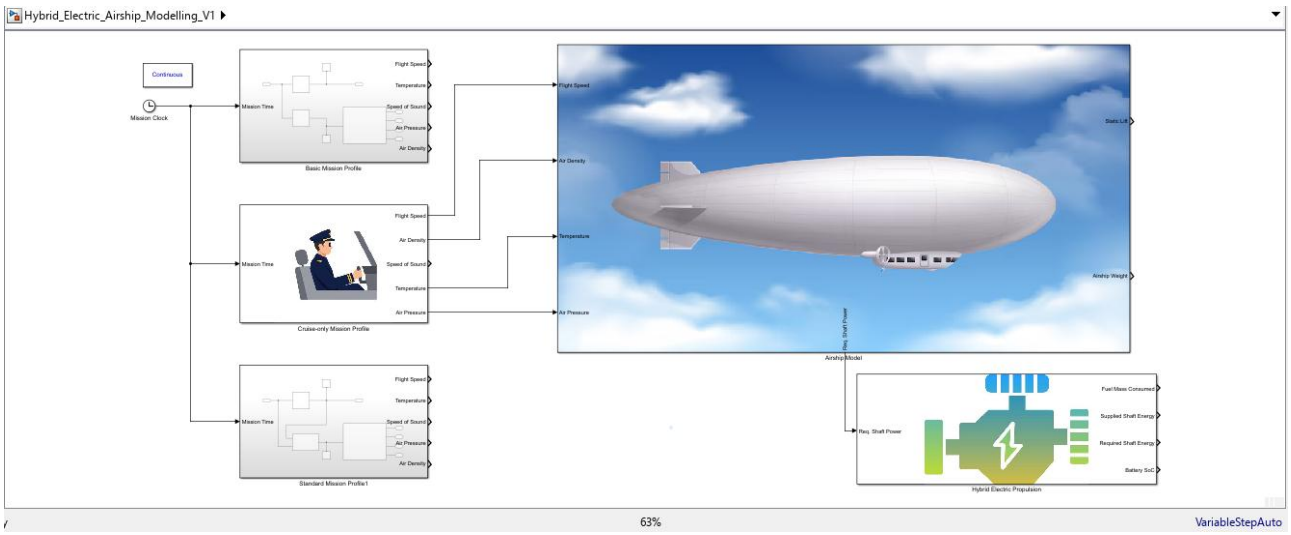


Figure 2 – MATLAB/Simulink Model Overview.

- Mission Profile Block

  The Mission Profile block, shown in Fig. 3, generates a simplified cruise-only mission, characterised by constant cruise velocity and altitude. The cruise altitude is provided as input to the ISA Atmosphere block from the Simulink library, which outputs the corresponding atmospheric properties, including air temperature, pressure, and density.

  The core assumption in this study is that cruise at constant altitude and $\frac{C_L}{C_D}$. In an actual cruise flight, that essentially means the cruise velocity changes due to loss of fuel mass. The same conditions are created in the simulation. The airship's static heaviness is updated at every simulation time step based on the remaining fuel mass, while battery mass remains constant. The model thus adjusts the cruise velocity and shaft power required at every time step to maintain cruise altitude and given $\frac{C_L}{C_D}$.

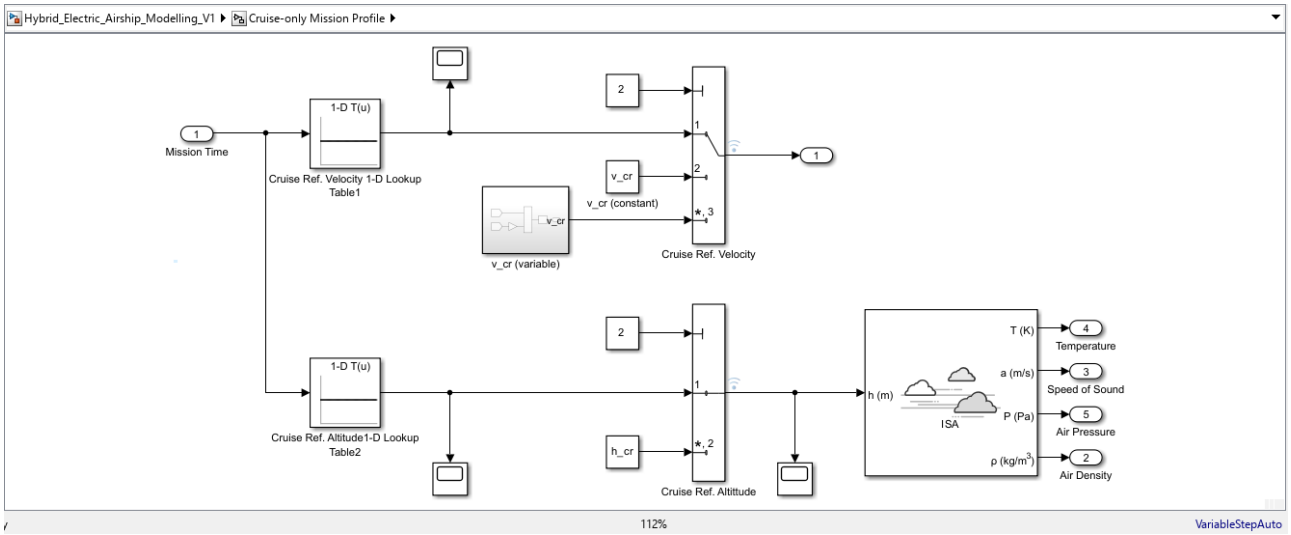


Figure 3 – Mission Profile Block.

- Airship Model Block

  The Airship Model block, illustrated in Fig. 4, computes the aerostatic and aerodynamic characteristics of the airship based on inputs from the Mission Profile block. Using these inputs, the block evaluates dynamic pressure, aerodynamic drag, and buoyant lift using standard equations [31], ultimately determining the shaft power required to maintain steady cruise under the specified conditions.

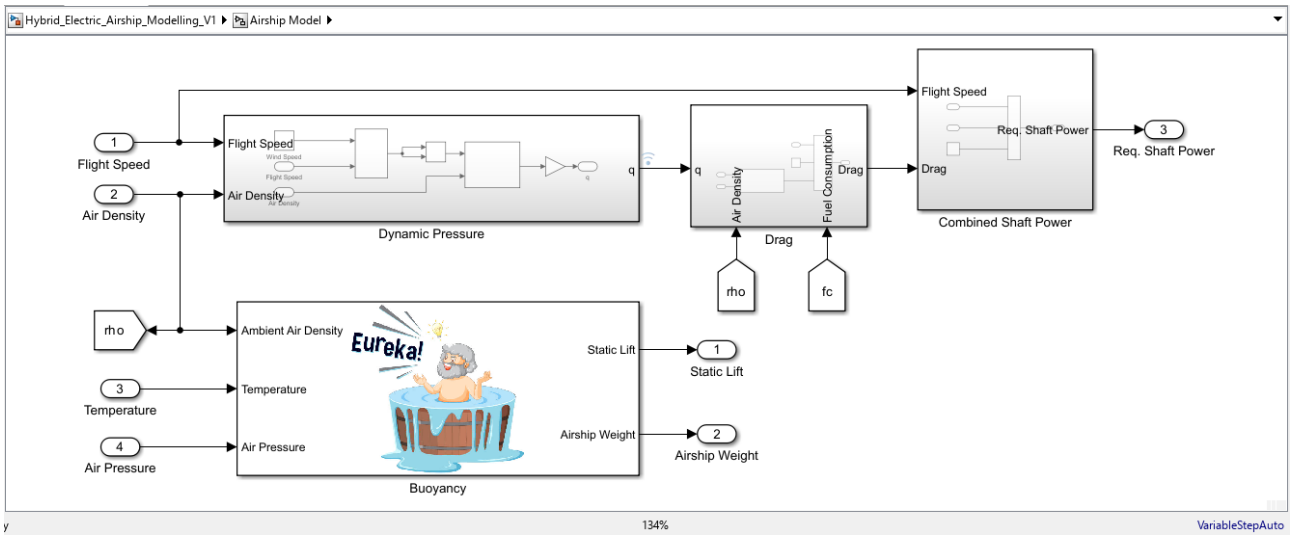


Figure 4 – Airship Model Block.

- Hybrid-Electric Propulsion Block

  The HEP block, shown in Fig. 5, generates the shaft power required by the Airship Model block. The demanded shaft power is first processed through a power-split logic, which determines the respective power contributions of the electric motor and the spark-ignition (SI) engine based on the specified degree of hybridisation. It must be noted that the present implementation represents a parallel HEP architecture in which shaft power demand is shared directly between the SI engine and electric motor according to the shaft power-split parameter *S*, determined from the degree of hybridisation Ψ (see Eq. 6).

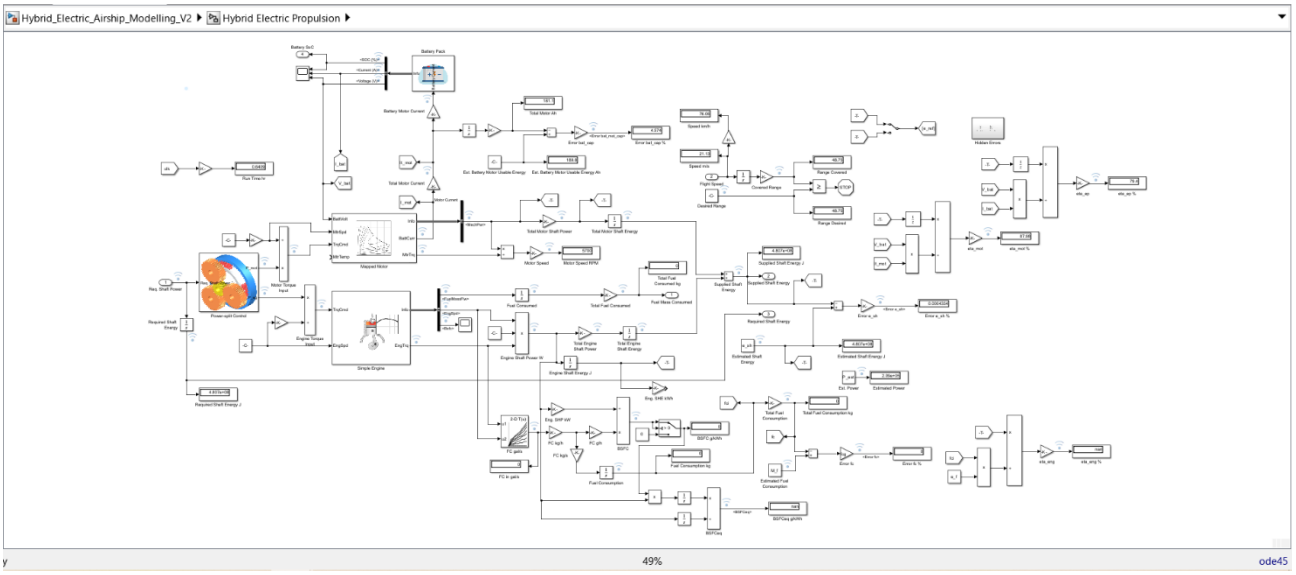


Figure 5 – Hybrid-Electric Propulsion Block.

The electric motor is modelled using the Mapped Motor block available in the Simulink library, with the “Electrical Torque” parameterised by “Tabulated torque-speed envelope” and the “Electrical Losses” parameterised by “Tabulated efficiency data with temperature and voltage”. The motor parameters are based on data from the MATLAB File Exchange [32], where the motor was modelled using public specifications for the Tesla Model 3 Long Range All-Wheel Drive (AWD). The modelled motor provides a maximum continuous power of 100 kW. The block interpolates motor performance under a torque-control configuration.

The SI engine is modelled using the Simple Engine block from the Simulink library. This block interpolates engine torque and speed based on input torque–speed characteristics. The

engine model is based on the Ford EcoBoost 1.6L engine, for which torque-speed-fuel consumption data are available in [32].

4.4.2 Model Operation

To facilitate parameter input and simulation control, a MATLAB-based graphical user interface (GUI) was developed. The input parameters used are shown in Figs. 6 and 7. The simulation was executed using the ode45 (Dormand-Prince) solver in variable-step mode, with relative tolerance of 1e-6. The simulation stops once the specified range is covered by the airship, determined as the time integral of the airship speed function.

The default input values used in the GUI are based on publicly available performance data of the Zeppelin NT airship, operated by Luftschiffbau Zeppelin in Germany and the United States [15,16].

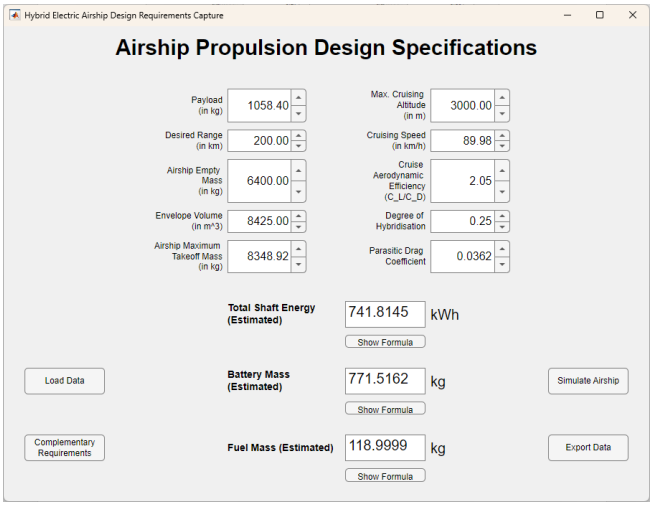


Figure 6 – MATLAB App GUI Screen 1 (Hybrid-Electric Airship Design Requirements Capture).

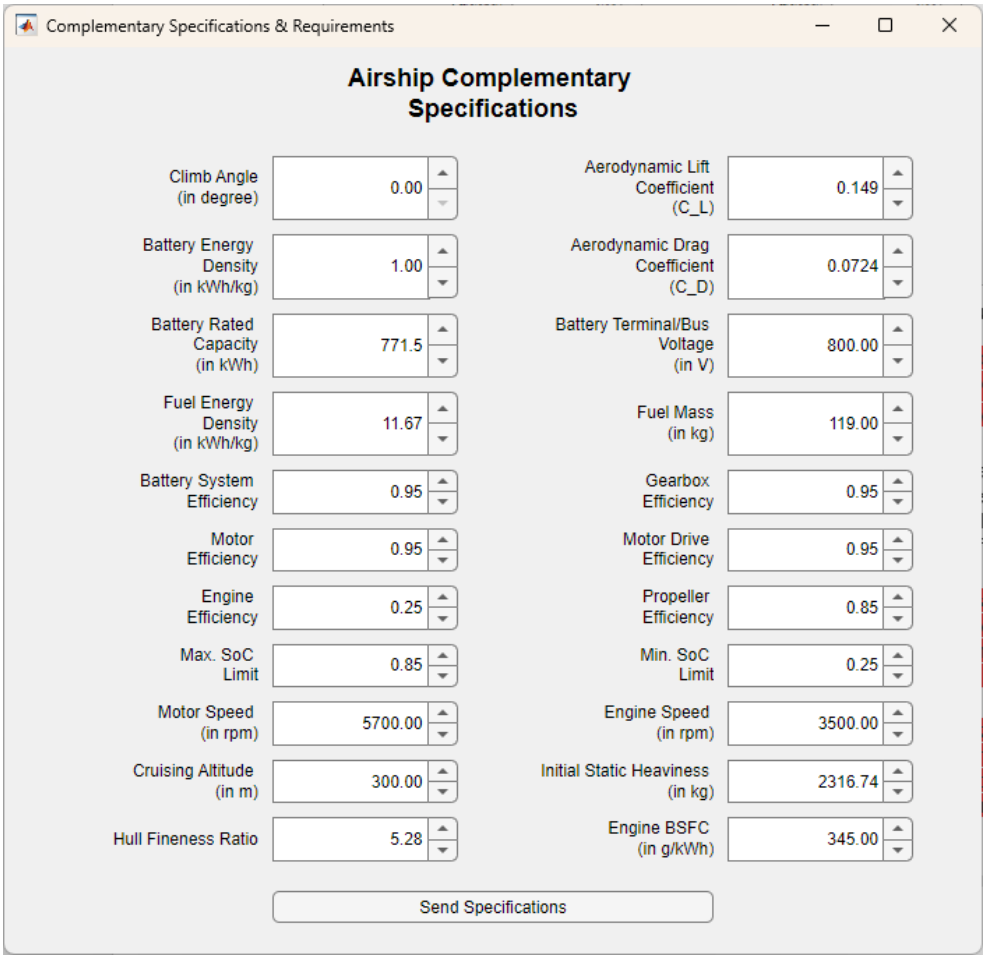


Figure 7 – MATLAB App GUI Screen 2 (Complementary Specifications & Requirements).

The simulation was performed using the airship parameters and mission profile specified in Figs. 6 and 7, under the assumption of constant aerodynamic efficiency $\frac{C_L}{C_D}$. This assumption is consistent with the analytical range formulation developed earlier, enabling a direct comparison between analytical and simulation-based predictions. The simulation determines the total shaft energy supplied by the propulsion system for the mission, as the sum of the time integrals of the total shaft powers of both powertrains.

For the mission profile considered in Figs 6 and 7, the comparison of simulation results and those estimated by Eq. (14) for varying degrees of hybridisation is listed in Table 4.

Table 4 Comparison of simulation results with the proposed range equation for 200 km range

Degree of Hybridisation (Ψ)	Error in Shaft Energy (%)	Error in Fuel Consumption (%)	Error in Battery Capacity (%)
0	0.0300	-0.08	NA
0.25	0.0100	-0.03	4.9
0.5	0.0010	0.01	4.8
0.75	0.0010	-0.16	5.8
1	0.0002	NA	5.2

The equation model validation was performed over a range of Ψ values. In all cases, mission shaft energy and fuel consumption estimation errors were within 1%, while battery capacity estimation errors were within 6%, which is equal to the error in battery mass. This level of agreement is good for the conceptual design stage.

The aerodynamic coefficients used in the model are estimated using the empirical methodology proposed by Carichner and Nicolai and may therefore differ slightly from the actual airship characteristics. Additionally, the given engine has been modelled using a full BSFC map implemented as a 2-D look-up table to obtain accurate fuel consumption and engine efficiency values during simulation, which effectively vary with operating conditions.

This comparison provides initial validation of the proposed hybrid-electric sizing methodology and its underlying analytical formulation across varying hybridisation levels and cruise ranges, under the assumptions adopted in the present study.

It must be noted that the current formulation does not include the following considerations:

- climb/descent
- transient maneuvers
- variable propeller efficiency
- variable aerodynamic coefficients
- battery ageing/degradation
- thermal effects
- power limits.

Future work will focus on incorporating these factors into the methodology.

5. Conclusion

This study presents a conceptual sizing methodology for hybrid-electric propulsion systems in airships by adapting hybrid-electric aircraft range formulations to account for buoyancy-driven flight through the concept of static heaviness. The resulting framework integrates hybrid-electric range analysis, conventional propulsion sizing corrections, battery sizing considerations, and component-level propulsion system sizing, enabling a preliminary assessment of hybridisation effects on airship propulsion system mass and energy requirements.

Validation against data from the Zeppelin NT airship demonstrated that conventional airship sizing methodologies underestimate the propulsion system mass by approximately 23%, primarily due to the omission of integration-related subsystems, such as transmission, cooling systems, and thrust-vectoring components. The introduction of Zeppelin NT correction factors enables the sizing methodology to reflect better the propulsion-system masses observed in the reference airship. The proposed battery sizing methodology, which incorporates deep-discharge protection and pack-level energy density effects, predicted battery mass within 9.03% of values reported in the HeRKoLus study, demonstrating suitability for conceptual design applications.

Parametric analysis of the adapted hybrid-electric range formulation showed that increasing electrification results in significant increases in take-off weight at currently achievable battery energy densities. For the Zeppelin NT case study, fully electric configurations increased take-off weight by approximately 43% at 300 Wh/kg and 14% at 400 Wh/kg relative to the conventional configuration. These results highlight the sensitivity of airship propulsion-system sizing to battery energy density.

A MATLAB/Simulink-based time-step simulation framework was developed to provide an independent validation of the proposed methodology. Across multiple hybridisation levels and cruise ranges, analytical predictions of mission shaft energy and fuel consumption agreed with simulation results within 1%, while battery capacity/mass estimates remained within 6%. These results demonstrate that the proposed methodology provides reliable estimates of mission energy requirements and propulsion-system sizing parameters for conceptual design studies.

Overall, the proposed methodology establishes a physically consistent and practically applicable framework for conceptual sizing of hybrid-electric propulsion systems in airships. Future work will focus on incorporating variable aerodynamic characteristics, propulsion-system operating limits, battery degradation and thermal effects, transient flight phases, and detailed component-level models, as well as extending the simulation framework to complete mission profiles.

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References

[1] Interesting Engineering. World's largest aircraft, Google co-founder's Pathfinder 1 tests flight. Available: https://interestingengineering.com/transportation/worlds-largest-aircraft-google-co-founders-pathfinder-1-tests-flight, accessed May 5, 2026.
[2] Safran. Safran onboard Flying Whales' LCA60T airship! Safran, 2025. Available: https://www.safran-group.com/news/safran-onboard-flying-whales-lca60t-airship-2025-07-01, accessed May 5, 2026.
[3] Allano S. Challenges and prospective solutions for propulsion of a zero-emission cargo airship. Presented at the *International Conference on Electric Airships - Decarbonizing Aviation*, Nürnberg, Germany, 2023.
[4] Airport Industry Review. Flying Whales eyes cargo revolution with a familiar solution. *Airport Industry Review*, 2024. Available: https://airport.nridigital.com/air_aug23/flying_whales_eyes_cargo_revolution_familiar_solution, accessed May 5, 2026.
[5] Hybrid Air Vehicles. Airlander 10. Available: https://www.hybridairvehicles.com/airlander/airlander-10/, accessed May 5, 2026.
[6] Allen R, Botchway D, Cox J, Grassi A, Hodgson R, Hudson C, Scruggs W and Pant R. Methodology for conceptual sizing of green airship. *Proc 11th AIAA Aviation Technology, Integration, and Operations Conference*, Virginia Beach, VA, Paper AIAA 2011-6915, 2011.
[7] Murugaiah M, Theng DF, Khan T, Sebaey TA and Singh B. Hybrid electric powered multi-lobed airship for sustainable aviation. *Aerospace*, Vol. 9, No. 12, Article 769, 2022.
[8] Voskuijl M, Van Bogaert J and Rao AG. Analysis and design of hybrid electric regional turboprop aircraft. *CEAS Aeronautical Journal*, Vol. 9, No. 1, pp 15–25, 2018.
[9] De Vries R, Hoogreef MFM and Vos R. Range equation for hybrid-electric aircraft with constant power split. *Journal of Aircraft*, Vol. 57, No. 3, pp 552–557, 2020.
[10] Batra A, Raute R and Camilleri R. On the range equation for hybrid-electric aircraft. *Aerospace*, Vol. 10, No. 8, Article 687, 2023.
[11] Brelje BJ and Martins JRRA. Electric, hybrid, and turboelectric fixed-wing aircraft: a review of concepts, models, and design approaches. *Progress in Aerospace Sciences*, Vol. 104, pp 1–19, 2019.
[12] Carichner GE and Nicolai LM. *Fundamentals of aircraft and airship design: Volume 2—airship design and case studies*. American Institute of Aeronautics and Astronautics, Blacksburg, Virginia, 2013.
[13] Institut für Flugzeugbau, University of Stuttgart. *Modellbildung von (hybrid)elektrischen Antrieben für Luftschiffe unter Berücksichtigung des Missionsprofils*. University of Stuttgart, Stuttgart, Germany, 2023.
[14] Bender A. Design and sizing of a hybrid electric powertrain for an airship. Presented at the *International Conference on Electric Airships - Decarbonizing Aviation*, Nürnberg, Germany, 2023.
[15] Zeppelin NT. Aufbau von einem Zeppelin Luftschiff. Available: https://zeppelinflug.de/en/zeppelin-nt/technik, accessed May 5, 2026.
[16] Airships.net. Zeppelin NT. Available: https://www.airships.net/zeppelin-nt/, accessed May 5, 2026.
[17] Wikner E, Björklund E, Fridner J, Brandell D and Thiringer T. How the utilised SOC window in commercial Li-ion pouch cells influence battery ageing. *Journal of Power Sources Advances*, Vol. 8, Article 100054, 2021.
[18] Adebajo K, Anthony G, Peskar J, Downey AR, Chen Y and Hu C. Impact of charging rate and state of charge on electric aircraft battery degradation using a multi-domain model with realistic southeastern U.S. flight paths. *Proc AIAA SCITECH 2025 Forum*, Orlando, FL, Paper AIAA 2025-2705, 2025.
[19] Viswanathan V, Epstein AH, Chiang YM, Takeuchi E, Bradley M, Langford J and Winter M. The challenges and opportunities of battery-powered flight. *Nature*, Vol. 601, No. 7893, pp 519–525, 2022.
[20] Spinelli A, Krupa GP, Kipouros T, Laskaridis P and Berseneff B. Battery pack technological considerations for hybrid-electric regional aircraft feasibility. *The Aeronautical Journal*, Vol. 129, No. 1338, pp 1142–1166, 2025.
[21] De Vries R, Wolleswinkel RE, Hoogreef M and Vos R. A new perspective on battery-electric aviation, Part II: conceptual design of a 90-seater. *Proc AIAA SCITECH 2024 Forum*, Orlando, FL, Paper AIAA 2024-1490, 2024.
[22] European Battery Alliance. *Strategic research agenda for batteries 2020*. European Battery Alliance, 2020.
[23] De Vries R, Wolleswinkel RE, Jacobson DR, Bonnema M and Thiede S. Battery performance metrics for large electric passenger aircraft. *Proc 34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024)*, Florence, Italy, 2024.

[24] Chin J, Look K, McNichols EO, Hall D, Gray J and Schnulo SL. Battery cell-to-pack scaling trends for electric aircraft. *Proc AIAA Propulsion and Energy 2021 Forum*, Paper AIAA 2021-3316, 2021.
[25] Jansen R, Bowman C and Jankovsky A. Sizing power components of an electrically driven tail cone thruster and a range extender. *Proc 16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C., Paper AIAA 2016-3766, 2016.
[26] Sadey DJ, Csank J, Hanlon PA and Jansen R. A generalized power system architecture sizing and analysis framework. *Proc 2018 Joint Propulsion Conference*, Cincinnati, Ohio, Paper AIAA 2018-4616, 2018.
[27] Leishman JG. Electrically-powered aircraft. *Introduction to Aerospace Flight Vehicles*, Embry-Riddle Aeronautical University, 2023. Available: https://eaglepubs.erau.edu/introductiontoaerospaceflightvehicles/chapter/electric-aircraft/, accessed June 15, 2026.
[28] Khoury GA. *Airship technology*. 2nd edition, Cambridge University Press, New York, NY, 2012.
[29] Wroblewski GE and Ansell PJ. Hybrid-electric Breguet range equation: development and validation against a hybrid-electric aircraft simulation. *Proc AIAA Propulsion and Energy 2020 Forum*, Paper AIAA 2020-3579, 2020.
[30] Finger DF, Bil C and Braun C. Initial sizing methodology for hybrid-electric general aviation aircraft. *Journal of Aircraft*, Vol. 57, No. 2, pp 245–255, 2020.
[31] Anderson JD. *Introduction to flight*. 5th edition, McGraw-Hill Higher Education, Boston, MA, 2005.
[32] MathWorks File Exchange. Simple idling engine model with fuel consumption map. MathWorks, 2026. Available: https://www.mathworks.com/matlabcentral/fileexchange/125265-simple-idling-engine-model-with-fuel-consumption-map, accessed June 8, 2026.