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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Mission-Based Energy Performance and Feasibility Assessment of a Multicopter eVTOL for Inter-Island Logistics in the Aeolian Islands

TESI DI LAUREA MAGISTRALE IN
AERONAUTICAL ENGINEERING - INGEGNERIA AERONAUTICA

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Academic Year: 2025-26

*“And so you touch this limit, something happens
and you suddenly can go a little bit further.”
Ayrton Senna*

Abstract

In recent years, the growing interest in sustainable mobility solutions and innovative transport systems has fostered the development of electric vertical take-off and landing aircraft (eVTOL), which are considered among the most promising technologies within Advanced Air Mobility. In addition to urban passenger transport, such aircraft may also represent a valid alternative for regional and island logistics missions, where rapid connectivity and limited infrastructure availability constitute strategic factors. In this context, the Aeolian Islands provide a particularly relevant case study for the aerial distribution of essential goods between the Sicilian coast and the main islands of the archipelago. The aim of this thesis is the development and application of a mission-based energy model for the assessment of the performance and operational feasibility of a multicopter eVTOL employed in inter-island logistics missions. The model, implemented in MATLAB, divides the mission into successive flight segments (taxi, hover, vertical take-off, climb, cruise, descent, landing and final taxi), estimating for each of them the corresponding time, required power and energy consumption. The reference aircraft adopted is the Volocopter VoloCity, selected on the basis of publicly available data and for its multicopter configuration, which is consistent with the scenario under investigation. Particular attention has been devoted to the modelling of the electrical energy storage system, including effects related to the available state of charge and to performance variations with ambient temperature, based on correlations available in the technical literature. The model has also been compared with and validated against formulations presented in reference studies within the sector. Subsequently, the developed framework has been applied to the reference mission and to other possible connections within the Aeolian archipelago, carrying out sensitivity analyses with respect to the main operational parameters, including cruise speed, transported payload, mission distance, number of rotors, external temperature, wind conditions and rate of climb. The results show that the energetic feasibility of the mission depends significantly on the combination of payload, required distance and environmental conditions. Furthermore, specific optimal operating speeds emerge, capable of minimising the overall energy consumption. The study therefore highlights the potential of multicopter eVTOL aircraft for short-range island logistics applications, while also underlining the limitations

currently imposed by battery technology and by reduced efficiency in more demanding missions. Finally, the work provides a useful tool for future design, optimisation and operational planning activities concerning eVTOL services dedicated to sustainable logistics in island and peripheral territories.

Abstract in lingua italiana

Negli ultimi anni, il crescente interesse verso soluzioni di mobilità sostenibile e sistemi di trasporto innovativi ha favorito lo sviluppo dei velivoli elettrici a decollo e atterraggio verticale (eVTOL), considerati tra le tecnologie più promettenti nell'ambito della Advanced Air Mobility. Oltre al trasporto passeggeri urbano, tali velivoli possono rappresentare una valida alternativa anche per missioni logistiche regionali e insulari, dove la rapidità di collegamento e la limitata disponibilità infrastrutturale costituiscono fattori strategici. In questo contesto, il territorio delle Isole Eolie risulta particolarmente interessante come caso studio per applicazioni di distribuzione aerea di beni di prima necessità tra la costa siciliana e le principali isole dell'arcipelago. L'obiettivo del presente lavoro di tesi è lo sviluppo e l'applicazione di un modello energetico mission-based per la valutazione delle prestazioni e della fattibilità operativa di un eVTOL multicottero impiegato in missioni logistiche inter-isola. Il modello, implementato in ambiente MATLAB, suddivide la missione in segmenti successivi di volo (taxi, hover, decollo verticale, salita, crociera, discesa, atterraggio e taxi finale), stimando per ciascuno di essi tempi, potenze richieste ed energia consumata. Il velivolo di riferimento adottato è il Volocopter VoloCity, scelto per la disponibilità di dati pubblici e per la configurazione multicottero coerente con lo scenario analizzato. Particolare attenzione è stata dedicata alla modellazione del sistema di accumulo elettrico, includendo effetti legati allo stato di carica disponibile e alla variazione delle prestazioni con la temperatura ambiente, sulla base di correlazioni presenti in letteratura tecnica. Il modello è stato inoltre confrontato e validato rispetto a formulazioni presenti in studi di riferimento del settore. Successivamente, il framework sviluppato è stato applicato alla missione di riferimento e ad altri possibili collegamenti dell'arcipelago eoliano, conducendo analisi di sensitività rispetto ai principali parametri operativi, alcuni dei quali velocità di crociera, payload trasportato, distanza di missione, numero di rotori, temperatura esterna, vento e rateo di salita. I risultati mostrano come la fattibilità energetica della missione dipenda in modo significativo dalla combinazione tra carico utile, distanza richiesta e condizioni ambientali. Emergono inoltre specifiche velocità operative ottimali in grado di minimizzare il consumo energetico complessivo. Lo studio evidenzia quindi il potenziale dei multicotteri eVTOL per applicazioni logistiche insulari a corto rag-

gio, pur sottolineando i limiti attualmente imposti dalla tecnologia delle batterie e dalla ridotta efficienza in missioni più gravose. Il lavoro fornisce infine uno strumento utile per future attività di progettazione, ottimizzazione e pianificazione operativa di servizi eVTOL dedicati alla logistica sostenibile in territori insulari e periferici.

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1 | Introduction

1.1. Background and Motivation

The global transport sector is undergoing a profound transformation driven by the need to reduce greenhouse gas emissions, improve energy efficiency, and develop more sustainable mobility systems. In this context, the progressive electrification of transport has become one of the main technological pathways for achieving international environmental targets, particularly in sectors traditionally characterised by high fuel consumption and significant environmental impact. Although electrification has already reached a relatively mature stage in road transport, its application to the aeronautical sector still presents considerable technical and operational challenges. Among the emerging solutions in this field, electric vertical take-off and landing aircraft, commonly referred to as eVTOLs, have attracted considerable attention from both industry and academia. These aircraft are designed to combine the operational flexibility typical of rotary-wing aircraft, such as vertical take-off and landing capability, with the potential advantages of electric propulsion systems, including reduced local emissions, lower noise levels, and simplified mechanical architectures. Initially conceived mainly for urban passenger transport within the framework of Advanced Air Mobility, eVTOL platforms are now increasingly being considered for a wider range of applications, including emergency response, medical transport, surveillance, and freight logistics. In particular, logistics missions based on light electric aircraft can offer significant advantages in geographical areas where conventional transport systems are limited by natural barriers, reduced infrastructure, or long journey times. Island territories represent a particularly significant example of such conditions. In these contexts, the transport of essential goods often depends on maritime connections, which may be affected by weather conditions, timetable constraints, and relatively slow response times. An aerial logistics network based on eVTOL aircraft could therefore provide a complementary solution capable of increasing flexibility, resilience, and service continuity. The Aeolian Islands, located off the northern coast of Sicily, represent a particularly relevant case study for this type of application. The archipelago includes several inhabited islands, characterised by different population sizes, tourist flows, and levels of accessi-

bility. Ensuring the regular and rapid distribution of urgent goods, medical supplies, or small payloads between the mainland and the islands, or between the islands themselves, remains a non-negligible logistical challenge. For this reason, the area offers a realistic and meaningful scenario in which to investigate the practical potential of eVTOL-based logistics operations. Despite the growing interest in these technologies, many current studies remain focused on aircraft conceptual design, certification pathways, or urban mobility scenarios. Comparatively, less attention has been devoted to mission-oriented energy assessments in real regional contexts, where route geometry, payload requirements, environmental conditions, and battery limitations strongly influence operational feasibility. In particular, multicopter configurations, although mechanically simple and highly controllable, are often penalised by high power requirements in hovering and limited cruise efficiency, making accurate energy modelling essential. Within this framework, the present thesis arises from the need to develop a quantitative and physically consistent methodology capable of assessing whether current multicopter eVTOL platforms can effectively support short-range logistics services in island environments. Rather than limiting the analysis to nominal range claims or simplified endurance estimates, this work adopts a mission-based approach in which each flight phase explicitly contributes to the total energy consumption. This makes it possible to identify the critical segments, the main factors influencing performance, and the operational feasibility envelopes. The combination of technological relevance, practical applicability, and engineering complexity makes this topic particularly suitable for academic investigation. Understanding the real energy capabilities and operational limitations of eVTOL systems is, in fact, a necessary step towards their realistic integration into future sustainable transport systems.

1.2. Problem Statement

Although electric vertical take-off and landing aircraft (eVTOLs) are widely recognised as promising solutions for the sustainable mobility of the future, their actual operational capabilities remain strongly constrained by current technological limitations, particularly in terms of battery performance, on-board available energy, and power required during flight. This issue becomes even more relevant in the case of multicopter configurations, whose operational simplicity and vertical flight capability are often offset by relatively high energy consumption, especially during hovering, take-off, landing, and low-speed flight phases. Consequently, the practical use of multicopter eVTOLs for logistics services cannot be assessed solely on the basis of nominal range values or manufacturers' claims. A real mission consists of multiple flight segments, each characterised by different power requirements, durations, and aerodynamic conditions. The cumulative contribution of

these phases can significantly influence the overall mission energy demand and therefore determine the actual operational feasibility of the route. This issue is particularly important in island and peripheral regions, where transport systems are frequently subject to geographical constraints, dependence on weather conditions, and limited service flexibility. In such contexts, eVTOL aircraft could provide valuable support for the rapid transport of essential goods, urgent supplies, or small payloads. However, these potential advantages can only be realised if the aircraft is capable of completing the required mission while satisfying payload constraints, battery reserve margins, and operational safety requirements. To date, there is a clear gap between the theoretical potential of eVTOL-based logistics applications and the quantitative assessment of their actual feasibility under specific mission conditions. Many available studies focus on aircraft design concepts, regulatory aspects, or generic urban mobility scenarios, while less attention has been devoted to realistic regional operations through detailed segment-based energy analyses. Furthermore, publicly available information regarding actual aircraft performance, battery limitations, and environmental sensitivity is often limited, making independent engineering assessments particularly valuable. Within this framework, the central problem addressed in this thesis lies in the absence of a robust and physically consistent methodology capable of assessing whether a multicopter eVTOL can effectively perform short-range logistics missions in real island environments. In particular, it is necessary to determine how mission distance, transported payload, cruise speed, ambient temperature, wind conditions, and aircraft configuration influence total energy consumption and overall feasibility. The case study of the Aeolian Islands clearly reflects this issue. Although the distances involved may appear compatible with the nominal capabilities of modern eVTOL aircraft, the actual feasibility of routes such as Milazzo–Vulcano depends on the combined effect of vertical flight segments, energy reserve constraints, battery performance degradation, and required operational margins. Without a dedicated mission-level analysis, such feasibility cannot be determined reliably. Therefore, the problem investigated in this work is not simply whether an eVTOL can fly between two locations, but rather whether it can do so efficiently, safely, and repeatedly under realistic operating conditions. Answering this question requires a detailed mission-based modelling approach capable of translating aircraft characteristics and route requirements into measurable performance indicators, such as energy demand, power peaks, state-of-charge evolution, and operational feasibility envelopes.

1.3. Research Objectives

The general objective of this thesis is to develop and apply a mission-based engineering framework for the assessment of the energy performance and operational feasibility of multicopter eVTOL aircraft employed in short-range logistics missions. The work is specifically focused on realistic inter-island transport scenarios, in which route constraints, payload requirements, and environmental conditions play a decisive role in defining the actual sustainability of the mission. To achieve this general aim, the first objective is to formulate a physically consistent energy model capable of representing the main flight phases of a mission performed by a multicopter eVTOL. Rather than relying on simplified range estimates, the model aims to describe the contribution of each mission segment, including taxi, hovering, vertical take-off, climb, cruise, descent, landing, and final ground operations. This enables a more realistic estimation of the overall energy demand and the required power peaks. A second objective concerns the implementation of the proposed framework in a numerical environment suitable for rapid simulations and parametric studies. To this end, the model is developed in MATLAB through a modular architecture, which allows different mission assumptions, aircraft parameters, and environmental conditions to be modified efficiently. This flexibility is essential both for repeated analyses and for possible future extensions of the model. A further objective concerns the modelling of the on-board energy storage system. Particular attention is devoted to battery-related constraints, including effectively usable energy, state-of-charge evolution, reserve margins, and performance sensitivity to ambient temperature. Since battery limitations currently represent one of the main obstacles to the widespread adoption of eVTOL aircraft, their explicit inclusion is considered fundamental for any realistic feasibility assessment. Another key objective is the validation of the developed methodology through comparison with reference formulations and mission models available in the technical literature. This phase is necessary to verify the consistency of the implemented equations, the plausibility of the obtained results, and the overall reliability of the framework before its application to real operational scenarios. Once validated, the model is subsequently applied to a practical case study concerning logistics operations in the Aeolian Islands archipelago. In particular, the Milazzo–Vulcano route is adopted as the reference mission, together with other possible inter-island connections. The objective of this phase is to determine whether a multicopter eVTOL can satisfy the required transport demand while maintaining adequate energy and operational margins. A further objective is to identify the main parameters influencing mission feasibility through dedicated sensitivity analyses. Cruise speed, payload mass, mission distance, number of rotors, ambient temperature, wind conditions, and climb rate are systematically varied in order to quantify their effects

on total energy consumption, power peaks, final state of charge, and operational feasibility envelopes. Finally, the thesis aims to provide engineering insight into the practical potential of multicopter eVTOL systems for sustainable logistics applications in island and peripheral territories. Beyond the specific case study, the work intends to highlight current technological limitations, operational trade-offs, and possible future developments required for wider real-world adoption. In doing so, starting from the reference mission, the thesis proposes a possible business model in which dedicated take-off, landing, and charging stations for eVTOL drones could be deployed within the Aeolian archipelago, creating an actual distribution network. In this model, the island of Lipari is considered as the main hub, owing to its geographically favourable position for all possible inter-island connections.

1.4. Research Methodology

The research methodology adopted in this thesis is based on a quantitative engineering approach aimed at assessing the energy performance and operational feasibility of multicopter eVTOL aircraft through mission-level simulation. The methodological framework combines physical modelling, numerical implementation, literature-based validation, and application to a realistic transport scenario. This structure was selected in order to ensure both technical rigour and practical relevance. The first phase of the methodology consists of defining the problem and identifying the main variables that influence mission feasibility. Starting from the operational characteristics of multicopter eVTOL aircraft, the study considers the main constraints associated with battery technology, payload capacity, mission distance, required power, and environmental conditions. In parallel, the logistics requirements of island territories are analysed in order to define a meaningful case study in which these variables can be investigated under realistic assumptions. The second phase concerns the development of a mission-based energy model. Rather than treating flight as a single time-averaged process, the mission is decomposed into successive operational segments, each characterised by specific dynamics and energy requirements. For each phase, suitable analytical or semi-empirical formulations are used to estimate the required power, duration, and energy consumption. The overall mission energy demand is then obtained from the cumulative contribution of all segments. The third methodological phase concerns the modelling of the aircraft and battery system. A reference multicopter eVTOL platform is selected on the basis of publicly available data, with the Volocopter VoloCity adopted as the representative aircraft for the present study. Mass properties, rotor configuration, and aircraft performance parameters are translated into model inputs. In parallel, the electric energy storage system is represented through

parameters such as specific energy, specific power, usable energy fraction, and state-of-charge limits. Additional correction laws are introduced to account for battery sensitivity to ambient temperature. The fourth phase consists of the numerical implementation of the model in MATLAB. A modular code architecture is adopted, in which the mission segments, aircraft data, battery-related calculations, and post-processing routines are managed through dedicated functions. This approach improves code transparency, facilitates debugging, and enables rapid repeated simulations as the operating assumptions are varied. A fifth methodological phase concerns model verification and validation. Internal verification is carried out by checking the dimensional consistency of the equations, the continuity between mission segments, and the plausibility of intermediate outputs, such as power levels, mission times, and state-of-charge evolution. External validation is instead conducted through comparison with reference formulations and results available in the technical literature, in order to ensure that the developed framework is consistent with established engineering approaches. Once validated, the methodology is applied to the selected case study concerning logistics operations in the Aeolian Islands. The Milazzo–Vulcano route is considered as the reference mission, while the distribution chain starting from the hub located on the island of Lipari is introduced subsequently. For each mission, the main outputs considered include total energy required, power peak, mission duration, battery margins, and feasibility indicators. The final phase of the methodology consists of parametric and sensitivity analyses. The main operational variables, such as cruise speed, payload mass, mission distance, number of rotors, ambient temperature, wind conditions, and climb rate, are systematically varied. Their influence on energy consumption and feasibility is quantified through comparative plots, operational envelopes, and analysis of the resulting trends. Overall, the adopted methodology combines theoretical modelling and practical assessment of the application scenario, with the aim of moving from general performance claims regarding eVTOL aircraft towards a mission-specific, quantitative, and data-driven evaluation.

1.5. Thesis Structure

The thesis is organised as follows.

Chapter 2 introduces the state of the art on Advanced Air Mobility, eVTOL aircraft and electric multicopter configurations, with particular attention to their potential role in short-range transport and island logistics.

Chapter 3 defines the case study, the reference aircraft assumptions and the Aeolian Islands transport scenario. The Milazzo–Vulcano route is introduced as the base mission,

while the Lipari-centred hub-and-spoke network is used to extend the analysis to inter-island operations.

Chapter 4 presents the mission-energy modelling approach. The flight is divided into individual segments, and the main equations used to estimate power demand, energy consumption, battery utilisation and mission feasibility are described.

Chapter 5 reports the MATLAB implementation and validation of the numerical model against the reference literature formulation. This step is used to verify the consistency of the code before applying it to the selected routes.

Chapter 6 presents the nominal mission results for the Milazzo–Vulcano base case and for the Lipari-centred inter-island network. The chapter discusses energy demand, power requirements, battery margins and route feasibility.

Chapter 7 investigates the sensitivity of the mission performance to the main operational and design parameters, including cruise speed, payload, distance, rotor count, rate of climb, temperature, wind and combined parametric effects.

Chapter 8 summarises and discusses the main outcomes of the analysis, focusing on the operational meaning of the results, the role of the eVTOL concept in the Aeolian Islands scenario, and the main strengths and limitations of the model.

Chapter 9 introduces certification and compliance considerations, including airworthiness, vertiport infrastructure, airspace integration and operational constraints relevant to a possible future implementation.

Chapter 10 discusses sustainability and future developments, including a comparison with maritime logistics in terms of operating energy cost, emissions and travel time, as well as possible improvements in batteries, aircraft design, infrastructure and certification maturity.

Chapter 11 concludes the thesis by summarising the main contributions, answering the research questions and identifying the most relevant directions for future work.

2 | State of the Art

2.1. eVTOL Aircraft Categories

Electric Vertical Take-Off and Landing aircraft represent a broad class of electrically powered vehicles capable of performing vertical take-off and landing without the need for a conventional runway. Within the wider framework of Advanced Air Mobility, several eVTOL architectures have been proposed, each characterised by different aerodynamic layouts, propulsion arrangements and operational capabilities. The choice of configuration has a direct impact on energy consumption, range, payload capability, noise, mechanical complexity and mission suitability. From an engineering point of view, eVTOL concepts can be grouped into a limited number of main categories according to the way lift is generated during hover and cruise. Some configurations rely entirely on rotors for both vertical and forward flight, while others combine rotor-based vertical lift with fixed-wing aerodynamic lift during cruise. This distinction is particularly important because the energy efficiency of an eVTOL mission depends strongly on whether the aircraft operates as a pure rotorcraft throughout the flight or transitions to wing-borne flight after take-off. The most common eVTOL categories discussed in the literature are multicopter, lift-and-cruise and vectored-thrust configurations. Multicopters are mechanically simpler and highly suited to vertical operations, but generally suffer from limited cruise efficiency and range. Lift-and-cruise aircraft introduce fixed wings and dedicated propulsion systems for forward flight, improving cruise efficiency at the cost of increased mass and architectural complexity. Vectored-thrust concepts seek to combine vertical and forward flight propulsion within the same propulsion units, offering potentially higher performance but requiring more complex control and mechanical systems. Understanding the characteristics, advantages and limitations of these configurations is essential for selecting a suitable reference aircraft and for interpreting the energy performance results obtained in this thesis. Since the present work focuses on a multicopter eVTOL applied to short-range logistics missions, the following subsections first provide a general overview of the main eVTOL categories and then highlight the specific features that make the multicopter architecture relevant for the selected case study.

2.1.1. Multicopter

Multicopter eVTOL aircraft represent one of the simplest and most direct configurations among electrically powered vertical take-off and landing vehicles. In this architecture, lift is generated by a set of multiple electrically driven rotors distributed around the aircraft structure. Unlike lift-and-cruise or vectored-thrust concepts, multicopters generally do not rely on a fixed wing to generate aerodynamic lift during cruise. As a consequence, the aircraft remains primarily rotor-borne throughout the entire mission, including hover, climb, cruise, descent and landing. The working principle of a multicopter is conceptually similar to that of conventional small unmanned multirotor aircraft, but scaled to carry passengers or useful payload. Vertical take-off and landing are achieved by producing a total rotor thrust greater than the aircraft weight, while translational motion is obtained by tilting the resultant thrust vector through differential rotor control or slight aircraft attitude changes. Yaw, pitch and roll control are typically generated by varying the thrust of individual rotors or rotor groups. This architecture eliminates the need for complex tilting mechanisms and allows a high degree of control authority during low-speed flight and hovering. One of the main advantages of multicopter configurations is their mechanical simplicity. Since the rotors are usually fixed in orientation, the propulsion system does not require the mechanical complexity associated with tilting wings, tilting rotors or transition mechanisms. This can lead to simplified maintenance, improved reliability and easier integration of redundant propulsion units. The presence of several independent rotors also provides a natural path towards fault-tolerant design, since the aircraft can potentially maintain controllability after the failure of one or more propulsion units, depending on the specific configuration and control strategy. Another important advantage is operational flexibility. Multicopters can take off and land vertically from compact areas and do not require runways or long approach paths. This makes them particularly attractive for urban mobility, emergency response and short-range logistics applications. In island or peripheral regions, where ground and maritime infrastructures may be limited or weather-dependent, the ability to operate from small landing areas can represent a significant practical benefit. However, the same features that make multicopters simple and flexible also impose relevant energetic limitations. Since these aircraft do not use wings to support their weight in forward flight, the rotors must continuously provide most of the required lift. This results in higher power consumption compared with wing-borne configurations, especially during hover and low-speed flight. Moreover, in cruise, the absence of a fixed wing limits the aerodynamic efficiency of the aircraft. As a result, multicopter eVTOL vehicles are generally characterised by shorter range and lower cruise efficiency than lift-and-cruise or vectored-thrust designs. For this reason, multi-

copter eVTOL aircraft are usually more suitable for short-range missions, where vertical take-off and landing capability, simplicity and operational flexibility are more important than maximum range. Typical applications include urban air taxi services, airport shuttle missions, medical transport, surveillance and lightweight cargo delivery. Their use in logistics applications is particularly interesting when the payload is moderate and the route distance remains within the energetic limits imposed by current battery technology. Several real aircraft illustrate the multicopter approach.

The Volocopter VoloCity is one of the most representative examples of passenger multicopter eVTOL architecture. It employs 18 fixed-pitch rotors and 18 electric motors, powered by nine rechargeable lithium-ion batteries with a battery-swapping concept intended to reduce turnaround time. Its published design specifications indicate a cruise speed of about 90 km/h, a maximum airspeed of about 100 km/h, and an expected range of approximately 20 km including safety margins under moderate headwind conditions. These characteristics make the VoloCity particularly relevant for short urban or regional missions rather than long-distance transport.



Figure 2.1: Volocopter VoloCity multicopter eVTOL configuration.

Another relevant example is the EHang EH216-S, an autonomous two-seat multicopter eVTOL developed for advanced air mobility operations. According to publicly available specifications, the aircraft has a maximum take-off weight of about 620 kg, a range of approximately 30 km and a maximum design speed of 130 km/h. These data confirm

the typical operating envelope of multicopter eVTOL vehicles, which is oriented towards short-range missions with limited endurance.



Figure 2.2: EHang EH216-S autonomous passenger multicopter eVTOL.

Smaller single-seat multicopter concepts are also present in the current eVTOL landscape. The LIFT Aircraft HEXA, for example, is an ultralight electric multicopter designed for personal flight, with 18 rotors and a flight endurance of approximately 15 minutes while retaining a battery reserve. Similarly, the Jetson ONE is a compact personal eVTOL with eight electric motors, a flight time of about 20 minutes and a top speed close to 102 km/h. Although these vehicles are not directly comparable to passenger air taxis in terms of mission purpose or certification basis, they further demonstrate the short-endurance nature of purely rotor-borne electric aircraft.

Overall, existing multicopter eVTOL examples show a consistent trend: the architecture offers excellent vertical-flight capability, compact operations and mechanical simplicity, but remains strongly constrained by battery energy density and rotor-borne cruise inefficiency. This trade-off is central to the present thesis, since the selected mission scenario involves short-range logistics operations in the Aeolian Islands, where the feasibility of the service depends not only on nominal aircraft range, but on the detailed energy consumption accumulated across all mission segments.

For this reason, the multicopter configuration is both attractive and challenging for the proposed application. It is attractive because it can operate without runways and can

potentially provide fast connections between islands or between the mainland and the archipelago. At the same time, it is challenging because the energy margins are expected to be limited, especially when payload, environmental conditions and reserve requirements are considered. A segment-based energy model is therefore necessary to assess whether the mission can be performed safely and repeatedly under realistic operating assumptions.

2.1.2. Lift-and-Cruise

Lift-and-cruise eVTOL aircraft represent an intermediate configuration between pure multicopters and vectored-thrust concepts. In this architecture, the functions of vertical lift and forward propulsion are generally assigned to separate propulsive systems. Dedicated lift rotors are used during vertical take-off, landing and low-speed manoeuvres, while one or more cruise propellers provide thrust during forward flight. At the same time, a fixed wing generates most of the lift in cruise, allowing the aircraft to operate in a wing-borne regime after the vertical phases of the mission. The main principle behind lift-and-cruise configurations is therefore the decoupling of hover and cruise requirements. During take-off and landing, the lift rotors provide the vertical thrust required to balance or exceed the aircraft weight. Once sufficient forward speed is reached, the aircraft transitions to wing-borne flight and the lift rotors are usually stopped, folded or left windmilling depending on the specific design. In cruise, the aircraft behaves more similarly to a conventional fixed-wing aircraft, with the wing supporting the vehicle weight and the cruise propulsor mainly overcoming aerodynamic drag. This architecture offers important energetic advantages compared with multicopter configurations. Since the aircraft is not required to remain fully rotor-borne throughout the whole mission, the power required during cruise can be significantly reduced. The lift-to-drag ratio of the wing becomes a key parameter, and the total mission energy is less dominated by rotor-induced power than in pure multicopters. As a result, lift-and-cruise aircraft are generally more suitable for longer routes and higher cruise speeds, especially when the mission includes a substantial cruise segment. Another advantage of lift-and-cruise concepts is their relative mechanical simplicity compared with vectored-thrust aircraft. Since the lift rotors and cruise propulsors are separate, the aircraft does not necessarily require complex tilting mechanisms to redirect thrust between vertical and horizontal flight. This can reduce mechanical risk and simplify some aspects of the design, even though the presence of both lift and cruise propulsion systems increases the number of components and the structural integration complexity. However, the configuration also presents relevant limitations. Dedicated lift rotors are primarily useful only during vertical phases and may become inactive mass during cruise. This can penalise overall aircraft efficiency, since the vehicle carries propulsion hardware that does

not contribute to forward-flight thrust. Furthermore, stopped or exposed lift rotors can generate aerodynamic drag if they are not properly integrated or stowed. The presence of both wing and multiple rotor systems also increases structural mass and may complicate maintenance compared with simpler multicopter layouts. From an operational point of view, lift-and-cruise aircraft are well suited to missions where the cruise distance is sufficiently long to compensate for the additional mass of the fixed wing and dedicated propulsion systems. In short-range missions, the benefits of wing-borne cruise may be less pronounced, since a significant fraction of the mission energy can still be associated with take-off, landing and transition phases. For this reason, the suitability of lift-and-cruise vehicles depends strongly on route length, payload, mission profile and required reserves. Several current eVTOL projects adopt or approximate the lift-and-cruise philosophy.

Wisk Aero’s Generation 6 aircraft, for example, is a four-passenger autonomous eVTOL designed for urban and regional air mobility. Publicly available specifications report a cruise speed of approximately 138 mph and a range of about 90 miles including reserves, values that are significantly higher than those typically associated with pure multicopter aircraft. The aircraft uses a wing for efficient forward flight, while distributed rotors provide vertical lift capability during take-off and landing.



Figure 2.3: Wisk Aero Generation 6 eVTOL, an example of a winged lift-and-cruise architecture developed for Advanced Air Mobility operations.

Another relevant example is BETA Technologies’ ALIA aircraft family. The ALIA-250 eVTOL prototype is characterised by a high wing, four vertical lift propellers and one rear pusher propeller for forward flight. This layout clearly illustrates the separation between lift and cruise propulsion typical of lift-and-cruise configurations. Public data indicate

that the aircraft is intended for passenger and cargo applications, with BETA reporting a five-passenger capability and a propulsion system composed of four electric lift motors and one electric cruise motor.



Figure 2.4: BETA Technologies ALIA lift-and-cruise eVTOL concept, showing separate vertical lift propellers and a dedicated rear cruise propeller.

A further relevant example of this architectural class is the Airbus CityAirbus NextGen. This aircraft is an all-electric, four-seat eVTOL prototype developed by Airbus for Advanced Air Mobility applications. According to Airbus, the CityAirbus NextGen is based on a lift-and-cruise concept and is designed for an operational range of approximately 80 km and a cruise speed of 120 km/h. Its configuration includes fixed wings, a V-shaped tail and eight electrically powered propellers arranged within a distributed propulsion system. Airbus presented the full-scale prototype in 2024, describing it as a two-tonne class aircraft with a wingspan of approximately 12 m. From an architectural point of view, the CityAirbus NextGen is particularly interesting because it combines wing-borne cruise with distributed electric propulsion while avoiding complex tilting mechanisms. The fixed wing contributes to lift generation during forward flight, thereby reducing the energy required in cruise compared with pure multicopter configurations. At the same time, the distributed propulsive layout provides vertical take-off and landing capability, making the aircraft suitable for urban and regional missions where runway-independent operations are required. Compared with a multicopter such as the Volocopter VoloCity, the CityAirbus NextGen represents a more range-oriented design philosophy. While the multicopter architecture prioritises mechanical simplicity, compactness and hover control, the lift-and-cruise arrangement adopted by Airbus aims to improve cruise efficiency through aerodynamic lift. This distinction is directly relevant to mission-energy analysis: for short missions dominated by vertical flight, a multicopter may remain attractive,

whereas for longer routes the presence of a fixed wing can significantly reduce the cruise energy demand.



Figure 2.5: Airbus CityAirbus NextGen lift-and-cruise eVTOL concept for Advanced Air Mobility applications.

2.1.3. Vectored Thrust

Vectored-thrust eVTOL aircraft represent one of the most advanced and performance-oriented configurations within the Advanced Air Mobility landscape. In this architecture, the same propulsion units are used to provide both vertical lift during take-off and landing and forward thrust during cruise. This is typically achieved by tilting propellers, rotors, nacelles or entire propulsion assemblies, allowing the thrust vector to be progressively reoriented from a vertical direction to a horizontal direction during the transition phase. The fundamental idea behind vectored-thrust configurations is to combine the vertical flight capability of rotorcraft with the cruise efficiency of wing-borne aircraft. During hover and vertical take-off, the propulsive system directs thrust predominantly upwards in order to balance the aircraft weight. As forward speed increases, the thrust vector is gradually tilted forward while the wing progressively assumes a larger fraction of the lift generation. Once the aircraft reaches cruise conditions, the wing supports most of the weight and the propulsion system primarily provides the thrust needed to overcome aerodynamic drag. Compared with multicopter configurations, vectored-thrust aircraft can achieve significantly better cruise efficiency because they are not required to remain fully rotor-borne during forward flight. The use of a fixed wing enables a higher lift-to-drag ratio and therefore reduces the power required in cruise. Compared with lift-and-cruise concepts, vectored-thrust architectures may also avoid carrying a fully separate set of lift-only rotors that become inactive during cruise. In this sense, the same propulsive

units are used throughout the mission, potentially improving propulsion utilisation and overall aircraft efficiency. However, these advantages are obtained at the cost of increased mechanical, aerodynamic and control complexity. The transition from vertical to forward flight is a critical phase in which the aircraft must remain stable while lift generation shifts from rotors to wings. This requires accurate flight control laws, reliable actuation systems and careful integration between propulsion, aerodynamics and flight mechanics. Furthermore, tilting mechanisms and articulated nacelles introduce additional structural mass, maintenance requirements and possible failure modes. The energetic performance of vectored-thrust aircraft is therefore strongly mission-dependent. For routes with a sufficiently long cruise segment, the improved aerodynamic efficiency can compensate for the added system complexity and make vectored-thrust concepts highly attractive. Conversely, for very short missions dominated by take-off, landing and transition, the benefit of wing-borne cruise may be less pronounced. This makes mission-level modelling essential when comparing vectored-thrust aircraft with multicopter and lift-and-cruise configurations.

A representative example of vectored-thrust eVTOL architecture is the Joby Aviation S4. Joby describes its aircraft as using a tilting propeller system that combines vertical take-off capability with high-speed fixed-wing cruise. The configuration includes six electric propellers integrated with a wing and tail surfaces, enabling the aircraft to operate vertically during take-off and landing and efficiently in wing-borne cruise. This architecture is intended to provide both runway independence and improved lift-to-drag efficiency compared with purely rotor-borne configurations.



Figure 2.6: Joby Aviation S4 vectored-thrust eVTOL concept, featuring tilting electric propellers for vertical take-off and efficient wing-borne cruise.

Another important example is Archer Aviation's Midnight aircraft. Midnight is a piloted four-passenger eVTOL designed for urban air mobility operations. The aircraft combines wing-borne cruise with a distributed electric propulsion system and is designed to reach speeds of up to 150 mph. Its architecture includes both lift and cruise capabilities, with the objective of providing efficient short-range air taxi missions while maintaining vertical take-off and landing capability.



Figure 2.7: Archer Midnight eVTOL aircraft, an example of a winged distributed-propulsion configuration designed for Advanced Air Mobility operations.

A further example is the Vertical Aerospace VX4, recently evolved into the Valo aircraft family. Vertical Aerospace presents the aircraft as a four-passenger, one-pilot eVTOL equipped with eight tilt-shift propellers, designed for a cruise speed of approximately 150 mph and a range of about 100 miles. This type of configuration illustrates the use of tilting propulsion systems to combine vertical flight capability with efficient wing-borne cruise.



Figure 2.8: Vertical Aerospace Valo/VX4 eVTOL concept, based on tilt-shift propellers to combine vertical flight capability with fixed-wing cruise efficiency.

Overall, vectored-thrust aircraft can be considered among the most energy-efficient eVTOL configurations for missions involving substantial cruise segments. Their ability to exploit wing-borne lift while reusing the same propulsion units for vertical and forward flight offers important performance advantages. Nevertheless, their higher mechanical and control complexity represents a significant design and certification challenge. In the context of the present thesis, vectored-thrust architectures provide a useful benchmark for understanding the limitations of multicopter configurations. Although the selected reference aircraft is a multicopter, the comparison with vectored-thrust vehicles highlights how cruise efficiency can be improved when lift generation is transferred from rotors to wings. This reinforces the importance of mission segmentation and energy modelling when evaluating the suitability of different eVTOL architectures for inter-island logistics operations.

2.2. Energy Performance of eVTOL Vehicles

2.2.1. General Energy Challenges in eVTOL Operations

The energy performance of electric Vertical Take-Off and Landing aircraft represents one of the central challenges for their practical deployment. Unlike conventional aircraft, which rely on hydrocarbon fuels with very high specific energy, eVTOL vehicles depend on electrochemical energy storage systems whose specific energy is still significantly lower. As a result, the available onboard energy is limited, and the balance between battery mass, payload capability and mission range becomes a primary design constraint. This limitation is particularly relevant for aircraft required to perform vertical take-off and landing. Vertical flight demands high propulsive power because the aircraft must generate lift directly through rotor or propeller thrust rather than through aerodynamic lift produced by a wing. Even when vertical phases are relatively short, they can strongly influence the peak power requirement and reduce the useful energy available for the remaining parts of the mission. For this reason, eVTOL performance cannot be assessed only in terms of nominal range, but must also consider the power demand associated with take-off, landing, hover and low-speed manoeuvres. Another important aspect is that eVTOL aircraft are generally characterised by strict mass sensitivity. Increasing battery capacity may extend the available energy, but it also increases the aircraft weight, which in turn raises the power required for lift generation. Similarly, increasing the payload directly affects both energy consumption and operational margins. This creates a strong coupling between vehicle mass, mission distance and battery sizing, making the energetic feasibility of a given route highly dependent on the specific operating conditions. In addition to total energy demand, power availability is also a critical performance factor. Some mission phases may require short but significant power peaks, especially during vertical take-off, climb or contingency conditions. Therefore, a mission can be limited not only by the total energy stored in the battery, but also by the maximum power that the propulsion and battery systems can safely deliver. This distinction between energy-limited and power-limited operation is particularly important in the evaluation of electric aircraft. Environmental and operational conditions further affect eVTOL energy performance. Wind can modify the effective ground speed and therefore the time spent in cruise, while ambient temperature can influence battery behaviour and available capacity. Reserve requirements and operational safety margins also reduce the portion of battery energy that can actually be used during a mission. Consequently, the real usable range of an eVTOL aircraft may differ significantly from ideal or nominal values. Overall, the energy challenge in eVTOL operations arises from the combination of limited battery energy density, high power demand during vertical flight, strong mass sensitivity and the need for adequate safety margins. These factors make mission-specific energy assessment essential when evaluating the feasi-

bility of eVTOL applications, especially for logistics missions in which payload and route length directly influence operational viability.

2.2.2. Influence of Aircraft Architecture on Energy Efficiency

The energy efficiency of an eVTOL aircraft is strongly influenced by its overall architecture. The way in which lift and thrust are generated during the different phases of flight determines the power required by the propulsion system and, consequently, the achievable range, endurance and payload capability. For this reason, the comparison between multicopter, lift-and-cruise and vectored-thrust configurations is not only a matter of layout or mechanical design, but also a fundamental aspect of energy performance. Multicopter configurations are generally the simplest from an architectural point of view, since lift is produced by multiple fixed rotors throughout the entire mission. This makes them highly suitable for vertical operations and low-speed manoeuvring, but it also means that the aircraft remains mainly rotor-borne during forward flight. As a result, the cruise phase does not benefit significantly from wing-generated aerodynamic lift. This leads to comparatively high energy consumption and limits the range of purely multicopter vehicles, especially when the cruise segment becomes a large portion of the mission. Lift-and-cruise aircraft address this limitation by introducing a fixed wing and separating the vertical lift system from the cruise propulsion system. During forward flight, the wing carries most of the aircraft weight, reducing the propulsive power required to remain airborne. This generally improves cruise efficiency and enables longer routes compared with pure multicopters. However, the presence of dedicated lift rotors that are mainly used during take-off and landing introduces additional mass and potential aerodynamic drag during cruise. Vectored-thrust configurations aim to further improve propulsion utilisation by using the same propulsive units for both vertical lift and forward thrust. In cruise, these aircraft can operate in a wing-borne condition, similarly to lift-and-cruise concepts, but without necessarily carrying a completely separate set of lift-only rotors. This can provide favourable energy performance for missions with substantial cruise segments. Nevertheless, the efficiency advantage is accompanied by greater mechanical and control complexity, particularly during the transition between vertical and forward flight. From an energy perspective, the key distinction among these architectures is the extent to which the aircraft can transfer lift generation from rotors to wings during cruise. Purely rotor-borne configurations tend to be more penalised in terms of range, whereas wing-borne configurations can achieve better cruise efficiency. However, this improvement is not free, since wings, transition systems and additional propulsion components increase mass and design complexity. Therefore, the most suitable architecture depends strongly

on the intended mission profile. For short missions dominated by vertical flight, hovering or frequent take-off and landing operations, multicopters may remain attractive because of their simplicity and operational flexibility. Conversely, for longer missions with a significant cruise portion, lift-and-cruise and vectored-thrust aircraft are generally expected to offer better energy efficiency. This architecture-dependent behaviour is one of the reasons why eVTOL performance must be evaluated in relation to the specific mission rather than through generic vehicle specifications alone.

2.2.3. Energy and Power as Performance Metrics

The performance of an eVTOL aircraft is commonly described through quantities such as range, endurance, cruise speed and payload capability. However, for electric aircraft, two additional indicators are particularly important: the total energy required to complete a mission and the maximum power required during the most demanding flight phases. These two quantities are related but not equivalent, and both must be considered when assessing operational feasibility. The total mission energy determines whether the aircraft can complete a route within the usable capacity of its battery system, including the required reserve margins. It is therefore directly linked to range capability and payload transport. The maximum power requirement, on the other hand, is associated with short-duration but critical phases such as vertical take-off, hover, climb or contingency manoeuvres. Even if the total energy demand is acceptable, a mission may still be infeasible if the battery and propulsion system cannot deliver the required peak power safely. For this reason, eVTOL performance is often constrained by a combined energy–power balance. Multicopter aircraft, for example, may experience high power demand during vertical and low-speed phases, while longer cruise segments mainly affect the total energy consumption. Winged configurations may reduce cruise energy demand, but still require sufficient power for vertical flight. The relative importance of energy and power constraints therefore depends on both aircraft architecture and mission profile. In practical mission assessment, useful performance indicators include total energy consumption, peak power, average power, final state of charge, energy margin and power margin. These metrics provide a more complete description of aircraft capability than nominal range alone, especially when payload, environmental conditions and safety reserves are included. Consequently, energy and power metrics represent essential tools for comparing eVTOL configurations and for evaluating their suitability for specific operational scenarios.

2.2.4. Reported Performance Trends of Existing eVTOL Concepts

The performance values reported for eVTOL aircraft vary significantly depending on the considered architecture, mission profile and operational assumptions. Manufacturer-declared range values are useful to identify the intended market segment of a vehicle, but they do not necessarily represent the achievable range under realistic operating conditions. For this reason, several studies emphasise that eVTOL performance should be interpreted together with mission-specific constraints such as hover time, wind conditions, reserve requirements and battery capacity [18]. A common trend in the literature is that purely rotor-borne aircraft, such as multicopters and quadcopters, are generally more constrained in range and endurance than winged eVTOL configurations. This is mainly due to the need to generate lift through rotor thrust during most or all phases of flight. Michel et al. identify energy performance as one of the main limiting factors for multirotor eVTOL systems, since it directly affects flight time and range. They also report that small multirotor systems are typically limited to flight times of the order of tens of minutes, while prospective passenger-scale eVTOL applications would require significantly higher energy-system performance [24]. Operational conditions can further reduce the effective range with respect to nominal values. Hagag et al. show that realistic operational constraints may strongly penalise the achievable range of eVTOL vehicles. In particular, extended hover phases can produce a severe range reduction, while strong headwind conditions can also significantly decrease the final achievable range. This confirms that eVTOL performance cannot be evaluated only from ideal specifications, but must account for external and operational factors [18]. The literature also shows that the energy demand of electric rotorcraft is not only a function of distance, but also of the selected speed and manoeuvre profile. Suwe et al. developed mission-based power profiles for different multirotor UAV missions and showed that the highest power requirements occur during accelerated climb manoeuvres. The same study also indicates that horizontal flight can represent the largest share of mission energy when it occupies most of the flight time, and that an energy-optimal horizontal speed can exist for a given aircraft mass [26]. Overall, reported performance trends confirm that eVTOL aircraft should be evaluated through mission-level indicators rather than isolated specifications. Range, endurance and payload capability depend on the combined effect of architecture, battery performance, hover duration, cruise efficiency, wind and operational reserves. This is particularly important for logistics applications, where the payload-distance combination directly determines the feasibility of the service.

2.3. Mission-Based Modelling Approaches

The evaluation of eVTOL performance cannot rely exclusively on nominal range or endurance values, since these quantities are strongly dependent on the assumed mission profile. For electric aircraft, the time spent in each flight phase and the corresponding power demand directly affect battery discharge and operational feasibility. As a result, several studies in the literature adopt mission-based modelling approaches, in which the flight is represented as a sequence of distinct operational segments rather than as a single averaged process. A typical eVTOL mission may include taxi, vertical take-off, climb, cruise, descent, landing and, depending on the aircraft architecture, transition phases between vertical and horizontal flight. This representation is particularly relevant because different segments have different energetic impacts. Vertical flight and hovering are usually associated with high power demand, while cruise may dominate the total energy consumption when it occupies most of the mission duration. Therefore, the distribution of time and power among the mission phases can significantly influence the estimated range and feasibility of the aircraft. Bruhl et al. propose a flight performance modelling framework for air taxi operations based on the calculation of power requirements for individual mission segments. Their work compares vectored-thrust, lift-and-cruise and multicopter eVTOL configurations, showing that the estimated range varies considerably with aircraft architecture and battery assumptions. In their application, the resulting ranges are approximately 115 km for a vectored-thrust configuration, 70 km for a lift-and-cruise configuration and 50 km for a multicopter configuration, highlighting the strong influence of both architecture and mission modelling assumptions on performance assessment [2]. Mission-based approaches are therefore useful because they provide a more realistic interpretation of eVTOL capabilities than isolated manufacturer specifications. They allow the effect of operational choices, such as hover duration, cruise segment length, vertical flight requirements and reserve margins, to be considered within the performance assessment. At the same time, their accuracy remains dependent on the availability and reliability of input parameters, which are often limited for aircraft still under development. Within the state of the art, mission-based modelling can thus be regarded as a necessary intermediate step between conceptual aircraft specifications and realistic operational assessment. This is especially important for short-range logistics applications, where payload, route length and vertical flight requirements may determine whether the mission is practically feasible.

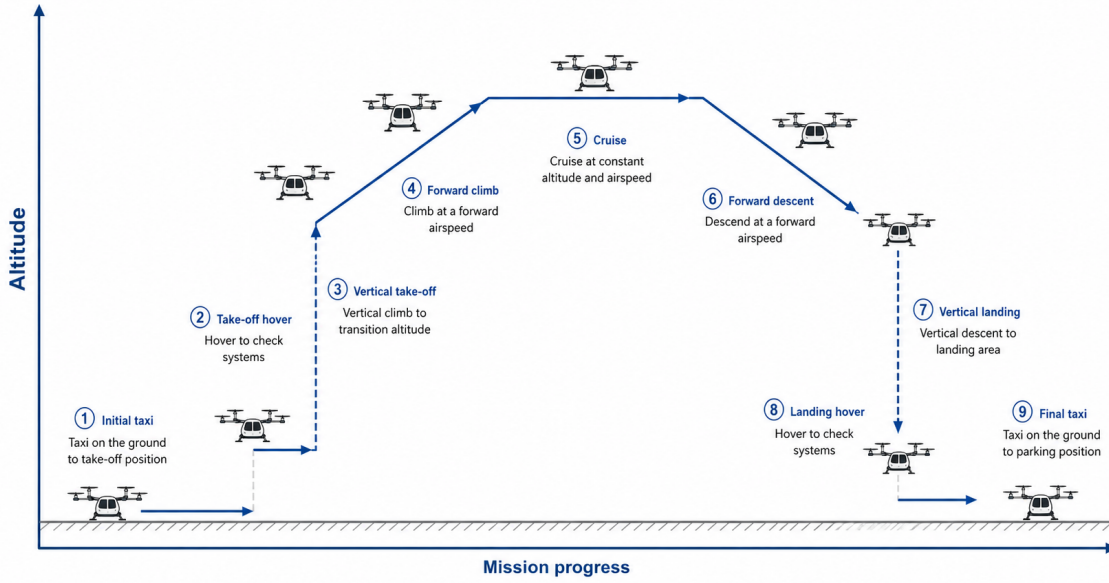


Figure 2.9: Representative mission profile of the multicopter eVTOL, including initial taxi, take-off hover, vertical take-off, forward climb, cruise, forward descent, vertical landing, landing hover and final taxi.

2.4. Battery Technologies for eVTOL Applications

Battery technology represents one of the most critical enabling factors for eVTOL aircraft. In fully electric vertical flight, the battery system directly affects range, endurance, payload capability, aircraft mass, safety margins and operational turnaround time. Unlike conventional aircraft, where the fuel mass decreases during flight, battery-powered aircraft carry almost the same battery mass throughout the mission. Therefore, the battery must provide sufficient energy and power while remaining compatible with strict weight, thermal and safety constraints [20]. Lithium-ion batteries are currently the dominant technology for electric aircraft concepts because of their relatively high specific energy, high power capability and technological maturity compared with other rechargeable battery chemistries. However, their performance remains significantly lower than that of hydrocarbon fuels in terms of gravimetric energy density. This limitation is particularly relevant for eVTOL vehicles, since vertical take-off and landing require high power while useful range depends mainly on the available energy capacity. As a result, the same battery system must satisfy both energy and power requirements [24]. Two parameters are especially important when assessing batteries for eVTOL applications: specific energy, usually expressed in Wh/kg, and specific power, usually expressed in W/kg. Specific en-

ergy determines how much energy can be stored per unit battery mass and therefore has a direct influence on range and endurance. Specific power determines how much power can be delivered per unit battery mass and is particularly important during vertical take-off, landing, hover and climb phases. A battery optimised only for energy capacity may not be able to deliver sufficient power during demanding vertical segments, while a battery optimised for high power may penalise range because of lower energy density. The distinction between cell-level and pack-level performance is also fundamental. Values reported at cell level are generally higher than those available at module or pack level, because the complete battery system includes packaging, cooling, structural containment, electrical connections, monitoring electronics and safety protections. Hagag et al. report typical lithium-ion specific energy values of approximately 160–260 Wh/kg at cell level and 150–200 Wh/kg at battery level, also noting performance losses when moving from cell to module and system level [18]. This difference is important because aircraft-level performance depends on the installed battery system, not on idealised cell data. Current battery technology imposes a strong constraint on multirotor and eVTOL performance. Michel et al. indicate that small multirotor systems are typically limited to flight times of the order of tens of minutes, while prospective passenger-scale eVTOL applications would require substantially higher energy-system performance. In particular, they report that mission targets around one hour of flight time and more than 70 miles of range would require energy densities of approximately 350–400 Wh/kg at system level, whereas current lithium-ion technology is closer to about 150 Wh/kg at system level [24]. This gap highlights why battery technology remains one of the main barriers to extended eVTOL operations. Besides nominal capacity, the usable portion of the battery energy must be considered. In practical operation, the full nominal battery capacity cannot be used, because minimum state-of-charge limits and reserve requirements are needed for safety, battery life and contingency management. Bruhl et al. account for this by distinguishing between total and usable battery energy and power, including the effects of battery efficiency and depth of discharge. They also refer to reserve constraints, with a remaining state of charge used as a safety margin rather than allowing full depletion of the battery [2]. This means that the effective energy available for a nominal mission is lower than the theoretical installed energy. Battery behaviour is also affected by operating conditions. Temperature can influence available capacity, internal resistance, power capability and long-term degradation. Low temperatures generally reduce available capacity and power delivery, while high temperatures may accelerate ageing and raise thermal management concerns. For this reason, battery modelling for aircraft applications often requires at least a simplified representation of temperature effects, especially when operational feasibility is assessed under realistic environmental conditions. Hagag et al. explicitly identify

temperature as a relevant factor for eVTOL range and report that cold conditions can reduce the achievable range compared with nominal assumptions [18]. The modelling of batteries for electric aircraft can be approached at different levels of fidelity. Horton et al. classify battery models into electrochemical, mathematical and electrical approaches. Electrochemical models are generally the most detailed, but require substantial information about cell chemistry and are computationally expensive. Mathematical models are simpler and often based on empirical relationships, while electrical equivalent-circuit models represent the battery through components such as voltage sources, resistances and capacitances. For conceptual aircraft design, the selected model must balance accuracy, computational cost and availability of input data [20]. For eVTOL applications, battery modelling is particularly important because battery dynamics are coupled with propulsion performance. Michel et al. show that changes in battery voltage during discharge can affect motor and propeller behaviour, reducing attainable thrust and therefore influencing acceleration limits and achievable flight performance [24]. This confirms that the battery should not be treated only as a static energy reservoir in high-fidelity studies, since its electrical behaviour can influence the propulsion system throughout the mission. Overall, the literature indicates that batteries remain one of the dominant constraints for eVTOL feasibility. Improvements in specific energy, specific power, thermal behaviour, cycle life and safety are necessary to expand the operational envelope of electric vertical flight. At the same time, current battery limitations make it essential to distinguish between nominal and usable energy, cell-level and pack-level data, and energy and power constraints. These considerations are especially relevant for multicopter eVTOL vehicles, where the combination of vertical-flight power demand and limited cruise efficiency places severe requirements on the onboard energy storage system.

2.5. Logistics Applications of eVTOL Systems

Although eVTOL aircraft are often associated with passenger transport and urban air taxi services, their potential field of application is broader and includes several logistics-oriented missions. Advanced Air Mobility is increasingly described as an ecosystem not limited to urban passenger mobility, but also including cargo delivery, public service operations, airport shuttle services, emergency response and connections with underserved or geographically constrained communities [19]. This broader perspective is particularly relevant because the operational advantages of eVTOL aircraft are not only related to speed, but also to their ability to operate without conventional runway infrastructure. Logistics applications are especially attractive when the transported payload is relatively small, time-sensitive or valuable. In this sense, eVTOL and multirotor platforms can be

considered for the distribution of medical supplies, urgent goods, lightweight commercial packages, spare parts and essential commodities. Studies on multirotor UAV missions already identify delivery as one of the main civil application sectors, together with monitoring and event-related operations [26]. In a representative delivery mission, the aircraft typically transports a package from an origin to a destination and may return without payload, leading to asymmetric outbound and return energy requirements due to the difference in carried mass [26]. From an operational point of view, eVTOL logistics may provide advantages in areas where conventional transport is limited by congestion, geography or infrastructure availability. The literature on Urban Air Mobility highlights that eVTOL systems could support not only dense urban areas, but also peripheral and underserved regions, where they may help bridge infrastructure gaps [19]. This aspect is relevant for cargo and supply missions because aerial distribution can reduce dependency on road or maritime links, particularly when rapid delivery or service continuity is required. However, logistics operations impose specific constraints that differ from passenger transport. Payload mass has a direct effect on total aircraft weight and therefore on power demand, energy consumption and achievable range. For multirotor delivery missions, Suwe et al. show that payload influences both power and energy requirements, and that the return flight after payload delivery can require noticeably less power because of the reduced mass [26]. This confirms that logistics feasibility cannot be evaluated only through route distance, but must also consider payload, mission profile and return conditions. Energy performance remains one of the main limiting factors for the practical use of eVTOL and multirotor aircraft in logistics. Michel et al. identify energy performance as a major constraint for both unmanned and manned multirotor applications, since it determines flight time and range [24]. For delivery-oriented missions, this limitation is particularly important because the aircraft must reserve part of its available energy for vertical flight, contingency margins and possible return operations. Another relevant aspect is the need for mission-level power and energy assessment. In logistics applications, the most demanding phase may not coincide with the phase consuming the largest amount of energy. For instance, multirotor power-profile studies show that accelerated climb can determine the maximum power requirement, whereas horizontal flight may dominate total energy consumption when it represents the largest portion of the mission time [26]. Therefore, both peak power and total energy must be considered when evaluating the suitability of an eVTOL platform for cargo transport. In addition to aircraft performance, the deployment of eVTOL logistics services requires suitable ground infrastructure and operational integration. Vertiports or landing areas must support take-off, landing, loading, unloading, charging or battery replacement, and safe interaction with other transport modes. In the context of UAM, airports and vertiports are expected to

play an important role as intermodal nodes, connecting emerging aerial mobility services with existing transport networks [19]. For logistics applications, this infrastructure role becomes even more important because turnaround time and charging availability directly affect service frequency. Overall, the literature suggests that eVTOL logistics is promising but strongly mission-dependent. The most favourable applications are expected to involve short-range routes, moderate payloads, high time sensitivity and locations where conventional transport is inefficient or constrained. At the same time, current limitations in battery energy density, payload capability and operational infrastructure make detailed feasibility assessment necessary before considering real deployment. This motivates the use of mission-based energy analysis for evaluating eVTOL logistics services in specific geographical scenarios.

2.6. Research Gaps and Motivation for This Thesis

The literature reviewed in the previous sections shows that eVTOL aircraft are a promising technology for future Advanced Air Mobility applications, including passenger transport, emergency services and lightweight logistics. However, several open issues remain when considering their practical use in realistic regional and island scenarios. In particular, there is still a gap between the conceptual promise of eVTOL-based logistics and the quantitative assessment of their operational feasibility under mission-specific constraints. A first limitation concerns the frequent use of nominal aircraft specifications, such as declared range, cruise speed or payload, as direct indicators of operational capability. These values are useful for comparing aircraft concepts, but they do not necessarily represent the actual performance achievable in a real mission. As shown by mission-based studies, eVTOL range and energy demand depend strongly on hover time, wind conditions, reserve requirements, battery assumptions and the time distribution among the different flight phases [2, 18]. Therefore, a more detailed mission-level assessment is required before drawing conclusions on the feasibility of a specific route. A second gap is related to the limited availability of detailed performance data for eVTOL aircraft. Many vehicles are still at prototype or pre-certification stage, and public information is often incomplete or based on manufacturer targets. This makes independent modelling particularly important. In this context, simplified but physically consistent models can provide useful engineering insight, provided that their assumptions are clearly stated and that the results are interpreted with appropriate caution [2]. A further limitation concerns the treatment of multicopter eVTOL vehicles. Multicopters are attractive because of their mechanical simplicity, vertical-flight capability and compatibility with compact landing areas. Nevertheless, they are also energetically demanding, since they remain mainly rotor-borne

during the mission. The literature identifies energy performance as a major constraint for multirotor systems, directly affecting flight time, range and payload capability [24]. For this reason, multicopter applications require careful assessment of energy consumption, peak power demand and battery margins. Most existing studies focus either on generic urban air mobility scenarios or on simplified reference missions. Less attention is devoted to regional and insular logistics networks, where the mission is not a single isolated flight but part of a wider distribution system. In such a context, several additional aspects become relevant: the position of a central hub, the distance between islands, the availability of peripheral vertiports or landing areas, charging or battery-swapping infrastructure, payload demand and mission frequency. These elements make the problem not only an aircraft-performance issue, but also an energy and network-planning problem. This thesis is motivated by the need to bridge this gap by developing a mission-based energy model that can be used as a first engineering tool for the assessment of eVTOL logistics operations in island environments. The objective is not only to estimate the energy required by a single flight, but also to provide a framework that can support future evaluations of an inter-island distribution network based on a central hub and multiple peripheral landing or charging points. In this perspective, the Aeolian Islands represent a meaningful case study, since they combine short-to-medium distances, logistical constraints, maritime dependency and the need for rapid distribution of essential goods. The proposed approach is therefore intended to connect vehicle-level energy modelling with future network-level planning. By estimating total mission energy, peak power, state of charge evolution and feasibility margins for different routes and operating conditions, the model can help identify which connections are technically feasible, which parameters most affect performance and which infrastructure requirements may become critical. Such information is necessary before considering more advanced optimisation of fleet size, charging strategy, vertiport placement or service scheduling. Overall, the research gap addressed by this thesis lies in the lack of a dedicated mission-based energy assessment for multicopter eVTOL logistics in insular scenarios. The work aims to contribute to this field by providing a physically coherent, modular and extendable modelling framework, applied to a realistic geographical context and capable of supporting future developments towards a complete aerial distribution network.

3 | Operational Context and Case Study Definition

3.1. The Aeolian Islands Transport Network

The Aeolian Islands are located in the southern Tyrrhenian Sea, off the northern coast of Sicily, and include Lipari, Vulcano, Salina, Panarea, Stromboli, Filicudi and Alicudi. Their insular distribution makes maritime transport the primary connection mode both with the Sicilian mainland and within the archipelago. Milazzo is one of the main mainland gateways to the islands. Regular maritime services from this port support passenger mobility, tourism and the supply of goods required by local communities. Within the archipelago, Lipari plays a particularly important role because of its population, services and central geographical position, making it a natural intermediate node for inter-island connections. The existing transport network is based mainly on hydrofoils, fast vessels and ferries. Hydrofoils and fast vessels provide shorter travel times and are primarily used for passenger transport, while ferries are essential for heavier freight, vehicles and regular supply operations. Together, these services form the backbone of mobility and logistics in the archipelago. From the perspective of this thesis, the maritime network represents the operational baseline rather than a system to be replaced. Ferries and hydrofoils remain indispensable for high-capacity passenger and freight movement. The purpose of the eVTOL analysis is instead to investigate whether an additional aerial layer could support selected missions in parallel with maritime operations, especially for lightweight, urgent and time-sensitive payloads. In this context, an eVTOL service would be most relevant as a complementary transport option. It could provide direct inter-island links or rapid mainland-to-island delivery for specific logistics needs, while the conventional maritime system would continue to handle the majority of passenger flows, vehicles and bulk cargo.



Figure 3.1: Geographical overview of the Aeolian Islands and their main connection with the Sicilian mainland.

3.2. Geographic and Logistic Constraints

The Aeolian Islands present a set of geographic and logistic constraints that make transport planning intrinsically more complex than in mainland areas. The archipelago is composed of several inhabited islands separated by sea channels, with different distances from the Sicilian coast and from each other. This spatial distribution creates a naturally fragmented transport system, in which mobility and goods distribution depend on a limited number of access points and scheduled maritime connections. A first constraint is related to insularity itself. Each island requires independent supply flows for residents, local services and tourism-related activities. Essential goods, medical supplies, maintenance materials and commercial products must be transported across the sea, often through routes that are not interchangeable. As a result, the logistics of the archipelago cannot be treated as a continuous land-based network, but rather as a set of discrete nodes connected by maritime links. A second important aspect is the different role played by each island. Lipari is the most populated island and acts as the main service centre of the archipelago, while smaller islands such as Alicudi, Ficulidi, Panarea and Stromboli have more limited infrastructure and lower accessibility. Vulcano is geographically close to the Sicilian mainland and represents one of the shortest connections from Milazzo, whereas the more remote islands require longer travel times and more complex routing. These differences influence both the frequency of transport services and the organisation of supply operations. The seasonal variation of demand represents another relevant

constraint. During the summer period, tourist flows significantly increase the need for passenger mobility, food supply, medical readiness and general logistics. In contrast, during the low season, the resident population is smaller and transport demand is reduced, but continuity of service remains essential. This variability makes the design of a flexible distribution system particularly challenging, since the same network must support both ordinary supply and peak-season demand. Weather and sea conditions also play a central role in island logistics. Maritime transport may be affected by rough sea, strong wind or reduced visibility, which can lead to delays, cancellations or reduced service frequency. Even when the maritime network remains operational, adverse conditions can increase uncertainty in delivery times. For time-sensitive goods, such as medical supplies or urgent spare parts, this uncertainty may represent a significant operational limitation. Finally, the availability of infrastructure differs considerably among the islands. Larger islands generally have better port facilities, services and storage capacity, while smaller islands may rely on more limited landing areas, port accessibility and logistics support. This affects not only the movement of passengers and goods, but also the possibility of introducing alternative transport modes. Any future aerial distribution system would therefore need to consider not only flight distance, but also the presence of suitable landing areas, charging infrastructure, ground handling procedures and integration with existing maritime logistics. Overall, the Aeolian Islands represent a constrained and heterogeneous operational environment. Their geography, seasonal demand, maritime dependency and uneven infrastructure distribution make the archipelago a meaningful case study for assessing complementary logistics solutions. These constraints justify the need for a structured evaluation of possible aerial distribution concepts, based on realistic route distances, payload requirements and operational margins.

3.3. Potential Role of Aerial Distribution Systems

Given the geographic and logistic constraints described above, aerial distribution systems may represent a complementary solution for selected transport needs within the Aeolian Islands. The objective would not be to replace the existing maritime network, which remains essential for passengers, vehicles and heavy freight, but rather to support it in specific missions where speed, flexibility and reduced dependence on fixed maritime schedules are relevant. Electric vertical take-off and landing aircraft are particularly interesting in this context because they can operate without conventional runway infrastructure. Their ability to take off and land vertically makes them potentially suitable for short-range point-to-point connections between a central hub and peripheral islands, provided that appropriate landing areas, charging systems and operational procedures are available.

This feature is especially relevant for insular territories, where the construction of conventional aviation infrastructure may be impractical, costly or environmentally invasive. From a logistics perspective, the most suitable applications would involve lightweight and time-sensitive cargo. Examples include medical supplies, urgent documents, small spare parts, emergency equipment and essential goods required with short notice. These payload categories are compatible with the limited carrying capacity of current eVTOL platforms and can benefit more directly from reduced delivery time compared with conventional transport modes. A further aspect concerns environmental impact. Since eVTOL aircraft use electric propulsion, they produce no direct exhaust emissions during flight. This may represent an advantage in environmentally sensitive territories such as small islands, where air quality, noise exposure and landscape preservation are relevant considerations. If the electricity used for charging were supplied partly or entirely from renewable sources, the overall environmental benefit could be further improved. Nevertheless, the environmental assessment must not be limited to local emissions: battery production, electricity generation mix, infrastructure installation, maintenance and end-of-life management also contribute to the total life-cycle impact of the system. Aerial distribution could also improve the resilience of the transport network. In situations where maritime services are delayed, reduced or temporarily unavailable, an eVTOL-based service could provide an additional layer of connectivity for critical supplies. Such a system would be particularly useful if organised around a hub-and-spoke logic, with a main hub located on the mainland or on a central island and smaller peripheral landing or charging areas distributed across the archipelago. However, the introduction of aerial distribution systems would require careful technical, environmental and operational assessment. The feasibility of each route depends on mission distance, payload mass, available battery energy, reserve requirements, environmental conditions and turnaround operations. In addition, infrastructure availability, safety procedures, airspace integration, noise footprint and local acceptance would need to be considered before any real deployment. For these reasons, the role of aerial distribution systems in the Aeolian Islands should be interpreted as complementary and mission-specific. Their potential value lies in providing fast, flexible and potentially lower-emission support for selected logistics operations, while the broader maritime network continues to serve as the main transport backbone. This thesis therefore focuses on the energy feasibility of representative eVTOL missions as a preliminary step towards the possible future development of a sustainable insular aerial distribution network.

3.4. Selected Mission Routes

The selection of representative mission routes is a key step in translating the operational context of the Aeolian Islands into a structured case study. Since the archipelago includes several islands with different distances from the Sicilian mainland and from each other, the analysis is organised into two complementary levels: a mainland-to-island base case and an internal hub-and-spoke distribution network. The first level of analysis is represented by the Milazzo–Vulcano route, which is selected as the base case study. Milazzo represents one of the main mainland gateways to the Aeolian Islands and is already a relevant departure point for existing maritime connections. Vulcano, being one of the closest islands to the Sicilian coast, represents a suitable first destination for assessing the feasibility of a short-range eVTOL logistics mission. This route is therefore used as an initial reference mission to evaluate energy demand, power requirements and operational margins under realistic insular conditions. The second level of analysis extends the study from a single route to an internal distribution concept within the Aeolian archipelago. In this configuration, Lipari is selected as the central island hub because of its geographical position, population, services and central role within the archipelago. From Lipari, goods can be redistributed towards the surrounding peripheral islands through shorter inter-island eVTOL missions. The peripheral nodes considered in the hub-and-spoke network are Vulcano, Salina, Panarea, Stromboli, Filicudi and Alicudi. Each of these islands is treated as a possible destination equipped, in principle, with a suitable landing and charging area. This network structure allows the analysis to move beyond the single Milazzo–Vulcano mission and to evaluate whether a multicopter eVTOL could support a broader inter-island distribution service. This distinction between the two levels of analysis is important. Milazzo is treated as the mainland logistics gateway, while Lipari is treated as the central archipelago hub for internal redistribution. The Milazzo–Vulcano route provides the base case for mainland-to-island operations, whereas the Lipari-based routes provide a quantitative assessment of the feasibility of an island-to-island aerial logistics network. The selected routes are not intended to replace the existing maritime transport system, but to define representative missions for evaluating the role of eVTOL aircraft as a complementary logistics solution. The quantitative analysis of both the base case and the Lipari-centred network enables the identification of feasible routes, critical distances and operational limits for a possible future aerial distribution system in the Aeolian Islands.

Table 3.1: Selected routes and operational roles for the eVTOL logistics analysis in the Aeolian Islands.

Route / Node	Operational role	Use in this thesis
Milazzo–Vulcano	Mainland-to-island base case	Quantitative analysis
Milazzo	Mainland logistics gateway	Departure point for the base case
Lipari	Central archipelago hub	Inter-island network analysis
Lipari–Vulcano	Hub-and-spoke inter-island route	Quantitative analysis
Lipari–Salina	Hub-and-spoke inter-island route	Quantitative analysis
Lipari–Panarea	Hub-and-spoke inter-island route	Quantitative analysis
Lipari–Stromboli	Hub-and-spoke inter-island route	Quantitative analysis
Lipari–Filicudi	Hub-and-spoke inter-island route	Quantitative analysis
Lipari–Alicudi	Hub-and-spoke inter-island route	Quantitative analysis

3.4.1. Base Case Route: Milazzo–Vulcano

The Milazzo–Vulcano route is selected as the base case mission for the first level of the analysis. This route represents a mainland-to-island connection between one of the main Sicilian gateways to the Aeolian archipelago and one of the closest islands to the coast. For this reason, it provides a suitable initial scenario for assessing the applicability of a multicopter eVTOL to short-range insular logistics operations. Milazzo is considered as the mainland logistics gateway, where goods can be collected, prepared and loaded before departure. Vulcano is selected as the reference island destination because of its proximity to the Sicilian coast and its role as one of the main access points to the archipelago. The mission therefore represents a realistic first application for the aerial distribution of lightweight and time-sensitive goods from the mainland towards the islands. The choice of a single base case route allows the analysis to focus on a clearly defined operational problem before extending the study to a wider inter-island network. From an engineering perspective, this is important because the feasibility of a more complex distribution system depends first on the ability of the aircraft to complete an individual mission while satisfying energy, power, payload and reserve constraints. In this thesis, the Milazzo–Vulcano mission is treated as a fixed-distance route. The route distance is used as one of the main inputs for the subsequent mission definition and energy assessment. The flight is considered as a point-to-point logistics mission, with the aircraft departing from the mainland gateway and reaching the island node. The detailed values of payload, cruise altitude, cruise speed and reserve assumptions are introduced in the mission requirements section. The Milazzo–Vulcano base case is therefore used as the first quantitative benchmark of the study. Its purpose is not to describe the complete future distribution system,

but to establish a representative reference mission against which the energetic capability of the selected eVTOL configuration can be assessed.

Table 3.2: Main characteristics of the Milazzo–Vulcano base case route.

Item	Description
Route	Milazzo–Vulcano
Mission type	Mainland-to-island logistics connection
Origin	Milazzo mainland logistics gateway
Destination	Vulcano island node
Role in the thesis	Base case quantitative mission
Operational purpose	Initial assessment of short-range eVTOL logistics feasibility
Main transported goods	Lightweight and time-sensitive cargo

3.4.2. Inter-Island Connections

After the definition of the Milazzo–Vulcano base case, the analysis is extended to an internal distribution network within the Aeolian archipelago. This second level of the study is based on a hub-and-spoke concept, in which Lipari is selected as the central island hub and the surrounding islands are treated as peripheral nodes. Lipari is chosen as the central hub because of its geographical position within the archipelago and its role as the main service centre among the Aeolian Islands. In the proposed eVTOL scenario, Lipari is not only considered as a departure point for flights, but also as a local logistics consolidation node. This means that a stock of lightweight goods, urgent supplies or high-priority items is assumed to be already available on the island before the inter-island eVTOL mission is activated. This assumption is important for the operational interpretation of the network. The inter-island eVTOL routes are not modelled as direct continuations of every mainland shipment arriving from Milazzo. Instead, the concept assumes that goods can be transported to Lipari through the existing maritime logistics system, stored or consolidated locally, and then redistributed by eVTOL when rapid delivery to another island is required. In this way, the aerial service acts as a fast last-mile or middle-mile island distribution layer, rather than as a complete replacement for maritime supply chains. The peripheral nodes considered in the network are Vulcano, Salina, Panarea, Stromboli, Filicudi and Alicudi. Each of these islands is assumed to represent a potential destination for lightweight logistics operations and, in principle, could host a suitable landing and charging area. The corresponding routes are analysed

as individual point-to-point missions departing from Lipari. The hub-and-spoke representation is useful because it reflects a scalable distribution logic. Instead of requiring direct eVTOL connections between every pair of islands, the distribution problem is structured around a central stock point. Shorter routes may represent more favourable applications, while longer routes towards the more remote islands are used to explore the operational limits of the system and the possible need for intermediate stops or additional charging points. In this thesis, the Lipari-centred network is treated as a quantitative extension of the Milazzo–Vulcano base case. The mainland-to-island route provides a demanding reference mission, while the Lipari hub-and-spoke network represents a more distributed operational concept based on pre-positioned goods and local inter-island redistribution. This framework connects the single route analysis with a broader logistics scenario for the Aeolian archipelago, while preserving the complementary role of maritime transport for bulk supply and regular stock replenishment.

Table 3.3: Routes considered in the Lipari-centred hub-and-spoke network.

Route	Peripheral node	Role in the analysis
Lipari–Vulcano	Vulcano	Quantitative inter-island route assessment
Lipari–Salina	Salina	Quantitative inter-island route assessment
Lipari–Panarea	Panarea	Quantitative inter-island route assessment
Lipari–Stromboli	Stromboli	Quantitative inter-island route assessment
Lipari–Filicudi	Filicudi	Quantitative inter-island route assessment
Lipari–Alicudi	Alicudi	Quantitative inter-island route assessment

3.5. Reference Aircraft Selection

The reference aircraft adopted in this thesis is based on the Volocopter multicopter design family. In particular, the VoloCity is used as the main architectural reference because it represents the more recent commercial eVTOL concept developed by Volocopter and is therefore closer to the aircraft class considered in this work. However, the thesis does not attempt to reproduce the real VoloCity aircraft in every proprietary detail.

Publicly available data for the VoloCity provide useful information about the general configuration, such as the multicopter layout, number of rotors, payload class, battery-swapping concept and order of magnitude of the vehicle mass. However, detailed aircraft-level and battery-level data are not fully disclosed. For this reason, selected technical parameters from the earlier Volocopter 2X prototype are also considered when more de-

tailed open information is required, such as rotor geometry, mass breakdown, climb and descent rates and battery-system architecture.

The resulting reference configuration should therefore be interpreted as a VoloCity-like multicopter eVTOL, not as the certified or commercially intended VoloCity aircraft. This distinction is important because the mission analysis explores routes and operating conditions that may extend beyond the publicly declared operational capability of the actual VoloCity. In particular, recent public specifications indicate an operational range of approximately 20 km when operational margins and safety constraints are included, while earlier public material reported higher calculated range values. This highlights the difference between design-level estimates and operational range values including reserves and constraints.

Consequently, the Milazzo–Vulcano mission is not introduced as a route that the real VoloCity is claimed to perform directly. Instead, it is treated as an energy-critical reference case used to evaluate how a representative multicopter eVTOL configuration behaves when applied to a demanding short-range island mission. All results obtained for routes beyond the published operational range should therefore be interpreted as mission-level feasibility explorations of a VoloCity-like configuration, not as statements about the certified capability of the actual aircraft.



Figure 3.2: Volocopter VoloCity multicopter eVTOL.

Table 3.4: Comparison between Volocopter 2X and VoloCity public specifications.

Parameter	Volocopter 2X	VoloCity
<i>General characteristics</i>		
Aircraft role	Prototype / demonstrator	Commercial air taxi concept
Aircraft category	Electric multicopter VTOL	Electric multicopter eVTOL
Passenger capacity	2 pax	2 seats
Certification target	German ultralight / light sport multicopter	EASA SC-VTOL enhanced category
<i>Mass and payload</i>		
Maximum take-off mass	450 kg	~900–1000 kg
Operating empty weight	290 kg	Not publicly specified
Maximum payload	160 kg	~200 kg
<i>Performance</i>		
Range	27 km at MTOM	~20–35 km
Cruise speed	70 km/h for maximum range	90 km/h
Maximum airspeed	100 km/h	100–110 km/h
Maximum flight time	27 min at MTOM	Not publicly specified
Rate of climb	3.0 m/s	Not publicly specified
Rate of descent	2.5 m/s	Not publicly specified
<i>Propulsion and energy system</i>		
Motors / rotors	18 / 18	18 / 18
Battery packs	9 independent Li-ion packs	9 rechargeable battery packs
Battery replacement	Quick-change plug-in system	Battery swapping concept
Battery cooling	Active air cooling	Not publicly specified
<i>Geometry and structure</i>		
Single rotor diameter	1.80 m	~2.30 m
Rotor rim diameter	9.15 m, including propellers	~11.3 m, including propellers
Overall height	2.15 m	~2.5–2.7 m
Primary structure	Fibre-composite lightweight structure	Composite structure

Table 3.4 shows the rationale behind the mixed-data approach adopted in this thesis. The VoloCity provides the most relevant conceptual reference for the target aircraft class, while the Volocopter 2X provides more detailed public technical data useful for modelling purposes. Whenever parameters are transferred from the Volocopter 2X or introduced through engineering assumptions, they are explicitly defined in the model input section and treated as approximations.

This approach allows the thesis to remain connected to a realistic eVTOL aircraft family while preserving a transparent and reproducible modelling framework. The mission requirements are therefore formulated for a representative short-range multicopter eVTOL configuration applied to the Aeolian Islands scenario, with particular attention to logistics and lightweight transport missions rather than to the direct reproduction of a specific passenger air-taxi service.

3.6. Mission Requirements

The definition of mission requirements is necessary to translate the selected routes into a consistent set of inputs for the energy assessment. In this thesis, the considered missions are defined as short-range logistics operations aimed at transporting lightweight and time-sensitive goods between selected nodes of the Aeolian Islands distribution network. The objective is not to model passenger transport or heavy freight operations, but to evaluate whether a multicopter eVTOL can support complementary aerial distribution services under realistic operating assumptions. Each route is treated as a point-to-point mission with fixed distance. The aircraft departs from the origin node, performs the complete flight sequence and reaches the destination node, where landing and potential recharging or battery replacement are assumed to be available in the broader network concept. Return flights or subsequent redistribution operations can be represented as additional point-to-point missions using the same modelling logic. A nominal logistics payload is assigned to the mission in order to represent the transported goods, packaging and handling equipment. This payload is treated as part of the aircraft take-off mass and therefore directly affects the power required during vertical flight, climb and cruise. Since payload is one of the most influential parameters for logistics applications, its effect is later investigated through dedicated sensitivity analyses. The mission profile is represented through a sequence of flight segments, including initial taxi, take-off hover, vertical take-off, forward climb, cruise, forward descent, vertical landing, landing hover and final taxi. This segment-based structure allows the different energetic contributions of vertical, horizontal and transitional phases to be considered separately while maintaining a simple and transparent mission definition. For the nominal case, reference atmospheric conditions and zero wind are assumed. Environmental effects are not neglected, but are analysed separately through temperature and wind sensitivity studies. This approach makes it possible to first define a clear baseline mission and then evaluate how external conditions modify the energy and feasibility margins. The feasibility of each mission is assessed with respect to both energy and power constraints. A route is considered feasible only if the total mission energy remains below the usable battery energy and the maximum required power remains below the available battery power, while maintaining the prescribed battery reserve. These requirements provide the operational basis for the numerical model developed in the following chapter.

3.6.1. Operational Mission Assumptions

The analysed missions are defined as point-to-point logistics flights between selected nodes of the Aeolian Islands distribution network. The aircraft is assumed to depart from a prepared landing area, complete the assigned route and land at the destination node, where ground handling and charging or battery replacement could be made available in a future operational implementation.

The following assumptions are adopted:

- the mission is intended for lightweight cargo transport or passenger service;
- each route is analysed as an independent fixed-distance flight;
- vertical take-off and landing are required at both origin and destination;
- the aircraft operates without conventional runway infrastructure;
- the destination node is assumed to provide a suitable landing area;
- charging or battery replacement is considered as part of the future network concept, but not explicitly sized in this chapter;
- return flights can be represented as additional point-to-point missions.

3.6.2. Route Distance Requirements

The route distance represents one of the main mission requirements because it directly affects cruise duration and total energy demand. In this work, distances are treated as fixed mission inputs for the energy model. The Milazzo–Vulcano route is used as the mainland-to-island base case, while the Lipari-centred routes are used for the hub-and-spoke network assessment.

Table 3.5: Route distance requirements adopted for the mission analysis.

Route	Distance [km]	Role
Milazzo–Vulcano	≈ 37	Base case mainland-to-island mission
Lipari–Vulcano	≈ 9	Hub-to-node route
Lipari–Salina	≈ 12	Hub-to-node route
Lipari–Panarea	≈ 20	Hub-to-node route
Lipari–Stromboli	≈ 42	Hub-to-node route
Lipari–Filicudi	≈ 34	Hub-to-node route
Lipari–Alicudi	≈ 53	Hub-to-node route

The distances are evaluated as direct point-to-point route lengths between the selected origin and destination nodes. Additional route corrections due to airspace constraints are not included at this stage.

3.6.3. Payload and Mass Assumptions

A nominal payload is assigned to the mission in order to represent the useful load transported by the aircraft. In the present analysis, the payload is treated as a generic mission payload, which may include lightweight goods, packaging, handling equipment, passengers, or a combination of these depending on the operational scenario considered. This choice allows the same modelling framework to be applied both to aerial distribution missions and to possible short-range passenger service applications. For the baseline case, a nominal payload of 200 kg is adopted. This value is consistent with a two-passenger configuration or, alternatively, with a compact logistics load including goods and supporting equipment. In both cases, the payload contributes directly to the aircraft take-off mass and therefore affects the power required during vertical flight, climb, cruise and landing. Since payload is one of the most influential parameters in eVTOL operations, its effect is further investigated through dedicated sensitivity analyses.

Table 3.6: Nominal payload and mass assumptions for the reference mission.

Parameter	Nominal value	Description
Payload mass	200 kg	Useful load for passengers, cargo or mixed payload
Battery mass	300 kg	Installed battery mass adopted in the model
Maximum take-off mass	900 kg	Reference multicopter mass assumption
Mission type	Logistics / passenger	Short-range mission depending on payload use

The adopted mass values are representative modelling assumptions based on publicly available Volocopter data and literature-based scaling. They are not intended to reproduce a proprietary certified aircraft configuration, but to define a realistic reference multicopter configuration suitable for mission-level energy assessment.

3.6.4. Flight Segment Definition

The mission is represented through a sequence of operational segments. This structure allows the different contributions of vertical flight, climb, cruise, descent and ground operations to be identified separately in the subsequent energy model.

Table 3.7: Mission segments considered in the energy assessment.

Segment	Description
Initial taxi	Low-power repositioning before take-off
Take-off hover	Short stabilisation phase before vertical climb
Vertical take-off	Vertical climb from the departure area
Forward climb	Climb to cruise altitude while covering horizontal distance
Cruise	Main horizontal flight segment along the route
Forward descent	Descent towards the destination while covering horizontal distance
Vertical landing	Final vertical descent before touchdown
Landing hover	Short stabilisation phase before landing completion
Final taxi	Low-power repositioning after landing

For the multicopter configuration considered in this thesis, no explicit transition segment is introduced, since the aircraft remains rotor-borne throughout the mission.

3.6.5. Nominal Environmental Conditions

The baseline mission is evaluated under reference environmental conditions. This choice allows the nominal energy demand of each route to be assessed before introducing external disturbances such as wind or temperature variation.

Table 3.8: Nominal environmental assumptions for the baseline mission.

Parameter	Nominal value	Description
Ambient temperature	25 °C	Reference battery and atmosphere condition
Wind speed	0 m/s	No headwind or tailwind in the baseline case
Air density	1.225 kg/m ³	Sea-level ISA reference value
Route type	Direct	Point-to-point route approximation

Temperature and wind effects are not neglected, but are investigated separately through dedicated sensitivity analyses.

3.6.6. Feasibility Criteria

The selected missions are evaluated according to a set of feasibility criteria. These criteria are used to determine whether a route can be completed while respecting aircraft, battery and operational constraints.

A mission is considered feasible only if the following conditions are satisfied:

- **Geometric feasibility:** the route distance must be sufficient to include climb, cruise and descent segments.
- **Energy feasibility:** the total mission energy must remain below the usable battery energy.
- **Power feasibility:** the maximum required mission power must remain below the available battery power.
- **Reserve requirement:** the final state of charge must remain compatible with the prescribed battery reserve.

These criteria provide the operational basis for the energy model developed in the following chapter. They also allow the results of different routes and sensitivity analyses to be compared through consistent feasibility indicators.

4 | Energy Model Development

4.1. General Modelling Framework

The energy model developed in this thesis is based on a mission-level, segment-based approach. The objective of the model is to estimate the power demand, energy consumption and battery utilisation of a multicopter eVTOL aircraft operating over predefined routes in the Aeolian Islands scenario. Rather than relying on nominal range values or average endurance estimates, the mission is decomposed into individual flight segments, each characterised by a specific duration, power requirement and energy contribution.

The modelling philosophy follows the approach proposed by Bruhl et al. in *Air Taxi Flight Performance Modeling and Application*, where the total energy consumption of an eVTOL mission is obtained by evaluating the power required in each flight segment and multiplying it by the corresponding segment duration [2]. This structure is particularly suitable for electric vertical take-off and landing aircraft, since different phases of flight may impose very different energy and power demands on the battery system.

In general form, the energy required by a generic mission segment i is calculated as:

$$E_i = P_i t_i \quad (4.1)$$

where E_i is the energy consumed in the segment, P_i is the mean power required during the segment and t_i is the segment duration. When power is expressed in watts and time in seconds, the corresponding energy in watt-hours is obtained as:

$$E_i[Wh] = \frac{P_i[W] t_i[s]}{3600} \quad (4.2)$$

The total mission energy is then computed as the sum of the energy contributions of all mission segments:

$$E_{\text{mission}} = \sum_{i=1}^N E_i \quad (4.3)$$

where N is the total number of segments considered in the mission. This formulation allows the contribution of each flight phase to be evaluated separately and makes it possible to identify the most energy-demanding portions of the mission.

In addition to total energy consumption, the model also evaluates the maximum power required during the mission. This value is relevant because electric aircraft feasibility is constrained not only by the total amount of energy stored in the battery, but also by the maximum power that the battery and propulsion system can deliver safely. The peak mission power is therefore defined as:

$$P_{\text{max}} = \max(P_1, P_2, \dots, P_N) \quad (4.4)$$

The overall feasibility of a mission is assessed by comparing the required mission energy and peak power with the available battery energy and battery power. A mission is considered energetically feasible if:

$$E_{\text{mission}} \leq E_{\text{batt,use}} \quad (4.5)$$

and power-feasible if:

$$P_{\text{max}} \leq P_{\text{batt,max}} \quad (4.6)$$

where $E_{\text{batt,use}}$ is the usable battery energy after accounting for efficiency and reserve constraints, and $P_{\text{batt,max}}$ is the maximum usable battery power. These two conditions are both required, since a mission may be limited either by total energy capacity or by peak power availability.

The state of charge evolution is obtained by progressively subtracting the cumulative mission energy from the available battery energy. At a generic time or segment index, the remaining usable state of charge can be expressed as:

$$SOC = 100 \left(1 - \frac{E_{\text{used}}}{E_{\text{batt,use}}} \right) \quad (4.7)$$

where E_{used} is the cumulative energy consumed up to that point. This quantity is used to evaluate the remaining battery margin at the end of the mission.

For the present thesis, the general framework is adapted to a multicopter eVTOL configuration. Since a multicopter remains rotor-borne throughout the mission and does not perform a conversion from vertical to wing-borne flight, no explicit transition segment is included. This differs from lift-and-cruise or vectored-thrust eVTOL models, where transition phases are required to describe the change between vertical and horizontal flight. The adopted mission structure is therefore simplified with respect to multi-configuration eVTOL aircraft, but remains physically consistent with the selected reference architecture. The implemented model receives as inputs the aircraft parameters, battery characteristics, mission geometry and environmental conditions. It then computes the derived quantities required for the energy assessment, including total weight, rotor disk area, disk loading, hover power, segment durations, segment energies, total mission energy, peak power, final state of charge and feasibility margins. The resulting framework provides a transparent basis for comparing the Milazzo–Vulcano base case and the Lipari-centred inter-island routes under consistent assumptions. Overall, the model is intended as a mission-level performance tool rather than a high-fidelity aerodynamic simulation. Its purpose is to provide an engineering estimate of the energetic feasibility of eVTOL operations in the Aeolian Islands scenario, while keeping the formulation simple enough to support parametric studies and sensitivity analyses.

4.2. Segment-Based Mission Architecture

The mission architecture adopted in this thesis follows a segment-based logic. The complete flight is divided into a sequence of operational phases, each characterised by a specific duration, power requirement and energy consumption. This approach is consistent with the modelling philosophy adopted in the reference eVTOL mission model by Bruhl and co-authors [2], where the total mission energy is obtained by evaluating the power required in each segment and integrating it over the corresponding time interval. For the present work, the mission structure is adapted to a multicopter eVTOL configuration. Since the selected aircraft does not require a dedicated transition phase between vertical and forward flight, no explicit transition segment is introduced. The flight profile is therefore represented through ground-operation, vertical-flight and forward-flight segments. The adopted sequence consists of initial taxi, take-off hover, vertical take-off, forward climb, cruise, forward descent, vertical landing, landing hover and final taxi. Taxi and hover account for low-speed operations before and after the main flight. Vertical take-off and

landing describe the near-ground vertical motion at departure and arrival. Forward climb and forward descent allow the aircraft to reach and leave the cruise altitude while covering part of the route distance. The cruise segment is assigned to the remaining horizontal distance flown at the nominal cruise speed. A key aspect of the model is that the total point-to-point distance is not assigned entirely to cruise. Part of the horizontal distance is covered during forward climb and forward descent. Therefore, the cruise distance is computed as:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{descent}} \quad (4.8)$$

where d_{mission} is the total route distance, while d_{climb} and d_{descent} are the horizontal distances covered during climb and descent.

The climb time is calculated from the altitude difference between the cruise altitude and the height reached after vertical take-off:

$$t_{\text{climb}} = \frac{h_{\text{cruise}} - h_{\text{VTO}}}{RoC_{\text{climb}}} \quad (4.9)$$

and the corresponding horizontal distance is:

$$d_{\text{climb}} = V_{\text{climb}} t_{\text{climb}} \quad (4.10)$$

Similarly, the descent time is:

$$t_{\text{descent}} = \frac{h_{\text{cruise}} - h_{\text{VLAND}}}{RoD_{\text{descent}}} \quad (4.11)$$

with horizontal descent distance:

$$d_{\text{descent}} = V_{\text{descent}} t_{\text{descent}} \quad (4.12)$$

Before computing the energy balance, the selected flight profile must satisfy the geometric condition:

$$d_{\text{mission}} > d_{\text{climb}} + d_{\text{descent}} \quad (4.13)$$

If this condition is not satisfied, the cruise distance becomes zero or negative, meaning

that the prescribed climb, cruise and descent structure is not compatible with the route length. This check is particularly relevant for short inter-island missions, where climb and descent can represent a significant portion of the total horizontal distance.

Table 4.1: Segment-based mission architecture adopted for the multicopter eVTOL model.

Segment	Physical meaning	Main output
Initial taxi	Low-power repositioning before take-off	Energy and time
Take-off hover	Stabilisation before vertical climb	Hover energy and power
Vertical take-off	Vertical climb from the departure area	Take-off energy and power
Forward climb	Climb to cruise altitude while covering horizontal distance	Climb time, distance and energy
Cruise	Main horizontal segment at nearly constant altitude	Cruise energy and duration
Forward descent	Descent to destination while covering horizontal distance	Descent time, distance and energy
Vertical landing	Final vertical descent before touchdown	Landing energy and power
Landing hover	Stabilisation before landing completion	Hover energy and power
Final taxi	Low-power repositioning after landing	Energy and time

This mission architecture provides a consistent basis for the subsequent power and energy calculations. Each segment is treated independently, but the total mission performance is obtained by combining all segment contributions into a single energy and feasibility assessment.

4.3. Hover Energy Model

Hovering flight is one of the most characteristic and energy-demanding operating conditions for a multicopter eVTOL. During hover, the aircraft maintains approximately zero translational speed and the rotor system must generate a total thrust equal to the aircraft weight. Since no fixed wing is present, the entire lift requirement is provided by the rotors. For this reason, the hover power represents a fundamental reference quantity for

the modelling of vertical take-off, landing and low-speed stabilisation phases.

The hover model adopted in this thesis is based on momentum theory and follows the same general formulation used in the reference air taxi performance model by Bruhl et al. [2]. The total aircraft weight is defined as:

$$W = m_{\text{TO}}g \quad (4.14)$$

where m_{TO} is the take-off mass and g is the gravitational acceleration.

For a multicopter with n_{rotor} rotors, each with radius R_{rotor} , the total rotor disk area is:

$$A_R = n_{\text{rotor}}\pi R_{\text{rotor}}^2 \quad (4.15)$$

The corresponding disk loading is then:

$$DL = \frac{W}{A_R} \quad (4.16)$$

Disk loading is an important parameter because it relates the aircraft weight to the total rotor area available for generating lift. A lower disk loading generally reduces the induced velocity required in hover and therefore decreases the ideal hover power. Conversely, a higher disk loading leads to higher induced power and lower hover efficiency.

Under ideal actuator disk theory, the induced velocity in hover is given by:

$$v_h = \sqrt{\frac{W}{2\rho A_R}} \quad (4.17)$$

where ρ is the air density. The ideal induced hover power is therefore:

$$P_{h,\text{ideal}} = Wv_h \quad (4.18)$$

Substituting Eq. (4.17) into Eq. (4.18), the ideal hover power becomes:

$$P_{h,\text{ideal}} = W\sqrt{\frac{W}{2\rho A_R}} \quad (4.19)$$

or, equivalently, using the disk loading definition:

$$P_{h,\text{ideal}} = W \sqrt{\frac{DL}{2\rho}} \quad (4.20)$$

In real operating conditions, additional losses are present due to non-ideal rotor behaviour, blade profile drag, inflow non-uniformity, motor losses and propulsive inefficiencies. These effects are included through an overall hover efficiency factor η_{hover} . The required hover power is therefore expressed as:

$$P_{\text{hover}} = \frac{W}{\eta_{\text{hover}}} \sqrt{\frac{DL}{2\rho}} \quad (4.21)$$

This formulation is particularly suitable for preliminary mission-level energy modelling because it captures the dominant dependence of hover power on aircraft weight, rotor disk area and air density while keeping the model sufficiently compact for parametric analysis.

The hover energy associated with a hover segment of duration t_{hover} is calculated as:

$$E_{\text{hover}} = \frac{P_{\text{hover}} t_{\text{hover}}}{3600} \quad (4.22)$$

where P_{hover} is expressed in watts, t_{hover} in seconds and E_{hover} in watt-hours.

In the mission architecture adopted in this thesis, the hover model is used for the short stabilisation phases before vertical take-off and before landing. These phases are included to represent the time required for aircraft stabilisation, control checks, clearance or final positioning near the landing area. Although their duration is limited, hover segments may contribute noticeably to total energy consumption because the required power is high compared with other low-speed operations.

For the multicopter configuration considered here, hover power is also a useful reference for interpreting vertical take-off and landing power. Since the aircraft remains rotor-borne throughout the mission, the hover model provides the baseline from which vertical climb and descent power are derived in the following sections.

Table 4.2: Main quantities used in the hover energy model.

Symbol	Unit	Description
W	N	Aircraft weight
m_{TO}	kg	Take-off mass
A_R	m^2	Total rotor disc area
DL	N/m^2	Disc loading
ρ	kg/m^3	Air density
v_h	m/s	Induced velocity in hover
η_{hover}	–	Hover efficiency factor
P_{hover}	W	Required hover power
E_{hover}	Wh	Hover segment energy

4.4. Vertical Take-Off and Landing Model

Vertical take-off and landing are fundamental phases of an eVTOL multicopter mission. During these segments, the aircraft performs primarily vertical motion while remaining supported by rotor thrust. Since the selected aircraft configuration does not rely on fixed-wing lift, the vertical phases are directly related to the hover model introduced in the previous section.

The formulation adopted in this thesis follows the approach used by Bruhl et al. for eVTOL air taxi performance modelling, in which vertical take-off and landing power are derived from hover power and corrected for the imposed vertical speed [2]. This is consistent with the multicopter architecture considered in the present work, where vertical flight is performed through the same rotor system used for hovering.

4.4.1. Vertical Take-Off

During vertical take-off, the aircraft climbs from the departure landing area to a prescribed height before starting the forward climb phase. The required power is larger than pure hover power because the aircraft must not only balance its weight, but also generate an upward rate of climb.

The vertical take-off power is expressed as:

$$P_{\text{VTO}} = P_{\text{hover}} \left[\frac{RoC_{\text{VTO}}}{2v_h} + \sqrt{\left(\frac{RoC_{\text{VTO}}}{2v_h} \right)^2 + 1} \right] \quad (4.23)$$

where P_{hover} is the hover power, RoC_{VTO} is the vertical rate of climb during take-off and v_h is the induced velocity in hover.

The duration of the vertical take-off segment is calculated as:

$$t_{\text{VTO}} = \frac{h_{\text{VTO}}}{RoC_{\text{VTO}}} \quad (4.24)$$

where h_{VTO} is the vertical height reached before the forward climb begins. The corresponding energy consumption is:

$$E_{\text{VTO}} = \frac{P_{\text{VTO}} t_{\text{VTO}}}{3600} \quad (4.25)$$

with P_{VTO} expressed in watts, t_{VTO} in seconds and E_{VTO} in watt-hours.

This formulation shows that the take-off power increases with the prescribed vertical climb rate. Therefore, a faster vertical take-off reduces the segment duration but increases the instantaneous power demand. This trade-off is relevant for battery power sizing and for the assessment of peak power requirements.

4.4.2. Vertical Landing

The vertical landing segment describes the final descent from a prescribed height above the destination area to touchdown. In principle, vertical descent power can also be derived from momentum theory. However, rotorcraft descent is more complex than vertical climb because some descent rates may lead to vortex ring state, where the flow through the rotor becomes highly disturbed.

Following the reference modelling approach, the vertical landing power is written as:

$$P_{\text{VL}} = P_{\text{hover}} \left[\frac{RoD_{\text{VL}}}{v_h} + \frac{v_i}{v_h} \right] \quad (4.26)$$

where RoD_{VL} is the vertical rate of descent and v_i is the induced velocity during vertical descent. In the sign convention adopted here, RoD_{VL} is negative for descending flight.

For descent rates outside the vortex ring state region, analytical momentum-theory expres-

sions may be used. However, for the low descent rates typically associated with passenger comfort and controlled landing operations, the aircraft may operate in the region:

$$-2 \leq \frac{RoD_{VL}}{v_h} \leq 0 \quad (4.27)$$

In this region, the induced velocity ratio is approximated through the empirical polynomial adopted in the reference paper:

$$\frac{v_i}{v_h} = k + k_1 \left(\frac{RoD_{VL}}{v_h} \right) + k_2 \left(\frac{RoD_{VL}}{v_h} \right)^2 + k_3 \left(\frac{RoD_{VL}}{v_h} \right)^3 + k_4 \left(\frac{RoD_{VL}}{v_h} \right)^4 \quad (4.28)$$

with:

$$k = 0.974, \quad k_1 = -1.125, \quad k_2 = -1.372, \quad k_3 = -1.718, \quad k_4 = -0.655 \quad (4.29)$$

The vertical landing duration is computed as:

$$t_{VL} = \frac{h_{VL}}{|RoD_{VL}|} \quad (4.30)$$

where h_{VL} is the height from which the final vertical landing segment begins. The landing energy is then:

$$E_{VL} = \frac{P_{VL} t_{VL}}{3600} \quad (4.31)$$

In the implemented model, vertical landing is treated consistently with the paper-based formulation. The use of the empirical induced-velocity approximation avoids applying a simple momentum-theory expression in a region where the flow can become physically complex. This is important because the descent rates adopted for a controlled eVTOL landing are usually moderate and may fall within the vortex ring state range.

4.4.3. Implementation in the Mission Model

In the mission architecture adopted in this thesis, vertical take-off and landing are treated as separate segments from hover and forward climb/descent. This distinction is useful

because each phase has a different physical meaning:

- hover segments represent short stabilisation or positioning phases;
- vertical take-off represents the initial upward climb near the departure area;
- vertical landing represents the final controlled descent near the destination area.

The outputs of the vertical take-off and landing model are the segment power, duration and energy. These quantities are then included in the total mission energy balance together with the contributions from taxi, hover, climb, cruise and descent.

Table 4.3: Main quantities used in the vertical take-off and landing model.

Symbol	Unit	Description
P_{hover}	W	Reference hover power
v_h	m/s	Hover induced velocity
RoC_{VTO}	m/s	Vertical take-off rate of climb
RoD_{VL}	m/s	Vertical landing rate of descent
h_{VTO}	m	Vertical take-off height
h_{VL}	m	Vertical landing height
t_{VTO}	s	Vertical take-off duration
t_{VL}	s	Vertical landing duration
P_{VTO}	W	Vertical take-off power
P_{VL}	W	Vertical landing power
E_{VTO}	Wh	Vertical take-off energy
E_{VL}	Wh	Vertical landing energy

Overall, the vertical take-off and landing model preserves the structure of the reference air taxi performance formulation while adapting it to the selected multicopter mission architecture. These phases are particularly important for the power feasibility assessment, since they can contribute significantly to the peak power demand even when their duration is relatively short.

4.4.4. Forward Climb and Forward Descent

After the vertical take-off phase, the aircraft performs a forward climb segment in order to reach the prescribed cruise altitude while also covering part of the route distance. Similarly, before the final vertical landing phase, the aircraft performs a forward descent

segment from cruise altitude towards the destination area. These phases are necessary to connect the purely vertical portions of the mission with the main cruise segment.

In the adopted segment-based model, climb and descent are treated both from a kinematic and energetic point of view. Their kinematic role is important because part of the total route distance is covered before and after cruise. Therefore, the cruise distance is not assumed equal to the total mission distance, but is obtained as the residual distance after subtracting the horizontal distance covered during climb and descent.

The altitude increment covered during forward climb is defined as:

$$\Delta h_{\text{climb}} = h_{\text{cruise}} - h_{\text{VTO}} \quad (4.32)$$

where h_{cruise} is the selected cruise altitude and h_{VTO} is the altitude reached after vertical take-off. Assuming a constant rate of climb, the climb time is:

$$t_{\text{climb}} = \frac{\Delta h_{\text{climb}}}{RoC_{\text{climb}}} \quad (4.33)$$

and the horizontal distance covered during climb is:

$$d_{\text{climb}} = V_{\text{climb}} t_{\text{climb}} \quad (4.34)$$

where V_{climb} is the forward climb speed.

Following the simplified force-balance approach adopted in the reference air taxi performance model, the climb power is estimated as:

$$P_{\text{climb}} = \frac{W}{\eta_{\text{climb}}} \left(RoC_{\text{climb}} + \frac{V_{\text{climb}}}{(L/D)_{\text{climb}}} \right) \quad (4.35)$$

where W is the aircraft weight, η_{climb} is the climb efficiency and $(L/D)_{\text{climb}}$ is the lift-to-drag ratio adopted for the climb condition. The first term represents the power associated with altitude gain, while the second term accounts for the power required to overcome aerodynamic drag during forward motion.

The climb energy is then:

$$E_{\text{climb}} = \frac{P_{\text{climb}} t_{\text{climb}}}{3600} \quad (4.36)$$

with P_{climb} in watts, t_{climb} in seconds and E_{climb} in watt-hours.

The forward descent segment is treated in an analogous way from the kinematic point of view. The altitude variation during descent is:

$$\Delta h_{\text{desc}} = h_{\text{cruise}} - h_{\text{VL}} \quad (4.37)$$

where h_{VL} is the altitude at which the final vertical landing segment begins. Assuming a constant rate of descent, expressed here as a positive magnitude, the descent time is:

$$t_{\text{desc}} = \frac{\Delta h_{\text{desc}}}{RoD_{\text{desc}}} \quad (4.38)$$

and the horizontal distance covered during descent is:

$$d_{\text{desc}} = V_{\text{desc}} t_{\text{desc}} \quad (4.39)$$

where V_{desc} is the forward descent speed.

For the descent power, the model follows the conservative logic adopted in the reference formulation, where detailed descent performance is not modelled through an independent aerodynamic descent law. Instead, the forward descent is treated consistently with forward-flight power requirements, without assuming energy recovery or glide benefits. This is appropriate for a multicopter eVTOL, since the aircraft remains powered and rotor-borne throughout the mission.

The descent power is therefore written as:

$$P_{\text{desc}} = \frac{WV_{\text{desc}}}{\eta_{\text{desc}}(L/D)_{\text{desc}}} \quad (4.40)$$

and the descent energy is:

$$E_{\text{desc}} = \frac{P_{\text{desc}} t_{\text{desc}}}{3600} \quad (4.41)$$

The climb and descent distances are then used to determine the remaining cruise distance:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (4.42)$$

A geometric feasibility condition is imposed to ensure that the selected mission profile is compatible with the assigned route distance:

$$d_{\text{cruise}} > 0 \quad (4.43)$$

or equivalently:

$$d_{\text{mission}} > d_{\text{climb}} + d_{\text{desc}} \quad (4.44)$$

If this condition is not satisfied, the prescribed climb and descent phases occupy the entire route length and no cruise segment remains. This check is particularly relevant for short inter-island routes, where the combination of cruise altitude, climb rate, descent rate and forward speeds can significantly affect the available cruise distance.

Table 4.4: Main quantities used for forward climb and descent modelling.

Symbol	Unit	Description
h_{cruise}	m	Cruise altitude
h_{VTO}	m	Altitude after vertical take-off
h_{VL}	m	Altitude before vertical landing
RoC_{climb}	m/s	Forward-climb rate of climb
RoD_{desc}	m/s	Forward-descent rate of descent
V_{climb}	m/s	Forward climb speed
V_{desc}	m/s	Forward descent speed
d_{climb}	m	Horizontal climb distance
d_{desc}	m	Horizontal descent distance
d_{cruise}	m	Residual cruise distance
P_{climb}	W	Required climb power
P_{desc}	W	Required descent power
E_{climb}	Wh	Forward climb energy
E_{desc}	Wh	Forward descent energy

4.5. Cruise Power Model

The cruise segment represents the main horizontal flight phase of the mission. After the aircraft has completed vertical take-off and forward climb, it flies the remaining route

distance at approximately constant altitude and nominal cruise speed. For the routes considered in this thesis, the cruise segment usually represents a significant portion of the total mission distance and can therefore have a major influence on the total energy demand.

The cruise power model adopted in this work follows the simplified formulation used in the reference air taxi performance model by Bruhl et al. [2]. In cruise, the required propulsive power is obtained from the product of thrust and flight speed, corrected by the cruise propulsive efficiency. Under steady forward-flight conditions, thrust is assumed to balance drag:

$$T_{\text{cruise}} = D_{\text{cruise}} \quad (4.45)$$

The aerodynamic drag is expressed through the aircraft weight and the equivalent lift-to-drag ratio:

$$D_{\text{cruise}} = \frac{W}{(L/D)_{\text{cruise}}} \quad (4.46)$$

where W is the aircraft weight and $(L/D)_{\text{cruise}}$ is the lift-to-drag ratio adopted for the cruise condition.

The cruise power is therefore written as:

$$P_{\text{cruise}} = \frac{T_{\text{cruise}} V_{\text{cruise}}}{\eta_{\text{cruise}}} = \frac{W V_{\text{cruise}}}{\eta_{\text{cruise}} (L/D)_{\text{cruise}}} \quad (4.47)$$

where V_{cruise} is the cruise speed and η_{cruise} is the cruise propulsive efficiency.

For winged eVTOL configurations, the lift-to-drag ratio represents the aerodynamic efficiency associated with wing-borne cruise. In the present thesis, however, the selected reference aircraft is a multicopter. Therefore, $(L/D)_{\text{cruise}}$ must be interpreted as an equivalent forward-flight efficiency parameter rather than as the aerodynamic efficiency of a conventional fixed-wing aircraft. This distinction is important because the multicopter remains primarily rotor-borne during the mission and does not benefit from an efficient wing in cruise. As a consequence, the adopted cruise efficiency is lower than that of lift-and-cruise or vectored-thrust architectures.

The cruise distance is not assumed equal to the total route distance. As described in the mission architecture, part of the horizontal distance is already covered during forward

climb and forward descent. The remaining cruise distance is computed as:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (4.48)$$

The cruise time is then obtained from:

$$t_{\text{cruise}} = \frac{d_{\text{cruise}}}{V_{\text{cruise}}} \quad (4.49)$$

and the corresponding cruise energy is:

$$E_{\text{cruise}} = \frac{P_{\text{cruise}} t_{\text{cruise}}}{3600} \quad (4.50)$$

where P_{cruise} is expressed in watts, t_{cruise} in seconds and E_{cruise} in watt-hours.

In the nominal mission analysis, the cruise speed is treated as a fixed input parameter. This allows the Milazzo–Vulcano base case and the Lipari-centred network routes to be compared under consistent operating assumptions. The effect of varying cruise speed is instead investigated separately through dedicated sensitivity analysis, since cruise speed influences both the instantaneous power demand and the time spent in the cruise segment.

In the baseline case, wind is not included and the cruise speed is assumed to coincide with the ground speed. When wind effects are considered, the distinction between airspeed and ground speed becomes relevant. In that case, the aerodynamic power depends on the airspeed, while the cruise duration depends on the ground speed along the route. This extension is introduced in the wind sensitivity analysis rather than in the nominal cruise model.

The cruise model adopted here is intentionally compact and consistent with the reference paper. It does not aim to reproduce the full aerodynamic and rotorcraft performance behaviour of a multicopter in forward flight, but provides a transparent mission-level estimate suitable for route feasibility assessment. This choice is appropriate for the objective of the thesis, where the main focus is the comparison of route energy demand, battery utilisation and feasibility margins rather than high-fidelity aerodynamic simulation.

Table 4.5: Main quantities used in the cruise power model.

Symbol	Unit	Description
W	N	Aircraft weight
V_{cruise}	m/s	Nominal cruise speed
$(L/D)_{\text{cruise}}$	–	Equivalent cruise lift-to-drag ratio
η_{cruise}	–	Cruise propulsive efficiency
d_{mission}	m	Total route distance
d_{climb}	m	Horizontal climb distance
d_{desc}	m	Horizontal descent distance
d_{cruise}	m	Remaining cruise distance
t_{cruise}	s	Cruise duration
P_{cruise}	W	Required cruise power
E_{cruise}	Wh	Cruise energy consumption

It is important to note that the simplified cruise model in Eq. (4.47) is not intended to predict an energy-optimal cruise speed by itself. Since the equivalent lift-to-drag ratio and cruise efficiency are treated as fixed parameters, the formulation provides a paper-consistent estimate of cruise power for a prescribed operating speed, but it does not reproduce the complete speed-dependent behaviour of a rotorcraft in forward flight. In particular, it cannot fully capture the trade-off between low-speed inefficiency, induced power effects and high-speed drag penalties. For this reason, the cruise speed optimisation analysis presented later in the thesis is performed using a dedicated speed-dependent model. That analysis is introduced as a sensitivity and optimisation extension, separate from the baseline mission model. The baseline model is instead used to evaluate route feasibility under fixed and consistent mission assumptions derived from the reference air taxi performance framework.

4.6. Battery Energy Model

The battery model represents the link between the aircraft energy demand and the actual feasibility of the mission. Since the selected eVTOL configuration is fully electric, all flight phases are powered by the onboard battery system. Therefore, the battery must provide both the total energy required to complete the route and the peak power required during the most demanding mission segments.

The battery modelling approach adopted in this thesis follows the simplified mission-level

treatment used by Bruhl et al. [2]. In this framework, the battery is not represented through a detailed electrochemical model, but through a set of aircraft-level parameters suitable for preliminary performance assessment. The main quantities are the battery mass, the specific energy, the specific power, the battery efficiency and the usable depth of discharge.

The nominal installed battery energy is computed as:

$$E_{\text{batt,nom}} = E^* M_{\text{batt}} \quad (4.51)$$

where E^* is the battery specific energy and M_{batt} is the installed battery mass. If E^* is expressed in Wh/kg and M_{batt} in kg, the resulting energy is obtained in Wh.

However, the full nominal battery energy cannot be used during a real mission. Part of the energy is unavailable because of electrical losses, reserve requirements and battery protection limits. Following the reference formulation, the usable battery energy is therefore expressed as:

$$E_{\text{batt,use}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (4.52)$$

where η_{batt} is the battery efficiency and DoD is the usable depth of discharge. The DoD term accounts for the fact that the battery should not be fully depleted during nominal operation. Equivalently, a final reserve state of charge is preserved to avoid operating close to the battery floor.

In the same way, the nominal battery power capability is calculated from the specific power:

$$P_{\text{batt,nom}} = P^* M_{\text{batt}} \quad (4.53)$$

where P^* is the battery specific power. The usable battery power is then defined as:

$$P_{\text{batt,max}} = P^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (4.54)$$

This expression is consistent with the simplified aircraft-level treatment used in the reference model, where battery efficiency and usable operating range are applied to both available energy and available power. In a higher-fidelity model, power capability would

depend more explicitly on state of charge, temperature, C-rate and voltage limits; however, these effects require detailed proprietary battery data and are therefore not included in the baseline formulation.

The total mission energy obtained from the segment-based model is compared with the usable battery energy. The energy margin is defined as:

$$\Delta E_{\text{margin}} = E_{\text{batt,use}} - E_{\text{mission}} \quad (4.55)$$

where E_{mission} is the total energy required by the complete mission. A positive value of ΔE_{margin} indicates that the mission can be completed within the available usable battery energy, while a negative value indicates an energy-infeasible mission.

Similarly, the power margin is defined as:

$$\Delta P_{\text{margin}} = P_{\text{batt,max}} - P_{\text{max}} \quad (4.56)$$

where P_{max} is the maximum power required among all mission segments. This quantity is important because an eVTOL mission may be energetically feasible but still infeasible from a power-delivery perspective if the battery cannot provide the required peak power.

The final usable state of charge is computed from the remaining usable battery energy at the end of the mission:

$$SOC_{\text{final,use}} = 100 \left(\frac{E_{\text{batt,use}} - E_{\text{mission}}}{E_{\text{batt,use}}} \right) \quad (4.57)$$

This value represents the remaining fraction of the usable energy window. In the implemented model, it is used as an immediate indicator of the residual mission margin. If $SOC_{\text{final,use}}$ becomes negative, the mission requires more energy than the usable battery capacity and is therefore not feasible.

A physical state of charge can also be defined with respect to the total available physical battery energy after efficiency losses but before applying the usable depth-of-discharge constraint:

$$E_{\text{batt,phys}} = E^* M_{\text{batt}} \eta_{\text{batt}} \quad (4.58)$$

and:

$$SOC_{\text{final,phys}} = 100 \left(\frac{E_{\text{batt,phys}} - E_{\text{mission}}}{E_{\text{batt,phys}}} \right) \quad (4.59)$$

The distinction between usable and physical state of charge is useful because the usable SOC describes the mission margin within the allowed operating window, whereas the physical SOC provides an indication of the remaining energy with respect to the total effective battery capacity.

The feasibility logic adopted in the model is therefore based on two main conditions:

$$E_{\text{mission}} \leq E_{\text{batt,use}} \quad (4.60)$$

$$P_{\text{max}} \leq P_{\text{batt,max}} \quad (4.61)$$

Both conditions must be satisfied for the mission to be considered feasible. The first condition checks the total energy balance, while the second verifies that the battery and propulsion system can sustain the highest power demand occurring during the mission.

The baseline battery model is intentionally simple and transparent. It is suitable for mission-level feasibility assessment because it captures the main sizing variables affecting eVTOL performance: battery mass, specific energy, specific power, efficiency and reserve fraction. More detailed effects, such as temperature-dependent capacity reduction, internal resistance variation, ageing and degradation, are treated as model extensions and sensitivity analyses rather than as part of the nominal battery formulation.

Table 4.6: Main quantities used in the battery energy model.

Symbol	Unit	Description
M_{batt}	kg	Installed battery mass
E^*	Wh/kg	Battery specific energy
P^*	W/kg	Battery specific power
η_{batt}	–	Battery efficiency factor
DoD	–	Usable depth of discharge
$E_{\text{batt,nom}}$	Wh	Nominal installed battery energy
$E_{\text{batt,use}}$	Wh	Usable battery energy
$P_{\text{batt,max}}$	W	Maximum usable battery power
E_{mission}	Wh	Total mission energy demand
P_{max}	W	Maximum mission power demand
ΔE_{margin}	Wh	Energy margin after mission
ΔP_{margin}	W	Power margin at peak demand
$SOC_{\text{final,use}}$	%	Final usable SOC
$SOC_{\text{final,phys}}$	%	Final physical SOC

4.7. Temperature Effects on Battery Performance

Battery performance is strongly influenced by operating temperature. For an eVTOL aircraft, this effect is relevant because the battery system determines both the available energy for completing the mission and the available power for the most demanding flight phases. In the baseline model presented in the previous sections, the battery is represented through nominal values of specific energy, specific power, efficiency and usable depth of discharge. However, these values are generally referred to standard or near-optimal temperature conditions and may not remain constant when the aircraft operates in colder or hotter environments.

The reference air taxi performance model adopted as the basis for this thesis does not explicitly include temperature effects in the battery model. In fact, Bruhl et al. state that the influence of temperature on range is not considered in their application, although they recognise that temperature should affect battery behaviour and therefore the achievable range [2]. For this reason, the present work introduces a temperature-dependent extension of the battery model, while keeping the main mission-energy formulation consistent with the reference paper.

The aim of this extension is not to develop a detailed electrochemical battery model, but to include the dominant temperature effect at mission level. In particular, the model corrects the available battery capacity and, optionally, the available battery power as functions of ambient temperature. This approach is suitable for preliminary eVTOL feasibility studies because it preserves the simplicity of the mission-based model while accounting for a physically meaningful battery limitation.

4.7.1. Capacity Correction Factor

The primary temperature effect considered in this thesis is the variation of available battery capacity with temperature. Experimental and modelling studies show that the discharge capacity of lithium-ion batteries generally decreases at low temperature and may increase slightly around moderate warm conditions, before high-temperature operation becomes critical mainly from an ageing and safety perspective.

Johnson et al. at NREL tested high-power lithium-ion cells and observed that capacity varies with temperature: at 0°C the measured capacity was approximately 15% lower than the ambient value, while at 40°C it increased by approximately 6% with respect to ambient conditions [22]. The same study also reports that open-circuit voltage does not vary strongly between ambient and 40°C, whereas low-temperature behaviour differs because of the reduction in available capacity [22].

A further NREL study on field-aged lithium-ion battery systems expresses the temperature dependence of battery capacity through an empirical relation implemented in battery performance and lifetime models [3]. The capacity at temperature T can be represented as:

$$Q_0(T) = Q_{0,r} \exp \left[-\frac{E_1}{k_B} \left(\frac{1}{T} - \frac{1}{T_0} \right) - \left(\frac{E_2}{k_B} \right)^2 \left(\frac{1}{T} - \frac{1}{T_0} \right)^2 \right] \quad (4.62)$$

where $Q_0(T)$ is the temperature-dependent capacity, $Q_{0,r}$ is the reference capacity, T is the battery temperature in kelvin, T_0 is the reference temperature, k_B is the Boltzmann constant, and E_1 , E_2 are empirical coefficients. This expression is used here as the mathematical basis for defining a normalised capacity correction factor.

The capacity correction factor is defined as:

$$k_Q(T) = \frac{Q_0(T)}{Q_0(T_{\text{ref}})} \quad (4.63)$$

where T_{ref} is the reference temperature adopted for the nominal battery model. In this thesis, the reference temperature is taken as:

$$T_{\text{ref}} = 25^{\circ}\text{C} \quad (4.64)$$

which is a standard reference value for battery characterisation and performance comparison.

The usable battery energy corrected for temperature is then written as:

$$E_{\text{batt,use}}(T) = E_{\text{batt,use,ref}} k_Q(T) \quad (4.65)$$

where $E_{\text{batt,use,ref}}$ is the usable battery energy at the reference temperature. Since:

$$E_{\text{batt,use,ref}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (4.66)$$

the complete temperature-corrected expression becomes:

$$E_{\text{batt,use}}(T) = E^* M_{\text{batt}} \eta_{\text{batt}} DoD k_Q(T) \quad (4.67)$$

This formulation means that the mission energy demand is compared against the actual usable battery energy available at the considered temperature, rather than against the nominal value at reference conditions.

4.7.2. Power Correction Factor

In addition to capacity reduction, temperature also affects the internal resistance of lithium-ion batteries. This is important for eVTOL applications because the battery must deliver high power during vertical take-off, hover, climb and landing. Higher internal resistance produces larger voltage drops and reduces the practical power capability of the battery system.

Johnson et al. report that the internal resistance variation between 25°C and 40°C is relatively small, while the resistance at 0°C increases by approximately three times compared with ambient values [22]. This behaviour justifies the introduction of a low-temperature power derating factor.

A simple temperature-dependent resistance ratio can be defined as:

$$k_R(T) = \frac{R_{\text{int}}(T)}{R_{\text{int}}(T_{\text{ref}})} \quad (4.68)$$

where $R_{\text{int}}(T)$ is the internal resistance at temperature T . Since the available power decreases as internal resistance increases, a corresponding power correction factor is introduced as:

$$k_P(T) = \frac{1}{k_R(T)} \quad (4.69)$$

The temperature-corrected available battery power is then:

$$P_{\text{batt,max}}(T) = P_{\text{batt,max,ref}} k_P(T) \quad (4.70)$$

where $P_{\text{batt,max,ref}}$ is the usable battery power at the reference temperature.

In the MATLAB implementation, the capacity correction is treated as the primary temperature effect, while the power derating can be activated as an optional conservative correction. This distinction is useful because the available literature provides clearer quantitative trends for capacity variation than for complete aircraft-level power limitation. The power derating is therefore interpreted as a conservative sensitivity extension rather than as a full battery management system model.

4.7.3. Temperature-Corrected Feasibility Assessment

The temperature correction is applied on the battery side of the mission model. The flight mechanics and segment power equations remain unchanged in the battery-only temperature sweep. Therefore, for a fixed mission profile, the total mission energy remains:

$$E_{\text{mission}} = \sum_{i=1}^N E_i \quad (4.71)$$

while the available usable battery energy becomes temperature-dependent:

$$E_{\text{batt,use}} = E_{\text{batt,use}}(T) \quad (4.72)$$

The temperature-dependent energy margin is therefore:

$$\Delta E_{\text{margin}}(T) = E_{\text{batt,use}}(T) - E_{\text{mission}} \quad (4.73)$$

and the corresponding temperature-dependent power margin is:

$$\Delta P_{\text{margin}}(T) = P_{\text{batt,max}}(T) - P_{\text{max}} \quad (4.74)$$

The final usable state of charge at temperature T is computed as:

$$SOC_{\text{final,use}}(T) = 100 \left(\frac{E_{\text{batt,use}}(T) - E_{\text{mission}}}{E_{\text{batt,use}}(T)} \right) \quad (4.75)$$

A mission is considered energy-feasible at a given temperature if:

$$\Delta E_{\text{margin}}(T) \geq 0 \quad (4.76)$$

and power-feasible if:

$$\Delta P_{\text{margin}}(T) \geq 0 \quad (4.77)$$

The complete temperature-dependent feasibility condition is therefore:

$$\text{Feasible}(T) = [\Delta E_{\text{margin}}(T) \geq 0] \cap [\Delta P_{\text{margin}}(T) \geq 0] \quad (4.78)$$

This formulation allows the model to identify the temperature range in which a given route remains feasible.

4.7.4. Modelling Assumptions

The temperature-dependent battery model adopted in this thesis is based on the following assumptions:

- the battery temperature is assumed equal to the ambient temperature;
- no transient thermal model of the battery pack is included;
- the main temperature effect is represented through the capacity correction factor $k_Q(T)$;

- low-temperature power reduction may be included through the optional factor $k_P(T)$;
- the mission energy demand is not modified in the battery-only temperature sweep;
- battery ageing and degradation are not included in the nominal mission simulation;
- high-temperature operation is treated in terms of available capacity, while long-term ageing and safety effects are discussed qualitatively.

The first assumption is a simplification. In a real aircraft, battery temperature would depend on ambient conditions, heat generation, thermal mass, cooling system operation and mission duration. Horton et al. show that more detailed battery models for electric aircraft may include voltage, resistance, capacitance, state of charge and temperature-dependent parameters, but such models require extensive cell-level testing and detailed battery data [20]. Since these proprietary data are not publicly available for the selected reference aircraft, a mission-level correction model is considered more appropriate for the present thesis. The exclusion of ageing from the nominal temperature sweep is also intentional. High temperatures may improve short-term measured capacity but can accelerate long-term degradation. Deline et al. distinguish between instantaneous performance effects, such as temperature-dependent capacity, and lifetime mechanisms such as calendar ageing and cycling loss, both of which depend on temperature and state of charge [3]. In this work, the focus is on single-mission feasibility, while ageing effects are left for future model development. Since detailed temperature-dependent battery data for the Volocopter battery pack are not publicly available, a surrogate-cell approach is adopted. The empirical coefficients used to implement the temperature-dependent capacity correction are based on publicly available data for the Molicel INR-21700-P42A lithium-ion cell. This cell is a cylindrical 21700 high-power Li-ion cell, with a nominal voltage of 3.6 V, a typical capacity of 4.2 Ah and a maximum continuous discharge current of 45 A. It is selected as a representative surrogate because it belongs to a high-power lithium-ion cell class suitable for demanding electric mobility applications, including drones and eVTOL-oriented systems. The Molicel INR-21700-P42A is not assumed to be the exact cell installed in the Volocopter battery pack. Rather, it is used as a surrogate cell to provide realistic temperature-dependent capacity behaviour in the absence of proprietary aircraft battery data. Therefore, the resulting temperature correction should be interpreted as a literature- and datasheet-based approximation for a high-power Li-ion battery system, not as a manufacturer-specific model of the VoloCity battery pack.

4.7.5. Interpretation for the eVTOL Mission

The practical consequence of the temperature correction is that the same route can have different feasibility outcomes depending on ambient temperature. At low temperature, the available battery capacity decreases and internal resistance increases; therefore, the energy margin, power margin and final state of charge are reduced. Around reference conditions, the battery operates close to its nominal performance. At moderately higher temperatures, the available capacity may increase slightly, but this should not be interpreted as unlimited improvement, because thermal management, safety limits and ageing effects become increasingly important. For the Aeolian Islands case study, this modelling choice is relevant because the aircraft may operate in different seasonal conditions. A route that is feasible under nominal conditions may become critical in colder conditions if the available battery energy decreases. Conversely, warmer conditions may slightly improve short-term capacity, but the model does not assume that high temperatures are automatically beneficial from an operational or lifetime perspective. The temperature-dependent battery model therefore provides a more realistic feasibility assessment than the nominal battery model alone. It allows the mission analysis to quantify how environmental conditions affect the usable energy reserve and to identify operating conditions where additional safety margins, reduced payload, shorter routes or charging strategies may be required.

Table 4.7: Main quantities used in the temperature-dependent battery model.

Symbol	Unit	Description
T	K	Battery or ambient temperature
T_{ref}	K	Reference temperature
$Q_0(T)$	Ah	Temperature-dependent capacity
$k_Q(T)$	–	Capacity correction factor
$R_{\text{int}}(T)$	Ω	Internal resistance at temperature T
$k_R(T)$	–	Internal resistance ratio
$k_P(T)$	–	Power correction factor
$E_{\text{batt,use}}(T)$	Wh	Corrected usable battery energy
$P_{\text{batt,max}}(T)$	W	Corrected available battery power
$\Delta E_{\text{margin}}(T)$	Wh	Temperature-dependent energy margin
$\Delta P_{\text{margin}}(T)$	W	Temperature-dependent power margin
$SOC_{\text{final,use}}(T)$	%	Final usable SOC at temperature T

4.8. Derived Parameters

Before the mission segments are evaluated, a set of derived parameters is computed from the aircraft, battery and environmental inputs. These quantities provide the physical basis for the subsequent calculation of power, energy consumption, state of charge evolution and feasibility margins. The purpose of this step is to ensure that all segment models are based on consistent aircraft-level parameters.

The first derived quantity is the aircraft take-off mass. In the present model, the take-off mass is obtained as the sum of empty mass, battery mass and useful payload:

$$m_{\text{TO}} = m_{\text{empty}} + M_{\text{batt}} + m_{\text{payload}} \quad (4.79)$$

where m_{empty} is the empty mass of the aircraft, M_{batt} is the installed battery mass and m_{payload} is the useful mission payload. The corresponding aircraft weight is:

$$W = m_{\text{TO}}g \quad (4.80)$$

where g is the gravitational acceleration.

For the multicopter architecture, the total rotor disk area is computed from the number of rotors and the radius of each rotor:

$$A_R = n_{\text{rotor}}\pi R_{\text{rotor}}^2 \quad (4.81)$$

where n_{rotor} is the number of rotors and R_{rotor} is the rotor radius. The corresponding disk loading is then:

$$DL = \frac{W}{A_R} \quad (4.82)$$

Disk loading is one of the most important derived parameters for a multicopter because it directly influences the induced velocity and the hover power requirement. A lower disk loading generally corresponds to lower induced power in hover, while a higher disk loading increases the power required for vertical flight.

The induced velocity in hover is calculated as:

$$v_h = \sqrt{\frac{W}{2\rho A_R}} \quad (4.83)$$

where ρ is the air density. This value is used in the hover, vertical take-off and vertical landing formulations.

The hover power is then computed as:

$$P_{\text{hover}} = \frac{W}{\eta_{\text{hover}}} \sqrt{\frac{DL}{2\rho}} \quad (4.84)$$

where η_{hover} is the hover efficiency. This quantity is stored as a reference power level for the vertical phases of the mission.

The battery-related derived parameters are calculated from the installed battery mass, specific energy, specific power, battery efficiency and usable depth of discharge. The usable battery energy is:

$$E_{\text{batt,use}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (4.85)$$

where E^* is the battery specific energy, η_{batt} is the battery efficiency and DoD is the usable depth of discharge. Similarly, the maximum usable battery power is:

$$P_{\text{batt,max}} = P^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (4.86)$$

where P^* is the battery specific power. These two quantities are later used to evaluate energy and power feasibility.

In addition to aircraft and battery parameters, the model also derives the geometric quantities associated with the flight profile. The forward climb time is:

$$t_{\text{climb}} = \frac{h_{\text{cruise}} - h_{\text{VTO}}}{RoC_{\text{climb}}} \quad (4.87)$$

and the corresponding horizontal distance covered during climb is:

$$d_{\text{climb}} = V_{\text{climb}} t_{\text{climb}} \quad (4.88)$$

The forward descent time is:

$$t_{\text{desc}} = \frac{h_{\text{cruise}} - h_{\text{VL}}}{RoD_{\text{desc}}} \quad (4.89)$$

where RoD_{desc} is treated as a positive magnitude. The corresponding horizontal descent distance is:

$$d_{\text{desc}} = V_{\text{desc}} t_{\text{desc}} \quad (4.90)$$

The remaining cruise distance is then obtained as:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (4.91)$$

A geometric feasibility check is applied before the energy calculation:

$$d_{\text{cruise}} > 0 \quad (4.92)$$

If this condition is not satisfied, the selected mission profile is not compatible with the assigned route distance, because the climb and descent segments would require more horizontal distance than the available mission length.

The derived-parameter block therefore acts as an intermediate layer between the input data and the mission simulation. It ensures that the quantities used in the segment models are internally consistent and that infeasible mission geometries are detected before the energy balance is evaluated.

Table 4.8: Main derived parameters computed before mission simulation.

Parameter	Unit	Description
m_{TO}	kg	Aircraft take-off mass
W	N	Aircraft weight
A_R	m^2	Total rotor disc area
DL	N/m^2	Rotor disc loading
v_h	m/s	Hover induced velocity
P_{hover}	W	Reference hover power
$E_{batt,use}$	Wh	Usable battery energy
$P_{batt,max}$	W	Maximum usable battery power
t_{climb}	s	Forward climb duration
d_{climb}	m	Horizontal climb distance
t_{desc}	s	Forward descent duration
d_{desc}	m	Horizontal descent distance
d_{cruise}	m	Residual cruise distance

The derived parameters are recalculated for every mission case and for every sensitivity analysis. This is particularly important when payload, battery mass, rotor number, temperature or route distance are varied, because each of these inputs modifies one or more derived quantities and therefore affects the final energy and feasibility assessment.

4.9. MATLAB Implementation Structure

The energy model described in the previous sections is implemented in MATLAB through a modular structure. The objective of the numerical implementation is to translate the segment-based analytical formulation into a flexible simulation framework capable of evaluating different routes, payload values, environmental conditions and aircraft assumptions. A modular approach is adopted in order to keep the model transparent, easy to verify and suitable for sensitivity analyses.

The MATLAB implementation is organised around three main levels:

- **input definition**, where aircraft, battery, mission and environmental parameters are assigned;
- **mission simulation**, where derived parameters and segment energy contributions are computed;

- **post-processing**, where mission summaries, feasibility indicators, battery profiles and plots are generated.

This structure allows the same energy model to be applied both to the Milazzo–Vulcano base case and to the Lipari-centred hub-and-spoke routes. Only the route distance, payload or selected operating conditions need to be modified, while the underlying mission architecture remains unchanged.

4.9.1. Input Definition

The input file contains all the parameters required by the mission model. These include aircraft mass properties, rotor configuration, battery parameters, mission geometry, flight speeds, climb and descent rates, efficiency factors and environmental assumptions. In the MATLAB implementation, these quantities are stored in a parameter structure, here denoted as **p**. This structure is passed through the different functions of the model, ensuring that all segments use consistent input data.

The main groups of input parameters are:

- **aircraft parameters**: empty mass, payload mass, battery mass, number of rotors and rotor radius;
- **battery parameters**: specific energy, specific power, battery efficiency and usable depth of discharge;
- **mission parameters**: route distance, cruise altitude, take-off and landing heights, segment durations and flight speeds;
- **environmental parameters**: air density, temperature and wind assumptions;
- **model settings**: cruise model, descent model and mission mode.

For the Aeolian Islands case study, a dedicated input file is used to define the reference aircraft and baseline mission assumptions. This file acts as the starting point for all subsequent simulations and sensitivity analyses.

4.9.2. Derived Parameter Calculation

After the input structure is created, the model computes the derived parameters required by the segment equations. This step corresponds to the theoretical quantities introduced in Section 4.8, such as take-off mass, aircraft weight, rotor disk area, disk loading, hover induced velocity, hover power, usable battery energy and usable battery power.

In the MATLAB workflow, this operation is performed before the segment simulation so that all flight phases receive a complete and consistent set of parameters. The derived-parameter function also evaluates the mission geometry, including climb distance, descent distance and residual cruise distance. If the selected route distance is not sufficient to include climb, cruise and descent, the mission is flagged as geometrically infeasible before the energy balance is evaluated.

4.9.3. Segment Functions

The mission simulation is performed by evaluating each flight segment independently. Each segment function receives the parameter structure and returns the main quantities associated with that phase: duration, distance, power and energy. The segment outputs are then collected into a mission segment list.

The segment-based implementation follows the same physical structure introduced in the analytical model:

- taxi and hover segments are evaluated through prescribed duration and reference power assumptions;
- vertical take-off is computed from the hover power and vertical rate of climb;
- forward climb is computed from climb speed, rate of climb and equivalent aerodynamic efficiency;
- cruise is computed from residual cruise distance, cruise speed and cruise power;
- forward descent is treated consistently with the paper-based forward-flight approach;
- vertical landing is computed using the descent formulation introduced in the vertical flight model.

The multicopter architecture does not include a transition segment, since no conversion between vertical and wing-borne flight is performed. This is consistent with the reference paper and with the physical behaviour of the selected aircraft configuration.

4.9.4. Mission Assembly and Summary

Once all segment contributions have been computed, the mission solver assembles them into a complete mission profile. The total mission time is obtained by summing all segment durations:

$$t_{\text{mission}} = \sum_{i=1}^N t_i \quad (4.93)$$

The total mission energy is obtained as:

$$E_{\text{mission}} = \sum_{i=1}^N E_i \quad (4.94)$$

and the maximum mission power is computed as:

$$P_{\text{max}} = \max(P_i) \quad (4.95)$$

These quantities are stored in a summary structure together with the final state of charge, energy margin, power margin and feasibility flags. The main feasibility indicators are:

- **geometry feasibility**, based on the availability of a positive cruise distance;
- **energy feasibility**, based on the comparison between mission energy and usable battery energy;
- **power feasibility**, based on the comparison between peak mission power and available battery power;
- **mission feasibility**, obtained when all previous feasibility checks are satisfied.

4.9.5. Battery Profile and Post-Processing

The battery state-of-charge profile is reconstructed after the mission segments are computed. Starting from a fully available usable battery window, the energy consumed in each segment is progressively subtracted from the available energy. This allows the evolution of state of charge over mission time to be plotted and inspected.

The post-processing routines are used to generate:

- mission energy breakdowns by segment;
- power profiles by segment;
- cumulative energy consumption;
- state-of-charge profiles;

- route feasibility summaries;
- sensitivity-analysis plots.

This separation between simulation and post-processing improves the readability of the code and allows the same mission solver to be reused for different analyses.

4.9.6. Sensitivity Analysis Workflow

One of the main advantages of the MATLAB implementation is the possibility of performing parametric studies. In each sensitivity script, one or more input parameters are varied while the mission solver remains unchanged. For each case, the model recomputes the derived parameters, runs the complete mission and stores the resulting performance indicators.

The sensitivity analyses developed in this thesis include variations of:

- cruise speed;
- payload mass;
- mission distance;
- rotor number;
- ambient temperature;
- wind condition;
- climb and descent parameters.

This workflow makes it possible to identify the parameters that most strongly affect energy consumption, peak power, final state of charge and feasibility margins.

4.9.7. Implementation Logic

The overall MATLAB workflow can be summarised as follows:

1. define aircraft, battery, mission and environmental inputs;
2. compute derived aircraft and battery parameters;
3. check mission geometry and cruise distance;
4. evaluate each mission segment independently;
5. assemble segment outputs into the full mission profile;

6. compute total energy, maximum power and mission duration;
7. evaluate battery state of charge and feasibility margins;
8. generate summary tables, plots and sensitivity outputs.

A simplified representation of the implementation structure is given in Table 4.9.

Table 4.9: Main MATLAB implementation blocks of the mission energy model.

Block	Purpose	Typical outputs
Input definition	Defines aircraft, battery, mission and environmental inputs	Parameter structure p
Derived parameters	Computes mass, weight, disc loading, hover power and battery limits	Updated parameter structure
Mission geometry	Computes climb, descent and residual cruise distance	Geometric feasibility flag
Segment models	Evaluates power, time and energy for each segment	Segment list
Mission assembly	Sums segment energy and identifies peak power	Mission summary
Battery profile	Computes cumulative energy and SOC evolution	SOC history
Post-processing	Produces plots, tables and feasibility maps	Figures and result structures
Sensitivity scripts	Repeats the mission over parameter sweeps	Parametric trends

Overall, the MATLAB implementation provides a transparent and reproducible numerical framework for applying the analytical model to the Aeolian Islands case study. Its modular structure allows the baseline mission, route network and sensitivity analyses to be evaluated using the same underlying equations and assumptions.

5 | Model Validation

5.1. Reference Literature Model

The validation of the proposed mission-based energy model is performed with respect to the reference framework presented by Bruhl et al. in *Air Taxi Flight Performance Modeling and Application*. This paper was selected because it provides a complete and transparent methodology for estimating the power demand, energy consumption and range capability of different eVTOL aircraft architectures using a segment-based mission approach.

The reference study addresses the problem of estimating realistic eVTOL flight performance by considering the limitations of current battery technology. The authors point out that publicly available performance data are often based on manufacturer declarations and may be optimistic when compared with the actual state of battery energy density and power capability. For this reason, they propose an independent analytical framework in which the mission is divided into individual flight segments and the required power is computed separately for each segment.

The model considers three representative eVTOL configurations:

- a vectored-thrust eVTOL;
- a lift-and-cruise eVTOL;
- a multicopter eVTOL.

This distinction is important because each architecture produces lift in a different way during the mission. Vectored-thrust and lift-and-cruise aircraft are assumed to behave as fixed-wing aircraft during cruise, while the multicopter remains rotor-borne and therefore has lower forward-flight efficiency. Since the present thesis focuses on a multicopter configuration, the multicopter case of the reference paper is used as the main validation benchmark.

The general mission profile adopted in the reference model includes taxi, vertical take-off,

transition, climb, cruise and descent, second transition, vertical landing and final taxi. However, the transition segments are only applied to vectored-thrust and lift-and-cruise aircraft. For the multicopter configuration, no transition is included because the aircraft does not perform a conversion between vertical and horizontal flight configurations. This assumption is directly relevant to the present work, where the selected aircraft remains rotor-borne throughout the mission.

In the reference paper, the energy consumption of each segment is calculated from the corresponding segment power and duration:

$$E_i = P_i t_i \quad (5.1)$$

and the total mission energy is obtained by summing all segment contributions:

$$E_{\text{tot}} = \sum_{i=1}^N E_i \quad (5.2)$$

This formulation is the same fundamental structure adopted in the MATLAB model developed in this thesis. The validation procedure therefore focuses on verifying that the implemented model can reproduce the reference multicopter mission behaviour under equivalent input assumptions. For the multicopter case, the reference paper adopts a Volocopter-like aircraft with a maximum take-off mass of 900 kg, a payload of 200 kg and a battery mass of 300 kg. The battery is characterised by a specific energy of 180 Wh/kg, a specific power of 1100 W/kg, a battery efficiency of 0.95 and a usable depth of discharge of 0.8. These assumptions lead to a usable battery energy of approximately 41 kWh and a usable battery power of approximately 251 kW. The main aerodynamic and propulsion parameters adopted for the multicopter in the reference model include a hover efficiency of 0.80, a cruise efficiency of 0.60, a climb efficiency of 0.70, a cruise lift-to-drag ratio of 4 and a climb lift-to-drag ratio of 3. The multicopter is modelled with 18 rotors and a rotor diameter of 2.3 m, resulting in a total rotor disk area of approximately 74.8 m². The reference mission duration is assumed to be 1800 s. For the multicopter, the transition times used for other configurations are redistributed into the climb and cruise/descent portions of the mission, since the multicopter does not perform explicit transition segments. The resulting mission energy for the multicopter is reported as approximately 45.41 kWh. This value is higher than the usable battery energy adopted in the reference paper, indicating that the mission is not feasible with the assumed usable battery capacity. However, the mission energy remains below the total installed battery energy, showing the importance

of depth of discharge and reserve assumptions in feasibility assessment. The same study estimates a theoretical range of approximately 52 km for the multicopter configuration, compared with approximately 73 km for the lift-and-cruise configuration and 115 km for the vectored-thrust configuration. These results confirm the expected architectural trend: multicopters are mechanically simple and effective in vertical flight, but are more limited in cruise efficiency and range than winged eVTOL configurations. The purpose of using this reference model is not to reproduce a certified Volocopter aircraft in every detail, but to verify the consistency of the implemented mission-energy framework. Since the reference paper provides aircraft parameters, segment definitions, battery assumptions, segment powers and segment energies, it represents a suitable benchmark for checking the correctness of the MATLAB implementation before applying the model to the Aeolian Islands case study.

5.2. Validation Assumptions

The validation process is performed by reproducing, as closely as possible, the multicopter case presented in the reference literature model. Since the objective of the validation is to verify the correctness of the MATLAB implementation, the input parameters, mission duration, aircraft mass properties, battery assumptions and modelling simplifications are aligned with the data reported by Bruhl et al. [2]. The validation is not intended to demonstrate that the reference aircraft can perform the Aeolian Islands missions. Instead, it is used as an intermediate verification step: before applying the model to the Milazzo–Vulcano base case and to the Lipari-centred network, the implemented equations must be able to reproduce the behaviour of a known literature case under equivalent assumptions. For this reason, the validation case is separated from the final case-study simulations. In the validation setup, the mission parameters are taken from the reference paper, whereas the Aeolian routes, temperature corrections, wind effects and network-specific assumptions are not included. This ensures that any difference between the MATLAB output and the reference results is mainly due to implementation choices rather than to different mission definitions.

The main assumptions adopted for the validation are summarised as follows:

- the aircraft is modelled as a multicopter configuration;
- the maximum take-off mass, payload mass and battery mass are set equal to the values reported in the reference paper;
- the same battery specific energy, specific power, efficiency and usable depth of dis-

charge are adopted;

- the same rotor number, rotor diameter and total rotor disk area are used;
- the same hover, climb and cruise efficiency factors are applied;
- the same equivalent lift-to-drag ratios for climb and cruise are adopted;
- the total mission duration is set to 1800 s, consistently with the reference mission;
- no transition segment is included, because the reference multicopter does not perform conversion between vertical and horizontal flight;
- temperature effects, wind effects and battery ageing corrections are disabled during validation.

The exclusion of the transition segment is particularly important. In the reference paper, transition phases are included only for vectored-thrust and lift-and-cruise eVTOL configurations. The multicopter is assumed to pass directly from vertical take-off to climb and from forward flight to landing without any explicit conversion segment. The MATLAB validation case follows the same assumption in order to remain physically consistent with the multicopter architecture.

The battery model is also kept consistent with the reference formulation. The usable battery energy is calculated as:

$$E_{\text{batt,use}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (5.3)$$

and the usable battery power as:

$$P_{\text{batt,use}} = P^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (5.4)$$

where E^* is the specific energy, P^* is the specific power, M_{batt} is the battery mass, η_{batt} is the battery efficiency and DoD is the usable depth of discharge. This treatment allows the validation to reproduce the energy and power limits used in the reference study.

During validation, the segment energy is computed using the same general relation adopted in the paper:

$$E_i = \frac{P_i t_i}{3600} \quad (5.5)$$

where P_i is the segment power in watts, t_i is the segment duration in seconds and E_i is the segment energy in watt-hours. The total mission energy is then obtained by summing all segment contributions:

$$E_{\text{mission}} = \sum_{i=1}^N E_i \quad (5.6)$$

A further assumption concerns the treatment of the cruise and descent phases. The reference paper groups cruise and descent in a simplified forward-flight formulation because detailed descent data are not available. In the validation case, this simplification is preserved so that the MATLAB model remains comparable with the published results. The more detailed mission geometry used for the Aeolian Islands case study is therefore introduced only after the validation step.

The validation is assessed by comparing the MATLAB outputs with the reference values reported in the literature model. The main quantities considered are:

- required power per segment;
- energy consumption per segment;
- total mission energy;
- usable battery energy;
- energy feasibility with respect to usable battery capacity;
- estimated multicopter range.

The validation is considered satisfactory if the implemented model reproduces the same order of magnitude and the same energetic trends reported in the reference paper. Small differences may arise from rounding, unit conversions, implementation details or slightly different treatment of segment timing. However, the model must preserve the fundamental conclusions of the reference case: the multicopter has relatively low hover power compared with the other eVTOL architectures, but its cruise efficiency is limited and the reference mission exceeds the usable battery energy.

Table 5.1: Main assumptions adopted for the validation case.

Assumption	Description
Reference configuration	Multicopter eVTOL case from the reference literature model
Mission duration	1800 s, consistent with the reference paper
Aircraft mass properties	Set equal to the reference multicopter values
Battery model	Specific energy, power, efficiency and DoD from the reference model
Rotor system	18 rotors with reference rotor diameter and disc area
Transition segment	Not included for the multicopter architecture
Cruise/descent treatment	Consistent with the simplified reference formulation
Temperature effects	Disabled during validation
Wind effects	Disabled during validation
Battery ageing	Not included in the validation case
Validation outputs	Segment power, energy and feasibility indicators

Overall, the validation assumptions are selected to isolate the implementation of the analytical model from the later case-study extensions. Once the MATLAB model is shown to reproduce the reference multicopter behaviour, it can be applied with greater confidence to the Aeolian Islands mission scenarios.

5.3. Comparison Metrics

The validation of the MATLAB implementation is based on a set of comparison metrics selected to verify both local and global consistency with the reference literature model. Since the model is segment-based, the comparison is not limited to the total mission energy, but also includes the power and energy contributions of the individual mission phases.

The first group of metrics concerns the required power per segment. Segment power is important because it allows the physical behaviour of each flight phase to be checked independently. For example, hover and vertical take-off power are mainly influenced by aircraft weight, rotor disk loading and hover efficiency, while climb and cruise power depend also on forward speed, climb rate, propulsive efficiency and equivalent lift-to-drag ratio. A correct implementation should therefore reproduce the same order of magnitude and relative distribution of segment powers reported in the reference paper.

The second group of metrics concerns the energy consumption per segment. Since segment energy is calculated as the product of segment power and duration, this metric verifies not only the correctness of the power equations, but also the consistency of the assumed segment times. For each segment, the energy contribution is computed as:

$$E_i = \frac{P_i t_i}{3600} \quad (5.7)$$

where P_i is the required power in watts, t_i is the segment duration in seconds and E_i is the corresponding energy in watt-hours.

The total mission energy is then used as a global validation metric:

$$E_{\text{mission}} = \sum_{i=1}^N E_i \quad (5.8)$$

This quantity is compared with the total multicopter mission energy reported in the reference study. Since the total energy is obtained by summing all segment contributions, it provides an overall check of the complete mission implementation.

In addition to energy consumption, the battery feasibility indicators are also compared. The usable battery energy is calculated as:

$$E_{\text{batt,use}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (5.9)$$

where E^* is the battery specific energy, M_{batt} is the battery mass, η_{batt} is the battery efficiency and DoD is the usable depth of discharge. The comparison between E_{mission} and $E_{\text{batt,use}}$ determines whether the mission is feasible from an energy point of view.

The energy margin is defined as:

$$\Delta E_{\text{margin}} = E_{\text{batt,use}} - E_{\text{mission}} \quad (5.10)$$

A positive value indicates that the mission can be completed within the usable battery capacity, while a negative value indicates that the required mission energy exceeds the usable battery energy.

The relative error between the MATLAB result and the reference value is used to quantify the agreement for numerical quantities:

$$\varepsilon_x = \frac{|x_{\text{MATLAB}} - x_{\text{ref}}|}{x_{\text{ref}}} \cdot 100 \quad (5.11)$$

where x_{MATLAB} is the value obtained from the implemented model and x_{ref} is the corresponding value reported in the reference paper. This metric can be applied to segment powers, segment energies, total mission energy and battery-related quantities.

However, validation is not based only on exact numerical matching. Since the reference model includes assumptions, rounded parameters and simplified segment durations, small discrepancies are expected. Therefore, the validation also considers qualitative consistency, namely:

- the same order of magnitude of segment powers;
- the same dominant energy-consuming phases;
- the same total mission energy trend;
- the same conclusion regarding energy feasibility;
- the same physical interpretation of the multicopter limitations.

For the multicopter case, the most important validation outcome is the ability of the model to reproduce the reference conclusion that the mission energy is slightly higher than the usable battery energy. This means that the aircraft may be close to feasibility when considering total installed energy, but not feasible when battery efficiency and usable depth of discharge are included. Reproducing this result is essential because it confirms that the implemented model correctly captures the role of battery reserves in eVTOL mission assessment.

The comparison metrics adopted for the validation are summarised in Table 5.2.

Table 5.2: Comparison metrics used for model validation.

Metric	Purpose	Validation role
Segment power	Power required in each mission phase	Checks the physical power models
Segment energy	Energy consumed by each segment	Checks power-time consistency
Total mission energy	Sum of all segment energy contributions	Main global energy comparison
Peak power	Maximum mission power demand	Verifies peak-demand consistency
Usable battery energy	Energy available within the usable window	Checks the battery model
Energy margin	Difference between usable energy and mission energy	Determines energy feasibility
Relative error	Percentage difference from reference values	Quantifies numerical agreement
Feasibility outcome	Energy-feasible or non-feasible mission result	Checks the reference conclusion

Overall, these metrics allow the validation to assess both the numerical accuracy and the physical consistency of the implemented model. Once the segment-level and mission-level outputs are shown to be aligned with the reference literature case, the model can be applied to the Aeolian Islands scenarios with a higher degree of confidence.

5.4. Validation Results

The validation case was simulated in MATLAB using the assumptions described in the previous sections. The objective was to reproduce the multicopter benchmark reported in the reference paper and to verify that the implemented segment-based model provides consistent results in terms of segment power, segment energy, total mission energy and battery feasibility.

Table 5.3 reports the comparison between the MATLAB model and the reference multicopter values. The agreement is very good for the main flight segments. In particular, the relative errors for take-off, climb, cruise/descent, landing and final taxi are close to zero. This confirms that the implemented equations for vertical flight, climb, cruise/descent

and landing correctly reproduce the reference model under equivalent assumptions.

Table 5.3: Comparison between MATLAB validation results and reference paper values.

Quantity	Model	Paper	Abs. error	Rel. error [%]
$P_{\text{taxi},1}$ [kW]	8.829	54.170	-45.341	-83.701
$P_{\text{take-off}}$ [kW]	57.001	57.000	0.001	0.001
P_{climb} [kW]	192.699	192.680	0.019	0.010
$P_{\text{cruise+desc}}$ [kW]	88.290	88.290	0.000	0.000
P_{landing} [kW]	52.776	52.780	-0.004	-0.007
$P_{\text{taxi},2}$ [kW]	8.829	8.830	-0.001	-0.011
$E_{\text{taxi},1}$ [kWh]	0.074	0.450	-0.376	-83.650
$E_{\text{take-off}}$ [kWh]	0.713	0.710	0.003	0.353
E_{climb} [kWh]	5.620	5.630	-0.010	-0.171
$E_{\text{cruise+desc}}$ [kWh]	37.891	37.890	0.001	0.003
E_{landing} [kWh]	0.660	0.660	-0.000	-0.045
$E_{\text{taxi},2}$ [kWh]	0.074	0.070	0.004	5.107
E_{total} [kWh]	45.031	45.410	-0.379	-0.835

The only significant discrepancy is observed in the first taxi segment. This difference is not due to an error in the flight model, but to the different physical interpretation assigned to the first taxi block. In the reference paper, the authors distinguish between different taxiing possibilities, including hovering flight, rolling on the aircraft landing gear, or the use of dedicated ground infrastructure. In their application case, the first taxi segment is modelled as a hovering taxi flight, whereas the second taxi segment is assumed to be performed on the aircraft landing gear. As a consequence, the first taxi segment has a power level close to hovering and vertical take-off, while the final taxi segment has a much lower power requirement. In the thesis implementation, instead, the Taxi 1 segment is treated as a low-power ground operation, consistently with the operational assumptions adopted for the Aeolian Islands case study. This explains why the implemented model gives approximately the same power for Taxi 1 and Taxi 2, while the reference paper reports a much higher value for Taxi 1. This interpretation was verified by performing an additional paper-equivalent validation check in which the first taxi block was treated as a hover taxi, consistently with the reference paper. Under this convention, the MATLAB model reproduced the complete benchmark with almost negligible error. Therefore, the discrepancy shown in Table 5.3 is not related to the hover, climb, cruise, descent or

landing equations, but only to the taxi-mode convention adopted for the initial low-speed segment.

The difference in Taxi 1 energy is approximately:

$$\Delta E_{\text{taxi},1} = 0.074 - 0.450 = -0.376 \text{ kWh} \quad (5.12)$$

which is almost equal to the total energy difference between the MATLAB model and the paper:

$$\Delta E_{\text{total}} = 45.031 - 45.410 = -0.379 \text{ kWh} \quad (5.13)$$

This confirms that the global mismatch is almost entirely explained by the different treatment of the first taxi block. The remaining flight segments reproduce the reference paper with negligible error.

The total mission energy obtained from the MATLAB model is:

$$E_{\text{mission,model}} = 45.031 \text{ kWh} \quad (5.14)$$

while the reference paper reports:

$$E_{\text{mission,paper}} = 45.410 \text{ kWh} \quad (5.15)$$

The resulting relative error is:

$$\varepsilon_E = \frac{45.031 - 45.410}{45.410} \cdot 100 = -0.835\% \quad (5.16)$$

This error is considered acceptable for a mission-level analytical model, especially because the discrepancy is concentrated in a short auxiliary segment rather than in the main energy-consuming flight phases. Moreover, when the Taxi 1 block is treated using the same hover-taxi convention as the reference paper, the total energy error becomes practically negligible.

The battery feasibility comparison is reported in Table 5.4. Both the MATLAB model and the reference paper use the same usable battery energy of 41.040 kWh. In both cases,

the total mission energy exceeds the usable battery energy, leading to a negative energy margin and therefore to an energy-infeasible mission.

Table 5.4: Energy feasibility comparison for the validation case.

Quantity	Model	Paper
Usable battery energy [kWh]	41.040	41.040
Mission energy [kWh]	45.031	45.410
Energy margin [kWh]	-3.991	-4.370
Energy feasible [-]	0	0

The validation therefore reproduces the main conclusion of the reference paper: under the adopted battery assumptions, the multicopter benchmark mission is not feasible within the usable battery energy window. This result is particularly important because it confirms that the implemented model correctly captures the influence of battery efficiency and usable depth of discharge on mission feasibility. The validation also confirms the physical consistency of the main mission phases. The climb segment is characterised by the highest power demand among the main forward-flight phases, while the cruise/descent block dominates the total energy consumption because of its long duration. This behaviour is consistent with the segment-based structure of the reference model and with the expected performance of a multicopter eVTOL, where long forward-flight phases can become energetically dominant even when vertical phases require high instantaneous power. Overall, the validation demonstrates that the MATLAB implementation is consistent with the reference multicopter model. The main flight segments show near-perfect agreement, the total mission energy differs by less than 1% when the thesis taxi convention is used, and the same feasibility conclusion is obtained. In addition, the paper-equivalent validation check showed that, when the first taxi segment is modelled as hover taxi as in the reference paper, the complete benchmark is reproduced with almost zero error. The model is therefore considered suitable for application to the Aeolian Islands case study.

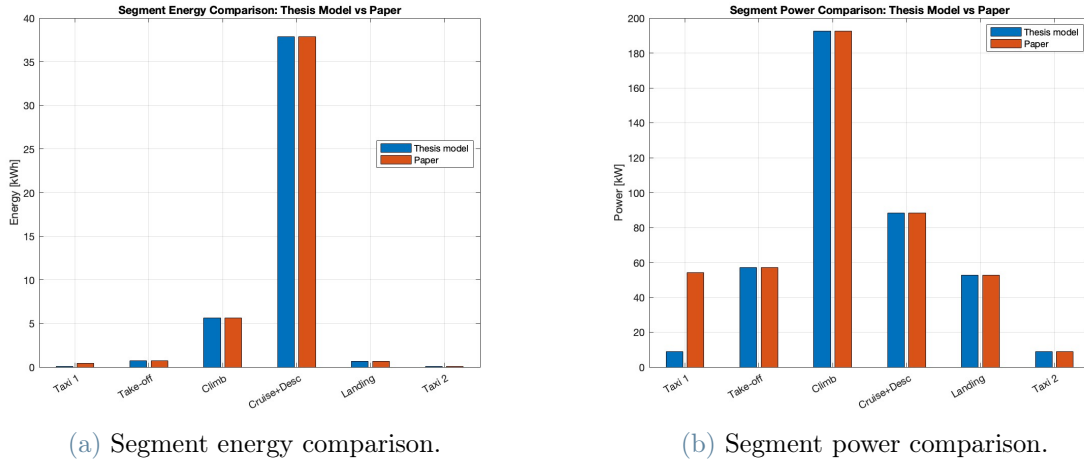


Figure 5.1: Benchmark validation of segment energy and power against the reference paper.

5.5. Model Credibility and Limitations

The validation presented in this chapter provides the basis for assessing the credibility of the developed mission-based energy model. By reproducing the multicopter benchmark from the reference literature model, the MATLAB implementation has been shown to be consistent with the analytical framework adopted by Bruhl et al. [2]. The main flight segments, including take-off, climb, cruise/descent and landing, show very small discrepancies with respect to the reference values, confirming that the core equations have been implemented correctly.

The only significant difference concerns the first taxi segment. This discrepancy is explained by the taxi-mode convention adopted in the reference paper. In the paper, the first taxi phase is treated as hover taxi, whereas the second taxi phase is performed on the landing gear. In the thesis model, Taxi 1 is instead represented as a low-power ground operation, consistently with the mission architecture adopted for the Aeolian Islands case study. When the first taxi block is treated according to the same hover-taxi convention as the reference paper, the complete benchmark is reproduced with almost negligible error. Therefore, the discrepancy does not affect the credibility of the main flight model. From a global perspective, the total mission energy obtained with the thesis segmentation differs from the reference value by less than 1%. This level of agreement is considered satisfactory for a mission-level analytical model. The objective of the model is not to reproduce the detailed certified performance of a specific aircraft, but to provide an engineering tool for estimating energy consumption, power demand, battery margins and route feasibility.

under consistent assumptions. The model credibility is further supported by its physical transparency. Each mission segment is associated with a specific power and duration, and the total mission energy is obtained as the sum of all segment contributions. This makes it possible to identify which phases dominate the energy consumption and which phases determine the peak power requirement. The model is therefore not a black-box tool, but a traceable calculation framework in which each result can be linked to a specific physical assumption. Nevertheless, several limitations must be acknowledged. First, the model is validated against a literature-based analytical framework rather than against experimental flight data. As a result, the validation confirms consistency with the selected reference model, but it does not represent a full experimental validation of a real aircraft. This limitation is particularly relevant because detailed flight-test data for the selected reference eVTOL are not publicly available. Second, the aircraft model is based on publicly available Volocopter information and literature-derived assumptions. The numerical configuration used in the thesis should therefore be interpreted as a representative Volocopter-like multicopter architecture, not as an exact reproduction of a certified VoloCity aircraft. Proprietary data such as detailed motor maps, propeller performance curves, battery pack architecture, battery management logic and thermal management characteristics are not available. Third, the aerodynamic model is intentionally simplified. The cruise and climb formulations are based on equivalent efficiency and lift-to-drag parameters, following the reference paper. This approach is appropriate for preliminary mission-level assessment, but it cannot capture the full speed-dependent rotorcraft aerodynamics, detailed propeller inflow effects, body drag variation, control losses or unsteady manoeuvres. For this reason, the baseline model is more suitable for route comparison and feasibility assessment than for detailed aircraft design. Fourth, the battery model is simplified at aircraft level. Battery capacity, usable energy and available power are represented through specific energy, specific power, efficiency and usable depth of discharge. Temperature effects are introduced through a literature-based correction, but the model does not include a full electrochemical representation, transient thermal dynamics, voltage sag, C-rate dependence, cell balancing, ageing or degradation mechanisms. These aspects would require detailed cell-level and pack-level data that are not publicly available for the reference aircraft. Fifth, the operational scenario is idealised. Routes are modelled as direct point-to-point connections, and the baseline case assumes nominal atmospheric conditions and zero wind. Airspace constraints, no-fly zones, detailed vertiport procedures, contingency routing, traffic separation, charging infrastructure sizing, turnaround operations and regulatory constraints are not explicitly modelled in the core energy calculation. These aspects are important for real deployment, but they are outside the primary scope of the present mission-energy analysis. Despite these limitations,

the model is considered credible for the objectives of this thesis. It reproduces the reference multicopter benchmark with good accuracy, captures the same energy-feasibility conclusion, and provides physically consistent trends when mission parameters are varied. The framework is therefore suitable for comparing route energy demand, evaluating battery margins, identifying critical operating conditions and performing sensitivity analyses for the Aeolian Islands case study. The results obtained in the following chapters should consequently be interpreted as mission-level feasibility estimates rather than exact operational predictions. Within this scope, the model provides a consistent and transparent engineering basis for assessing whether multicopter eVTOL operations could support short-range insular transport applications.

6 | Application to the Aeolian Islands Distribution Mission

6.1. Mission Setup: Milazzo–Vulcano

The first application of the validated mission-energy model is the Milazzo–Vulcano route, which is selected as the base case for the Aeolian Islands distribution mission. This route represents a mainland-to-island connection between one of the main Sicilian gateways to the archipelago and one of the closest islands to the northern coast of Sicily. For this reason, it provides a suitable initial case for evaluating the feasibility of short-range eVTOL operations in an insular environment. The purpose of the base case is to translate the general modelling framework into a realistic operational mission. Milazzo is treated as the mainland departure node, while Vulcano is considered as the destination island node. The mission is analysed as a point-to-point flight, with the aircraft completing the full sequence of taxi, hover, vertical take-off, forward climb, cruise, forward descent, vertical landing and final taxi. This allows the complete segment-based energy balance to be evaluated under a fixed route-distance constraint. In the numerical implementation, the Milazzo–Vulcano mission is simulated using the `fixed_distance` mode. This means that the total mission distance is imposed as an input, rather than being derived from a prescribed mission duration. The model first computes the horizontal distances covered during forward climb and forward descent; the remaining distance is then assigned to the cruise segment. Therefore, the cruise distance is obtained as:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (6.1)$$

where d_{mission} is the imposed Milazzo–Vulcano route distance, while d_{climb} and d_{desc} are the horizontal distances covered during climb and descent. This formulation ensures that the mission geometry is consistent with the selected altitude, climb rate, descent rate and flight speeds. The base case is evaluated using the paper-consistent cruise formulation introduced in Chapter 4. In this approach, cruise power is computed from the aircraft

weight, cruise speed, cruise efficiency and equivalent lift-to-drag ratio. This choice preserves consistency with the reference model used for validation while allowing the same framework to be applied to the real route distance of the Aeolian Islands scenario. The payload adopted in the base case represents the useful load carried by the aircraft. Depending on the operational interpretation, this payload may correspond to lightweight logistics goods, passengers, or a mixed useful load. In all cases, the payload contributes to the take-off mass and therefore directly affects the power and energy required during the mission. This is particularly relevant for multicopter eVTOL aircraft, where vertical flight and rotor-borne cruise are strongly mass-dependent.

The nominal base case assumptions are summarised in Table 6.1. These values define the reference operating condition against which the subsequent route comparison and sensitivity analyses are evaluated.

Table 6.1: Nominal assumptions for the Milazzo–Vulcano base case mission.

Parameter	Value	Description
Mission route	Milazzo–Vulcano	Mainland-to-island base case
Mission mode	Fixed distance	Route distance imposed as model input
Route distance	37 km	Approximate point-to-point mission distance
Aircraft configuration	Multicopter eVTOL	Reference Volocopter-like architecture
Payload	200 kg	Useful load for cargo, passengers or mixed mission
Cruise model	Paper-consistent	Based on equivalent cruise efficiency and lift-to-drag ratio
Descent model	Paper-consistent	Forward-flight descent included in mission energy
Wind condition	0 m/s	No headwind or tailwind in the nominal case
Temperature condition	25 °C	Reference condition for nominal battery performance

The Milazzo–Vulcano mission is used as the first quantitative application of the validated model to a real route. The results obtained from this base case provide a reference point for understanding the energy demand, power requirements, battery utilisation and feasibility

margins of the selected multicopter eVTOL configuration.

6.2. Lipari-Centred Hub-and-Spoke Network Setup

After the definition of the Milazzo–Vulcano base case, the analysis is extended to a Lipari-centred hub-and-spoke distribution network. This second application is introduced to evaluate whether the same multicopter eVTOL model can support inter-island operations within the Aeolian archipelago, beyond the single mainland-to-island reference route. In this network configuration, Lipari is selected as the central island hub. This choice is motivated by its geographical position within the archipelago and by its role as one of the main service centres of the Aeolian Islands. From an operational perspective, Lipari can be interpreted as an internal distribution node where goods, equipment or passengers may be consolidated before being redistributed towards the peripheral islands. The peripheral nodes considered in the network are Vulcano, Salina, Panarea, Stromboli, Filicudi and Alicudi. Each connection is analysed as an independent point-to-point mission departing from Lipari and reaching the selected destination island. Therefore, the hub-and-spoke network is not simulated as a single continuous multi-stop flight, but as a set of individual route missions evaluated with the same modelling assumptions. The adopted route set is summarised in Table 6.2. The route distance represents the main geometric input for each mission and directly affects the cruise duration, total energy consumption and final battery margin.

Table 6.2: Lipari-centred hub-and-spoke routes considered in the network analysis.

Route	Distance [km]	Operational role
Lipari–Vulcano	9	Short hub-to-node connection
Lipari–Salina	12	Short hub-to-node connection
Lipari–Panarea	20	Medium hub-to-node connection
Lipari–Stromboli	42	Long hub-to-node connection
Lipari–Filicudi	34	Long hub-to-node connection
Lipari–Alicudi	53	Critical hub-to-node connection

For each route, the same segment-based mission architecture introduced in Chapter 4 is applied. The aircraft performs taxi, hover, vertical take-off, forward climb, cruise, forward descent, vertical landing and final taxi. The total distance is imposed as a fixed input, and the model computes the residual cruise distance after subtracting the horizontal distances covered during climb and descent:

$$d_{\text{cruise},j} = d_{\text{mission},j} - d_{\text{climb}} - d_{\text{desc}} \quad (6.2)$$

where j identifies the considered route of the network. The climb and descent distances are kept consistent with the nominal aircraft and mission assumptions, while $d_{\text{mission},j}$ changes from one island connection to another.

A route is geometrically admissible only if the resulting cruise distance is positive:

$$d_{\text{cruise},j} > 0 \quad (6.3)$$

This condition is especially relevant for the shortest routes, such as Lipari–Vulcano and Lipari–Salina. If the prescribed climb and descent profiles require too much horizontal distance, the mission may become geometrically inconsistent before the energy balance is even evaluated. This aspect is considered explicitly in the feasibility assessment.

The same reference aircraft configuration used for the Milazzo–Vulcano base case is adopted for the network analysis. The payload, battery assumptions, cruise model, descent model, wind condition and nominal temperature are kept unchanged. This allows the different routes to be compared under consistent operating conditions, so that differences in energy consumption and feasibility are mainly driven by route distance.

The network setup is therefore based on the following assumptions:

- Lipari is treated as the central archipelago hub;
- Vulcano, Salina, Panarea, Stromboli, Filicudi and Alicudi are treated as peripheral nodes;
- each hub-to-node route is simulated independently;
- the aircraft starts each mission from a fully available usable battery window;
- charging or battery replacement at the hub is assumed possible at network level, but is not explicitly sized in this chapter;
- the same aircraft, payload and environmental assumptions are used for all routes.

This approach allows the network to be analysed at mission level without introducing fleet scheduling, infrastructure sizing or multi-stop routing constraints. The objective is to determine which individual inter-island routes are compatible with the selected multi-copter eVTOL configuration and which routes become critical from an energy, power or geometric feasibility perspective.

The Lipari-centred network analysis complements the Milazzo–Vulcano base case. While the base case evaluates a mainland-to-island mission, the hub-and-spoke setup assesses the potential of an internal aerial distribution system within the archipelago. Together, these two levels provide a quantitative basis for discussing the possible role of eVTOL aircraft in future Aeolian Islands transport and distribution applications.

6.3. Segment Results

The first level of output of the mission-energy model is represented by the segment results. For each simulated route, the model computes the duration, horizontal distance, mean power, peak power and energy consumption associated with each flight phase. This allows the mission to be analysed before considering global indicators such as total energy demand, final state of charge, energy margin and feasibility. The segment-based representation is particularly useful for multicopter eVTOL missions because different flight phases have different physical meanings and different energetic impacts. Vertical flight and climb are generally associated with high power demand, while cruise may dominate the total energy consumption when it occupies a large fraction of the mission duration. Therefore, separating the mission into individual segments makes it possible to identify which phases are critical for power sizing and which phases drive the total energy requirement. For the Milazzo–Vulcano base case, the complete set of segment outputs is reported in Table 6.3. The same modelling logic is then applied to the Lipari-centred hub-and-spoke routes, whose route-level segment summaries are reported in Table 6.5.

Table 6.3: Segment results for the Milazzo–Vulcano base case mission.

Segment	Duration [s]	Mean power [kW]	Peak power [kW]	Energy [kWh]
Initial taxi	30.00	8.83	8.83	0.074
Take-off hover	10.00	54.17	54.17	0.150
Vertical take-off	35.00	57.00	57.00	0.554
Forward climb	105.00	192.70	192.70	5.620
Cruise	1295.21	88.29	88.29	31.765
Forward descent	105.00	88.29	88.29	2.575
Vertical landing	35.00	52.78	52.78	0.513
Landing hover	10.00	54.17	54.17	0.150
Final taxi	30.00	8.83	8.83	0.074
Total	1655.21	90.22	192.70	41.48

Table 6.4: Mission distance partition for the Milazzo–Vulcano base case.

Contribution	Distance [km]	Description
Forward climb	3.40	Horizontal distance covered during climb
Cruise	31.08	Residual cruise distance
Forward descent	2.52	Horizontal distance covered during descent
Total mission distance	37.00	Milazzo–Vulcano route distance

The segment results for the Milazzo–Vulcano base case are reported in Table 6.3. The total mission time is 1655.21 s, corresponding to approximately 27.59 min, while the total mission energy is 41.48 kWh. The mission distance is equal to 37.00 km and is divided into forward climb, cruise and forward descent contributions, as shown in Table 6.4. The results show that the cruise segment is the dominant contributor to total mission energy. Although its mean power is lower than the climb power, its long duration leads to an energy consumption of 31.765 kWh, corresponding to the largest share of the mission energy. The forward descent segment is also modelled as a powered phase and contributes 2.575 kWh to the total energy, consistently with the multicopter architecture and with the paper-based modelling approach. The forward climb segment is the most demanding phase in terms of instantaneous power. Its mean power is 192.70 kW, which is significantly higher than the cruise power of 88.29 kW. This behaviour is expected because the climb phase combines forward motion with altitude gain, requiring power both to overcome aerodynamic drag and to increase the aircraft potential energy. The vertical take-off, vertical landing and hover phases have relatively short durations, but their power levels remain high because the aircraft is fully rotor-borne. Their energy contribution is therefore smaller than the cruise contribution, but they remain relevant for the power demand analysis. The taxi segments, instead, have a negligible contribution to total mission energy in the present mission setup.

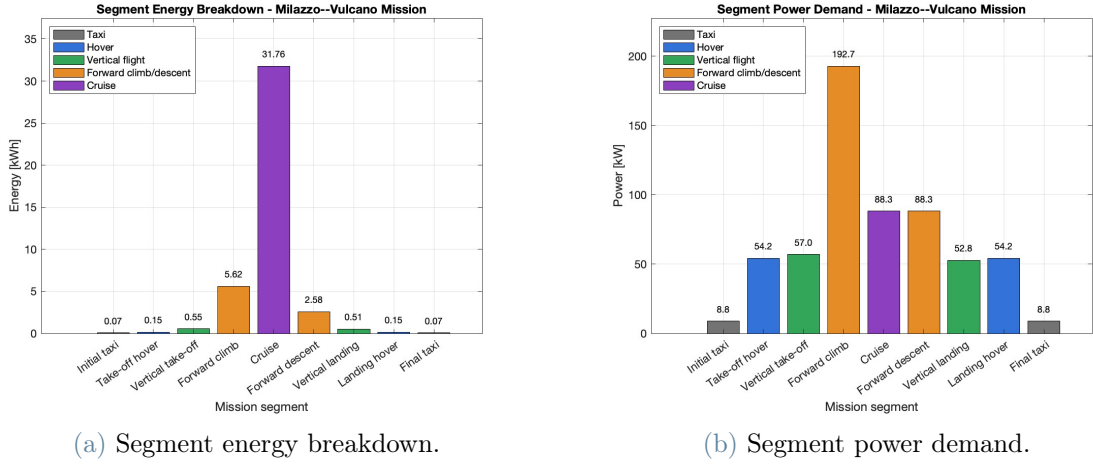


Figure 6.1: Segment-level energy and power results for the Milazzo–Vulcano base case mission.

For the Lipari-centred hub-and-spoke network, the same segment-based model is applied to each route independently. Since the aircraft configuration, payload, battery assumptions and environmental conditions are kept unchanged, the differences among the routes are mainly driven by the imposed mission distance and by the resulting cruise distance. A detailed segment table for each route would be repetitive, because the fixed-duration phases such as taxi, hover, vertical take-off, vertical landing and final taxi remain unchanged. The main variation occurs in the cruise segment, whose duration and energy contribution increase with route distance. For this reason, the Lipari-centred results are reported through a route-level segment summary, focusing on mission distance, residual cruise distance, mission time, total energy and maximum power.

Table 6.5: Mission results for the Lipari-centred hub-and-spoke routes.

Route	d [km]	t [s]	P_{mean} [kW]	P_{max} [kW]	E_{tot} [kWh]
Lipari–Vulcano	9.0	488.54	94.77	192.70	12.86
Lipari–Salina	12.0	613.54	93.49	192.70	15.93
Lipari–Panarea	20.0	946.87	91.64	192.70	24.10
Lipari–Filicudi	34.0	1530.21	90.36	192.70	38.41
Lipari–Stromboli	42.0	1863.54	89.99	192.70	46.59
Lipari–Alicudi	53.0	2321.87	89.66	192.70	57.83

Table 6.5 reports the main numerical outputs obtained by applying the segment-based model to the Lipari-centred hub-and-spoke routes. At this stage, the objective is only

to present the direct mission results in terms of duration, mean power, peak power and total energy consumption. A detailed interpretation of battery utilisation, state of charge evolution, energy margins and mission feasibility is not introduced here, since these aspects are discussed separately in the following sections. The route-level results show that total mission energy increases with route distance. This is mainly due to the longer cruise duration required by the more distant islands, while the fixed-duration segments, such as taxi, hover, vertical take-off, climb, descent and landing, remain unchanged under the nominal assumptions. For short routes, such as Lipari–Vulcano and Lipari–Salina, these fixed contributions represent a larger fraction of the total mission. For longer routes, such as Lipari–Filicudi, Lipari–Stromboli and Lipari–Alicudi, the cruise segment becomes progressively more influential in the total energy balance. The peak power remains constant across the Lipari-centred routes because the same aircraft mass, climb settings and vertical-flight assumptions are used for all missions. In the nominal model, the maximum power demand is associated with the forward climb segment and is therefore not directly affected by the route length. Consequently, the route distance mainly affects mission duration and total energy, while the peak power demand remains governed by the common climb and vertical-flight conditions. These results provide the numerical basis for the following analyses. The energy performance section discusses the energy trends in greater detail, the battery utilisation section relates the required energy to the available battery capacity and state of charge, and the feasibility assessment determines which routes are compatible with the adopted energy and power constraints.

6.4. Energy Performance

The energy performance analysis focuses on the total energy required by the mission and on the relative contribution of each flight segment. While the previous section presented the direct segment outputs in terms of time, power and energy, this section interprets those results from an energy-consumption perspective. For the Milazzo–Vulcano base case, the total mission energy is equal to 41.48 kWh. This value is obtained by summing the energy contributions of all mission segments, including taxi, hover, vertical take-off, climb, cruise, descent, landing and final taxi. The energy result therefore represents the complete point-to-point mission demand, not only the cruise requirement.

Table 6.6: Energy contribution by segment for the Milazzo–Vulcano base case.

Segment	Energy [kWh]	Contribution [%]
Initial taxi	0.074	0.18
Take-off hover	0.150	0.36
Vertical take-off	0.554	1.34
Forward climb	5.620	13.55
Cruise	31.765	76.58
Forward descent	2.575	6.21
Vertical landing	0.513	1.24
Landing hover	0.150	0.36
Final taxi	0.074	0.18
Total	41.48	100.00

The cruise segment is the dominant energy contribution, accounting for approximately 76.6% of the total mission energy. This is mainly due to its long duration and to the fact that the aircraft remains powered throughout the forward-flight phase. The forward climb segment is the second most important contribution, accounting for approximately 13.6% of the total energy. Although its duration is much shorter than cruise, the required power is significantly higher because the aircraft must gain altitude while maintaining forward motion.

The remaining segments have smaller individual contributions because their duration is limited. However, they are not negligible from a modelling perspective, especially for shorter routes where the cruise segment becomes less dominant and fixed-duration phases represent a larger fraction of the mission.

Table 6.7: Energy performance comparison for the analysed routes.

Route	Distance [km]	E_{tot} [kWh]	E_{tot}/d [kWh/km]
Lipari–Vulcano	9.0	12.86	1.43
Lipari–Salina	12.0	15.93	1.33
Lipari–Panarea	20.0	24.10	1.21
Lipari–Filicudi	34.0	38.41	1.13
Milazzo–Vulcano	37.0	41.48	1.12
Lipari–Stromboli	42.0	46.59	1.11
Lipari–Alicudi	53.0	57.83	1.09

Table 6.7 shows that the total mission energy increases with route distance, as expected.

However, the energy required per kilometre decreases slightly as the mission distance increases. This occurs because several mission phases, such as taxi, hover, vertical take-off, climb, descent, landing and final taxi, have approximately fixed duration and energy contribution under the nominal assumptions. On short routes, these fixed contributions are distributed over a small distance, increasing the energy per kilometre. On longer routes, the cruise segment becomes dominant and the fixed contributions are spread over a larger distance. This result is important for the interpretation of short inter-island missions. A short route is not automatically energy-efficient in terms of energy per kilometre, because the aircraft must still perform the same take-off, climb, descent and landing phases. Conversely, longer routes are more demanding in absolute energy, but the fixed contributions have a smaller relative weight. It should be noted that the energy values reported in this section represent the required mission energy only. The comparison with available battery energy, final state of charge and energy feasibility is discussed in the following battery utilisation and mission feasibility sections.

6.5. Battery Utilization

The battery utilisation analysis relates the mission energy demand to the energy available from the onboard battery system. While the previous section focused on the energy required by each route, this section evaluates how much of the available battery capacity is consumed during the mission and how much energy margin remains at the end of the flight.

In the nominal configuration, the installed battery mass is equal to 300 kg and the battery specific energy is assumed equal to 180 Wh/kg. Considering the battery efficiency and the usable depth of discharge, the usable battery energy is:

$$E_{\text{batt,use}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD = 41.04 \text{ kWh} \quad (6.4)$$

This value represents the energy that can be used during nominal operation while preserving the prescribed battery reserve. The effective physical battery energy after battery efficiency, but before applying the usable depth-of-discharge limit, is:

$$E_{\text{batt,phys}} = E^* M_{\text{batt}} \eta_{\text{batt}} = 51.30 \text{ kWh} \quad (6.5)$$

The distinction between usable and physical battery energy is important. The usable energy defines the operational energy window adopted for feasibility assessment, whereas

the physical energy provides an indication of the remaining energy with respect to the effective battery capacity. In this thesis, both quantities are reported in order to distinguish between operational reserve violation and complete physical energy depletion.

The energy margin is computed as:

$$\Delta E = E_{\text{batt,use}} - E_{\text{mission}} \quad (6.6)$$

A positive value indicates that the mission remains within the usable battery window, while a negative value indicates that the required energy exceeds the nominal usable capacity.

For the Milazzo–Vulcano base case, the total mission energy is 41.48 kWh. Since the usable battery energy is 41.04 kWh, the resulting energy margin is:

$$\Delta E_{\text{Milazzo--Vulcano}} = 41.04 - 41.48 = -0.44 \text{ kWh} \quad (6.7)$$

This means that the base case slightly exceeds the usable battery energy under the nominal assumptions. The difference is small in absolute terms, but it is relevant because the mission does not remain inside the prescribed usable operating window.

The final usable state of charge is evaluated as:

$$SOC_{\text{final,use}} = 100 \left(\frac{E_{\text{batt,use}} - E_{\text{mission}}}{E_{\text{batt,use}}} \right) \quad (6.8)$$

For the Milazzo–Vulcano route, this gives:

$$SOC_{\text{final,use}} = -1.06\% \quad (6.9)$$

The negative value indicates that the mission exceeds the usable battery window. However, the final physical state of charge remains positive:

$$SOC_{\text{final,phys}} = 19.15\% \quad (6.10)$$

This means that the mission does not deplete the effective physical battery energy, but it violates the operational usable-energy constraint imposed by the reserve requirement.

Therefore, the issue is not complete physical battery depletion, but the inability to complete the route while preserving the selected usable battery reserve.

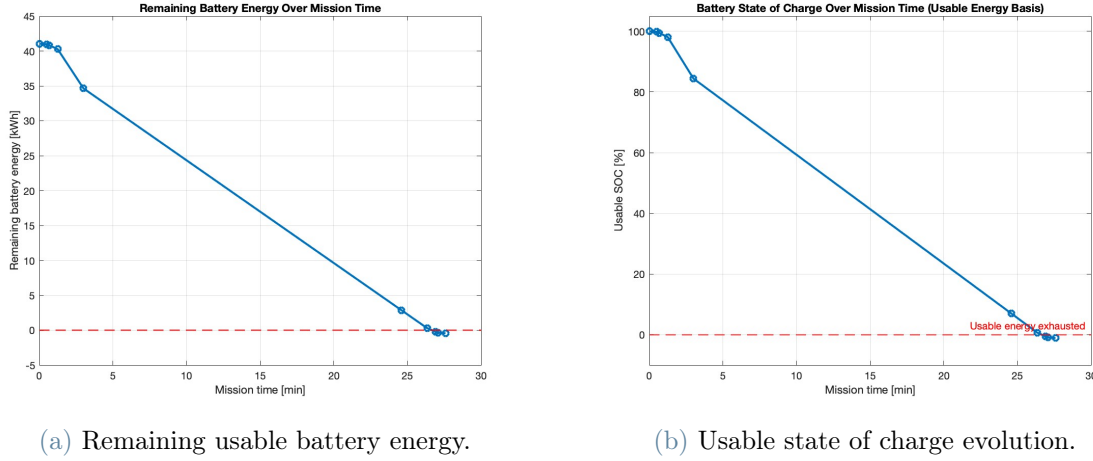


Figure 6.2: Battery utilisation during the Milazzo–Vulcano base case mission on a usable-energy basis.

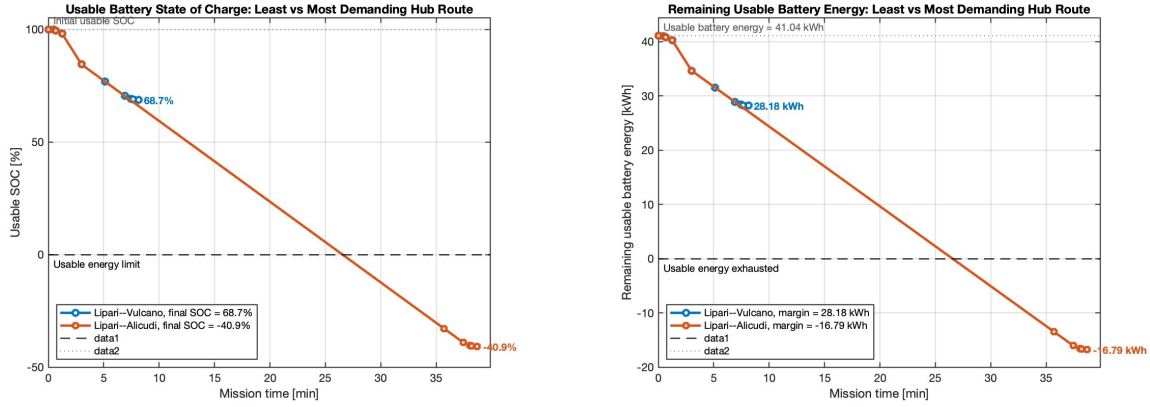
Figure 6.2 shows the battery depletion during the Milazzo–Vulcano mission. The remaining usable battery energy decreases throughout the mission and becomes slightly negative near the end of the flight. The same behaviour is visible in the usable SOC profile, which crosses the zero threshold before mission completion. This confirms that the base case is very close to the usable battery limit under the nominal assumptions.

The physical SOC provides a complementary interpretation. Although the usable battery window is exceeded, the physical battery energy is not completely depleted. This distinction is relevant because the mission is critical from an operational reserve perspective, but not from the standpoint of total effective energy exhaustion.

Table 6.8: Battery utilisation for the analysed routes.

Route	E_{mission} [kWh]	ΔE [kWh]	$SOC_{\text{final,use}}$ [%]	$SOC_{\text{final,phys}}$ [%]
Lipari–Vulcano	12.86	28.18	68.66	74.93
Lipari–Salina	15.93	25.11	61.18	68.95
Lipari–Panarea	24.10	16.94	41.28	53.02
Lipari–Filicudi	38.41	2.63	6.41	25.13
Milazzo–Vulcano	41.48	-0.44	-1.06	19.15
Lipari–Stromboli	46.59	-5.55	-13.52	9.18
Lipari–Alicudi	57.83	-16.79	-40.91	-12.73

Table 6.8 shows a progressive increase in battery utilisation as route length increases. Short hub-and-spoke routes, such as Lipari–Vulcano and Lipari–Salina, consume only a limited fraction of the available usable battery energy and retain large positive end-of-mission margins. Intermediate routes, such as Lipari–Panarea, remain comfortably within the nominal operating window, although with a visibly larger fraction of battery capacity consumed. Lipari–Filicudi represents the most critical route among those that remain nominally within the usable battery window. Its residual usable SOC is positive but limited, approximately 6.41%, which makes the mission more sensitive to disturbances or off-design conditions such as adverse wind, increased payload, low-temperature operation or battery ageing. The Milazzo–Vulcano base case lies slightly beyond the usable battery-energy threshold. Although the exceedance is small in absolute terms, the route does not remain within the prescribed operational battery window and must therefore be regarded as energy-critical under the nominal assumptions. At the same time, the final physical SOC remains positive, indicating that the issue concerns reserve violation rather than complete physical battery depletion. The longest routes, namely Lipari–Stromboli and Lipari–Alicudi, exceed the nominal usable battery capacity more significantly. Lipari–Stromboli still retains positive physical SOC, but violates the usable operating window. Lipari–Alicudi also leads to a negative final physical SOC, indicating that the mission would not be achievable with the selected battery configuration under the adopted assumptions. Rather than plotting all route SOC histories together, which would produce an excessively crowded representation, it is more effective to compare the two extreme hub-and-spoke cases. In this way, the reader can clearly identify the battery behaviour associated with the least demanding route and the most demanding route in the analysed network.



(a) Usable SOC evolution for the least and most demanding hub-and-spoke routes. (b) Remaining usable battery energy for the least and most demanding hub-and-spoke routes.

Figure 6.3: Comparison between the least demanding route (Lipari-Vulcano) and the most demanding route (Lipari-Alicudi) on a usable-energy basis.

Figure 6.3 highlights the wide spread of battery utilisation within the Lipari-centred network. Lipari-Vulcano retains a large usable-energy margin throughout the mission and ends with a comfortable residual SOC, confirming that short inter-island connections are well supported by the selected configuration. By contrast, Lipari-Alicudi exhibits a continuous decrease in usable battery energy that extends well below the zero threshold before mission completion. This confirms that the route cannot be supported within the nominal usable battery window and represents the most critical case in the analysed network. These results show that battery utilisation is one of the primary constraints for the considered multicopter eVTOL missions. The same aircraft configuration can support short and medium inter-island routes with adequate margin, but longer connections become limited by available energy rather than by the ability to generate sufficient power. At this stage, the objective is to quantify battery usage, residual energy and state-of-charge evolution for each route. Although these results already indicate which missions are close to or beyond the nominal battery operating window, the formal mission feasibility classification is discussed separately in the following mission feasibility assessment section.

6.6. Power Demand Analysis

The power demand analysis focuses on the maximum instantaneous power required during the mission and on its comparison with the available battery power. Unlike total energy consumption, which depends strongly on route distance and cruise duration, the peak power demand is mainly determined by the most demanding flight segment. Under the

nominal assumptions adopted in this chapter, this segment is the forward climb phase.

The maximum usable battery power is computed from the battery specific power, installed battery mass, battery efficiency and usable depth of discharge:

$$P_{\text{batt,max}} = P^* M_{\text{batt}} \eta_{\text{batt}} DoD = 250.80 \text{ kW} \quad (6.11)$$

For the Milazzo–Vulcano base case, the maximum mission power is:

$$P_{\text{max}} = 192.70 \text{ kW} \quad (6.12)$$

This value occurs during the forward climb segment. The corresponding power margin is:

$$\Delta P = P_{\text{batt,max}} - P_{\text{max}} = 250.80 - 192.70 = 58.10 \text{ kW} \quad (6.13)$$

Therefore, the Milazzo–Vulcano base case is not power-limited under the nominal assumptions. The battery system is able to provide the required peak power with a positive margin of approximately 58.10 kW.

Table 6.9: Power demand summary for the analysed routes.

Route	P_{max} [kW]	Critical segment	$P_{\text{batt,max}}$ [kW]	ΔP [kW]
Lipari–Vulcano	192.70	Forward climb	250.80	58.10
Lipari–Salina	192.70	Forward climb	250.80	58.10
Lipari–Panarea	192.70	Forward climb	250.80	58.10
Lipari–Filicudi	192.70	Forward climb	250.80	58.10
Milazzo–Vulcano	192.70	Forward climb	250.80	58.10
Lipari–Stromboli	192.70	Forward climb	250.80	58.10
Lipari–Alicudi	192.70	Forward climb	250.80	58.10

Table 6.9 shows that the peak power demand is the same for all analysed routes. This result is expected because the same aircraft mass, payload, rotor configuration, climb rate and climb speed are used in all nominal simulations. Route distance affects mainly the duration of the cruise segment and therefore the total energy consumption, but it does not modify the maximum power required during the common climb phase.

The power profile of the Milazzo–Vulcano mission is shown in Figure 6.4. The profile clearly identifies the forward climb segment as the power-critical phase. Hover, vertical

take-off and vertical landing also require significant power, but their levels remain below the forward climb demand in the adopted model. Cruise and forward descent require lower power than climb, although their duration can be important for total energy consumption.

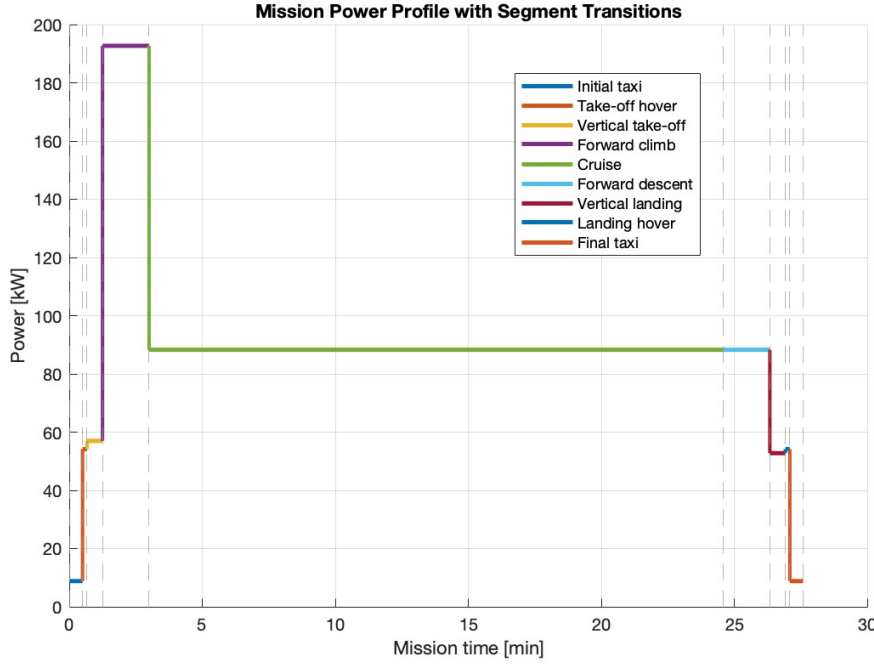


Figure 6.4: Mission power profile for the Milazzo–Vulcano base case.

The fact that all routes remain power-feasible is important for interpreting the overall mission results. The limiting factor of the longest routes is not the ability of the battery to provide instantaneous power, but the amount of usable energy available over the full mission. In other words, the selected battery configuration can sustain the required peak power, but some routes still require more total energy than the usable battery window allows. This distinction between power limitation and energy limitation is essential for multicopter eVTOL mission assessment. A mission may be power-feasible and energy-infeasible at the same time. In the present case, the nominal power demand remains within the available battery power for all analysed routes, while the energy balance varies significantly with route distance.

6.7. Mission Feasibility Assessment

The mission feasibility assessment combines the geometric, energy and power constraints introduced in the previous sections. A route is considered feasible only if the mission profile can be geometrically completed, if the total energy demand remains within the

usable battery energy window, and if the maximum required power does not exceed the available battery power.

The complete feasibility condition can be expressed as:

$$\text{Feasible} = \text{Feasible}_{\text{geom}} \cap \text{Feasible}_{\text{energy}} \cap \text{Feasible}_{\text{power}} \quad (6.14)$$

This formulation is useful because it separates different types of mission limitations. A route may be geometrically admissible and power-feasible, but still not feasible from an energy point of view if the usable battery energy is not sufficient.

6.7.1. Geometric Feasibility

The geometric feasibility condition verifies that the imposed route distance is compatible with the selected climb, cruise and descent profile. Since part of the horizontal distance is covered during forward climb and forward descent, the remaining cruise distance is:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (6.15)$$

A mission is geometrically feasible only if:

$$d_{\text{cruise}} > 0 \quad (6.16)$$

For the nominal mission settings adopted in this chapter, all analysed routes satisfy this condition. The shortest route, Lipari–Vulcano, remains geometrically feasible, although the cruise segment is relatively short compared with the fixed climb and descent contributions. This confirms that the selected mission profile can be applied to the complete set of analysed routes.

6.7.2. Energy Feasibility

The energy feasibility condition compares the total mission energy with the usable battery energy:

$$E_{\text{mission}} \leq E_{\text{batt,use}} \quad (6.17)$$

where:

$$E_{\text{batt,use}} = 41.04 \text{ kWh} \quad (6.18)$$

This is the most restrictive condition in the present analysis. Short and medium routes remain within the usable battery window, while longer routes exceed the available usable energy.

6.7.3. Power Feasibility

The power feasibility condition compares the maximum mission power with the maximum usable battery power:

$$P_{\text{max}} \leq P_{\text{batt,max}} \quad (6.19)$$

For the nominal configuration:

$$P_{\text{batt,max}} = 250.80 \text{ kW} \quad (6.20)$$

All analysed routes have the same maximum mission power:

$$P_{\text{max}} = 192.70 \text{ kW} \quad (6.21)$$

Therefore, all routes are power-feasible under the nominal assumptions. The limiting constraint is not peak power delivery, but usable battery energy.

Table 6.10: Mission feasibility assessment for the analysed routes.

Route	Geometric	Energy	Power	Overall
Lipari–Vulcano	Feasible	Feasible	Feasible	Feasible
Lipari–Salina	Feasible	Feasible	Feasible	Feasible
Lipari–Panarea	Feasible	Feasible	Feasible	Feasible
Lipari–Filicudi	Feasible	Feasible	Feasible	Feasible, low margin
Milazzo–Vulcano	Feasible	Not feasible	Feasible	Energy-critical
Lipari–Stromboli	Feasible	Not feasible	Feasible	Not feasible
Lipari–Alicudi	Feasible	Not feasible	Feasible	Not feasible

Table 6.10 summarises the complete feasibility classification. The short hub-and-spoke

routes, namely Lipari–Vulcano, Lipari–Salina and Lipari–Panarea, are feasible under the nominal assumptions. Lipari–Filicudi is also feasible, but its residual usable battery margin is limited; for this reason, it should be considered sensitive to off-design conditions such as increased payload, adverse wind, lower battery performance or more conservative reserve requirements. The Milazzo–Vulcano base case is classified as energy-critical. It satisfies the geometric and power constraints, but its required mission energy slightly exceeds the usable battery energy. Since the exceedance is small, this route is close to feasibility and could become feasible through modest improvements in operating conditions, battery capacity, reserve policy, payload reduction or mission optimisation. Lipari–Stromboli and Lipari–Alicudi are not feasible under the nominal direct-flight assumptions. Both routes satisfy the geometric and power constraints, but they exceed the usable battery energy by a significant margin. In particular, Lipari–Alicudi also exceeds the effective physical battery energy, making it the most demanding and least compatible route for the selected configuration. However, the non-feasible classification of the longest routes refers specifically to the direct point-to-point missions simulated in this chapter. In the present analysis, Lipari is assumed to be the only departure hub of the network, and each destination island is reached through a single uninterrupted flight. Under this assumption, the longest connections are limited by usable battery energy. This does not necessarily exclude these islands from a future eVTOL-based service, but indicates that they would require a different operational strategy. One possible solution is to consider intermediate islands of the archipelago as operational checkpoints. In such a configuration, the aircraft could land at an intermediate island, unload or board payload if required, recharge or swap the battery, and then continue towards the final destination. This would transform a long direct route into a sequence of shorter mission legs, each characterised by a lower individual energy demand and a new battery state at departure. For example, a direct Lipari–Alicudi or Lipari–Stromboli connection may be energy-critical when analysed as a single flight, but it could be reconsidered as part of a multi-leg network involving intermediate stops. In that case, the feasibility assessment would depend not only on the total distance from Lipari to the final destination, but also on the energy requirement of each individual leg and on the availability of suitable landing, charging and turnaround infrastructure at the intermediate nodes. This possibility is not explicitly modelled in the present chapter, whose objective is to evaluate the direct point-to-point performance of the selected multicopter configuration. Nevertheless, it represents an important operational extension of the proposed framework. The development of multi-stop routing strategies, intermediate charging nodes, battery swapping procedures and network-level scheduling is therefore identified as a relevant topic for future work. Overall, the assessment shows that the considered multicopter eVTOL configuration is suitable for short and medium inter-

island routes, but becomes energy-limited for longer direct connections. The principal constraint is usable energy capacity rather than peak power capability. This distinction is important for the following chapters, where sensitivity analyses are used to investigate how payload, distance, temperature, wind and other parameters affect the operational limits of the mission.

7 | Sensitivity Analyses and Operational Limits

The previous chapter applied the validated mission-energy model to the nominal Aeolian Islands scenario, including the Milazzo–Vulcano base case and the Lipari-centred hub-and-spoke network. The results showed that the feasibility of multicopter eVTOL missions is strongly affected by the balance between route distance, payload, cruise duration and usable battery energy. However, a nominal analysis alone is not sufficient to understand the robustness of the proposed operational concept. For this reason, the present chapter investigates how the mission performance changes when the main design, operational and environmental parameters are varied. The objective is to identify which variables have the strongest influence on energy consumption, battery utilisation, power demand and mission feasibility. This sensitivity analysis also makes it possible to define the operating limits of the selected multicopter configuration and to understand under which conditions the analysed routes become feasible, critical or infeasible. The parameters considered in this chapter include cruise speed, payload mass, mission distance, rotor number, rate of climb, ambient temperature and wind condition. Each parameter is varied independently in order to isolate its effect on the mission results. A final combined analysis is then introduced to evaluate the interaction of multiple parameters and to provide a more realistic interpretation of operational constraints. The sensitivity analyses are performed using the same segment-based MATLAB framework described in Chapter 4 and validated in Chapter 5. Unless otherwise specified, the aircraft configuration, battery assumptions and mission architecture remain consistent with the nominal case. In this way, changes in the results can be directly attributed to the parameter being investigated. The chapter concludes by summarising the energy-based operational limits emerging from the parametric analyses. These limits provide useful indications for route planning, payload allocation, battery sizing, reserve management and future infrastructure development within the Aeolian Islands scenario.

7.1. Cruise Speed Sweep

The first sensitivity analysis investigates the effect of cruise speed on the energy performance of the Milazzo–Vulcano mission. In the nominal simulations presented in Chapter 6, the cruise segment was modelled using the paper-consistent formulation based on an equivalent lift-to-drag ratio and a cruise efficiency. This approach is appropriate for comparison with the reference literature model, but it does not explicitly describe how cruise power varies with forward speed. For this reason, a dedicated cruise-speed sweep was developed. In this analysis, the nominal cruise model is replaced by a speed-dependent cruise power model. The purpose is to evaluate how total mission energy, final usable state of charge, energy per unit distance and mission time change when cruise speed is varied. All other mission parameters are kept consistent with the nominal Milazzo–Vulcano case, so that the observed variations can be attributed mainly to the cruise-speed effect.

The cruise speed is varied within a prescribed range, while the following assumptions are maintained:

- the mission route is kept equal to the Milazzo–Vulcano base case;
- the aircraft mass, payload and battery parameters are kept constant;
- the climb, descent, hover, taxi and vertical-flight segments are not re-optimised;
- the cruise segment is assumed to be steady and level;
- air density is kept constant at the nominal value;
- wind is neglected, so cruise airspeed and ground speed are assumed equal;
- the same cruise distance is used for all speed cases;
- the model is intended for mission-level sensitivity analysis, not for high-fidelity rotor aerodynamic optimisation.

The modified cruise model decomposes the cruise power into three main contributions:

$$P_{\text{cruise}}(V) = P_{\text{ind}}(V) + P_{\text{profile}}(V) + P_{\text{parasite}}(V) \quad (7.1)$$

where V is the cruise speed, P_{ind} is the induced power, P_{profile} is the rotor profile power and P_{parasite} is the parasite power associated with the aerodynamic drag of the aircraft body.

The induced power represents the power required by the rotors to generate lift. In forward

flight, the induced velocity decreases as forward speed increases. Therefore, the induced contribution is generally more important at low cruise speeds and decreases as the aircraft accelerates. In the implemented model, the induced power is expressed as:

$$P_{\text{ind}}(V) = \frac{\kappa W v_i(V)}{\eta_{\text{ind}}} \quad (7.2)$$

where W is the aircraft weight, κ is an induced-power correction factor, η_{ind} is the induced-power efficiency and $v_i(V)$ is the induced velocity in forward flight. The hover induced velocity is calculated as:

$$v_h = \sqrt{\frac{W}{2\rho A_R}} \quad (7.3)$$

where ρ is the air density and A_R is the total rotor disc area. The forward-flight induced velocity is obtained from a momentum-theory relation. In simplified form, it is evaluated as a decreasing function of forward speed, so that the induced-power term captures the expected reduction of rotor induced losses as V increases.

The profile power accounts for the aerodynamic losses associated with the rotor blades. In the sweep model, it is represented by a reference profile-power term corrected as a function of the ratio between cruise speed and rotor tip speed:

$$P_{\text{profile}}(V) = P_{\text{profile},0} \left[1 + k_{\text{prof}} \left(\frac{V}{V_{\text{tip}}} \right)^2 \right] \quad (7.4)$$

where $P_{\text{profile},0}$ is the reference profile power, k_{prof} is a correction coefficient and V_{tip} is the representative rotor tip speed. This term varies more gradually with speed than the parasite power and represents the increase in blade aerodynamic losses during forward flight.

The parasite power is associated with the aerodynamic drag of the aircraft body and exposed components. The drag model is based on an equivalent flat-plate area, defined as:

$$f_{\text{eq}} = C_D S_{\text{ref}} \quad (7.5)$$

where C_D is an equivalent drag coefficient and S_{ref} is the reference frontal area of the vehicle. In the MATLAB model, the reference frontal area is estimated from the cabin

dimensions and corrected through a geometric factor:

$$S_{\text{ref}} = k_{\text{geom}} \frac{\pi}{4} b_{\text{cab}} h_{\text{cab}} \quad (7.6)$$

where b_{cab} and h_{cab} are representative cabin width and height, and k_{geom} accounts for the simplified geometric approximation. The parasite power is then computed as:

$$P_{\text{parasite}}(V) = \frac{\frac{1}{2} \rho V^3 f_{\text{eq}}}{\eta_{\text{cruise}}} \quad (7.7)$$

This term scales with the cube of cruise speed. As a result, parasite power is relatively small at low speed but becomes increasingly important at high speed. This behaviour is responsible for the rapid increase in total cruise power at the upper end of the speed range.

For each cruise speed, the cruise time is calculated as:

$$t_{\text{cruise}}(V) = \frac{d_{\text{cruise}}}{V} \quad (7.8)$$

where d_{cruise} is the residual cruise distance after subtracting the horizontal climb and descent distances from the imposed mission distance. The cruise energy is then:

$$E_{\text{cruise}}(V) = \frac{P_{\text{cruise}}(V) t_{\text{cruise}}(V)}{3600} \quad (7.9)$$

with power expressed in watts and time in seconds, so that the resulting energy is obtained in watt-hours.

The total mission energy is computed by combining the speed-dependent cruise energy with the remaining segment contributions:

$$E_{\text{mission}}(V) = E_{\text{fixed}} + E_{\text{cruise}}(V) \quad (7.10)$$

where E_{fixed} includes the energy required for taxi, hover, vertical take-off, forward climb, forward descent, vertical landing and final taxi. These contributions are kept unchanged in the speed sweep. This modelling choice isolates the cruise-speed effect and avoids mixing it with changes in climb profile, payload, battery size or environmental conditions.

The existence of an optimum cruise-speed region results from the opposite behaviour of

the different power components. At low speed, induced power and long cruise duration penalise the mission energy. At high speed, parasite power increases rapidly and again raises the energy demand. Between these two extremes, an intermediate cruise-speed range is expected to provide the best compromise.

The resulting cruise power components are shown in Figure 7.1.

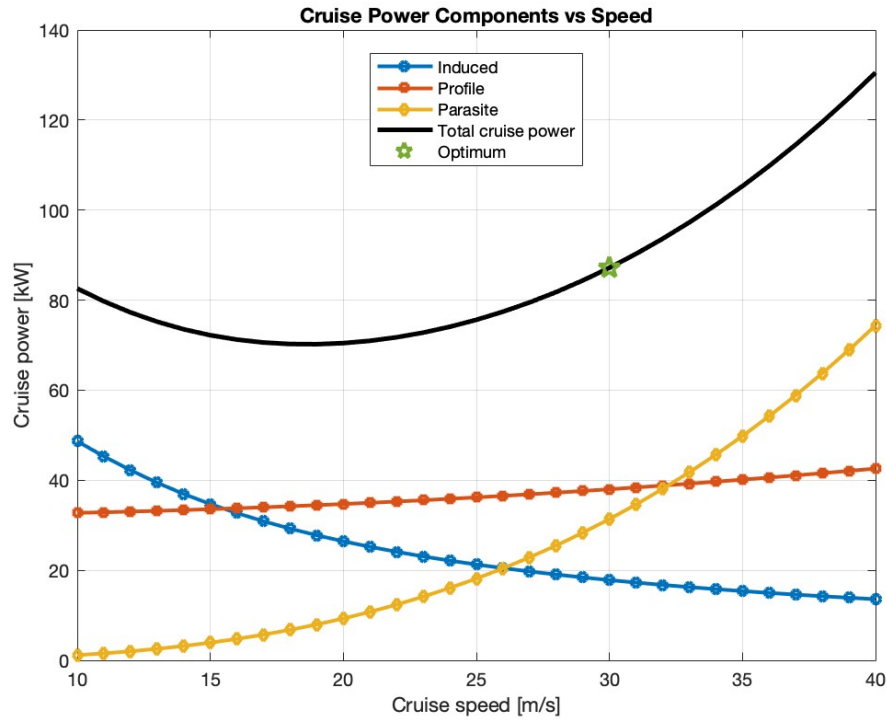


Figure 7.1: Cruise power components as a function of cruise speed for the speed-dependent cruise model.

Figure 7.1 shows the physical origin of the cruise-speed optimum. The induced power decreases as cruise speed increases, because the rotor-induced velocity contribution becomes less demanding in forward flight. The profile power varies more gradually over the analysed speed range, while the parasite power increases rapidly at high speed because of its cubic dependence on cruise speed. The total cruise power is therefore obtained from the balance between these contributions. At low speed, the induced component is dominant; at high speed, the parasite component becomes dominant. Between these two regions, the total cruise power reaches a minimum region.

It is worth noting that the minimum of total cruise power is not necessarily identical to the minimum of total mission energy. Mission energy also depends on flight time, which decreases as cruise speed increases. Therefore, the following figures analyse mission

energy, energy per unit distance and mission time in order to identify the most favourable cruise-speed region from a mission-level perspective.

The total mission energy and final usable state of charge as functions of cruise speed are reported in Figure 7.2.

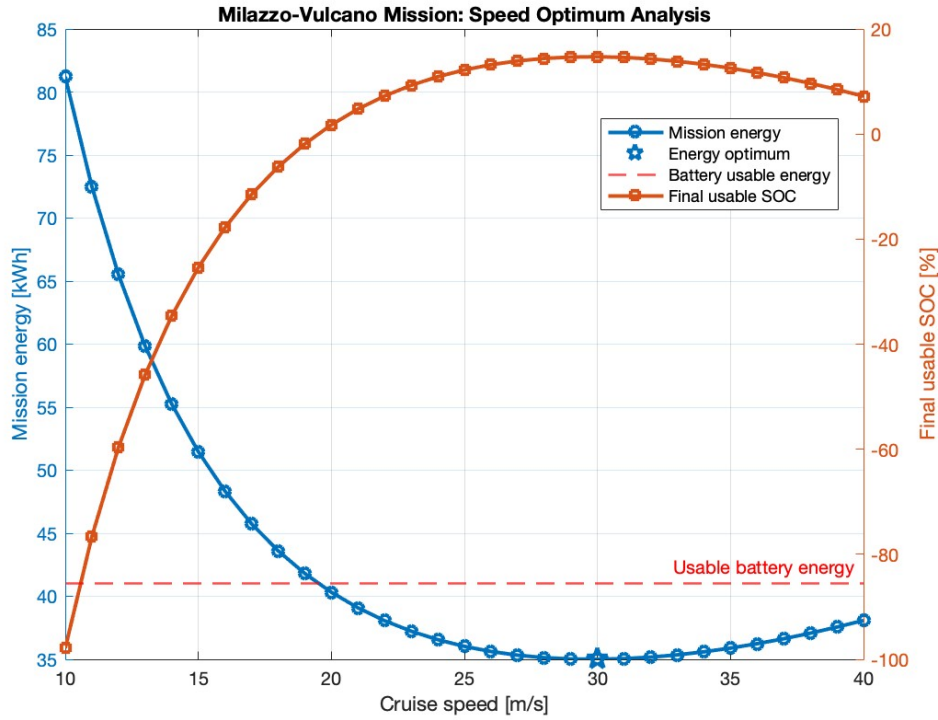


Figure 7.2: Mission energy and final usable SOC as a function of cruise speed for the Milazzo–Vulcano mission.

The results show that the mission energy decreases as cruise speed increases from low values, reaches a minimum region, and then increases again at higher speeds. The same behaviour is reflected in the final usable SOC, which improves as the mission approaches the most efficient speed region and decreases again when the aircraft flies too fast.

It is important to note that the analysis does not identify a single sharp optimum speed, but rather an optimum speed range. Around the minimum, the energy curve is relatively flat, meaning that small variations in cruise speed produce only minor changes in mission energy. This is relevant from an operational point of view, because it suggests that the aircraft does not need to fly at one exact speed to remain close to optimal performance. Instead, a practical cruise-speed band can be selected by considering energy efficiency, mission duration, traffic management, passenger comfort and operational margins.

The energy per unit distance provides a clearer indication of the energetic efficiency of the cruise-speed selection. This metric is reported in Figure 7.3.

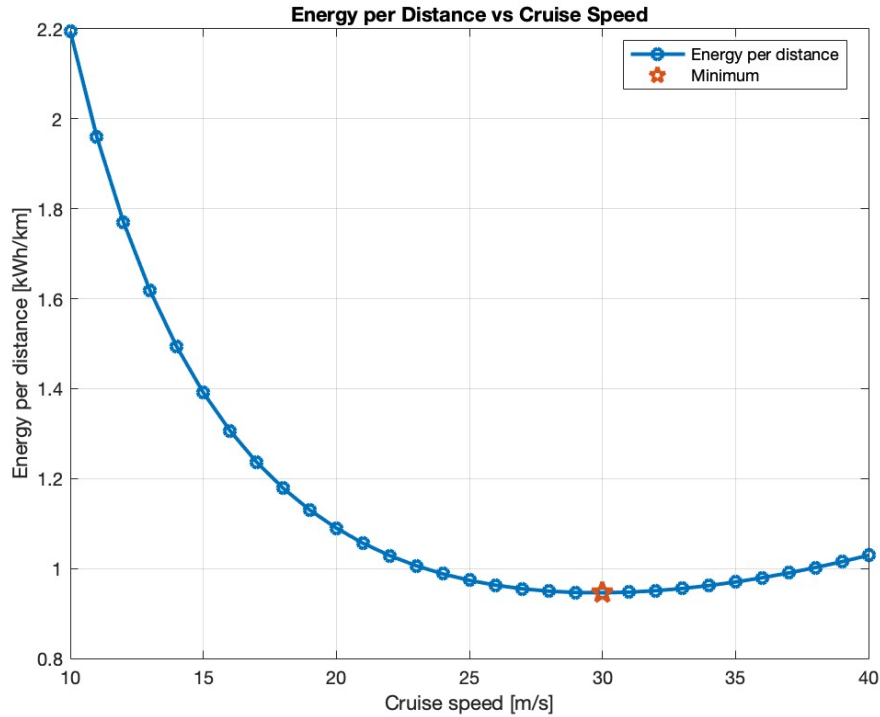


Figure 7.3: Energy per unit distance as a function of cruise speed.

Figure 7.3 confirms the existence of an energetically favourable speed region. At very low speeds, the energy per kilometre is high because the mission duration is long and induced-power effects are significant. As speed increases, the energy per kilometre decreases until it reaches a minimum. Beyond this region, further speed increases cause the parasite power to grow, and the energy per kilometre starts increasing again.

The mission time trend is shown in Figure 7.4.

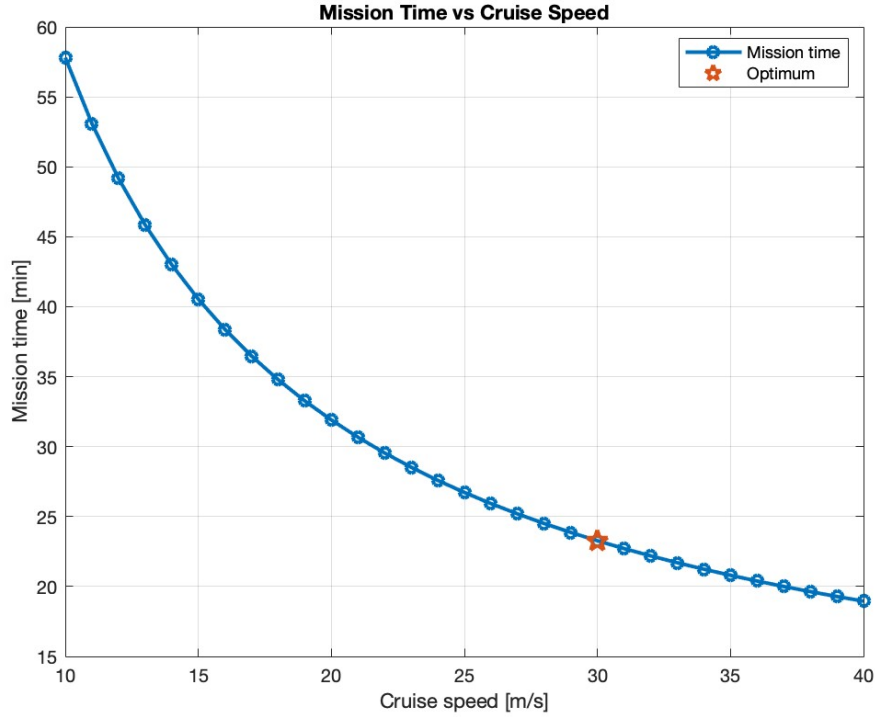


Figure 7.4: Mission time as a function of cruise speed.

As expected, mission time decreases monotonically with cruise speed. This trend is not sufficient by itself to select the cruise speed, because the reduction in time must be balanced against the increase in power at high speeds. The most efficient operating region is therefore not the fastest one, but the region where the combined effect of cruise power and mission duration minimises the total energy demand. Overall, the cruise speed sweep shows that cruise speed is a key operational parameter for the Milazzo–Vulcano mission. Flying too slowly penalises the mission because induced power and long flight time increase energy consumption. Flying too fast reduces mission time but increases parasite power, leading again to higher energy demand. The most favourable condition is found in an intermediate cruise-speed range, around the minimum of the energy and energy-per-distance curves. This result is important for the subsequent operational interpretation of the model. The nominal cruise speed should not be selected only on the basis of travel time, but also considering battery utilisation and energy margin. A moderate cruise-speed range close to the energetic optimum can improve mission feasibility without requiring changes in battery size, payload or aircraft configuration.

7.2. Payload Sweep

The second sensitivity analysis investigates the effect of payload mass on the Milazzo–Vulcano mission. Payload is one of the most important operational parameters for a multicopter eVTOL, because any increase in useful load directly increases the take-off mass and therefore the aircraft weight. As a result, the power required in hover, vertical flight, climb and cruise increases, leading to higher total mission energy and lower battery margin. The payload sweep is performed by varying the payload mass while keeping the remaining mission and aircraft parameters consistent with the nominal Milazzo–Vulcano case. In particular, the route distance, cruise speed, climb and descent settings, rotor configuration, battery mass and environmental conditions are kept unchanged. Therefore, the observed variations in energy consumption, state of charge and peak power are mainly driven by the payload-induced change in take-off mass.

For each payload value, the take-off mass is recomputed as:

$$m_{\text{TO}} = m_{\text{empty}} + m_{\text{payload}} + M_{\text{batt}} \quad (7.11)$$

where m_{empty} is the empty mass, m_{payload} is the useful load and M_{batt} is the installed battery mass. The updated take-off mass is then used in the segment-based mission model to recompute the required energy, maximum power and final battery state of charge.

The main assumptions adopted in the payload sweep are:

- the mission route is kept equal to the Milazzo–Vulcano base case;
- the battery mass and battery characteristics are kept constant;
- the aircraft empty mass is kept constant;
- the cruise speed and mission altitude profile are not re-optimised;
- climb rate, descent rate, hover times and taxi times are kept unchanged;
- wind and temperature are kept at their nominal values;
- only the payload mass and the resulting take-off mass are varied.

This analysis is therefore intended to quantify how much useful load can be carried before the mission becomes constrained by the available battery energy or by the available battery power.

The effect of payload mass on total mission energy is shown in Figure 7.5.

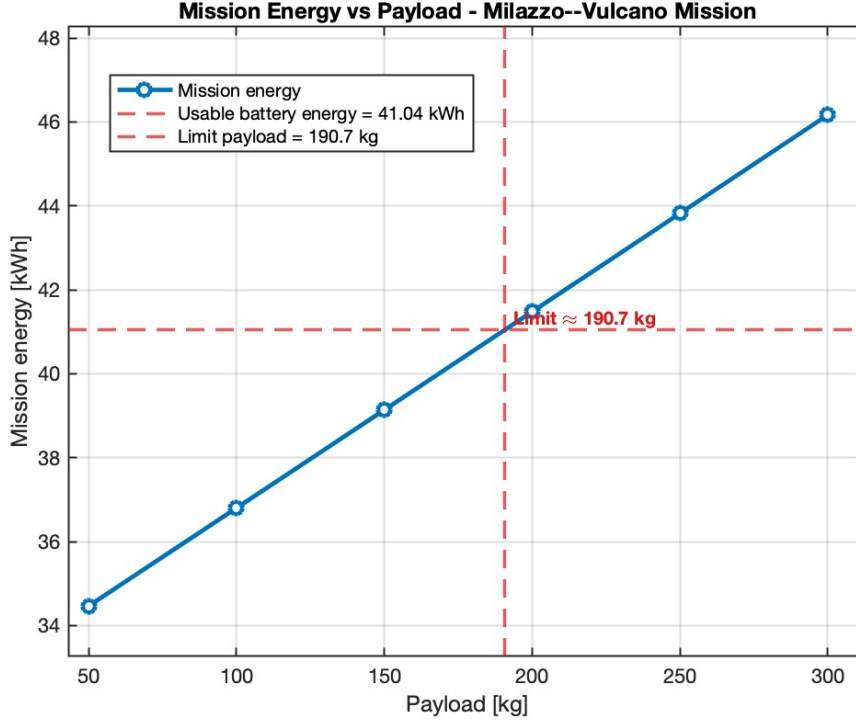


Figure 7.5: Total mission energy as a function of payload mass for the Milazzo–Vulcano mission.

Figure 7.5 shows that the total mission energy increases almost linearly with payload mass. This behaviour is physically expected because a larger payload increases the aircraft weight and therefore the power required throughout the mission. The effect is especially important in the climb and vertical-flight phases, where the aircraft must directly overcome its weight, but it also affects the cruise segment through the increased power required to sustain flight.

The nominal payload used in the base case is 200 kg. At this payload level, the mission energy is slightly higher than the usable battery energy. This confirms the result obtained in Chapter 6: the Milazzo–Vulcano route is close to the energy feasibility boundary under nominal assumptions.

A clearer representation of this boundary is given by the energy margin, defined as:

$$\Delta E = E_{\text{batt,use}} - E_{\text{mission}} \quad (7.12)$$

where $E_{\text{batt,use}}$ is the usable battery energy and E_{mission} is the total mission energy. The corresponding result is reported in Figure 7.6.

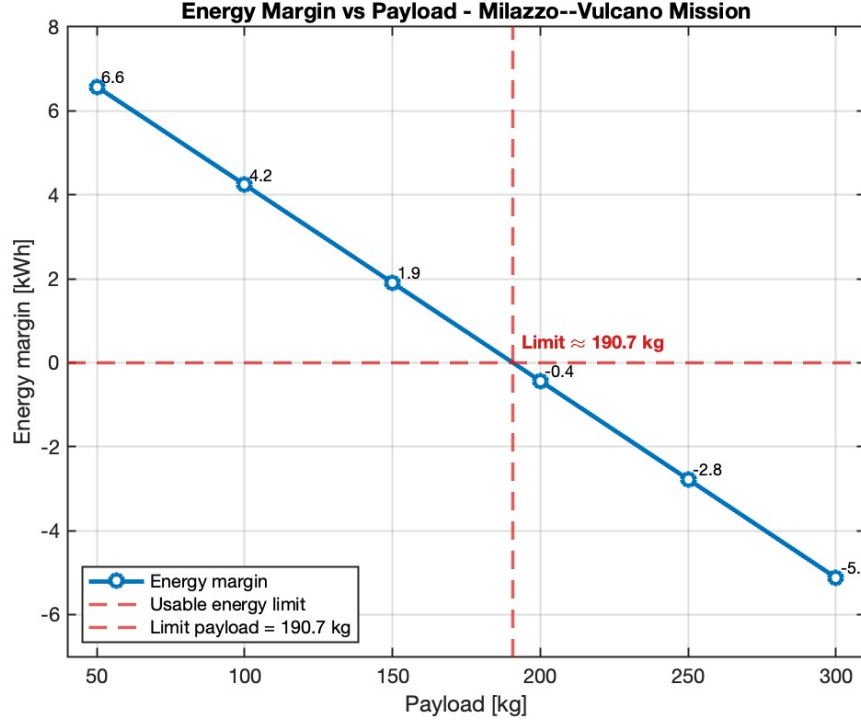


Figure 7.6: Energy margin as a function of payload mass for the Milazzo–Vulcano mission.

Figure 7.6 shows that the energy margin decreases as payload increases. The zero-margin crossing identifies the approximate payload limit for the Milazzo–Vulcano mission under the adopted battery and reserve assumptions. In the present sweep, this limit is approximately:

$$m_{\text{payload,lim}} \simeq 190.7 \text{ kg} \quad (7.13)$$

Payload values below this threshold remain within the usable battery window, whereas payload values above this threshold require more energy than the nominal usable battery capacity. The nominal 200 kg payload is therefore slightly above the estimated energy feasibility limit, which explains the small negative energy margin observed for the base case.

The payload effect can also be interpreted in terms of final physical battery state of charge. This is shown in Figure 7.7.

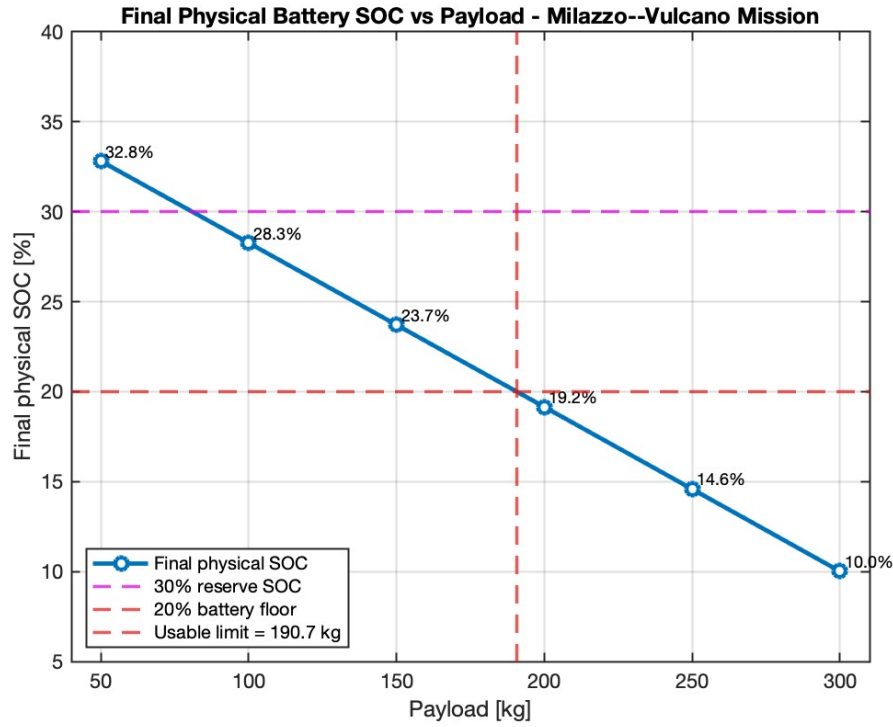


Figure 7.7: Final physical battery state of charge as a function of payload mass.

Figure 7.7 shows that the final physical SOC decreases progressively as payload increases. At low payload values, the mission ends with a physical SOC above the 30% reserve level. As payload increases, the final physical SOC approaches and then falls below the reserve threshold. Around the energy feasibility payload limit, the final physical SOC is close to the 20% battery floor, meaning that the mission starts to violate the operational usable-energy window even though the physical battery is not fully depleted. This distinction is important. The payload limit identified in Figure 7.6 is not a complete physical depletion limit, but an operational energy limit associated with the prescribed usable battery window. Therefore, payload values slightly above the limit may still leave positive physical SOC, but they do not satisfy the reserve requirement adopted in this thesis.

The effect of payload mass on peak mission power is reported in Figure 7.8.

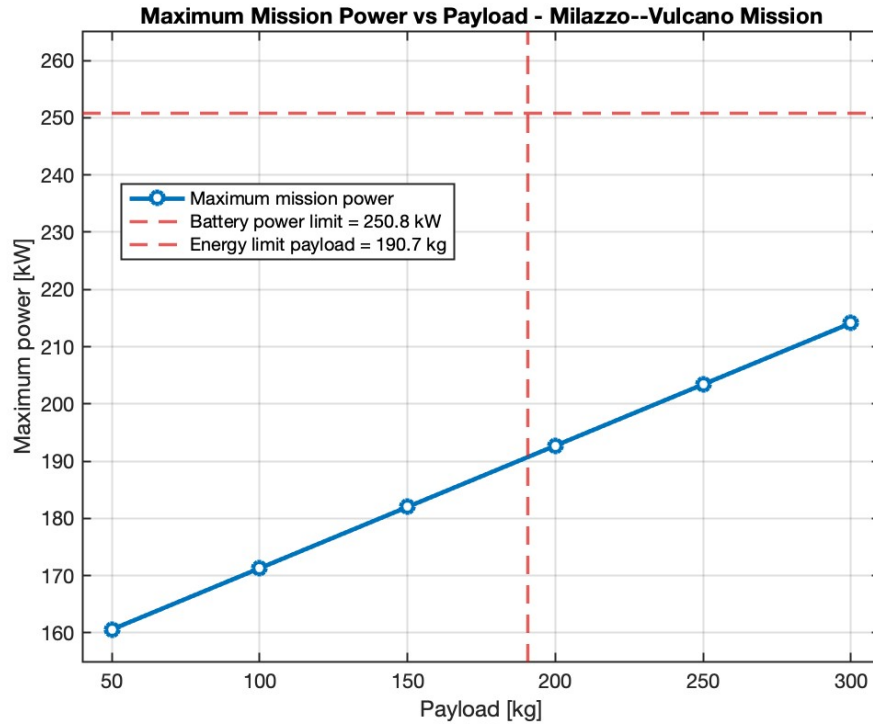


Figure 7.8: Maximum mission power as a function of payload mass.

The maximum mission power increases almost linearly with payload mass. This result is expected because the most demanding segment remains the forward climb phase, whose power requirement is strongly affected by aircraft weight. Nevertheless, over the payload range considered in this sweep, the peak power remains below the available battery power. This confirms that, for the Milazzo–Vulcano mission, the primary limitation associated with payload increase is energy capacity rather than instantaneous power delivery.

The battery state-of-charge profiles for different payload values are shown in Figure 7.9. These profiles provide a time-domain interpretation of the same trend.

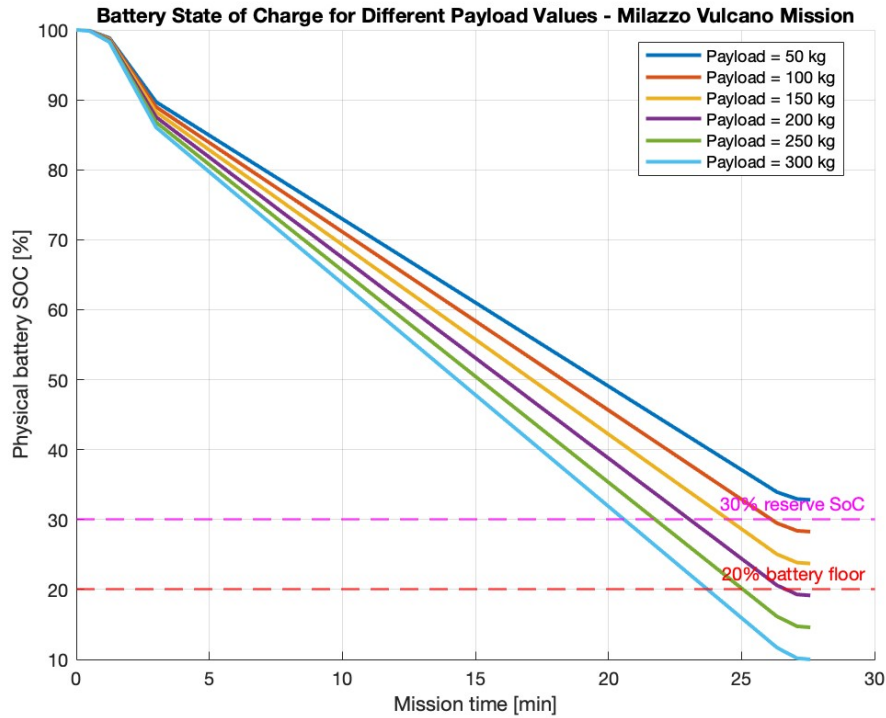


Figure 7.9: Physical battery state of charge profiles for different payload values during the Milazzo–Vulcano mission.

Figure 7.9 shows that higher payload values produce a faster decrease in battery state of charge throughout the mission. The separation between the curves becomes more evident during the long cruise portion, where the increased mass continues to affect the required power over an extended time interval. Lower payload cases remain above the reserve threshold, while heavier payload cases approach or fall below the preferred reserve band and battery floor. The payload sweep therefore highlights a strong trade-off between useful load and mission feasibility. Reducing payload improves the energy margin and increases the final state of charge, while increasing payload rapidly moves the mission toward or beyond the usable battery limit. For the Milazzo–Vulcano route, the nominal 200 kg payload is very close to the energy feasibility boundary, and the estimated payload limit is approximately 190.7 kg under the adopted assumptions. Overall, the analysis shows that payload is one of the dominant parameters controlling eVTOL mission feasibility. The mission remains power-feasible over the analysed payload range, but it becomes energy-constrained when the payload exceeds the usable-energy limit. This confirms that payload management is a critical operational lever for short-range multicopter eVTOL missions, especially when the route distance is close to the maximum achievable range of the selected battery configuration.

7.3. Distance Sweep

The third sensitivity analysis investigates the effect of mission distance on the energy performance and feasibility of the multicopter eVTOL mission. Unlike the previous payload sweep, where the route geometry was kept fixed and the aircraft mass was varied, this analysis keeps the aircraft configuration unchanged and varies only the imposed point-to-point mission distance. The objective is to determine how total mission energy, energy margin, required battery mass and energy per unit distance evolve as the route length increases. This analysis is particularly important for the Aeolian Islands scenario, because the considered network includes both short inter-island connections and longer routes towards the more distant islands. The distance sweep is performed by varying the mission distance over a prescribed range while keeping the nominal aircraft and mission parameters unchanged. In particular, the payload mass, battery mass, rotor configuration, cruise speed, climb rate, descent rate, hover times and environmental conditions are kept equal to the nominal Milazzo–Vulcano case. Therefore, the observed variations are mainly caused by the increase or decrease of the cruise segment. For each imposed mission distance, the model first verifies the geometric compatibility of the route. Since part of the horizontal distance is covered during forward climb and forward descent, the residual cruise distance is computed as:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (7.14)$$

where d_{mission} is the imposed point-to-point distance, while d_{climb} and d_{desc} are the horizontal distances covered during the climb and descent phases. A mission is geometrically feasible only if:

$$d_{\text{cruise}} > 0 \quad (7.15)$$

This condition is relevant for very short routes. If the imposed distance is lower than the sum of the climb and descent horizontal distances, the aircraft cannot complete the prescribed altitude profile and still include a positive cruise segment. Under the nominal assumptions adopted in this analysis, the minimum geometric distance is approximately:

$$d_{\text{min,geom}} = d_{\text{climb}} + d_{\text{desc}} \simeq 5.9 \text{ km} \quad (7.16)$$

Therefore, route distances below this value are not compatible with the selected mission

geometry unless the climb and descent profiles are modified.

The total mission energy as a function of mission distance is shown in Figure 7.10.

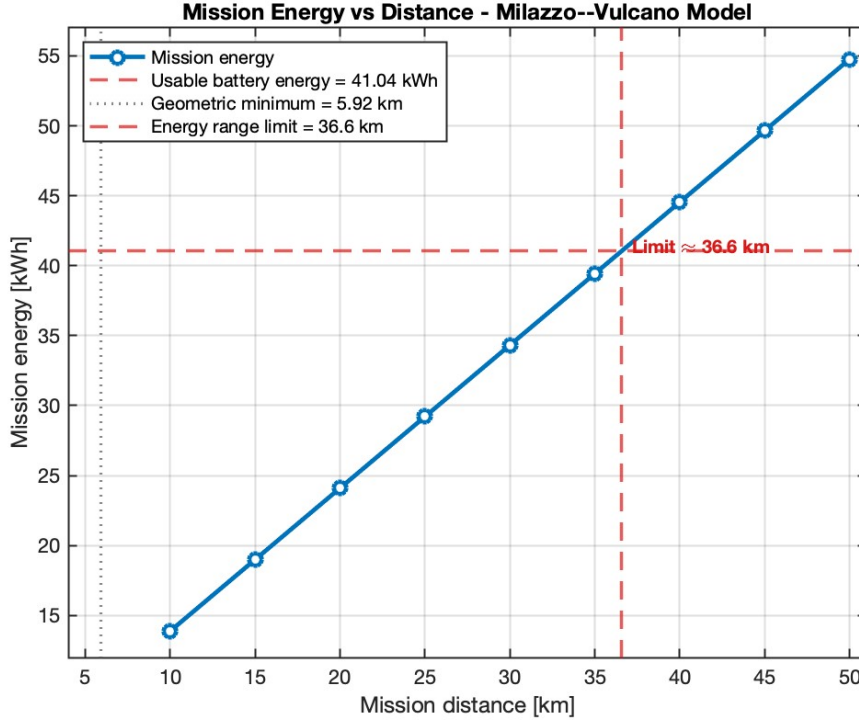


Figure 7.10: Mission energy as a function of mission distance.

Figure 7.10 shows that the mission energy increases with distance. This behaviour is expected because, after the fixed climb and descent contributions have been accounted for, any additional distance mainly increases the duration of the cruise segment. Since the nominal cruise power is approximately constant in this sweep, the increase in cruise time produces an almost linear increase in total mission energy.

The usable battery energy is also reported in the figure as a reference threshold. The intersection between the mission energy curve and the usable battery energy level identifies the approximate maximum distance that can be flown while remaining inside the nominal usable battery window. This distance represents the energy-limited range of the selected configuration under the adopted payload, battery and reserve assumptions.

The same result can be interpreted more directly through the energy margin:

$$\Delta E = E_{\text{batt,use}} - E_{\text{mission}} \quad (7.17)$$

The energy margin as a function of mission distance is reported in Figure 7.11.

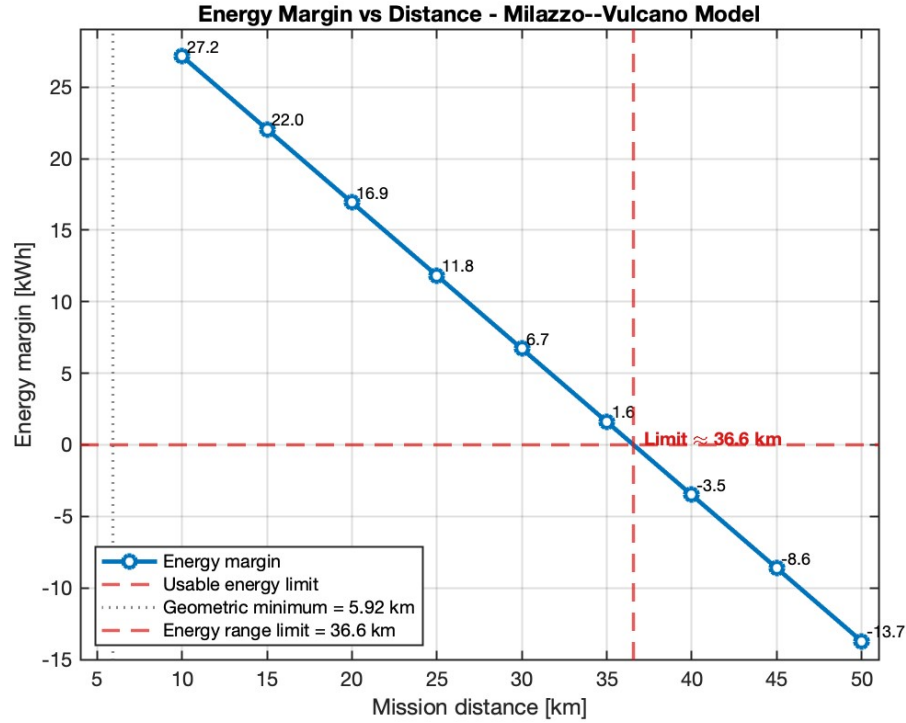


Figure 7.11: Energy margin as a function of mission distance.

Figure 7.11 clearly shows the transition from feasible to energy-critical distances. Positive margin values indicate missions that remain within the usable battery window, while negative values indicate missions that require more energy than the nominal usable capacity. The zero-margin crossing provides the approximate energy range limit. For the nominal configuration, this limit is close to the Milazzo–Vulcano distance, confirming that the 37 km base case lies very close to the boundary of the available usable battery energy.

This result is consistent with the findings of Chapter 6, where the Milazzo–Vulcano mission was shown to exceed the usable battery energy by a small amount. The distance sweep generalises that result by showing that the base case is not an isolated condition, but part of a broader transition region between feasible and infeasible mission distances.

The required battery mass as a function of mission distance is shown in Figure 7.12.

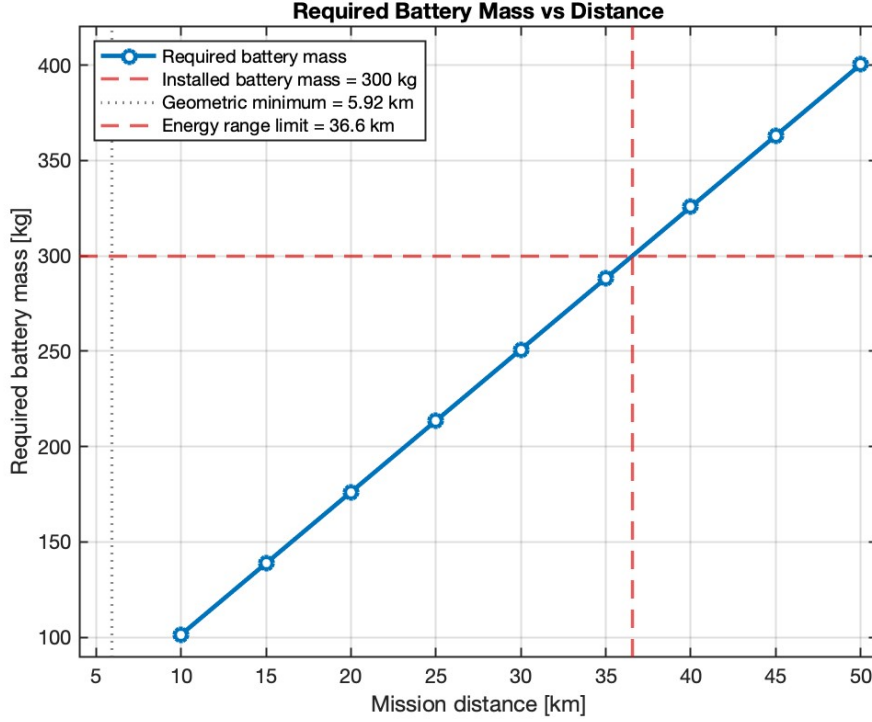


Figure 7.12: Required battery mass as a function of mission distance.

Figure 7.12 provides a complementary interpretation of the range limitation. For each mission distance, the required battery mass is computed as the battery mass that would be needed to supply the mission energy while preserving the same specific energy, efficiency and usable depth-of-discharge assumptions:

$$M_{\text{batt,req}} = \frac{E_{\text{mission}}}{E^* \eta_{\text{batt}} DoD} \quad (7.18)$$

where E^* is the battery specific energy, η_{batt} is the battery efficiency and DoD is the usable depth of discharge. The installed battery mass is shown as a reference value. When the required battery mass exceeds the installed battery mass, the mission cannot be completed within the nominal usable battery capacity.

This representation is useful because it shows how much additional battery mass would be required to extend the route distance without changing the battery technology or the reserve policy. However, increasing battery mass is not a neutral modification for a multicopter eVTOL, because it also increases take-off mass and therefore affects the power and energy required by the aircraft. For this reason, the required battery mass curve should be interpreted as a first-order indicator rather than as a complete aircraft

resizing solution.

The energy required per unit distance is reported in Figure 7.13.

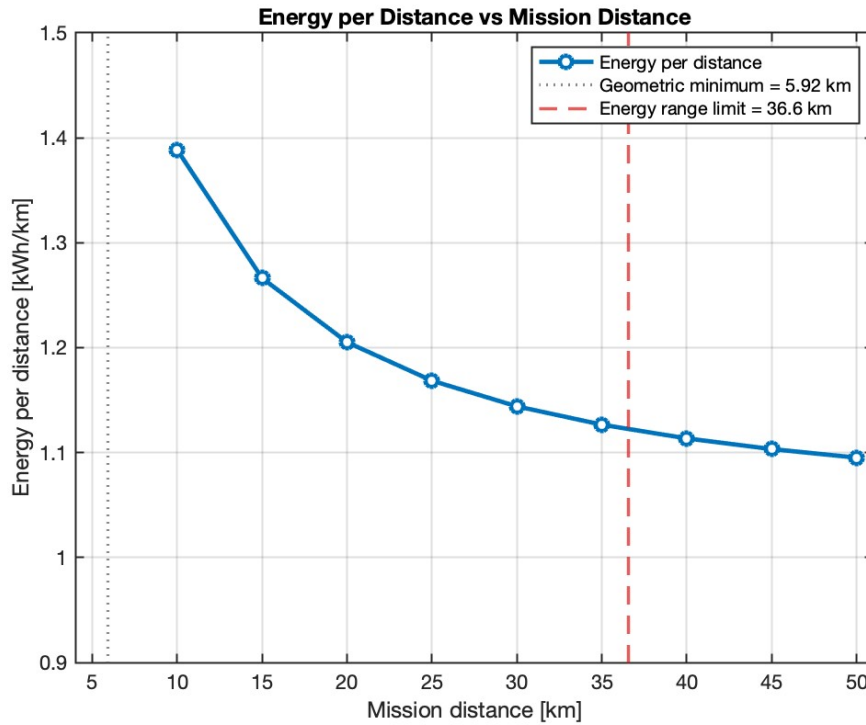


Figure 7.13: Energy per unit distance as a function of mission distance.

Figure 7.13 shows that the energy per kilometre is higher for short routes and decreases as the distance increases. This behaviour is caused by the fixed energy contributions associated with taxi, hover, vertical take-off, climb, descent, landing and final taxi. These contributions are almost independent of the imposed route distance in the present sweep. On short routes, they represent a large fraction of the total energy and are distributed over a small distance, increasing the energy per kilometre. On longer routes, the cruise segment becomes dominant and the fixed contributions are spread over a larger distance.

This result is important for the interpretation of short inter-island missions. A shorter route does not necessarily imply a lower energy consumption per kilometre, because the aircraft must still complete the same take-off, climb, descent and landing sequence. Therefore, distance alone is not sufficient to describe mission efficiency; the ratio between fixed segment contributions and cruise distance must also be considered.

If included, the final usable state of charge as a function of distance is shown in Figure 7.14.

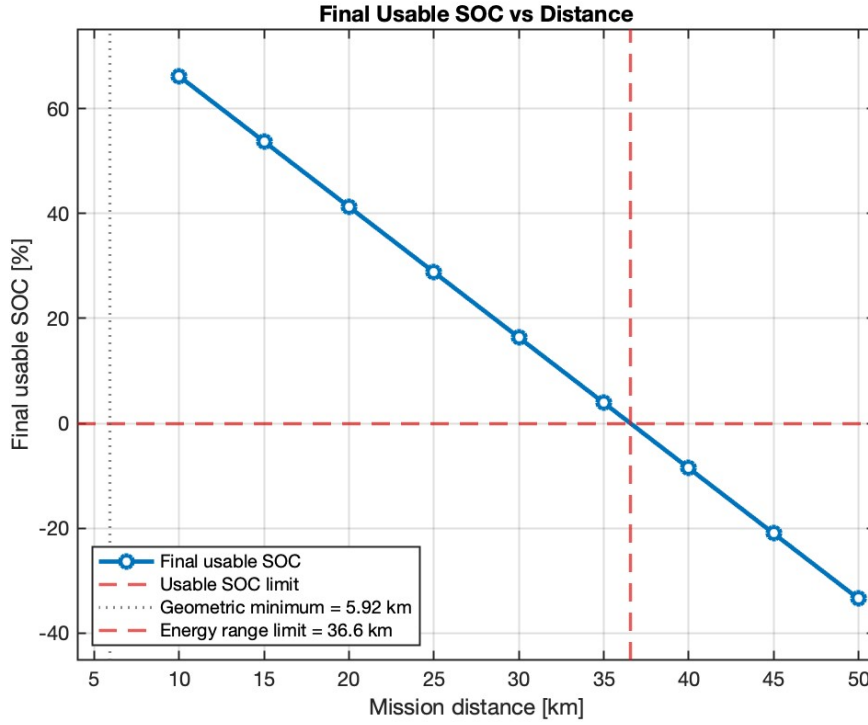


Figure 7.14: Final usable state of charge as a function of mission distance.

Figure 7.14 expresses the same energy limitation in terms of battery state of charge. As mission distance increases, the final usable SOC decreases and eventually crosses the zero threshold. This crossing corresponds to the same range limit identified by the energy margin plot. The SOC representation is useful because it directly connects the distance sweep to the operational battery window used throughout the thesis. Overall, the distance sweep confirms that mission distance is one of the dominant drivers of energy feasibility. The peak power demand remains essentially governed by the common climb and vertical-flight conditions, while the total mission energy and battery margin are strongly affected by the length of the cruise segment. The nominal Milazzo–Vulcano route is located close to the energy range boundary, which explains why it appears energy-critical under the baseline assumptions. The analysis also shows that the selected multicopter configuration is well suited to short and medium inter-island routes, but becomes progressively constrained as the route distance approaches and exceeds the energy-limited range. Longer routes would require either reduced payload, improved battery energy density, increased usable battery capacity, more favourable operating conditions or an alternative network architecture based on intermediate stops and recharging opportunities.

7.4. Rotor Count Sweep

The rotor count sweep investigates the influence of the number of rotors on the Milazzo–Vulcano mission performance. In this analysis, the rotor diameter is kept constant while the number of rotors is varied. As a consequence, changing the rotor count directly modifies the total rotor disc area and therefore the disc loading of the aircraft.

The purpose of this sweep is to evaluate whether increasing the number of rotors can reduce the power required in rotor-borne flight and improve the overall energy balance of the mission. All other aircraft and mission parameters are kept consistent with the nominal Milazzo–Vulcano case, including payload mass, battery mass, mission distance, climb and descent settings, cruise speed and environmental conditions.

For each rotor count, the total rotor disc area is computed as:

$$A_R = n_{\text{rotor}} \frac{\pi D_R^2}{4} \quad (7.19)$$

where n_{rotor} is the number of rotors and D_R is the single rotor diameter. Since D_R is kept constant in this sweep, increasing the rotor count increases the total rotor disc area. The corresponding disc loading is:

$$DL = \frac{W}{A_R} \quad (7.20)$$

where W is the aircraft weight. A lower disc loading generally reduces the induced velocity required to generate lift and therefore reduces the hover and vertical-flight power demand.

The main assumptions adopted in this sweep are:

- the Milazzo–Vulcano route distance is kept fixed;
- the aircraft mass, payload and battery mass are kept constant;
- the single rotor diameter is kept constant;
- varying rotor count changes the total rotor disc area;
- the cruise and descent models are kept consistent with the nominal mission setup;
- climb, descent, hover and taxi settings are not re-optimised;
- the analysis is intended as a mission-level sensitivity study, not as a detailed rotor-system redesign.

The effect of rotor count on disc loading is shown in Figure 7.15.

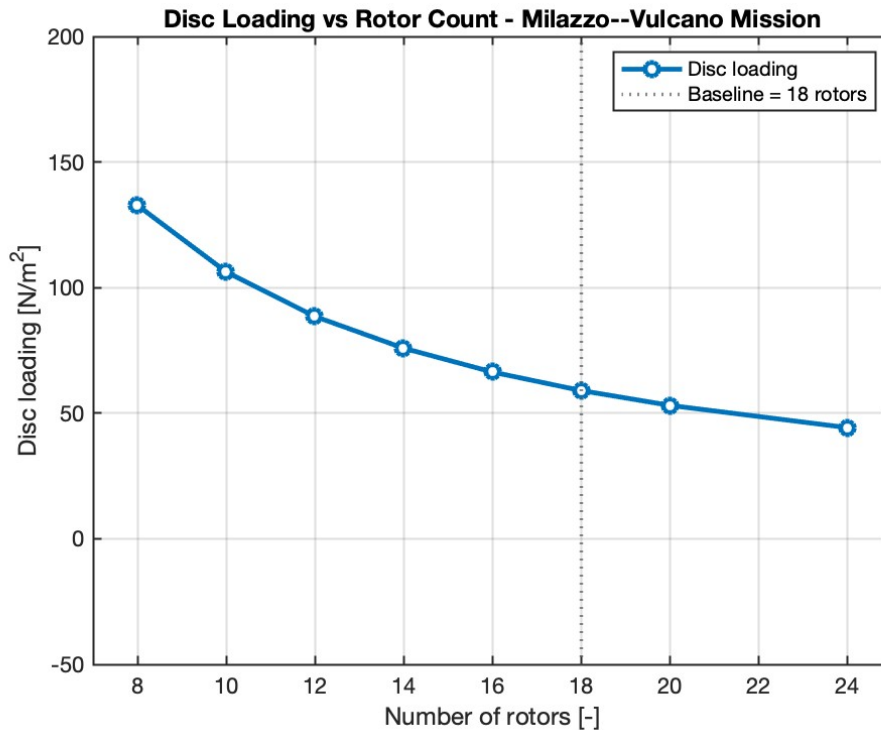


Figure 7.15: Disc loading as a function of rotor count for the Milazzo–Vulcano mission.

Figure 7.15 shows that disc loading decreases as the number of rotors increases. This is a direct consequence of the larger total rotor disc area. The reduction is more pronounced when moving from low rotor counts to intermediate rotor counts, while the curve becomes progressively flatter at higher rotor numbers. This indicates diminishing returns: adding rotors continues to reduce disc loading, but the incremental benefit becomes smaller.

The corresponding hover power trend is reported in Figure 7.16.

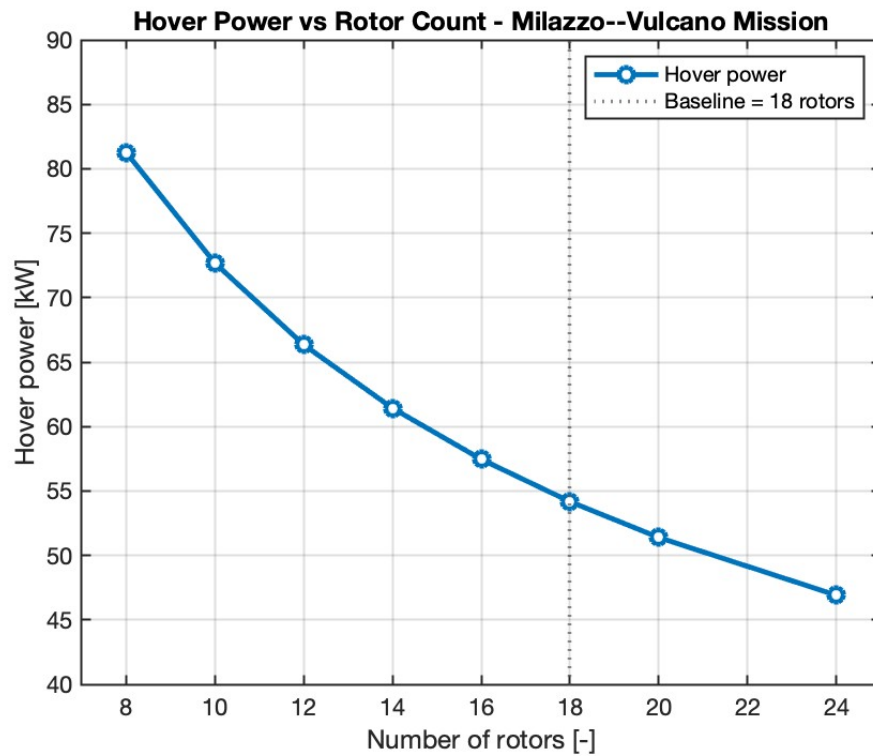


Figure 7.16: Hover power as a function of rotor count for the Milazzo–Vulcano mission.

Figure 7.16 confirms that hover power decreases when the number of rotors increases. This behaviour is physically consistent with momentum theory: for a given aircraft weight, increasing the total disc area reduces the induced velocity and therefore the induced power required to remain in hover. However, as for disc loading, the improvement becomes less pronounced at higher rotor counts.

The impact of rotor count on total mission energy is shown in Figure 7.17.

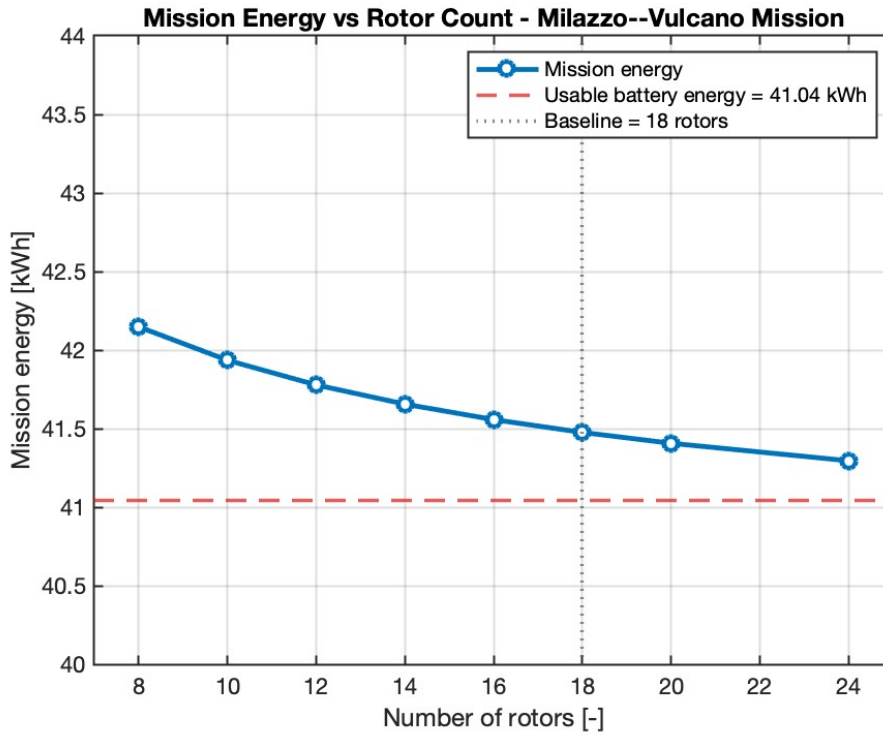


Figure 7.17: Mission energy as a function of rotor count for the Milazzo–Vulcano mission.

Figure 7.17 shows that total mission energy decreases as rotor count increases. The reduction is not as large as the reduction observed in hover power, because the Milazzo–Vulcano mission is dominated by the cruise segment. In the adopted mission model, the main effect of rotor count is therefore concentrated on rotor-borne and climb-related phases, while the cruise contribution remains comparatively less sensitive to this parameter.

This result is important because it shows that increasing rotor count can improve the energy balance, but it cannot completely compensate for a route that is dominated by cruise energy. The benefit is real, but limited by the relative weight of the affected segments in the total mission energy.

The same trend is shown more directly through the energy margin in Figure 7.18.

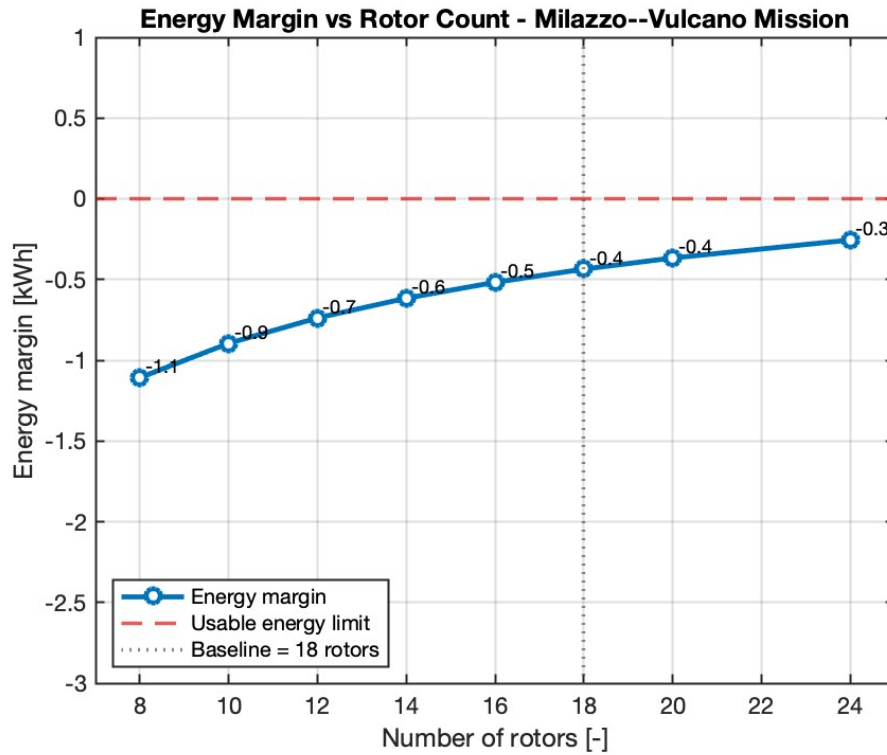


Figure 7.18: Energy margin as a function of rotor count for the Milazzo–Vulcano mission.

Figure 7.18 shows that the energy margin improves as the number of rotors increases. Nevertheless, in the analysed range the margin remains close to zero and slightly negative for the nominal configuration. This confirms that the Milazzo–Vulcano mission is located near the usable battery-energy boundary. Increasing rotor count improves the result, but the effect is not large enough to radically change the mission classification unless additional improvements are also introduced. The maximum mission power was also evaluated during the sweep. The results show that the peak power remains essentially constant with rotor count in the implemented model. This occurs because the maximum power is governed by the forward climb segment, which is treated through the paper-consistent mission formulation and is not strongly affected by the rotor-count variation adopted in this sweep. For this reason, the peak-power plot is not reported as a separate figure. The relevant effect of rotor count is instead captured by disc loading, hover power, total energy and energy margin. Overall, the rotor count sweep shows that increasing the number of rotors reduces disc loading and hover power, leading to a modest improvement in total mission energy and energy margin. However, the benefit is limited because the cruise segment remains the dominant contributor to total energy consumption for the Milazzo–Vulcano route. Therefore, rotor count is an important design parameter for ver-

tical and low-speed flight efficiency, but it is not sufficient by itself to overcome the main energy limitation of the mission. From an aircraft design perspective, increasing rotor count would also introduce additional considerations not explicitly modelled in this analysis, such as structural mass, motor and inverter mass, maintenance complexity, control redundancy, aerodynamic interference and integration constraints. Therefore, the sweep should be interpreted as a mission-level sensitivity study under simplified assumptions rather than as a complete rotor-system optimisation.

7.5. Rate of Climb Sweep

The rate of climb sweep investigates the influence of the selected climb rate on the geometric structure of the mission. Unlike the previous sensitivity analyses, this section does not focus primarily on total energy consumption, but on the minimum mission distance required to complete the prescribed climb and descent profile while retaining a positive cruise segment. This analysis is particularly relevant for short inter-island routes. In a segment-based mission model, part of the horizontal distance is covered during forward climb and forward descent. Therefore, if the route distance is too short, the aircraft may not have enough horizontal distance to perform the selected climb and descent manoeuvres while also including a cruise phase. In this sense, the rate of climb affects the geometric feasibility of the mission.

For a given cruise altitude, the forward-climb height is:

$$h_{\text{climb}} = h_{\text{cruise}} - h_{\text{VTO}} \quad (7.21)$$

while the forward-descent height is:

$$h_{\text{desc}} = h_{\text{cruise}} - h_{\text{VLAND}} \quad (7.22)$$

For each value of rate of climb, the climb time is evaluated as:

$$t_{\text{climb}} = \frac{h_{\text{climb}}}{RoC} \quad (7.23)$$

and, assuming the rate of descent is varied consistently with the rate of climb, the descent time is:

$$t_{\text{desc}} = \frac{h_{\text{desc}}}{RoD} \quad (7.24)$$

The corresponding horizontal distances covered during climb and descent are then computed as:

$$d_{\text{climb}} = V_{\text{climb}} t_{\text{climb}} \quad (7.25)$$

$$d_{\text{desc}} = V_{\text{desc}} t_{\text{desc}} \quad (7.26)$$

The minimum mission distance required to preserve a positive cruise segment is therefore:

$$d_{\text{min}} = d_{\text{climb}} + d_{\text{desc}} \quad (7.27)$$

A route is geometrically compatible with the selected altitude profile only if:

$$d_{\text{mission}} > d_{\text{min}} \quad (7.28)$$

The main assumptions adopted in this sweep are:

- the cruise altitude, vertical take-off height and vertical landing height are kept constant;
- the forward climb and descent speeds are kept constant;
- the rate of descent is varied consistently with the rate of climb;
- the analysis is geometric and does not recompute the full mission energy balance;
- higher rate-of-climb values are interpreted as more performance-oriented operating conditions;
- lower rate-of-climb values are interpreted as more comfort-oriented and less aggressive vertical profiles.

The effect of rate of climb on the minimum required mission distance is shown in Figure 7.19.

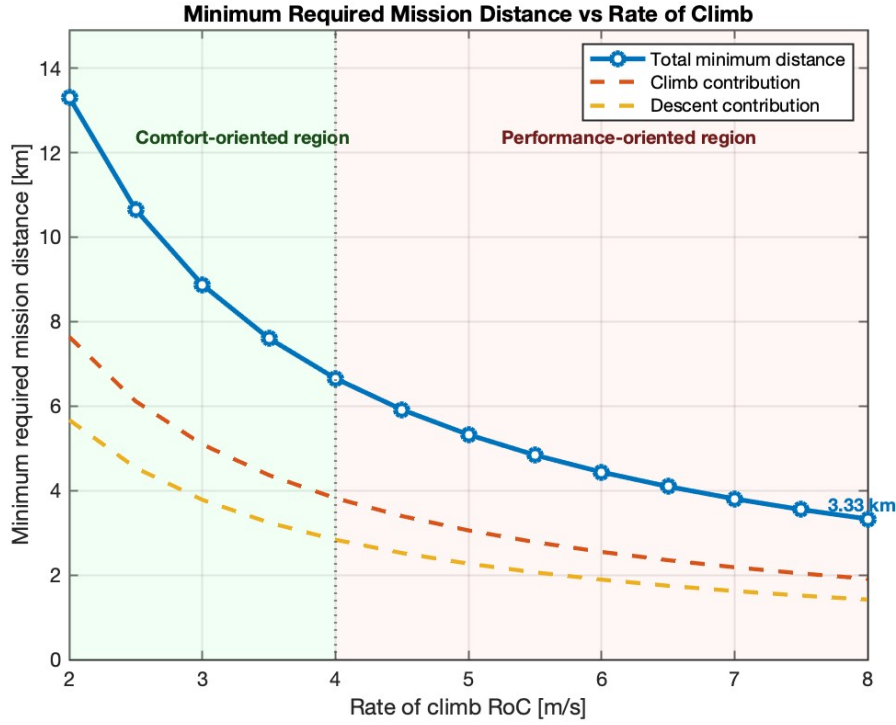


Figure 7.19: Minimum required mission distance as a function of rate of climb.

Figure 7.19 shows that the minimum required mission distance decreases as the rate of climb increases. This behaviour is expected because, for a fixed climb height and fixed forward climb speed, a higher rate of climb reduces the time spent in the climb segment. As a consequence, the horizontal distance covered during climb decreases. The same reasoning applies to the descent segment when the rate of descent is increased consistently.

The total minimum distance is the sum of the climb and descent contributions. At low rate-of-climb values, the aircraft spends more time in climb and descent, and therefore consumes a larger horizontal distance before and after the cruise phase. This makes very short routes more difficult to accommodate within the selected altitude profile. At higher rate-of-climb values, the climb and descent manoeuvres become more compact, reducing the minimum distance required by the mission geometry.

The numerical results highlight this trend clearly. For example, at:

$$RoC = 3 \text{ m/s} \quad (7.29)$$

the minimum required mission distance is approximately:

$$d_{\min} \simeq 8.87 \text{ km} \quad (7.30)$$

whereas at:

$$RoC = 6 \text{ m/s} \quad (7.31)$$

the minimum required mission distance decreases to approximately:

$$d_{\min} \simeq 4.44 \text{ km} \quad (7.32)$$

This result is important for the interpretation of short routes in the Aeolian Islands network. The Lipari–Vulcano route, for example, has a distance of approximately 9 km. With a low rate of climb, this route is only marginally compatible with the selected altitude profile, because most of the mission distance is consumed by climb and descent. With a higher rate of climb, the same route becomes geometrically less constrained, leaving a larger portion of the mission available for cruise. However, increasing the rate of climb should not be interpreted as a free improvement. A higher rate of climb generally implies a more demanding vertical performance requirement and may increase the power demand during the climb segment. It may also affect passenger comfort, noise, operational procedures and safety margins. Therefore, the rate of climb introduces a trade-off between geometric compactness and operational aggressiveness. For this reason, the figure distinguishes between a more comfort-oriented region and a more performance-oriented region. Lower values of rate of climb are associated with smoother vertical profiles but require longer horizontal distances to complete the altitude transition. Higher values reduce the minimum mission distance and can enlarge the set of geometrically feasible short routes, but they may require more demanding aircraft performance. Overall, the rate of climb sweep shows that climb-profile selection can influence the operational envelope of short eVTOL missions. In particular, it can affect whether short inter-island routes can be flown using the prescribed cruise altitude and segment structure. This parameter therefore plays an important role in the definition of mission geometry, especially for short routes where climb and descent distances represent a large fraction of the total route length.

7.6. Temperature Sweep

The temperature sweep investigates the influence of ambient temperature on the battery energy available for the Milazzo–Vulcano mission. Unlike the previous sensitivity analyses, the mission trajectory, aircraft mass, payload, rotor configuration and aerodynamic model are kept unchanged. The total mission energy therefore remains essentially constant, while the available battery energy is corrected as a function of temperature. This analysis is introduced because lithium-ion battery capacity is sensitive to operating temperature. At low temperature, electrochemical limitations reduce the amount of usable energy that can be extracted from the cell. At higher temperature, the short-term available capacity may increase; however, this does not necessarily imply that high-temperature operation is preferable, since elevated temperatures can accelerate ageing and degradation mechanisms. In this thesis, the temperature sweep is therefore interpreted as a mission-level available-energy analysis, not as a complete battery ageing study. Publicly available information on the reference eVTOL aircraft does not provide a complete pack-level capacity-temperature curve or cell-level identification. For this reason, a surrogate-cell approach is adopted. The empirical temperature-capacity correction is based on published data for the Molicel INR21700-P45B high-power lithium-ion cell at 4.5 A discharge. This surrogate is not intended to represent the exact battery pack of the reference aircraft, but it provides a transparent and data-based way to include temperature effects without inventing unavailable pack-level coefficients.

The capacity correction factor is obtained from an exponential empirical relation of the form:

$$Q(T) = Q_{\text{ref}} \exp \left[A_1 \left(\frac{1}{T} - \frac{1}{T_{\text{ref}}} \right) + A_2 \left(\frac{1}{T} - \frac{1}{T_{\text{ref}}} \right)^2 \right] \quad (7.33)$$

where T is the absolute temperature in Kelvin, T_{ref} is the reference temperature and A_1 , A_2 are empirical coefficients identified from the surrogate-cell capacity data. In the implemented model, the correction is used in normalised form:

$$k_Q(T) = \frac{Q(T)}{Q_{\text{ref}}} \quad (7.34)$$

The usable battery energy is then corrected as:

$$E_{\text{batt,use}}(T) = E_{\text{batt,use,ref}} k_Q(T) \quad (7.35)$$

where $E_{\text{batt,use,ref}}$ is the nominal usable battery energy at the reference temperature. Similarly, the physical battery energy after efficiency but before applying the usable depth-of-discharge window is corrected using the same factor:

$$E_{\text{batt,phys}}(T) = E_{\text{batt,phys,ref}} k_Q(T) \quad (7.36)$$

Only the battery energy capacity is corrected in this analysis. The available battery power is kept at the nominal value because no reliable public pack-level power-temperature curve is available for the considered aircraft. Therefore, the temperature sweep evaluates the effect of temperature on energy feasibility, while power feasibility remains governed by the nominal power margin.

The main assumptions adopted in this sweep are:

- the Milazzo–Vulcano route distance is kept fixed;
- the aircraft mass, payload and battery mass are kept constant;
- the mission energy demand is not temperature-corrected;
- only the available battery energy is corrected as a function of temperature;
- battery power capability is kept nominal;
- the correction factor is derived from a declared surrogate cell, not from the actual aircraft battery pack;
- the analysis represents short-term mission feasibility and does not model long-term thermal degradation.

The resulting capacity correction factor is shown in Figure 7.20.

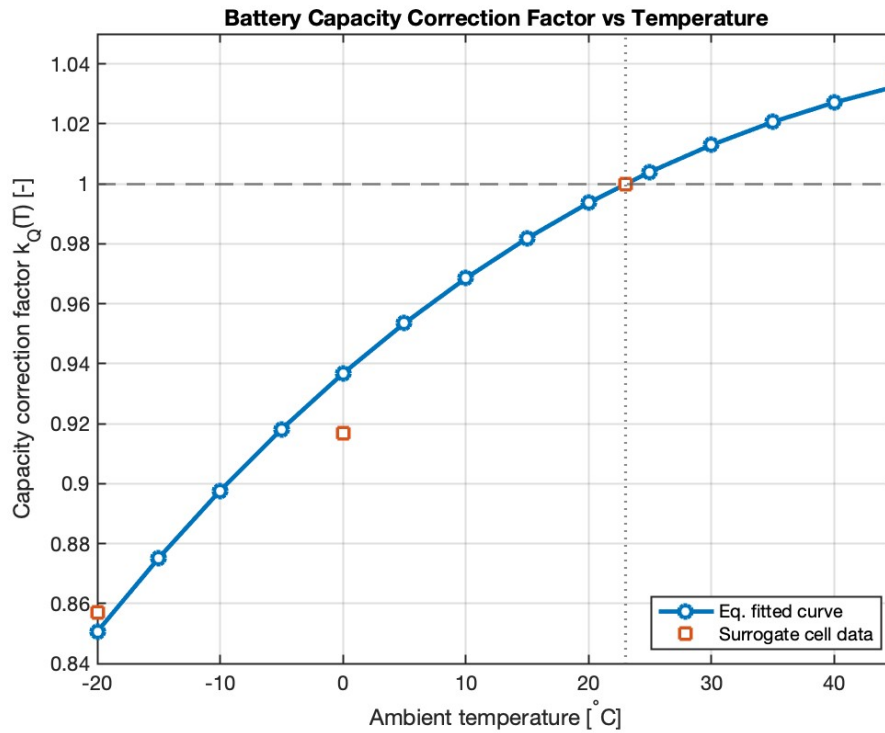


Figure 7.20: Battery capacity correction factor as a function of ambient temperature, based on the surrogate-cell empirical fit.

Figure 7.20 shows that the available capacity decreases significantly at low temperature and increases slightly above the reference temperature. The fitted curve follows the surrogate-cell data and provides the correction factor used to scale the available battery energy in the mission analysis.

The effect of this correction on the available energy is shown in Figure 7.21, where the mission energy is compared with the corrected usable battery energy.

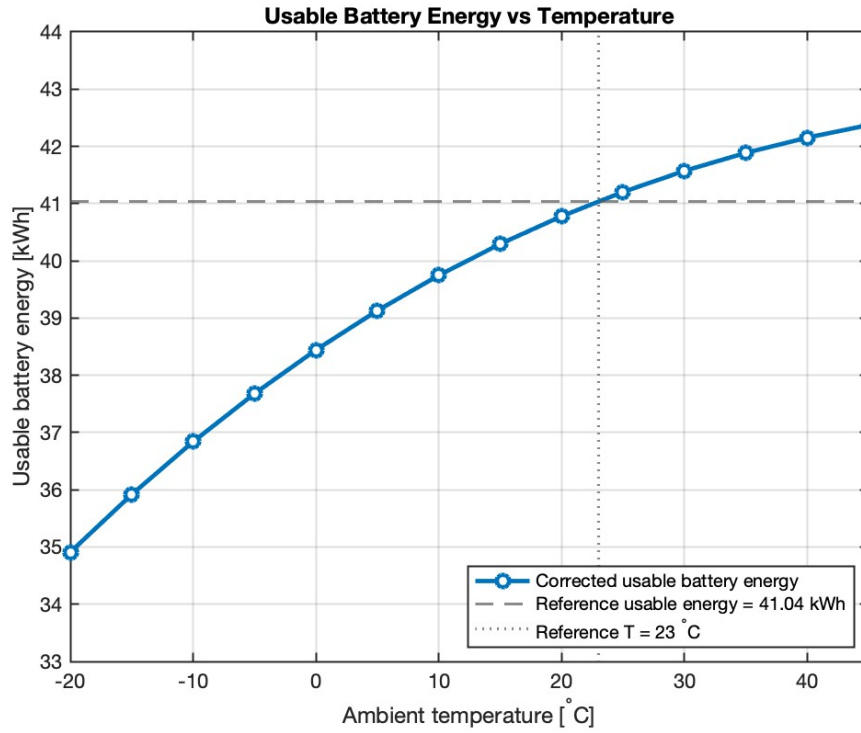


Figure 7.21: Mission energy and corrected usable battery energy as a function of ambient temperature.

The mission energy remains approximately constant because the flight trajectory, payload, aerodynamic model and segment structure are unchanged. By contrast, the available usable battery energy varies with temperature. At low temperature, the corrected usable energy is lower than the mission requirement, making the mission infeasible from an energy point of view. As temperature increases, the corrected usable energy increases and eventually becomes sufficient to cover the mission energy.

This behaviour is more clearly represented by the energy margin:

$$\Delta E(T) = E_{\text{batt,use}}(T) - E_{\text{mission}} \quad (7.37)$$

The corresponding result is reported in Figure 7.22.

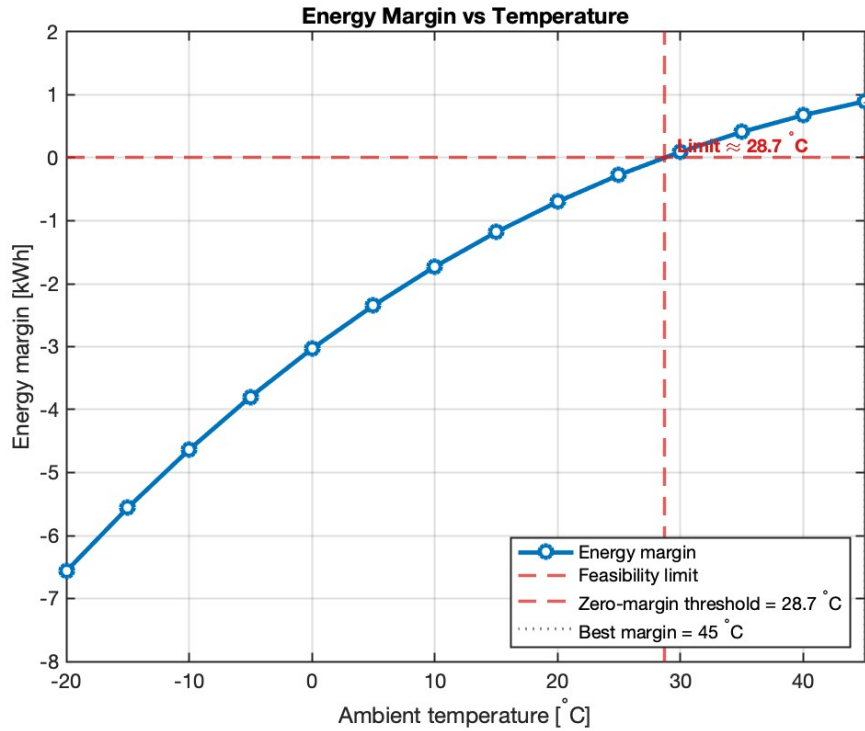


Figure 7.22: Energy margin as a function of ambient temperature.

Figure 7.22 shows that the energy margin increases with ambient temperature. Under the adopted surrogate-cell correction, the Milazzo–Vulcano mission is not energy-feasible at low temperature because the available usable battery energy is reduced. The zero-margin crossing identifies the approximate temperature above which the mission enters the usable battery-energy window. In the investigated range, the feasible temperature region starts at approximately 30 °C and extends up to the highest analysed temperature.

This result must be interpreted carefully. It does not mean that high-temperature operation is always preferable. The sweep only captures the short-term increase in available capacity predicted by the surrogate-cell data. Thermal ageing, safety constraints, cooling requirements and battery lifetime effects are not included in the mission-level model and would require a dedicated electro-thermal and degradation analysis.

The final physical state of charge is shown in Figure 7.23.

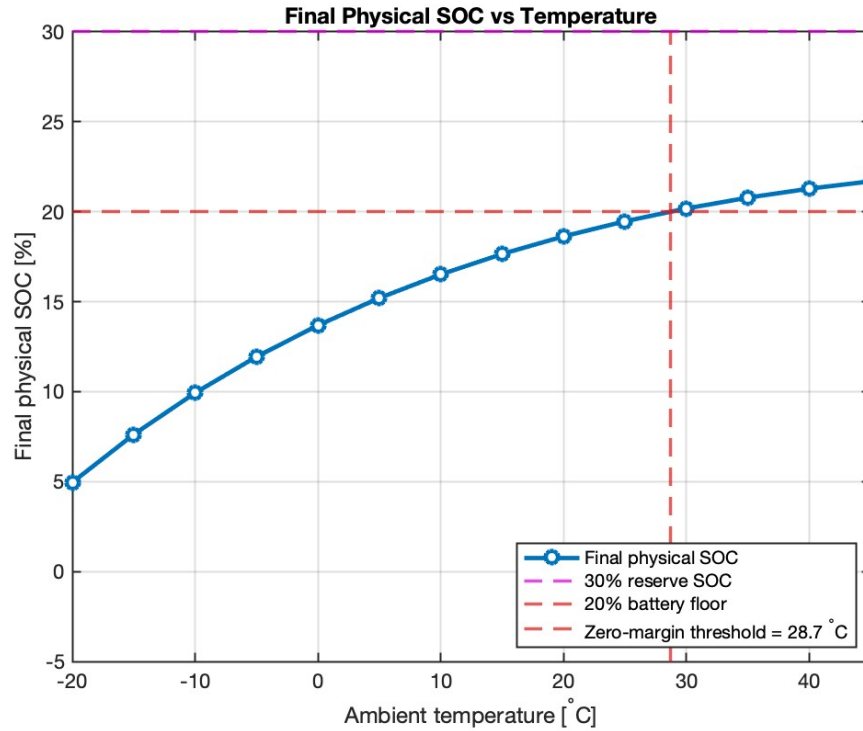


Figure 7.23: Final physical battery state of charge as a function of ambient temperature.

Figure 7.23 provides a complementary interpretation of the battery state at mission completion. At low temperatures, the final physical SOC is strongly reduced because the effective physical energy available from the battery is lower. As temperature increases, the final physical SOC rises and approaches the preferred operating region. The comparison with the 20% battery floor and the 30% reserve level highlights the difference between complete physical energy depletion and violation of the preferred operational reserve.

The feasibility result can be summarised by the mission feasibility flag shown in Figure 7.24. This figure is optional, but it provides a clear binary interpretation of the temperature range.

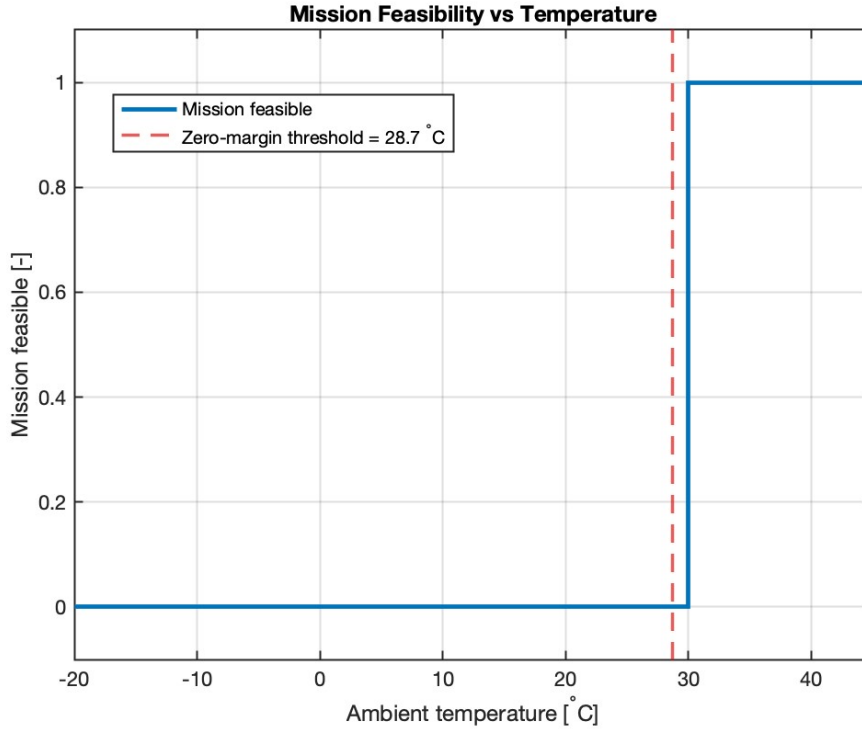


Figure 7.24: Mission feasibility as a function of ambient temperature.

The feasibility plot confirms that the limiting mechanism in this sweep is energy availability rather than power delivery. Since battery power is kept nominal and the mission peak power does not change with temperature in the adopted model, the power constraint remains satisfied throughout the analysed range. The transition from infeasible to feasible operation is therefore driven by the corrected usable battery energy. Overall, the temperature sweep shows that ambient temperature can significantly affect the energy feasibility of the Milazzo–Vulcano mission. Low-temperature operation reduces the available battery capacity and can make an already energy-critical route infeasible. Warmer conditions improve the short-term available capacity and may recover a positive energy margin, but this should not be interpreted as a complete thermal optimisation result. In practice, temperature effects should be considered together with thermal management, battery ageing, reserve policy and operational safety requirements.

7.7. Wind Sweep

The wind sweep investigates the influence of along-track wind on the Milazzo–Vulcano mission. In this analysis, the aircraft configuration, payload, battery parameters, mission altitude profile and aerodynamic assumptions are kept unchanged. The only parameter

varied is the wind component aligned with the route.

The wind is modelled as a steady longitudinal component acting along the mission direction. Crosswind, gusts, turbulence and wind shear are not considered. Therefore, the analysis does not address lateral controllability, crosswind landing limitations or trajectory deviations. Its purpose is limited to evaluating how headwind and tailwind conditions modify the effective ground speed, mission time, energy consumption and battery margin.

The sign convention adopted in the model is:

$$V_{\text{wind}} > 0 \quad \Rightarrow \quad \text{headwind} \quad (7.38)$$

$$V_{\text{wind}} < 0 \quad \Rightarrow \quad \text{tailwind} \quad (7.39)$$

The aircraft is assumed to maintain its nominal airspeed. The wind therefore modifies the effective ground speed according to:

$$V_g = V_{\text{air}} - V_{\text{wind}} \quad (7.40)$$

where V_g is the ground speed and V_{air} is the nominal airspeed of the considered segment. A positive wind component reduces the ground speed and increases the time required to cover the same distance. A negative wind component increases the ground speed and reduces mission time.

The main assumptions adopted in the wind sweep are:

- the wind is steady and aligned with the route;
- positive wind corresponds to headwind and negative wind corresponds to tailwind;
- crosswind, gusts, turbulence and wind shear are neglected;
- the aircraft maintains the nominal airspeed;
- wind modifies the effective ground speed and therefore segment duration;
- battery properties, payload and aircraft configuration are kept unchanged;
- the analysis is intended as a mission-level longitudinal wind sensitivity, not as a complete flight-mechanics or operational weather assessment.

The effect of wind on the effective cruise ground speed is shown in Figure 7.25.

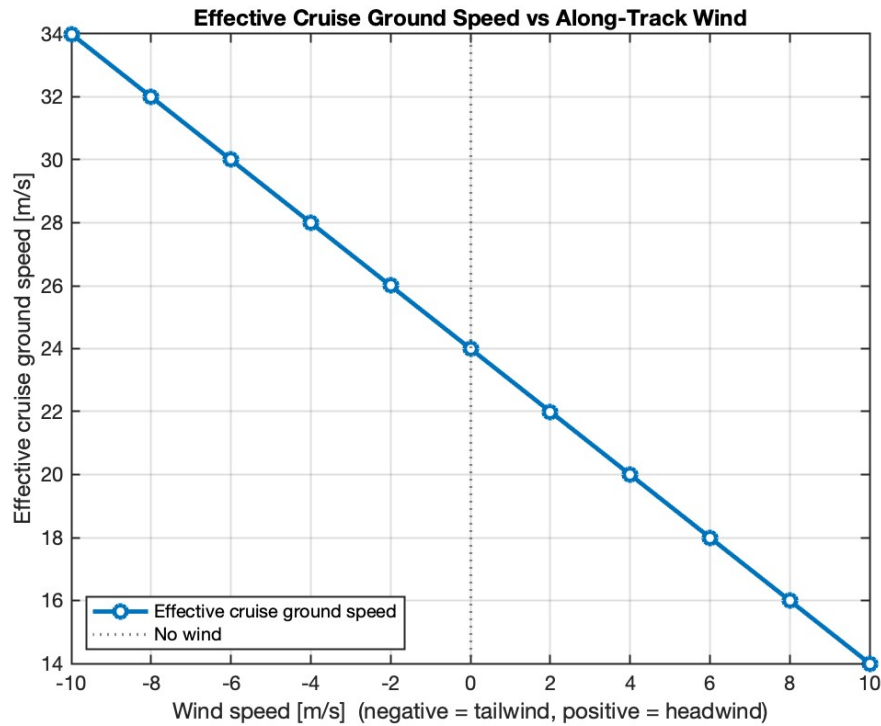


Figure 7.25: Effective cruise ground speed as a function of along-track wind speed.

Figure 7.25 shows the direct kinematic effect of the adopted wind model. Tailwind conditions increase the effective ground speed, while headwind conditions reduce it. Since the aircraft airspeed is kept constant, this variation does not represent a change in the aerodynamic cruise speed of the vehicle, but rather a change in the speed at which the aircraft progresses along the route.

The corresponding mission time variation is shown in Figure 7.26.

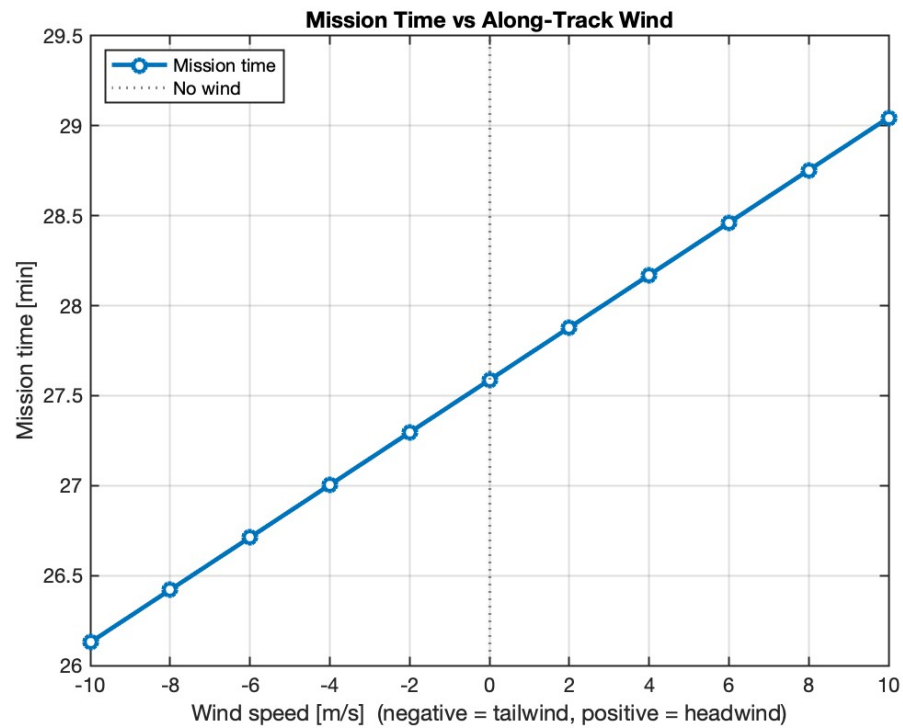


Figure 7.26: Mission time as a function of along-track wind speed.

As expected, mission time increases under headwind conditions and decreases under tailwind conditions. This is because the mission distance is fixed, while the effective ground speed changes with the wind component. The effect is particularly relevant for the cruise segment, which represents the longest portion of the Milazzo–Vulcano mission.

The effect of wind on total mission energy is reported in Figure 7.27.

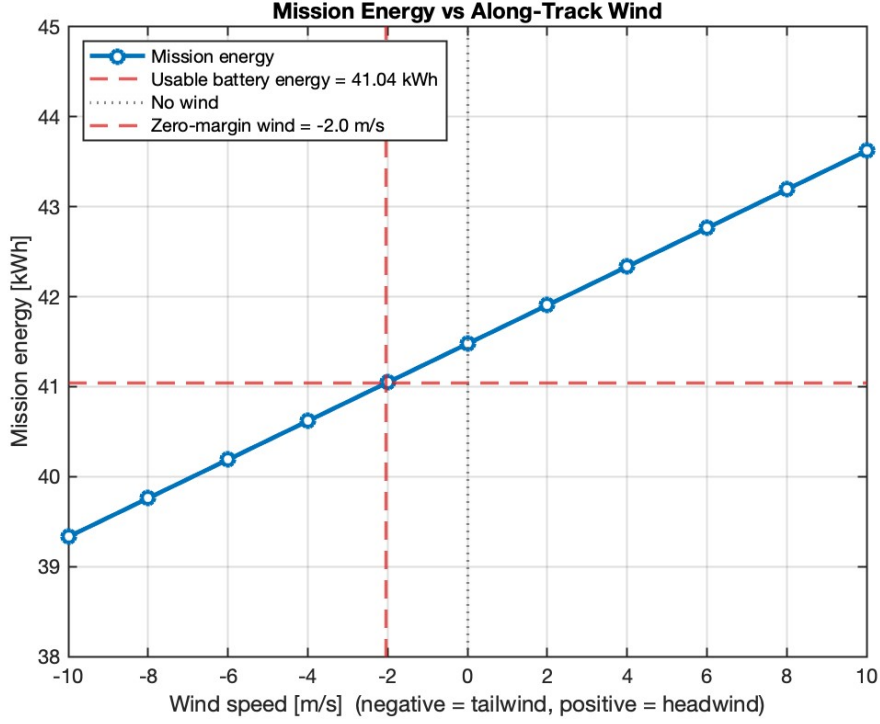


Figure 7.27: Mission energy as a function of along-track wind speed.

Figure 7.27 shows that mission energy increases in headwind conditions and decreases in tailwind conditions. In the implemented model, the main mechanism is the change in segment duration. Under headwind, the aircraft requires more time to cover the same route, so the energy consumed during powered forward flight increases. Under tailwind, the opposite occurs: the same route is completed in less time, reducing the energy required.

The energy margin provides a more direct interpretation of wind effects on mission feasibility:

$$\Delta E(V_{\text{wind}}) = E_{\text{batt,use}} - E_{\text{mission}}(V_{\text{wind}}) \quad (7.41)$$

The resulting trend is shown in Figure 7.28.

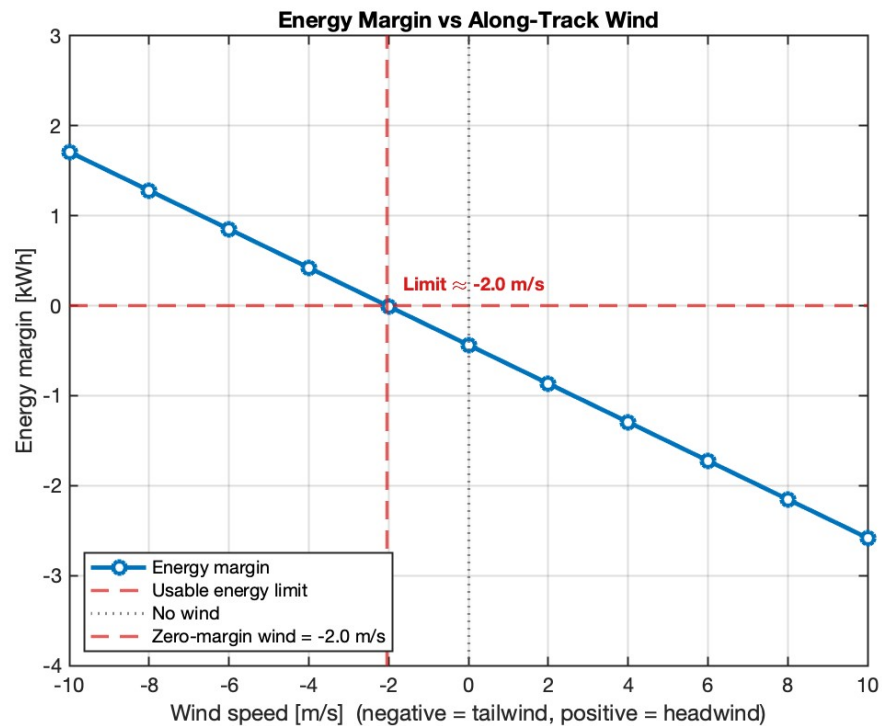


Figure 7.28: Energy margin as a function of along-track wind speed.

Figure 7.28 shows that tailwind improves the energy margin, while headwind reduces it. This result is important because the nominal Milazzo–Vulcano mission is already close to the usable battery-energy limit. Even moderate headwind conditions can therefore make the route more energy-critical, whereas favourable tailwind conditions can recover a positive margin.

If included, the final usable state of charge is shown in Figure 7.29.

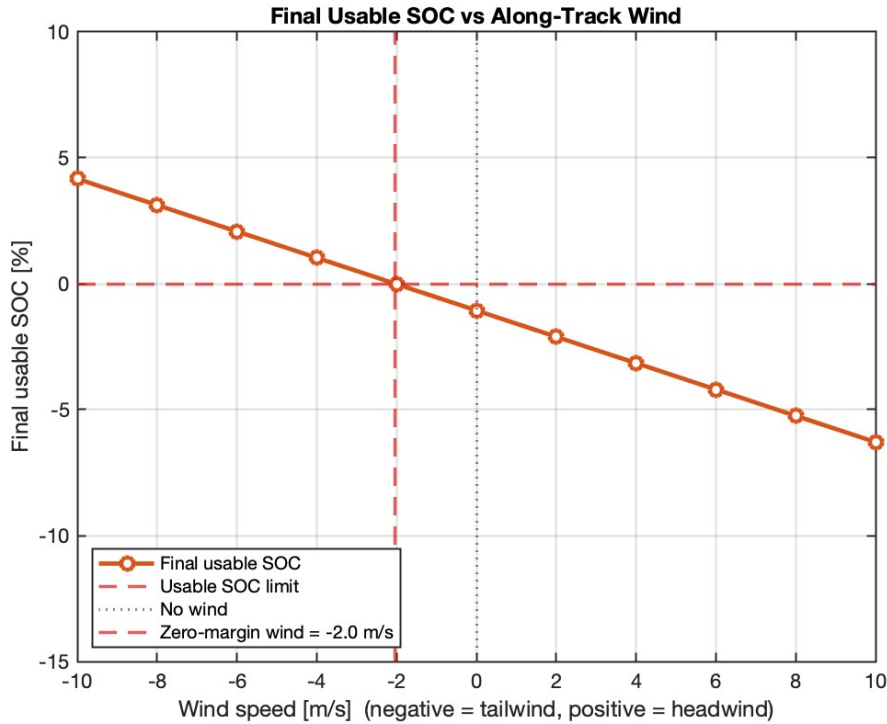


Figure 7.29: Final usable state of charge as a function of along-track wind speed.

Figure 7.29 expresses the same result in terms of battery state of charge. Tailwind cases end the mission with a higher residual usable SOC, while headwind cases reduce or eliminate the available margin. This confirms that wind direction and intensity can significantly affect the operational robustness of a mission that is already close to its energy boundary. The peak power demand is not reported as a dedicated figure because, under the adopted wind model, the aircraft airspeed and climb settings are kept nominal. The wind modifies the time required to cover the route, but it does not significantly alter the maximum power demand, which remains governed by the common climb and vertical-flight conditions. Therefore, as in the previous analyses, the main wind-related limitation is energetic rather than power-based. Overall, the wind sweep shows that along-track wind is an important operational parameter for the Milazzo–Vulcano mission. A headwind increases mission time and energy consumption, reducing the final battery margin. A tailwind reduces mission time and can improve the feasibility margin. Since the nominal mission is close to the usable battery-energy limit, wind effects should be considered in route planning, reserve policy and go/no-go operational decisions. It should be emphasised that this analysis is simplified. Real atmospheric conditions may include crosswind, gusts, turbulence, vertical wind gradients and direction changes along the route. These effects can influence controllability, passenger comfort, landing procedures and operational

safety. They are not included in the present mission-level energy model and would require a more detailed flight-dynamics and operational weather assessment.

7.8. Combined Parametric Effects

The previous sensitivity analyses investigated the effect of individual parameters on the Milazzo–Vulcano mission. This approach is useful to isolate the role of each variable, but real mission feasibility is determined by the simultaneous interaction of several parameters. Payload, route distance and environmental conditions do not act independently: a mission that is feasible under nominal assumptions may become critical when a higher payload is combined with longer distance, low temperature or headwind.

For this reason, the present section extends the one-parameter sweeps to selected two-parameter maps. The objective is to identify the operational envelope of the selected multicopter configuration and to visualise the boundary between feasible and infeasible conditions. The analysed combinations are:

- payload mass and mission distance;
- ambient temperature and along-track wind;
- payload mass and ambient temperature.

The feasibility criterion is based on the same mission-level constraints adopted in the previous sections. A mission is considered feasible only if the route is geometrically compatible with the prescribed climb and descent profile, the mission energy remains within the usable battery energy and the maximum power demand remains below the available battery power. In the maps presented below, the most relevant boundary is the zero energy-margin contour:

$$\Delta E = E_{\text{batt,use}} - E_{\text{mission}} = 0 \quad (7.42)$$

This contour separates the region where the mission remains inside the usable battery window from the region where the mission exceeds the available usable energy.

7.8.1. Payload–Distance Envelope

The first combined analysis considers payload mass and mission distance. This is the most direct representation of the mission envelope, because it relates the useful load carried by the aircraft to the distance that can be covered with the selected battery configuration.

For each combination of payload and distance, the take-off mass is updated according to:

$$m_{\text{TO}} = m_{\text{empty}} + m_{\text{payload}} + M_{\text{batt}} \quad (7.43)$$

while the imposed mission distance is varied independently. The mission model is then recomputed and the final usable state of charge is stored. The resulting map is shown in Figure 7.30.

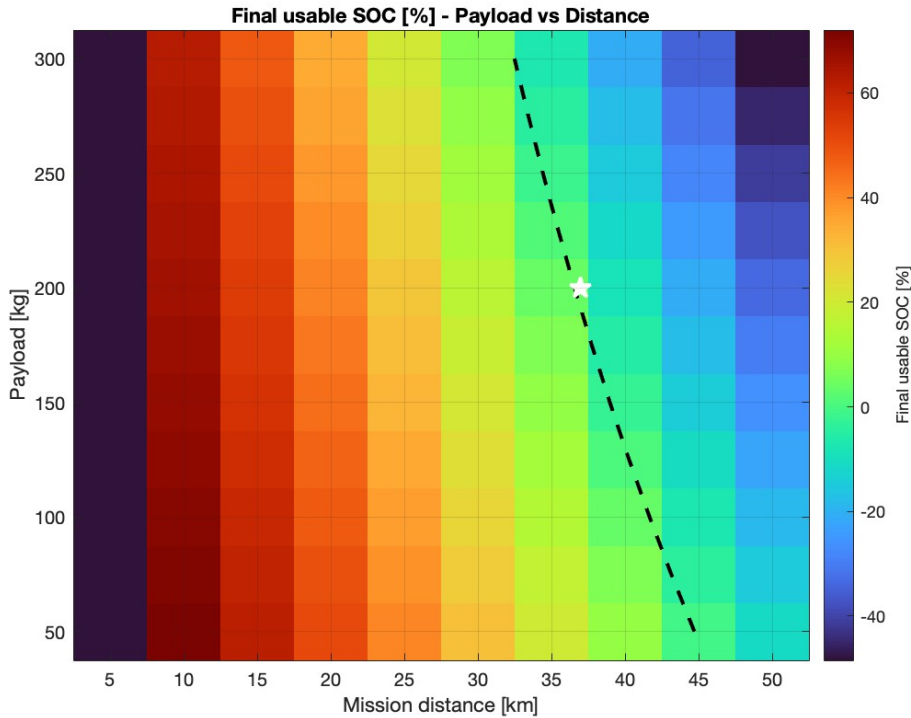


Figure 7.30: Final usable SOC map as a function of payload mass and mission distance.

Figure 7.30 shows the combined effect of payload and distance on the usable battery state at the end of the mission. As expected, increasing either parameter reduces the final usable SOC. Higher payload increases aircraft weight and therefore power demand, while longer distance increases the duration of the cruise segment and the corresponding energy consumption.

The zero-SOC contour represents the energy boundary of the selected configuration. Points below this boundary remain inside the usable battery window, while points above it exceed the nominal usable energy. This contour is more informative than a single range value because it shows that range capability depends on payload. A lower payload allows longer missions, whereas a higher payload reduces the maximum achievable distance.

The same result can be expressed as a binary mission-feasibility map, shown in Figure 7.31.

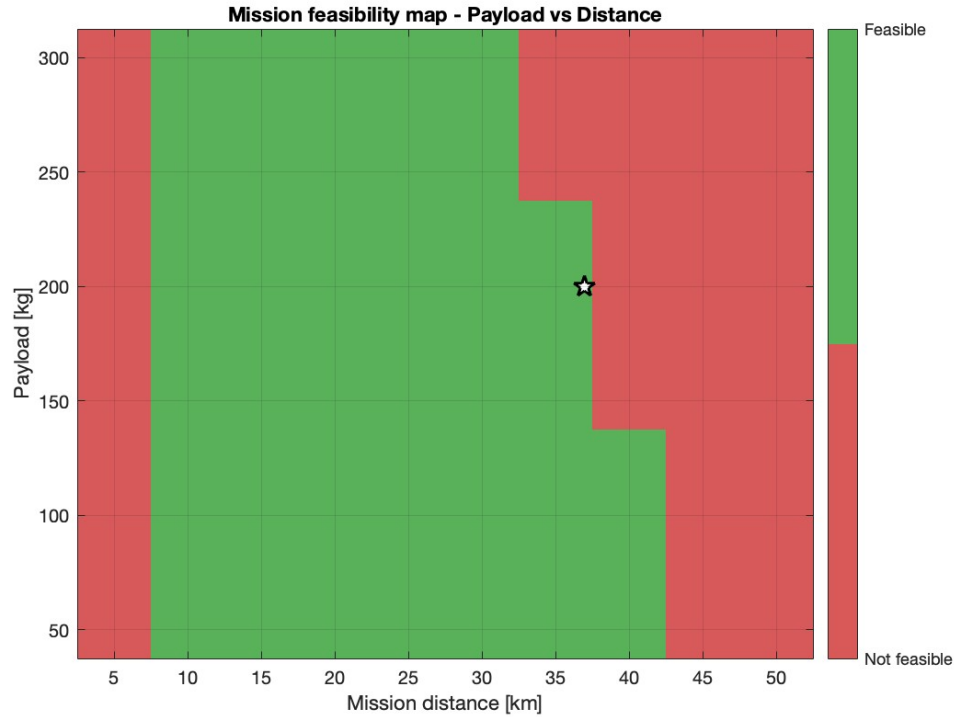


Figure 7.31: Mission feasibility map as a function of payload mass and mission distance.

Figure 7.31 provides a direct visual classification of the feasible and infeasible regions. The transition between the two regions confirms that the operational capability of the aircraft cannot be represented by a unique maximum distance or a unique maximum payload. Instead, the feasible domain is defined by a payload–distance trade-off. For the nominal Milazzo–Vulcano case, the aircraft operates close to the energy boundary. This is consistent with the previous individual sweeps: the 37 km route with the nominal payload lies near the limit of the usable battery window. The map also indicates that a moderate reduction in payload can recover feasibility, while an increase in distance or payload quickly moves the mission outside the feasible region.

7.8.2. Temperature–Wind Interaction

The second combined analysis considers ambient temperature and along-track wind. These two parameters represent environmental effects that can significantly modify mission robustness. Temperature affects the available battery capacity through the correction factor introduced in the temperature sweep, while wind affects the effective ground speed and therefore the mission time.

The wind convention is the same adopted in the dedicated wind analysis:

$$V_{\text{wind}} > 0 \quad \Rightarrow \quad \text{headwind} \quad (7.44)$$

$$V_{\text{wind}} < 0 \quad \Rightarrow \quad \text{tailwind} \quad (7.45)$$

The aircraft is assumed to maintain its nominal airspeed, while the effective ground speed is modified by the along-track wind component. Temperature modifies only the available battery energy, while battery power capability is kept nominal due to the lack of reliable pack-level power-temperature data. The resulting energy-margin map is shown in Figure 7.32.

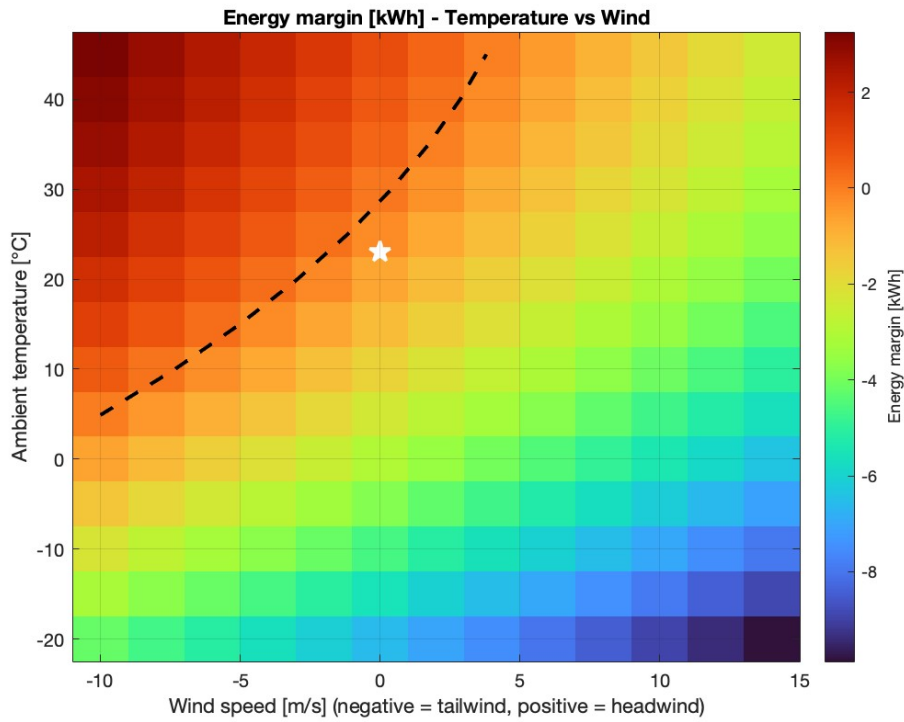


Figure 7.32: Energy margin map as a function of ambient temperature and along-track wind.

Figure 7.32 shows that the most critical region corresponds to the combination of low temperature and headwind. Low temperature reduces the usable battery energy, while headwind increases mission time and therefore mission energy. These effects act in the same unfavourable direction and can make the route infeasible even if each parameter

alone appears only moderately penalising.

Conversely, tailwind and warmer operating conditions improve the energy margin. Tailwind reduces the time required to cover the route, while higher temperature increases the short-term available battery capacity in the adopted surrogate-cell model. However, this result should not be interpreted as a recommendation to operate batteries at high temperature without limitation. The map represents short-term mission energy availability and does not include thermal ageing, cooling requirements or battery lifetime degradation. The zero-margin contour highlights the environmental boundary of the mission. On one side of the contour, the aircraft retains a positive usable energy margin; on the other side, the mission exceeds the usable battery window. This representation is particularly relevant for operational planning, because it shows that a borderline mission can become feasible or infeasible depending on weather conditions.

7.8.3. Payload–Temperature Robustness

The third combined analysis investigates the interaction between payload mass and ambient temperature. This map is useful because it links an operational variable, the useful load, with an environmental variable that affects battery capacity.

For each payload value, the take-off mass is updated, while the available battery energy is corrected using the temperature-dependent capacity factor. The mission distance is kept equal to the Milazzo–Vulcano base case and no wind is applied. The resulting final usable SOC map is shown in Figure 7.33.

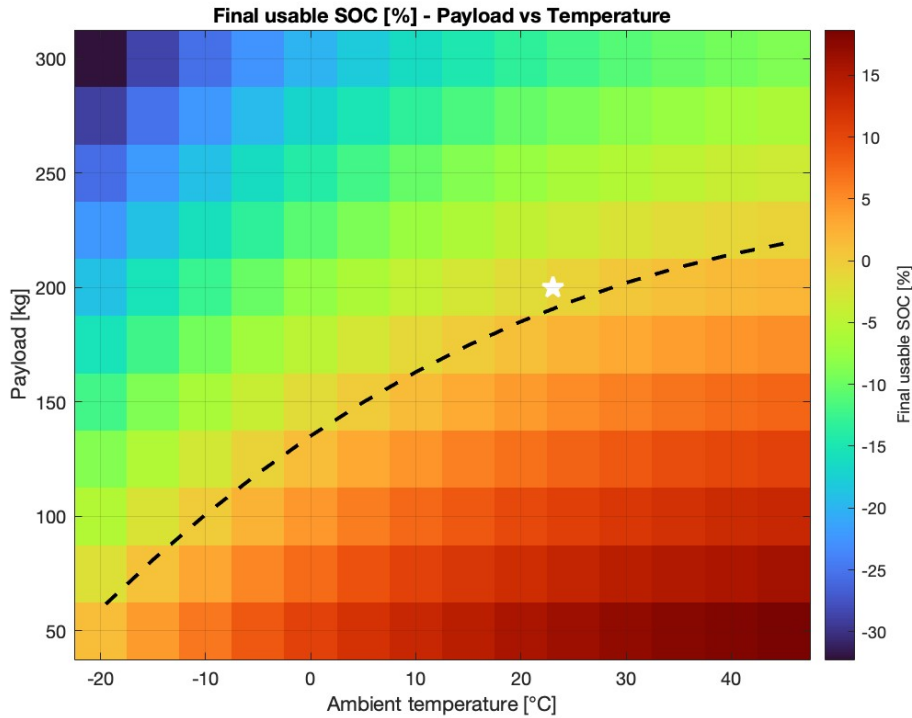


Figure 7.33: Final usable SOC map as a function of payload mass and ambient temperature.

Figure 7.33 shows that payload capability is temperature-dependent. At low temperatures, the usable battery capacity is reduced and the aircraft can carry less payload while remaining inside the usable energy window. At higher temperatures, the corrected available capacity increases and the payload limit shifts upward. This result is important for mission planning because the maximum allowable payload should not be treated as a fixed number. For an energy-critical route such as Milazzo–Vulcano, the payload margin depends on the effective battery capacity available at the time of operation. In colder conditions, a reduction in payload may be required to maintain the same reserve policy. In more favourable thermal conditions, the same mission may retain a larger usable energy margin. The payload–temperature map also reinforces the distinction between vehicle capability and operational capability. The vehicle configuration is unchanged, but the feasible payload region changes because the available battery energy changes with temperature. This confirms that the practical payload limit is not only a structural or performance parameter, but also an energy-management constraint.

7.8.4. Interpretation of the Combined Envelope

The combined maps show that the operational envelope of the selected multicopter eVTOL is defined by a set of interacting constraints rather than by a single limiting parameter. Payload and distance define the primary mission envelope, while temperature and wind modify the available margin around that envelope.

The main engineering conclusions are:

- increasing payload and mission distance simultaneously reduces the final usable SOC and shifts the mission towards the infeasible region;
- the nominal Milazzo–Vulcano mission is close to the energy boundary, so moderate changes in payload, distance or environment can change its feasibility classification;
- low temperature and headwind form a particularly critical combination because they reduce available battery energy and increase mission energy demand at the same time;
- payload capability is not fixed, but depends on the effective battery capacity available under the operating thermal condition;
- the power constraint is generally less restrictive than the energy constraint for the analysed cases, confirming that the dominant limitation is usable battery energy.

Overall, the combined parametric analysis provides a more realistic interpretation of mission feasibility than the individual sweeps alone. It shows that the aircraft should not be operated based only on nominal range or nominal payload values. Instead, route planning should account for payload, distance, battery state, temperature, wind and reserve policy at the same time. In this sense, the feasibility maps can be interpreted as preliminary operational envelopes for the considered eVTOL mission architecture.

8 | Results and Discussion

8.1. Synthesis of the Main Outcomes

The work carried out in this thesis provides a mission-level assessment of a representative multicopter eVTOL configuration applied to short-range operations in the Aeolian Islands scenario. The analysis does not aim to reproduce the certified performance of a specific aircraft, but to evaluate how a VoloCity-like multicopter configuration behaves when explicit mission, battery and operational assumptions are applied. The main outcome is that the feasibility of the analysed missions is governed primarily by the available usable battery energy. In the investigated cases, the peak power requirement remains below the available battery power, whereas the energy margin becomes critical when distance, payload or adverse environmental conditions increase. Therefore, the key feasibility condition is not simply whether the aircraft can generate enough instantaneous power, but whether the mission can be completed while remaining inside the prescribed usable battery window. The Milazzo–Vulcano route represents the most informative reference case. Its distance places it close to the energy boundary of the selected configuration, making it suitable for testing how sensitive the mission is to changes in operating assumptions. This result is important because it shows that nominal feasibility alone is not sufficient: a mission close to the energy boundary must be assessed together with payload, reserve policy and environmental conditions. A second relevant outcome is that route capability cannot be described by a single range value. The feasible operating region is defined by the combined effect of payload and distance. Lower payload increases the allowable mission distance, while higher payload reduces the available range. For this reason, the payload–distance envelope is more meaningful than a single maximum-range number. The sensitivity analyses also show that environmental effects may become decisive when the energy margin is small. Temperature modifies the effective battery capacity, while along-track wind changes the time required to complete the route. These effects do not define the aircraft configuration itself, but they affect whether a specific mission can be operated with sufficient margin. Overall, the results indicate that the proposed multicopter eVTOL concept is technically more suitable for short and medium inter-island missions

than for longer direct routes without intermediate support. Its strongest potential lies in operations where limited payload, short distances and rapid response are more important than high transport capacity. The following sections discuss what these findings imply for the Aeolian Islands network, how the eVTOL service could complement conventional maritime logistics, and what limitations remain in the present model.

8.2. Implications for the Aeolian Islands Distribution Network

The results obtained in the previous chapters have direct implications for the design of an eVTOL-based distribution network in the Aeolian Islands. The archipelago is characterised by dispersed islands, variable route lengths and a strong dependence on maritime connections. In this context, the value of an aerial electric network is not necessarily associated with replacing conventional transport, but with adding a fast and flexible layer for selected missions. The Lipari-centred hub-and-spoke architecture appears to be the most coherent configuration for this type of operation. Lipari occupies a central position within the archipelago and can act as a primary operational node from which short and medium inter-island legs are performed. The numerical results show that these shorter legs are more compatible with the selected multicopter configuration because they remain further from the usable battery-energy boundary. Longer islands should not be interpreted as excluded from the network only because direct point-to-point missions are more demanding. A route that is not feasible as a single uninterrupted flight may become feasible if it is divided into shorter legs through intermediate stops. In this case, islands located between the hub and the final destination can act as operational checkpoints where the aircraft lands, unloads or boards payload if required, recharges or swaps the battery, and then continues the mission. This multi-leg logic is particularly relevant for the most distant islands. Instead of considering Lipari–Alicudi or Lipari–Stromboli only as direct flights, these routes can be analysed as sequences of shorter segments. The feasibility condition then depends on the energy demand of each individual leg rather than on the total distance from the hub to the final destination. This changes the operational interpretation of the network: the limiting factor is not only aircraft range, but also the availability of suitable intermediate nodes and turnaround infrastructure. The sensitivity analyses also show that weather and environmental conditions can be decisive in an island scenario. Wind, temperature and reserve requirements can significantly affect the available margin, especially for missions close to the energy boundary. This is important for the Aeolian Islands because operations over sea are exposed to seasonal variability, changing wind

conditions and weather-dependent accessibility. A route that is feasible under nominal assumptions may require payload reduction, additional reserve, delay, or an intermediate stop under less favourable conditions. For this reason, the network should not be designed around fixed nominal route distances alone. A realistic operational strategy should include route-specific margins, weather-aware dispatching, battery state monitoring and alternative landing or charging locations. The same physical route may have different operational classifications depending on payload, wind direction, ambient temperature and required reserve at the time of departure. The results therefore support a flexible network concept. Short routes can be operated as direct hub-and-spoke missions, while longer or more critical routes may require staged operation. This approach is more robust than assuming that every island must be served by a single direct flight from Lipari. It also makes the infrastructure problem more explicit: the feasibility of the aerial network depends not only on the aircraft, but also on the distribution of charging or battery-swapping points across the archipelago. From a logistics perspective, this suggests that eVTOL aircraft would be most effective for lightweight and time-sensitive missions, such as urgent supplies, small parcels, medical items, technical equipment or high-priority deliveries. These missions are compatible with the payload and energy limitations identified in the analysis and can benefit from reduced travel time and direct island-to-island connectivity. Overall, the Aeolian Islands case study shows that the operational potential of multicopter eVTOL aircraft depends on network design as much as on vehicle performance. Direct range capability remains important, but intermediate stops, local infrastructure and weather-aware planning can significantly expand the practical usefulness of the system. The most realistic application is therefore a distributed aerial service integrated with the existing island transport network, rather than a stand-alone replacement for all maritime connections.

8.3. Comparison with Conventional Maritime Logistics

The results of this thesis should be interpreted in relation to the existing maritime transport system, rather than as a direct replacement scenario. Conventional maritime logistics remains the most suitable solution for high-volume transport, passenger flows, heavy goods and routine supply operations. Ferries and hydrofoils can carry larger payloads, operate with established infrastructure and serve multiple islands within a consolidated transport network. The potential role of a multicopter eVTOL is different. Its main advantage is not transport capacity, but response time, route flexibility and direct point-to-point connectivity. For lightweight and urgent missions, an aerial electric service could

avoid part of the dependency on maritime schedules and reduce the delay associated with harbour operations, boarding procedures and indirect routing. This is particularly relevant for small high-priority payloads, such as medical supplies, technical components, documents, emergency equipment or time-sensitive deliveries. From an operational perspective, the comparison is therefore not based on replacing one mode with the other, but on identifying complementary functions. Maritime transport is more appropriate for large-scale and scheduled logistics, while eVTOL aircraft can provide a rapid-response layer for selected missions where speed and accessibility are more valuable than transported mass. This distinction is important because the payload and energy limitations identified in the mission analysis would make a multicopter eVTOL unsuitable for bulk logistics. Even when a route is energetically feasible, the useful payload remains limited compared with maritime vehicles. Therefore, the eVTOL concept should be considered as a specialised logistics tool rather than as a general-purpose transport platform. The island context strengthens this complementary interpretation. In an archipelago, the operational value of a fast aerial link can be high even if the transported mass is small. The ability to connect islands directly, reach locations with limited maritime frequency, or operate urgent deliveries outside standard logistics flows can provide benefits that are not captured by payload capacity alone. At the same time, the maritime system is less constrained by battery energy and payload-range trade-offs. Longer routes, adverse weather and larger cargo requirements are more naturally handled by sea transport. The eVTOL system, instead, requires careful mission planning, battery management and weather-aware dispatching. This makes it more sensitive to operational conditions, especially for routes close to the energy boundary. A reasonable future transport architecture for the Aeolian Islands would therefore combine both modes. Maritime logistics would remain the backbone for regular passenger and cargo movement, while eVTOL aircraft could support fast, lightweight and time-critical missions. Intermediate charging points or battery-swapping locations could further improve the usefulness of the aerial layer, especially for routes that are too demanding as direct flights. In summary, the comparison with conventional maritime logistics confirms that the main value of multicopter eVTOL aircraft is not in replacing existing transport capacity, but in increasing operational flexibility. Their contribution would be most relevant where rapid delivery, direct routing and service resilience justify the limited payload and energy constraints of the aircraft.

8.4. Model Strengths and Limitations

The model developed in this thesis should be interpreted as a mission-level energy and feasibility tool, not as a complete aircraft design framework. The objective of the work

was not to design a new eVTOL aircraft from the ground up, nor to produce a detailed aerodynamic, structural or certification-ready vehicle model. Instead, the analysis was focused on evaluating the energy consumption, battery utilisation and mission feasibility of a representative multicopter configuration applied to an Advanced Air Mobility scenario. The reference configuration was derived from existing multicopter eVTOL concepts, especially the Volocopter aircraft family, and then adapted through explicit assumptions and open technical data. This approach allowed the study to remain connected to realistic vehicle orders of magnitude, while keeping the model transparent and reproducible. However, the resulting aircraft should be understood as a VoloCity-like reference configuration rather than as an exact representation of the actual VoloCity or any certified aircraft. A main strength of the model is its segment-based structure. The mission is divided into taxi, hover, vertical take-off, forward climb, cruise, descent, vertical landing and final taxi phases. This makes it possible to identify which portions of the mission contribute most to total energy demand and to evaluate how changes in payload, distance, cruise speed, temperature, wind or climb profile affect the overall result. The model is therefore suitable for preliminary mission screening and for comparing different route and operating scenarios. Another strength is the explicit treatment of battery constraints. The distinction between physical battery energy, usable battery energy and final state of charge allows the analysis to separate complete energy depletion from reserve violation. This is important because mission feasibility in real operations is not defined only by whether the aircraft can technically complete the route, but also by whether it can do so while respecting an operational energy margin. The validation against a reference multicopter literature model also improves the credibility of the framework. Although the validation does not prove that the model can reproduce every real-world operating condition, it shows that the implemented segment logic and energy calculations are consistent with published mission-level results when comparable assumptions are used. At the same time, the model has several limitations. First, the aircraft geometry and propulsion system are not the result of a complete design optimisation. Rotor count, rotor diameter, mass properties and battery assumptions are imposed as input parameters rather than derived from an integrated aircraft sizing process. Therefore, changes such as increasing rotor count or battery mass should be interpreted as parametric studies, not as fully redesigned aircraft configurations. Second, the aerodynamic modelling remains simplified. The cruise and descent models are appropriate for mission-level energy estimation, but they do not include high-fidelity rotor aerodynamics, rotor-rotor interference, detailed fuselage aerodynamics, unsteady effects or control-related losses. Similarly, the wind analysis considers only a steady along-track component and does not model crosswind, gusts, turbulence or trajectory deviations. Third, the battery model is necessarily approximate. The nominal

battery parameters are based on explicit assumptions, while the temperature correction uses a declared surrogate cell because complete public pack-level data for the reference aircraft are not available. As a result, the battery analysis is useful for sensitivity assessment, but it should not be interpreted as a detailed electro-thermal or ageing model of a certified aircraft battery pack. Fourth, the model does not include a full operational infrastructure simulation. Charging time, battery swapping logistics, fleet scheduling, vertiport capacity, turnaround procedures and maintenance requirements are not modelled in detail. These aspects would be essential for evaluating the performance of a real service network, but they are beyond the scope of the present mission-energy study. Finally, the model does not address certification compliance in a quantitative way. Safety, redundancy, failure cases, emergency procedures, reserve rules, airspace integration and vertiport requirements are discussed at a conceptual level in the following regulatory chapter, but they are not embedded as formal certification constraints inside the numerical model. Despite these limitations, the model is useful for the intended purpose of the thesis. It provides a transparent framework for estimating mission energy, identifying critical routes, evaluating battery margins and understanding the main parameters that drive feasibility in a short-range eVTOL application. Its value lies in early-stage engineering assessment: it can indicate where a mission concept appears promising, where it becomes energy-critical and which parameters should be improved or investigated in future higher-fidelity studies.

9 | Certification and Compliance Considerations

9.1. Purpose and Scope of the Regulatory Discussion

The previous chapters evaluated the energy performance and mission feasibility of a representative multicopter eVTOL configuration applied to the Aeolian Islands scenario. These analyses are necessary to understand whether a route can be completed from an energy, power and battery-margin point of view. However, energy feasibility alone is not sufficient to determine whether the proposed concept could be implemented in a real Advanced Air Mobility operation. A real eVTOL service would also require compliance with airworthiness requirements, vertiport and ground infrastructure standards, airspace integration rules, operational procedures and emergency planning. For this reason, the present chapter introduces the main certification and compliance aspects that would influence the transition from a mission-level feasibility study to an operationally deployable system.

The scope of this chapter is intentionally limited. The objective is not to define a complete certification basis for the aircraft, nor to demonstrate compliance with all applicable requirements. Similarly, the chapter does not replace a formal safety assessment, operational approval process or vertiport design study. Instead, it identifies the main regulatory and compliance drivers that are relevant to the mission concept developed in this thesis.

For the aircraft side, the most relevant European reference is the EASA Special Condition for small-category VTOL-capable aircraft, which was introduced because these aircraft differ from conventional fixed-wing aeroplanes and rotorcraft and therefore require a dedicated certification framework [12]. This reference is particularly important for multicopter eVTOL aircraft intended for passenger or high-integrity operations.

For the infrastructure side, the EASA Prototype Technical Specifications for Vertiports provide non-regulatory design material for VFR vertiports serving manned VTOL-capable aircraft certified in the enhanced category [10]. These specifications are relevant to the Aeolian Islands scenario because the feasibility of an eVTOL network depends not only

on aircraft energy performance, but also on the availability of suitable take-off, landing, charging and turnaround areas.

Airspace integration is another key element. The European U-space framework defines a regulatory structure for UAS operations in designated U-space airspace and introduces services intended to support safe, digital and automated low-altitude operations [7]. Although the present thesis does not assume a fully autonomous certified passenger service, U-space concepts remain relevant when considering future unmanned cargo operations, traffic information, strategic deconfliction and digital flight authorisation services [9].

The regulatory discussion is therefore used as a bridge between the numerical mission analysis and the practical implementation of an eVTOL service. The aim is to show which additional requirements would have to be considered before the proposed Aeolian Islands concept could move from a feasibility model to a real operational framework.

In this context, the following sections discuss: airworthiness considerations for eVTOL aircraft, vertiport and ground infrastructure requirements, airspace and U-space integration aspects, operational constraints specific to the Aeolian Islands case study, and the main compliance drivers emerging from the analysis.

9.2. Airworthiness Considerations for eVTOL Aircraft

The airworthiness assessment of an eVTOL aircraft cannot be reduced to the verification of energy consumption or battery endurance. A mission may be energetically feasible under nominal assumptions and still be unacceptable from a certification perspective if the aircraft cannot demonstrate adequate safety margins, failure tolerance, battery safety, controllability and emergency capability.

In the European regulatory framework, the main reference for this class of aircraft is the EASA Special Condition for small-category VTOL-capable aircraft. EASA introduced this framework because VTOL-capable aircraft do not fit entirely within conventional aeroplane or rotorcraft certification categories. The Special Condition applies to small-category VTOL-capable aircraft and provides dedicated airworthiness requirements for this emerging class of vehicles [12].

A first important distinction introduced by SC-VTOL is the separation between Category Enhanced and Category Basic. Category Enhanced is associated with a higher safety objective and is relevant for passenger transport and operations over congested areas.

Category Basic is associated with a lower operational exposure and a controlled emergency landing capability. In SC-VTOL, the key safety concepts are expressed through the terms “*continued safe flight and landing*” and “*controlled emergency landing*” [12].

This distinction is important for the present thesis because the Aeolian Islands concept could be interpreted in different ways depending on the future operational scenario. If the system were developed as a passenger-carrying air-taxi service, or if it routinely operated over populated areas, the Enhanced category would likely become the relevant certification target. If the concept were limited to lower-risk cargo or logistics missions, a different classification could be considered. However, this would depend on the final aircraft, operating rules, route exposure, airspace environment and intended service type. Therefore, this thesis does not assign a definitive certification category, but identifies the main airworthiness implications that would need to be addressed in a future certification programme.

The concept of continued safe flight and landing is especially relevant to the mission-energy analysis. SC-VTOL links this concept to the ability of the aircraft to continue controlled flight and landing after relevant failures. The associated Means of Compliance further clarify that this capability should not require “*exceptional piloting skills, alertness, or strength*” [8]. This requirement goes beyond the nominal energy balance used in the present model. A certified aircraft must not only complete the planned route under normal conditions, but also retain sufficient capability under defined abnormal and failure conditions.

This has direct implications for the battery margins used in this thesis. The numerical model evaluates whether the mission remains within the usable battery energy under nominal conditions. A certification-oriented assessment would also need to consider degraded cases, including diversion to an alternate landing site, loss or degradation of propulsion units, reduced climb performance, abnormal landing procedures and emergency reserves. Therefore, the energy margin computed in this thesis should be interpreted as a preliminary mission-level margin, not as a certification reserve.

The propulsion battery system is another critical airworthiness driver. In an eVTOL aircraft, the battery is part of the propulsion system and directly affects flight continuation, landing capability and fire safety. EASA MOC-3 SC-VTOL addresses propulsion battery thermal runaway and introduces compliance approaches based on containment and non-propagation testing [11]. In particular, the document refers to thermal-runaway containment testing and includes the verification condition that “*At least 20% of the cells*” achieve thermal runaway during the referenced test condition [11].

This regulatory point is important because the battery model used in this thesis is intentionally limited to mission-level energy behaviour. The model accounts for battery mass, specific energy, usable energy, state of charge and temperature-dependent capacity effects. It does not model cell-level failure modes, thermal-runaway propagation, module containment, venting, battery management system fault detection, repeated cycling degradation or fire-zone design. Consequently, the battery analysis is suitable for energy-feasibility assessment, but it is not sufficient to demonstrate propulsion battery airworthiness compliance.

SC-VTOL also includes requirements related to systems, structures and protection against hazardous failures. For distributed electric propulsion aircraft, this is particularly important because lift and thrust are generated by multiple rotors, motors and associated electrical systems. Requirements related to structural protection, high-energy fragments, electrical systems, lightning, high-intensity radiated fields and system safety would all become relevant in a complete aircraft certification programme [12].

The environmental aspects considered in the numerical model must also be interpreted within this limitation. The wind sweep in Chapter 7 considered only a steady along-track wind component. This is useful for estimating the effect of headwind and tailwind on mission energy, but it does not cover the full set of operational and certification-relevant environmental conditions. A complete assessment would also need to consider crosswind, gusts, turbulence, visibility, precipitation, icing exposure, degraded navigation and emergency procedures. EASA Means of Compliance material provides additional guidance for demonstrating compliance with performance, handling qualities, systems and environmental requirements under the SC-VTOL framework [15].

From the perspective of this thesis, the main conclusion is that the mission-energy model represents only the first layer of feasibility. It can identify whether a nominal route is energetically plausible and which parameters drive the energy margin. However, a certifiable eVTOL operation would require additional demonstrations related to failure tolerance, continued safe flight and landing or controlled emergency landing, propulsion battery safety, structural integrity, system safety, environmental qualification and operational limitations.

Therefore, the numerical results should be interpreted as support for early mission screening, not as evidence of aircraft-level compliance. The model can indicate which routes and operating conditions are promising or critical from an energy perspective, but airworthiness approval would require a broader certification programme based on the applicable SC-VTOL requirements and Means of Compliance.

9.3. Vertiport and Ground Infrastructure Requirements

The feasibility of an eVTOL network does not depend only on aircraft energy performance. Even if a route is energetically feasible, the operation cannot be implemented unless suitable take-off, landing, turnaround, charging and emergency facilities are available at the origin, destination and, when required, at intermediate stops. This aspect is particularly important for the Aeolian Islands scenario, where the territory is insular, geologically irregular and often constrained by limited flat areas, coastal exposure, populated villages, port activities and protected landscapes.

In the European context, the main reference for vertiport design is the EASA *Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category* [10]. EASA explicitly states that these specifications are developed as “*non-regulatory material for the design of VFR vertiports or parts thereof*” and are applicable to “*manned VTOL-capable aircraft certified in the enhanced category*” [10]. Therefore, they should not be interpreted as a complete operational approval framework, but as the most relevant European technical reference for the preliminary design of vertiport infrastructure.

The same document clarifies that PTS-VPT-DSN contains technical specifications for “*physical characteristics, obstacle environment, and visual aids*” for vertiport design [10]. These three elements are directly relevant to the present case study. In an island environment, the physical characteristics of the landing area depend strongly on available terrain and ground bearing capacity; the obstacle environment is affected by slopes, coastal terrain, buildings, port cranes, antennas and volcanic relief; and visual aids become relevant because operations may occur close to sea surfaces, harbour lights and visually complex coastal backgrounds.

A vertiport is not only a landing pad. It is a system of defined areas and supporting services. EASA PTS-VPT-DSN identifies key infrastructure elements such as the final approach and take-off area (FATO), the touchdown and lift-off area (TLOF), the safety area, obstacle limitation surfaces, visual aids, approach/departure paths and rescue and firefighting services [10]. These elements must be assessed together with the characteristics of the design VTOL-capable aircraft. In particular, EASA states that, when designing a vertiport, the following parameters should be considered: “*the set of the largest dimensions*”, “*the maximum take-off mass (MTOM)*”, and “*the most critical obstacle avoidance criteria*” of the VTOL-capable aircraft population that the vertiport

is intended to serve [10].

This requirement has a direct implication for the thesis scenario. The reference multi-copter configuration used in the mission model is VoloCity-like and has a relatively large rotor footprint compared with its payload capability. Therefore, the design of a vertiport for this type of aircraft cannot be based only on payload or mass. The limiting aircraft dimensions, rotor disc arrangement, downwash footprint, obstacle clearance and maximum allowable take-off and landing mass must all be considered.

The physical layout must also be compatible with the available ground conditions. The Aeolian Islands are volcanic in origin, and many potential sites are affected by sloped terrain, rocky outcrops, limited flat surfaces, coastal erosion, loose pyroclastic deposits or constrained urban fabric. From an infrastructure perspective, this means that site selection should consider not only the horizontal space required by the FATO, TLOF and safety area, but also foundation stability, surface regularity, drainage, erosion resistance and the ability to support repeated aircraft loads.

This point is especially relevant for possible vertiport locations near harbours or coastal platforms. Port areas may offer logistical advantages because they are already connected to island mobility, cargo handling and emergency services. However, they may also introduce constraints related to obstacles, people and vehicle movement, maritime operations, limited expansion space, salt exposure and interference with existing transport flows. A harbour-adjacent vertiport would therefore require careful separation between aviation operations, maritime activities and public access.

Ground-surface design is another important factor. The landing area must provide sufficient strength and stability for the design aircraft, including the maximum take-off mass considered in the operation. For an electric multicopter, the loads may be lower than for conventional helicopters, but repeated operations, concentrated landing gear loads, battery-swapping equipment and ground-service vehicles can still impose significant local requirements. On volcanic or uneven terrain, a prepared reinforced surface would likely be required rather than an untreated natural surface.

Downwash and outwash must also be considered. Although the EASA PTS provides the European reference framework, the FAA Engineering Brief 105A is useful as an additional technical reference because it explicitly introduces a downwash and outwash caution area for VTOL operations [16]. The FAA document states that EB 105A provides standards and guidance for the “*planning, design, and construction*” of facilities serving VTOL aircraft and notes the introduction of a “*downwash and outwash caution area*” [16]. For island operations, this is relevant because take-off and landing areas may be close to pedestrians,

vehicles, harbour equipment, lightweight objects, dust, volcanic ash or sea spray.

The electrical infrastructure is another fundamental requirement. The mission analysis in this thesis showed that battery energy margin is a dominant constraint. Therefore, a practical hub-and-spoke network would require reliable charging or battery-swapping capability at the main hub and, for longer routes, at selected intermediate islands. For Lipari, this means that the hub should not only provide landing capability, but also high-power electrical supply, battery storage, charging management, thermal monitoring, fire protection and turnaround procedures.

Intermediate stops are particularly relevant for the Aeolian Islands network. Routes that are demanding as direct flights can become more realistic if divided into shorter legs, provided that intermediate locations offer adequate landing and energy-support infrastructure. This implies that the network should not be designed as a single vertiport at Lipari only. Instead, a distributed infrastructure concept may be required, with a primary hub and smaller satellite landing or charging points on selected islands.

Fire safety and emergency response are critical because eVTOL aircraft rely on high-energy lithium-ion battery systems. The vertiport infrastructure should therefore include emergency access, firefighting capability, battery incident procedures, isolation areas for damaged battery packs and coordination with local emergency services. EASA PTS-VPT-DSN includes rescue and firefighting services among the relevant vertiport design considerations [10]. In an island environment, this requirement is particularly important because emergency resources may be limited and response times can vary significantly between islands.

Weather exposure must also influence site selection. Coastal and island vertiports are exposed to wind, salt, humidity and rapid weather changes. Wind direction and turbulence may be affected by local topography, especially near volcanic slopes, ridges or coastal cliffs. Therefore, the approach and departure paths should be selected not only for obstacle clearance, but also for wind exposure and operational consistency. This aspect is directly linked to the wind sensitivity discussed in the previous chapters: a site that is geometrically possible may still be operationally weak if it is exposed to frequent unfavourable wind conditions.

The main infrastructure requirements for the Aeolian Islands scenario are summarised in Table 9.1.

Table 9.1: Main vertiport and ground infrastructure requirements for the Aeolian Islands scenario.

Infrastructure aspect	Technical requirement	Relevance for the Aeolian Islands case
Landing area geometry	FATO, TLOF and safety area compatible with the design VTOL aircraft.	Limited flat land and constrained coastal spaces make site selection critical.
Obstacle environment	Clear approach and departure paths with acceptable obstacle margins.	Volcanic relief, ports, antennas and compact settlements may restrict usable directions.
Ground bearing capacity	Prepared surface for aircraft loads, repeated operations and ground equipment.	Volcanic terrain may require reinforcement, levelling, drainage and erosion control.
Downwash and outwash	Protection of people, vehicles, loose objects and nearby activities.	Important near ports, pedestrian areas, volcanic dust, sea spray and light equipment.
Energy infrastructure	Charging or battery swapping, storage, thermal monitoring and grid connection.	Essential for Lipari as hub and for intermediate stops on longer routes.
Fire safety and emergency response	Rescue access, firefighting capability and battery incident procedures.	Island emergency resources may be limited and battery events require specific response.
Turnaround operations	Payload handling, battery exchange, inspection and dispatch procedures.	Determines whether multi-leg hub-and-spoke operations can be efficient.
Weather exposure	Site selection considering wind, turbulence, salt, visibility and microclimate.	Operations are sensitive to seasonal wind and local topographic effects.
Integration with local mobility	Connection to ports, roads, emergency services and logistics nodes.	Harbour-adjacent sites are useful but must be separated from maritime/public activity.

From the perspective of this thesis, the most important conclusion is that infrastructure feasibility must be considered together with aircraft energy feasibility. A route may be energetically possible but operationally impractical if the destination island cannot provide a suitable landing area, safe approach path, battery support and emergency response capability. Conversely, intermediate infrastructure can extend the practical usefulness of the network by dividing longer routes into shorter and more manageable legs.

Therefore, the Aeolian Islands eVTOL concept should be interpreted as an integrated aircraft–infrastructure system. Lipari may act as the primary hub, but the operational

value of the network depends on the availability of compatible satellite sites on other islands. The geological and spatial constraints of the archipelago make this infrastructure assessment particularly important. Future work should therefore combine the energy model developed in this thesis with a site-selection analysis based on terrain morphology, obstacle environment, grid availability, emergency access, environmental constraints and local transport integration.

9.4. Airspace Integration and U-Space Considerations

Airspace integration is a central requirement for any future eVTOL operation. Even if the aircraft and vertiport infrastructure were technically suitable, the service could not be implemented without a safe and coordinated integration into the existing airspace system. This is particularly relevant in the Aeolian Islands scenario, where operations would take place over sea, near populated island settlements, close to harbour areas and potentially in interaction with helicopter traffic, emergency flights, general aviation and future unmanned aircraft operations.

The regulatory discussion must distinguish between two possible operational interpretations of the concept. If the service is developed as a manned or piloted passenger-carrying eVTOL operation, it would primarily need to be integrated within the conventional aviation framework, including air traffic services, flight rules, route approval, communication requirements and coordination with controlled or uncontrolled airspace. If, instead, the concept evolves towards unmanned cargo operations, especially beyond visual line of sight, the U-space framework becomes directly relevant.

In the European regulatory framework, U-space is introduced by Commission Implementing Regulation (EU) 2021/664. The regulation defines U-space as a specific airspace framework for UAS operations and establishes the conditions under which unmanned aircraft may operate within designated U-space airspace [7]. EASA describes the U-space Regulation as introducing “*a regulatory framework for the U-space*”, where U-space is associated with UAS geographical zones and the use of specific services by UAS operators [13].

This distinction is important. U-space should not be presented as a complete certification or operating framework for a piloted passenger eVTOL service. Its current regulatory scope is centred on unmanned aircraft systems. However, U-space concepts are still highly relevant for the present thesis because a lightweight logistics use case may in the future involve unmanned cargo missions, digital flight authorisation, strategic deconfliction and low-altitude traffic information services.

The U-space framework is based on the idea that certain airspace volumes can be designated by Member States as U-space airspace. Access to those volumes is then associated with the use of specific digital services. Regulation (EU) 2021/664 states that U-space airspace is a UAS geographical zone designated by Member States where UAS operations are allowed only with the support of U-space services [7]. In practical terms, this means that an operator cannot simply fly in such airspace without interacting with the required service infrastructure.

The mandatory U-space services include network identification, geo-awareness, UAS flight authorisation and traffic information. EASA describes these services as follows: network identification provides live flight data of each unmanned aircraft; geo-awareness provides information about airspace constraints and geo-zones; UAS flight authorisation ensures that flights in U-space airspace are authorised; and traffic information supports awareness of other relevant air traffic [14]. These services are directly connected to the operational challenges of a dense or structured low-altitude environment.

For the Aeolian Islands scenario, the most relevant U-space functions are summarised in Table 9.2.

Table 9.2: Main U-space functions relevant to a future Aeolian Islands eVTOL logistics concept.

U-space function	Regulatory role	Relevance for the Aeolian Islands scenario
Network identification	Provides identification and live flight information for unmanned aircraft.	Relevant for cargo-flight traceability and authority oversight of low-altitude operations.
Geo-awareness	Provides information on airspace constraints, geographical zones and limitations.	Important near protected areas, settlements, ports, heli routes and restricted areas.
UAS flight authorisation	Ensures that each UAS flight in U-space airspace is authorised before operation.	Useful for managing point-to-point or multi-leg cargo flights and avoiding conflicts.
Traffic information	Provides information on other relevant air traffic.	Critical where routes may interact with helicopters, emergency flights or general aviation.
Weather information	Provides meteorological data when required as an additional U-space service.	Relevant in an island environment exposed to wind, visibility changes and sea weather.
Conformance monitoring	Monitors consistency with the authorised trajectory or operational intent.	Relevant for BVLOS logistics flights over sea or between islands with limited landing options.

In Italy, U-space implementation must also be read together with national geographical-zone management. ENAC states that U-space is a particular type of UAS geographical zone introduced by Regulation (EU) 2021/664 and that, at present, no portion of U-space has yet been activated in Italy [6]. This is an important point for the thesis: the Aeolian Islands concept cannot simply assume the existence of an operational U-space environment. A future implementation would require designation of the relevant airspace volume, definition of applicable services, identification of service providers and coordination with the competent national authority.

The Italian context also highlights that geographical zones may impose specific operational conditions. ENAC guidance explains that, when defining UAS geographical zones, Member States may impose conditions on UAS operations or require particular technical characteristics and authorisations [5]. For the Aeolian Islands, this could become relevant near ports, settlements, environmentally protected areas, tourist zones, emergency

facilities and any airspace used by helicopters or other low-altitude traffic.

From an operational perspective, the most critical issue is the coexistence between eVTOL operations and other airspace users. A future island network could include several types of traffic: piloted eVTOL aircraft, unmanned cargo drones, emergency helicopters, search-and-rescue operations, general aviation and maritime-related aerial activity. Therefore, route planning should not only minimise energy consumption, but also consider separation, detect-and-avoid capability, communication links, contingency routes and emergency landing options.

The distinction between manned and unmanned operations is also relevant for communications and surveillance. A piloted eVTOL passenger service would likely require voice communication, air traffic coordination and compliance with applicable flight rules. An unmanned cargo service would rely more heavily on digital services, remote identification, flight authorisation, command-and-control link reliability and conformance monitoring. In both cases, the aircraft must be integrated into an operational environment where other airspace users and ground risks are explicitly managed.

The Aeolian Islands create specific integration challenges. The routes are short but cross open sea, which reduces ground population exposure along parts of the route but also limits emergency landing opportunities. Approaches and departures would concentrate near coastal settlements and ports, increasing the importance of obstacle clearance, noise exposure, public safety and coordination with local traffic. Wind patterns affected by island topography may also influence approach direction, route selection and operational availability.

For this reason, airspace integration should be treated as part of the network design. Lipari could act as the main operational hub, but the aerial corridors connecting Lipari to the other islands would need to be assessed in terms of airspace classification, terrain and obstacle environment, emergency alternatives, communication coverage, weather exposure and interaction with existing aviation activity. For multi-leg missions, each intermediate stop would also require compatible airspace access and departure/arrival procedures.

The present thesis does not model airspace capacity, traffic separation or digital flight authorisation. However, the mission-energy results provide useful input to an airspace-integration assessment because they identify the routes, intermediate stops and operational conditions most likely to be used. In a future development, the energy model could therefore be coupled with a route-availability and airspace-risk model to determine which missions are not only energetically feasible, but also operationally acceptable.

Overall, U-space and airspace integration considerations show that the practical implementation of the Aeolian Islands eVTOL concept would require more than aircraft performance and vertiport infrastructure. For unmanned or highly automated logistics operations, U-space services would be essential to support identification, authorisation, geo-awareness, traffic information and conformance monitoring. For piloted passenger or mixed operations, coordination with the existing aviation framework would remain central. In both cases, safe integration into the low-altitude island airspace is a fundamental condition for real-world applicability.

9.5. Operational Constraints for the Aeolian Islands Case Study

The Aeolian Islands case study introduces operational constraints that are more specific than the general regulatory requirements discussed in the previous sections. The archipelago is not only a set of point-to-point distances between islands. It is a volcanic, insular and weather-exposed environment in which route planning, vertiport siting, emergency management and operational availability must be considered together.

The Aeolian Islands are a volcanic archipelago located north of Sicily. The UNESCO description of the site highlights the presence of two active volcanoes, Stromboli and Vulcano, and notes that volcanic activity such as fumaroles and thermal waters is present throughout the archipelago [28]. This geological context is directly relevant to eVTOL operations because the availability of suitable infrastructure sites depends on terrain morphology, ground stability, slopes, rocky surfaces, volcanic deposits and local environmental constraints.

From an operational perspective, the first constraint is the separation between energy feasibility and service availability. A route may be feasible in the mission model, but this does not imply that it can be operated reliably throughout the year. The Aeolian Islands are exposed to sea weather, seasonal wind variability and local topographic effects. Wind conditions can affect both the energy required along the route and the usability of approach and departure paths. Therefore, the operational availability of an eVTOL service would depend on weather minima, dispatch rules and the availability of alternative routes or landing sites.

The second constraint is the limited number of suitable take-off and landing locations. Many island areas are characterised by steep terrain, compact settlements, coastal cliffs, protected landscapes or limited flat surfaces. This makes vertiport placement a critical

design variable. A theoretically central location may be unsuitable if it does not provide adequate ground stability, obstacle clearance, emergency access, separation from public areas or electrical infrastructure. Conversely, harbour-adjacent locations may offer logistical advantages but introduce conflicts with maritime traffic, pedestrian flows, port equipment and public access.

The geological nature of the islands is particularly important for infrastructure feasibility. Volcanic terrain may include hard rock, irregular surfaces, slopes or unconsolidated deposits. For this reason, a vertiport or satellite landing site should not be selected only on the basis of geographic position. It would require a site-specific assessment of surface bearing capacity, foundation requirements, drainage, erosion resistance, slope, exposure to sea spray and compatibility with repeated aircraft operations. This is consistent with the vertiport design logic discussed by EASA, where the physical characteristics of the landing area and the obstacle environment are fundamental elements of vertiport design [10].

The third constraint is the need for intermediate operational nodes. The energy analysis showed that some distant routes may be demanding if treated as direct flights from the main hub. In an island network, however, infeasibility of a direct leg does not necessarily exclude service to the final island. The route can be divided into shorter legs, with intermediate stops used for landing, payload handling, recharging or battery swapping. This is particularly relevant for distant islands such as Alicudi or Stromboli, where a direct route may be energy-critical but a staged route could remain operationally viable if suitable intermediate infrastructure exists.

This implies that the network should be designed as an integrated system rather than as a set of independent direct routes. Lipari can operate as the primary hub, but satellite sites on other islands would determine how far the practical service envelope can extend. The feasibility of the network is therefore not only an aircraft-range problem. It also depends on the distribution, capability and reliability of intermediate nodes.

The fourth constraint concerns emergency and contingency planning. Sea-crossing routes reduce the exposure to population on the ground for part of the flight, but they also reduce the availability of emergency landing options. For a real operation, each route would require predefined contingency procedures, including return-to-base decisions, diversion to an alternate island, landing at an intermediate site or coordination with maritime rescue resources. This is particularly important for eVTOL aircraft, where battery state, propulsion redundancy and emergency landing capability are central elements of the safety case.

The fifth constraint is energy infrastructure. The mission concept becomes more realistic

if charging or battery swapping is available at the hub and at selected intermediate points. However, this requires local electrical capacity, battery storage, fire protection, thermal monitoring, operational procedures and maintenance capability. On small islands, grid limitations and seasonal demand peaks may become relevant. Therefore, the installation of eVTOL infrastructure would need to be evaluated together with local energy availability, renewable generation potential, grid reinforcement and emergency power supply.

The sixth constraint is operational seasonality. The Aeolian Islands experience strong seasonal variations in tourism, maritime traffic and local service demand. During the summer period, the potential demand for rapid logistics and emergency transport may increase, but port congestion, public crowding, noise sensitivity and thermal battery effects may also become more relevant. During winter or adverse-weather periods, the value of an aerial logistics layer could increase when maritime connections are reduced or delayed, but wind, visibility and weather minima may limit flight availability. Therefore, the service should be assessed not only by average annual feasibility, but also by seasonal operational windows.

The seventh constraint is environmental and social compatibility. The Aeolian Islands are environmentally sensitive and culturally valuable territories. The introduction of eVTOL operations would require attention to noise, visual impact, protected areas, tourism perception, local acceptance and integration with existing mobility patterns. Even if electric propulsion reduces local emissions compared with combustion-based aviation, it does not eliminate all environmental impacts. Rotor noise, downwash, infrastructure footprint and battery logistics would still require assessment.

The operational constraints specific to the Aeolian Islands are summarised in Table 9.3.

Table 9.3: Operational constraints for an eVTOL network in the Aeolian Islands.

Constraint	Practical implication	Relevance for the eVTOL concept
Volcanic terrain and morphology	Site selection must consider slopes, non-rocky surfaces, stability, erosion and drainage.	Some central locations may be unsuitable for safe vertiport or landing-site installation.
Limited flat land	FATO, TLOF, safety area and access routes may be difficult to accommodate.	Infrastructure feasibility may be more restrictive than aircraft range on some islands.
Obstacle environment	Approach and departure paths may be constrained by terrain, buildings, antennas and port equipment.	Route design must include obstacle clearance and safe climb/descent corridors.
Sea-crossing routes	Emergency landing options are limited between islands.	Requires contingency planning, alternate sites and maritime rescue coordination.
Weather exposure	Wind, visibility and local topographic effects may reduce operational availability.	Energy feasibility must be combined with weather-aware dispatch rules.
Intermediate stops	Long direct routes can be divided into shorter operational legs.	Extends the service envelope if satellite charging or battery-swapping sites are available.
Energy infrastructure	Charging or battery swapping requires grid capacity, storage, fire protection and turnaround procedures.	Determines whether the network can operate repeatedly, not only as isolated missions.
Seasonality	Tourism, port traffic, weather and demand vary across the year.	Service planning must account for seasonal demand and operational limitations.
Environmental and social acceptance	Noise, downwash, visual impact and protected areas must be considered.	Local acceptance may become limiting even if technical feasibility is achieved.

For the mission concept developed in this thesis, the most relevant operational implication is that direct route feasibility should not be interpreted as the only criterion for network feasibility. A route that is too demanding as a direct flight may still be viable through intermediate stops, provided that the intermediate island offers adequate landing, energy and emergency infrastructure. This is particularly important for a distributed archipelago, where operational resilience can be improved by using multiple nodes rather than relying exclusively on one central hub.

At the same time, adding intermediate stops changes the nature of the operation. It in-

troduces turnaround time, infrastructure requirements, additional landing cycles, battery management procedures and operational coordination. Therefore, it can improve range feasibility but may reduce time advantage if not properly designed. The practical solution would require a balance between direct flights for short routes and staged operations for longer or more critical routes.

Overall, the Aeolian Islands scenario confirms that eVTOL feasibility is not only an aircraft performance problem. It is an integrated aircraft–infrastructure–environment problem. The mission-energy model developed in this thesis identifies which routes are promising from an energy point of view, while the regulatory and operational considerations indicate what additional conditions would be required for real implementation. Future work should therefore combine the energy model with site-selection analysis, seasonal weather data, emergency planning, electrical infrastructure assessment and stakeholder acceptance studies.

9.6. Summary of Main Compliance Drivers

The previous sections show that the transition from mission-level energy feasibility to real eVTOL operation would require several additional compliance layers. The model developed in this thesis can identify route energy demand, battery margins and critical operating conditions, but it does not replace aircraft certification, vertiport approval, airspace integration or operational safety assessment.

The main compliance drivers for the Aeolian Islands scenario are summarised in Table 9.4.

Table 9.4: Main compliance drivers for the Aeolian Islands eVTOL concept.

Compliance area	Main driver	Relevance for the thesis scenario
Aircraft certification	SC-VTOL basis, category selection and safety objectives.	Defines whether the aircraft can be certified for the intended operation [12].
Failure capability	Continued safe flight and landing, or controlled emergency landing.	Nominal feasibility must be extended to abnormal and failure cases [8, 12].
Battery safety	Thermal runaway, containment, non-propagation and battery protection.	Mission-level SOC analysis does not replace battery compliance demonstrations [11].
Energy reserves	Operational margin, diversion capability and emergency landing energy.	The computed energy margin is preliminary, not a certification reserve.
Vertiport infrastructure	FATO, TLOF, safety areas, obstacle environment, visual aids and firefighting.	Determines whether Lipari and the other islands can host safe landing sites [10].
Ground energy system	Charging, battery swapping, storage and grid connection.	Essential for repeated hub-and-spoke operations and intermediate stops.
Airspace integration	Traffic information, flight authorisation, geo-awareness and route coordination.	Required for safe low-altitude operations and future unmanned logistics [7, 13].
Weather and environment	Wind, visibility, temperature, sea-crossing exposure and local topography.	Affects dispatch decisions, route availability and operational robustness.
Emergency planning	Alternate landing sites, intermediate nodes and rescue coordination.	Critical because routes cross the sea and emergency landing options are limited.
Local integration	Noise, downwash, public access, port activity and protected areas.	Relevant for harbour-adjacent sites, tourism areas and island communities.

The table highlights that real applicability depends on the combined aircraft–infrastructure–

operation system. A route may be energetically feasible in the model, but it would still require a compliant aircraft, suitable landing sites, safe obstacle clearance, adequate reserves, emergency options, compatible airspace access and ground energy support.

For the Aeolian Islands, the most critical aspects are limited infrastructure, volcanic morphology, sea-crossing routes and weather exposure. Longer routes may become more realistic through intermediate stops, but only if those locations can support safe landing, turnaround and battery replenishment.

Therefore, the results of this thesis should be interpreted as an early mission-level feasibility assessment. The energy model identifies promising routes and critical parameters, while a real implementation would require certification, vertiport design, airspace integration, battery safety and emergency planning to be addressed in detail.

10 | Sustainability and Future Developments

10.1. Energy Cost and Emission Comparison with Maritime Logistics

This section compares the operating energy cost, CO₂ emissions and travel time of the analysed eVTOL mission with representative fast maritime transport serving the Aeolian Islands. The objective is not to reproduce the exact fuel consumption of a specific Liberty Lines service, because route-specific operational fuel logs are not publicly available. Instead, Liberty Lines is used as a realistic public reference for high-speed maritime transport in the archipelago.

A key distinction must be introduced before interpreting the results. The eVTOL mission considered in this thesis is a lightweight and time-sensitive transport mission, whereas the maritime reference vessels are high-capacity passenger vessels designed to carry hundreds of passengers and larger payloads. Therefore, the comparison is first presented at mission level and then complemented by normalised indicators. This avoids interpreting a small eVTOL mission as directly equivalent to a full maritime service.

The maritime reference cases are derived from public Liberty Lines fleet specifications. Representative values include hydrofoils with engines of approximately 2×2000 kW and speeds around 35–36 kn, monohulls with 3×1080 kW and speeds around 30 kn, and HSC hybrid vessels with 2×2560 kW diesel engines and speeds around 30 kn [23]. These data are used to define representative vessel classes, not exact route-specific operational fuel measurements.

For the maritime cases, the crossing time is first estimated from the route distance and vessel speed:

$$t_{\text{sea,kin}} = \frac{d_{\text{route}}}{V_{\text{sea}}} \quad (10.1)$$

where d_{route} is the Milazzo–Vulcano route distance and V_{sea} is the representative vessel speed. Since:

$$1 \text{ kn} = 1.852 \text{ km/h} \quad (10.2)$$

a representative 35 kn hydrofoil gives:

$$t_{\text{sea,kin}} = \frac{37}{35 \cdot 1.852} = 0.571 \text{ h} = 34.3 \text{ min} \quad (10.3)$$

This is an ideal kinematic crossing time. Public ferry-route information indicates that the commercial Milazzo–Vulcano crossing typically ranges from about 45 minutes for fast hydrofoil services to almost 2 hours depending on the vessel, operator and schedule [4, 17]. Therefore, the maritime time comparison should distinguish between ideal kinematic time and scheduled service time.

For the eVTOL, the mission time is obtained directly from the segment-based MATLAB model:

$$t_{\text{eVTOL}} = \sum_i t_i \quad (10.4)$$

For the Milazzo–Vulcano base case, the resulting value is:

$$t_{\text{eVTOL}} = 1655.21 \text{ s} = 27.59 \text{ min} \quad (10.5)$$

This value includes taxi, hover, vertical take-off, forward climb, cruise, descent, vertical landing and final taxi. It does not include additional handling time such as loading, unloading, pre-flight checks, charging, battery swapping or vertiport access procedures.

Table 10.1: Indicative travel-time comparison for the Milazzo–Vulcano connection.

Transport mode	Time	Comment
eVTOL reference mission	27.6 min	MATLAB mission time, excluding vertiport handling
Hydrofoil, kinematic estimate	34.3 min	Based on 37 km and 35 kn vessel speed
Hydrofoil, commercial crossing	45–60 min	Typical scheduled fast maritime service [4]
Maritime service range	45 min–almost 2 h	Depends on vessel, operator and schedule [17]

The travel-time comparison suggests that the eVTOL may reduce the pure connection

time for a dedicated lightweight mission. However, this result must be interpreted carefully because the eVTOL value is a modelled mission time, while maritime values are commercial crossing times. A complete door-to-door comparison would also require waiting time, loading and unloading operations, port or vertiport access, charging or battery swapping, and schedule availability.

The maritime fuel consumption is estimated through a model-based approach. Public vessel data define the installed power and speed, while the fuel demand is computed from operating time, engine load factor and specific fuel consumption:

$$m_f = P_{\text{inst}} LF t_{\text{sea,kin}} SFC \quad (10.6)$$

where P_{inst} is the installed propulsion power, LF is the average engine load factor, and SFC is the specific fuel consumption. The corresponding fuel volume is:

$$V_f = \frac{m_f}{\rho_f} \quad (10.7)$$

where ρ_f is the diesel fuel density. The maritime fuel cost is then:

$$C_{\text{sea}} = V_f c_{\text{diesel}} \quad (10.8)$$

where c_{diesel} is the diesel price. In this work, the MIMIT regional public fuel-price reference for Sicily is adopted as a transparent benchmark [25]. This value should not be interpreted as the actual contracted marine fuel price paid by a specific operator.

For the eVTOL case, the relevant quantity is the electrical energy required to recharge the battery after the mission. This is not exactly equal to the energy consumed during flight because charger losses must be included:

$$E_{\text{grid}} = \frac{E_{\text{mission}}}{\eta_{\text{charger}}} \quad (10.9)$$

For the Milazzo–Vulcano base case, the mission-energy model gives:

$$E_{\text{mission}} = 41.48 \text{ kWh} \quad (10.10)$$

Assuming:

$$\eta_{\text{charger}} = 0.90 \quad (10.11)$$

the required grid energy becomes:

$$E_{\text{grid}} = \frac{41.48}{0.90} = 46.09 \text{ kWh} \quad (10.12)$$

The eVTOL electricity cost is then:

$$C_{\text{eVTOL}} = E_{\text{grid}} c_{\text{el}} \quad (10.13)$$

where c_{el} is the electricity price. The ARERA electricity-price reference for the second quarter of 2026 is used as a public retail benchmark [1]. This value is not a dedicated industrial charging tariff for vertiports, but provides a transparent reference for comparison.

The emission comparison is based on direct fuel combustion for maritime transport and electricity-related emissions for the eVTOL. For maritime transport:

$$m_{\text{CO}_2, \text{sea}} = V_f EF_{\text{diesel}} \quad (10.14)$$

where EF_{diesel} is the diesel emission factor. The UK Government GHG Conversion Factors provide annually updated conversion factors for reporting applications and are used here as a transparent reference for diesel emissions [27]. In the numerical comparison, the diesel factor is taken as:

$$EF_{\text{diesel}} = 2.512 \text{ kgCO}_2\text{e/L} \quad (10.15)$$

For the eVTOL, direct operational emissions are zero because there is no onboard fuel combustion:

$$m_{\text{CO}_2, \text{eVTOL, direct}} = 0 \quad (10.16)$$

However, indirect emissions associated with electricity generation are not necessarily zero and depend on the electricity mix:

$$m_{\text{CO}_2, \text{eVTOL, grid}} = E_{\text{grid}} EF_{\text{grid}} \quad (10.17)$$

ISPRA provides the Italian reference framework for CO₂ emission factors associated with electricity generation and consumption [21]. In this comparison, the grid emission factor is assumed equal to:

$$EF_{\text{grid}} = 0.215 \text{ kgCO}_2/\text{kWh} \quad (10.18)$$

This value is used as an indicative Italian grid-average factor. If the charging energy were supplied by certified renewable electricity or local renewable generation, the indirect operational emissions would be significantly reduced.

The main assumptions adopted in the comparison are summarised in Table 10.2.

Table 10.2: Main assumptions adopted for the maritime-eVTOL operating cost and emission comparison.

Quantity	Value	Comment
Route distance	37 km	Milazzo–Vulcano reference route
eVTOL mission energy	41.48 kWh	Obtained from the mission-energy model
eVTOL mission time	27.59 min	Segment-based MATLAB result
Charger efficiency	0.90	Assumed charging efficiency
Grid energy for recharge	46.09 kWh	$E_{\text{grid}} = E_{\text{mission}}/\eta_{\text{charger}}$
Electricity price	0.3024 €/kWh	ARERA public retail benchmark, Q2 2026 [1]
Diesel price	2.070 €/L	MIMIT public regional diesel price for Sicily [25]
Marine diesel density	0.835 kg/L	Representative diesel density
Marine diesel SFC	0.205 kg/kWh	Representative high-speed marine diesel value
Diesel emission factor	2.512 kgCO ₂ e/L	Reporting conversion factor [27]
Grid emission factor	0.215 kgCO ₂ /kWh	Indicative Italian electricity mix factor [21]

The resulting mission-level operating energy cost comparison is reported in Table 10.3.

Table 10.3: Mission-level operating energy cost comparison for the Milazzo–Vulcano route.

Case	Power	Speed	Energy/fuel demand	Energy cost
eVTOL reference mission	–	–	46.09 kWh grid energy	13.94 €
Hydrofoil reference	4000 kW	35 kn	364.4 L diesel	754.3 €
Monohull HSC reference	3240 kW	30 kn	344.3 L diesel	712.7 €
HSC hybrid diesel reference	5120 kW	30 kn	502.3 L diesel	1039.8 €

Table 10.3 shows a large mission-level difference between the electricity cost of the eVTOL flight and the modelled fuel cost of the maritime reference cases. This difference is physically plausible because the compared systems have very different scale and purpose. The maritime vessels are high-power, high-capacity vehicles designed for regular passenger service, while the eVTOL mission considered here is a lightweight transport task with much lower transported mass.

The corresponding CO₂ comparison is reported in Table 10.4.

Table 10.4: Mission-level operational CO₂ comparison for the Milazzo–Vulcano route.

Case	Emission basis	Estimated emissions
eVTOL direct operation	No onboard combustion	0 kg CO ₂
eVTOL with Italian grid electricity	46.09 kWh, $EF_{\text{grid}} = 0.215$ kgCO ₂ /kWh	9.9 kg CO ₂
eVTOL with renewable electricity	Certified renewable or local renewable supply	≈ 0 kg CO ₂ operationally
Hydrofoil reference	364.4 L diesel, $EF_{\text{diesel}} = 2.512$ kgCO ₂ e/L	915.4 kg CO ₂ e
Monohull HSC reference	344.3 L diesel, $EF_{\text{diesel}} = 2.512$ kgCO ₂ e/L	865.1 kg CO ₂ e
HSC hybrid diesel reference	502.3 L diesel, $EF_{\text{diesel}} = 2.512$ kgCO ₂ e/L	1261.8 kg CO ₂ e

The previous tables compare complete missions, but they do not account for the different transport capacity of the vehicles. To address this limitation, additional normalised indicators are introduced. For the eVTOL, the natural reference is the useful payload:

$$I_{C,\text{payload}} = \frac{C_{\text{eVTOL}}}{m_{\text{payload}}} \quad (10.19)$$

$$I_{\text{CO}_2, \text{payload}} = \frac{m_{\text{CO}_2, \text{eVTOL, grid}}}{m_{\text{payload}}} \quad (10.20)$$

For the maritime case, a direct payload comparison is more difficult because the hydrofoil is primarily a passenger vessel. Therefore, a passenger-equivalent capacity basis is introduced:

$$m_{\text{cap, sea}} = N_{\text{pax}} m_{\text{pax, ref}} \quad (10.21)$$

where N_{pax} is the passenger capacity and $m_{\text{pax, ref}}$ is a representative passenger-equivalent mass. Public Liberty Lines fleet data report hydrofoils with 207 passengers, 2×2000 kW installed power and 35 kn speed [23]. Therefore:

$$N_{\text{pax}} = 207 \quad (10.22)$$

and:

$$m_{\text{pax, ref}} = 75 \text{ kg} \quad (10.23)$$

which gives:

$$m_{\text{cap, sea}} = 207 \cdot 75 = 15525 \text{ kg} \quad (10.24)$$

The corresponding maritime capacity-normalised indicators are:

$$I_{C, \text{cap, sea}} = \frac{C_{\text{sea}}}{m_{\text{cap, sea}}} \quad (10.25)$$

$$I_{\text{CO}_2, \text{cap, sea}} = \frac{m_{\text{CO}_2, \text{sea}}}{m_{\text{cap, sea}}} \quad (10.26)$$

The normalised indicators are shown in Table 10.5.

Table 10.5: Mission-level and normalised cost/emission indicators for the Milazzo–Vulcano comparison.

Indicator	eVTOL	Hydrofoil	Meaning
Mission energy cost	13.94 €	754.3 €	Total operating energy cost for one mission
Mission emissions	9.9 kg CO ₂	915.4 kg CO ₂ e	Mission-level operational emissions
Payload / capacity basis	200 kg payload	15525 kg passenger-equivalent capacity	Different transport scale
Cost per kg basis	0.0697 €/kg payload	0.0486 €/kg capacity	Normalised cost indicator
CO ₂ per kg basis	0.0495 kgCO ₂ /kg payload	0.0590 kgCO ₂ e/kg capacity	Normalised emission indicator

The normalised indicators change the interpretation of the comparison. At mission level, the eVTOL shows much lower energy cost and emissions because it is a small aircraft performing a lightweight task, whereas the hydrofoil is a high-capacity vessel. When the maritime result is normalised by passenger-equivalent capacity, the difference becomes much less extreme. This confirms that maritime transport remains efficient for high-capacity passenger flows, while the eVTOL advantage is mainly associated with small, urgent and time-sensitive payloads.

The same interpretation applies to emissions. The eVTOL has zero direct operational emissions because it does not burn fuel onboard. Its indirect emissions depend on the electricity source and are therefore much lower if the charging infrastructure is supplied by renewable energy. The maritime cases generate direct combustion emissions during the crossing, but they also provide a much larger transport capacity.

The results in this section do not include the full life cycle of either system. Battery manufacturing, aircraft production, vessel construction, maintenance, infrastructure, battery replacement, recycling and end-of-life processes are outside the scope of the comparison. Therefore, the conclusion is specific and limited: for lightweight, time-sensitive logistics missions, an eVTOL layer can offer lower direct emissions, shorter dedicated mission time and lower mission-level energy cost. This does not imply that eVTOL aircraft can replace maritime transport for regular passenger or high-volume cargo operations. Rather, it supports a complementary system in which maritime transport remains the backbone for mass mobility, while eVTOL aircraft serve selected urgent missions where payload is small and response time is critical.

10.2. Sustainability and Logistic Potential in the Aeolian Islands

The comparison with maritime logistics shows that the eVTOL concept is most meaningful when applied to missions that match its scale: lightweight, urgent and short-range transport. Its value is not in replacing ferries or hydrofoils, but in providing a smaller and faster vehicle for tasks that do not require the capacity of conventional maritime transport.

In the Aeolian Islands, this role can be relevant for medical items, spare parts, documents, emergency equipment, high-priority parcels and other time-sensitive payloads. These missions are not primarily capacity-driven, but time-driven. For this reason, a small electric aerial vehicle can be more appropriate than waiting for the next scheduled maritime connection or relying on a larger vessel for a limited payload.

From an environmental point of view, the main advantage of the eVTOL is the absence of direct onboard emissions during flight. However, it should be described as a zero-direct-emission vehicle rather than as a zero-emission system in absolute terms. If the aircraft is charged from the grid, indirect emissions depend on the electricity mix. The benefit becomes stronger if charging or battery swapping is supplied by renewable electricity or integrated with local energy storage.

The economic potential follows the same logic. The relevant benefit is not only the lower energy cost per mission, but the better match between vehicle size and transport task. For small urgent payloads, the eVTOL can reduce energy use and response time. For high-volume passenger or cargo flows, maritime transport remains the more appropriate solution.

Overall, the sustainability and logistic potential of the eVTOL concept lies in selective deployment. In the Aeolian Islands scenario, the aircraft is best interpreted as a complementary rapid-response layer for lightweight missions, integrated with maritime transport rather than opposed to it.

10.3. Integration into Smart Island Mobility

The eVTOL concept analysed in this thesis can be interpreted as one component of a broader smart island mobility system. Its role would not be limited to the aircraft itself, but would depend on the integration between aerial routes, maritime transport, local ground mobility, energy infrastructure and digital coordination tools.

In this framework, the eVTOL service could operate as a flexible connection layer between islands. Maritime transport would remain the backbone for regular passenger and cargo flows, while eVTOL missions could be activated for urgent, lightweight or time-sensitive needs. This requires coordination with existing ferry and hydrofoil schedules, port logistics, emergency services and local delivery networks.

A smart island implementation would also require digital mission planning. Route selection, payload allocation, battery state, weather conditions, charging availability and intermediate stops should be managed together. This is particularly important in an archipelago, where the same destination may be reached either directly or through staged routes depending on operational conditions.

Energy management is another key element. Charging or battery-swapping points could be linked to local renewable generation, storage systems and grid constraints. In this way, the aerial mobility network would not be an isolated transport system, but part of the wider island energy ecosystem.

Overall, the integration of eVTOL operations into smart island mobility should be based on selective and coordinated use. The aircraft would provide the greatest value when connected to existing transport modes, local energy resources and digital dispatching systems, rather than operating as a standalone service.

10.4. Future Model and Aircraft Developments

The results obtained in this thesis provide a preliminary mission-level assessment of a multicopter eVTOL concept for island mobility. Future developments should move in two directions: improving the fidelity of the numerical model and extending the analysis towards a more complete aircraft and operational design framework.

A first improvement concerns the battery model. In the present work, the battery is represented mainly through specific energy, usable depth of discharge, efficiency and temperature-dependent capacity correction. Future work should include a more detailed electro-thermal battery model, accounting for cell temperature evolution during the mission, charging and discharging C-rates, thermal management, degradation, cycle life and power derating. This would allow the mission feasibility analysis to be linked not only to available energy, but also to battery ageing, cooling requirements and long-term operating cost.

Battery technology evolution is also a major driver for future feasibility. Higher specific energy, improved power density, faster charging, safer chemistries and better thermal

stability would directly expand the payload–range envelope identified in this thesis. Since the analysed missions are mainly energy-limited, even moderate improvements in battery specific energy or usable capacity could significantly increase the number of feasible routes or reduce the need for intermediate stops.

A second development concerns the aircraft configuration. The present model is based on a representative VoloCity-like multicopter architecture and does not perform a complete aircraft sizing or optimisation. Future studies should investigate alternative configurations, including different rotor counts, rotor diameters, disc loading levels, battery masses and aerodynamic layouts. In particular, lift-plus-cruise or wing-assisted eVTOL configurations could be compared with the pure multicopter architecture, since they may offer lower cruise energy consumption on longer routes.

The aerodynamic model could also be refined. The current mission-level formulation is suitable for route screening, but it does not include high-fidelity rotor aerodynamics, rotor–rotor interference, detailed fuselage drag, gust response or transition effects. Coupling the energy model with higher-fidelity aerodynamic tools would improve the prediction of power demand, especially in forward flight and in non-ideal wind conditions.

A third area of development is the operational energy infrastructure. Future work should model charging time, battery swapping, turnaround operations, local grid constraints and renewable-energy integration. This is particularly important for island networks, where electrical infrastructure may be limited and where local renewable generation could reduce indirect emissions. A complete assessment should evaluate not only whether the aircraft can complete a mission, but also how many missions can be operated per day with the available charging and battery-replacement infrastructure.

The network model could also be extended. The present study analyses point-to-point missions and selected hub-and-spoke routes. A future model should optimise the full inter-island network, including intermediate stops, fleet size, charging locations, payload demand, weather-dependent availability and scheduling. This would allow the evaluation of service reliability, daily transport capacity and operational resilience.

Certification and compliance represent another necessary development. The present thesis only identifies the main regulatory drivers, such as airworthiness, battery safety, vertiport infrastructure and airspace integration. A future project should translate these elements into formal requirements, including failure cases, emergency landing strategies, reserve policy, vertiport siting, U-space services where applicable and operational approval constraints. This would be essential to move from mission feasibility to a realistic Advanced Air Mobility concept.

Finally, future work should include a broader sustainability and economic assessment. The operating energy comparison presented in this thesis is useful, but it does not represent a complete life-cycle analysis. Aircraft manufacturing, battery production, battery replacement, infrastructure construction, maintenance, recycling and fleet utilisation should be included to evaluate the real environmental and economic performance of the system.

Overall, the next step is to evolve the present mission-energy model into an integrated aircraft–battery–infrastructure–operation framework. This would allow future studies to assess not only whether a single route is energetically feasible, but whether an eVTOL network can be technically, economically, environmentally and regulatorily viable in an island mobility scenario.

11 | Conclusions

11.1. Summary of Contributions

This thesis developed a mission-based energy assessment of a representative multicopter eVTOL configuration applied to short-range Advanced Air Mobility operations in the Aeolian Islands. The work focused on energy consumption, battery utilisation and mission feasibility, rather than on the complete design of a new aircraft.

The main contribution is the development of a segment-based mission model able to estimate the energy and power demand of an eVTOL mission composed of taxi, hover, vertical take-off, forward climb, cruise, descent, vertical landing and final taxi phases. The model was first aligned with a reference literature formulation and then adapted to the Milazzo–Vulcano route and to a Lipari-centred inter-island network.

The thesis also extended the nominal mission analysis through several sensitivity studies. Cruise speed, payload, distance, rotor count, rate of climb, temperature and wind were varied to identify the main parameters affecting feasibility. Combined parametric maps were then used to describe the operational envelope in terms of payload, distance and environmental conditions.

A further contribution is the integration of regulatory, infrastructure and sustainability considerations. The work does not claim aircraft-level certification compliance, but it identifies the main compliance drivers that would affect a real implementation, including airworthiness, battery safety, vertiport infrastructure, airspace integration and island-specific operational constraints. Finally, an indicative operating energy cost and emission comparison with maritime logistics was introduced to place the eVTOL concept within the broader sustainability context of the Aeolian Islands.

11.2. Answers to Research Questions

The first research question concerned whether a multicopter eVTOL configuration could perform short-range inter-island missions in the Aeolian Islands. The results show that

short and medium routes are compatible with the selected configuration, while longer direct routes become energy-critical. The Milazzo–Vulcano mission is close to the usable battery-energy boundary and therefore represents a demanding reference case rather than a robust nominal operation.

The second research question concerned the main drivers of mission energy consumption. The analyses show that usable battery energy is the dominant limitation. Peak power remains within the available battery power in the investigated cases, whereas energy margin is strongly affected by mission distance, payload, wind, temperature and cruise speed. The cruise segment becomes increasingly important for longer routes, while vertical and climb-related phases are more relevant for short missions.

The third research question concerned the operational suitability of a Lipari-centred hub-and-spoke network. The results support this architecture as a more realistic solution than relying only on long direct routes. Short legs from Lipari are more compatible with the multicopter configuration, and distant islands may still be served through intermediate stops, provided that landing, charging or battery-swapping infrastructure is available.

The fourth research question concerned the role of eVTOL operations compared with maritime logistics. The results indicate that eVTOL aircraft should not be interpreted as replacements for ferries or hydrofoils. Maritime transport remains essential for passengers and high-volume logistics. The eVTOL concept is more suitable as a complementary rapid-response layer for lightweight, urgent and time-sensitive missions.

11.3. Final Remarks

The main conclusion of this thesis is that multicopter eVTOL aircraft can be technically meaningful for selected island mobility missions, but their applicability is strongly constrained by battery energy, payload, route length and operating conditions. The concept is most promising when used selectively, within a clearly defined energy and infrastructure envelope.

The Aeolian Islands represent a challenging but relevant scenario for this type of analysis. Their geography creates a strong need for flexible inter-island connections, but their weather exposure, volcanic terrain, limited infrastructure and sea-crossing routes make real implementation more complex than a simple range calculation.

The proposed model provides a useful preliminary tool for identifying feasible missions, critical routes and dominant energy drivers. However, future work should include higher-fidelity aircraft modelling, detailed battery thermal and degradation analysis, infrastruc-

ture sizing, network optimisation, certification requirements and full life-cycle assessment.

Overall, the thesis shows that eVTOL technology may contribute to future island mobility if it is integrated with maritime transport, renewable energy infrastructure and carefully planned operational procedures. Its value lies not in replacing existing transport systems, but in adding a fast, low-direct-emission and flexible service layer for missions where speed and accessibility are more important than payload capacity.

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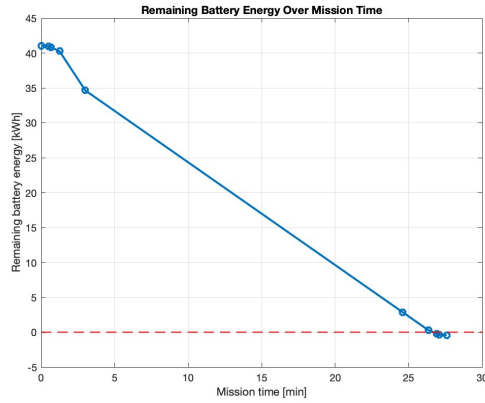
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A | Additional MATLAB Results

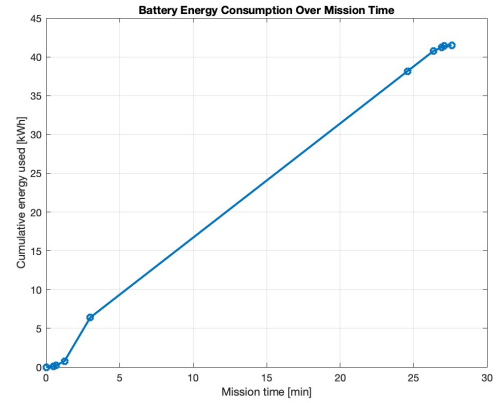
Additional plots and supplementary numerical results for the Milazzo–Vulcano reference mission are reported in this appendix. These figures support the mission analysis and sensitivity studies discussed in the main chapters, while keeping the main text focused on the most relevant results.

A.1. Additional Milazzo–Vulcano Mission Profiles

The following figures report supplementary mission-level outputs for the Milazzo–Vulcano base case, including battery evolution and segment-level results.

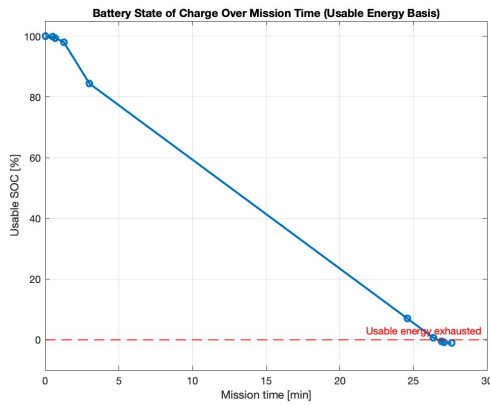


(a) Remaining battery energy.

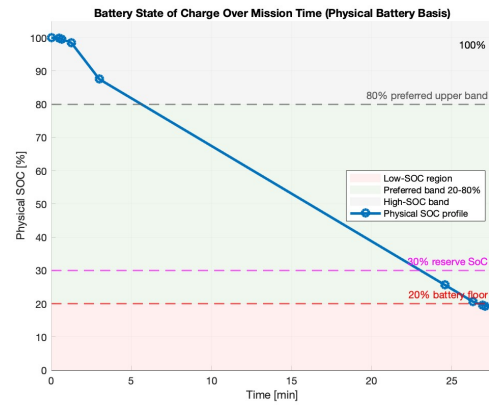


(b) Battery energy consumption.

Figure A.1: Additional battery energy profiles for the Milazzo–Vulcano mission.

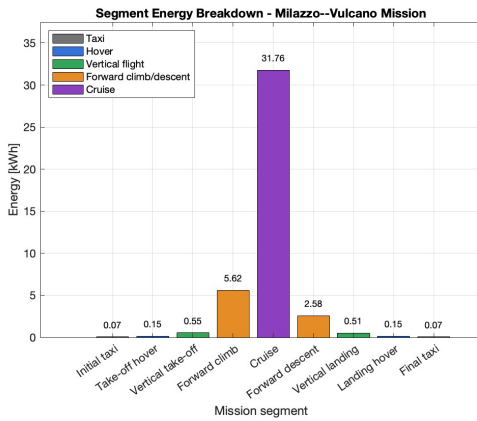


(a) Usable state of charge.

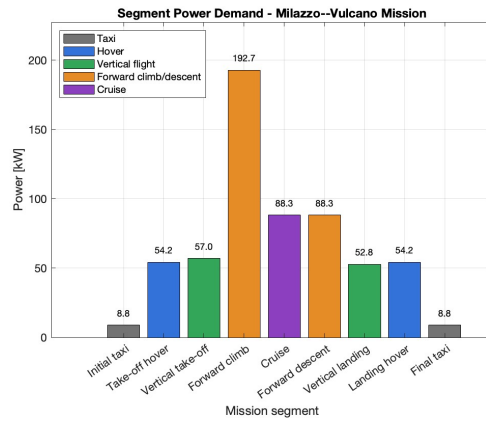


(b) Physical state of charge.

Figure A.2: Additional battery SOC profiles for the Milazzo–Vulcano mission.



(a) Segment energy breakdown.

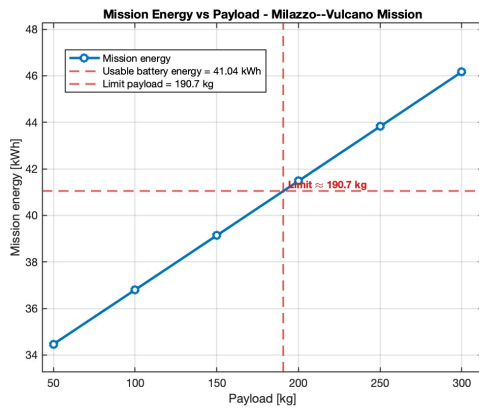


(b) Segment power breakdown.

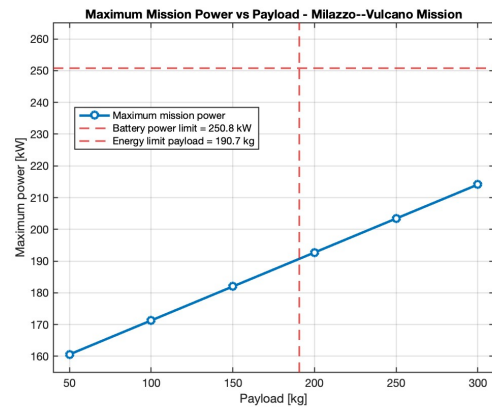
Figure A.3: Additional segment-level energy and power results for the Milazzo–Vulcano mission.

A.2. Additional Sensitivity Plots

The following plots report supplementary outputs from the sensitivity analyses performed around the Milazzo–Vulcano reference case. These figures are useful for completeness, but were not essential to the main discussion.

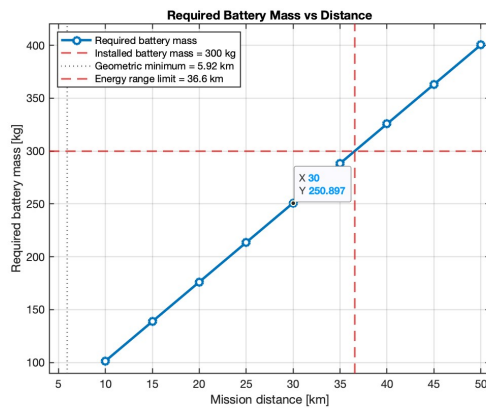


(a) Payload sweep: energy per payload.

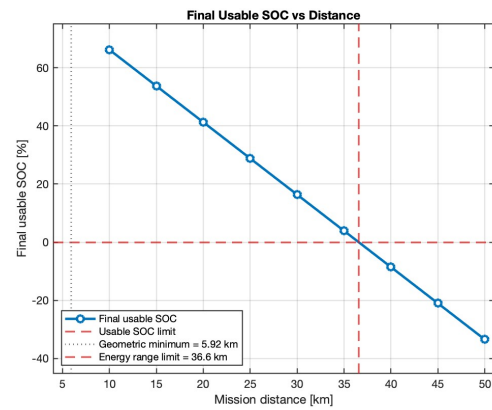


(b) Payload sweep: peak power.

Figure A.4: Additional payload sweep metrics for the Milazzo-Vulcano mission.

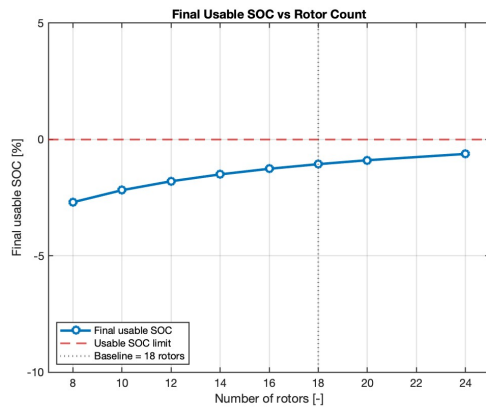


(a) Required battery mass.

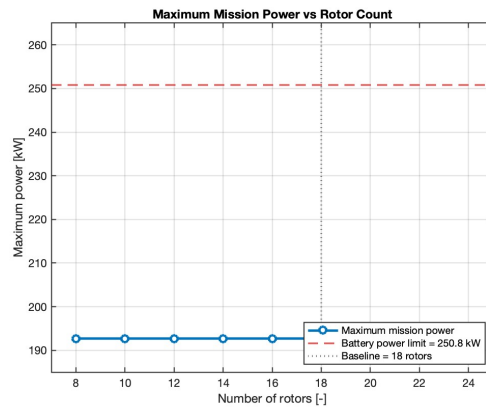


(b) Final usable SOC.

Figure A.5: Additional distance sweep results for the Milazzo-Vulcano mission.

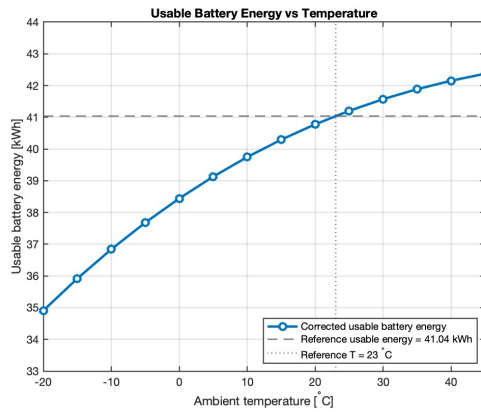


(a) Rotor count: final usable SOC.

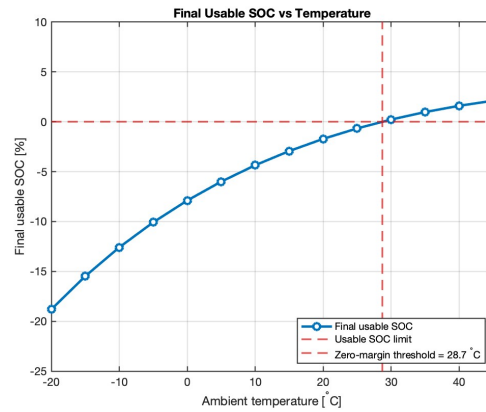


(b) Rotor count: peak power.

Figure A.6: Additional rotor-count sweep results for the Milazzo–Vulcano mission.

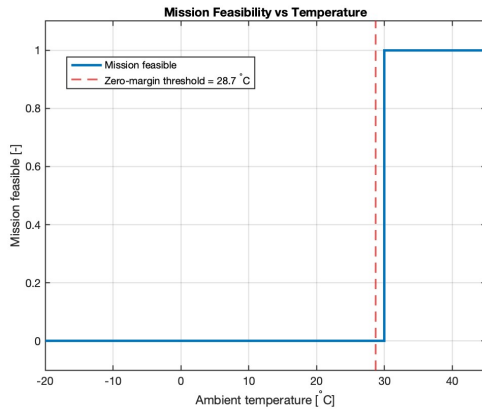


(a) Temperature sweep: usable battery energy.

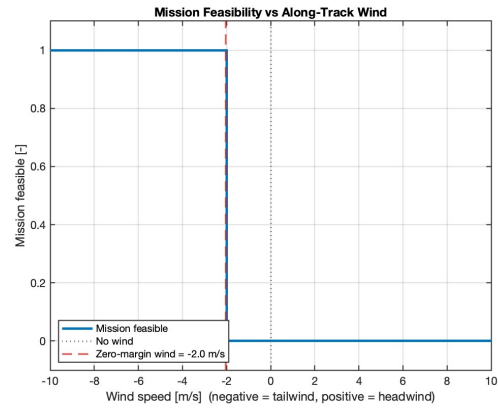


(b) Temperature sweep: final usable SOC.

Figure A.7: Additional temperature sweep results for the Milazzo–Vulcano mission.

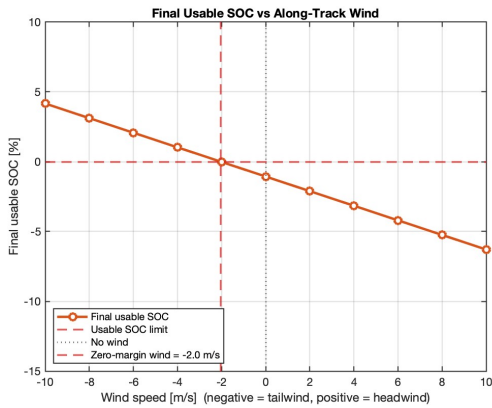


(a) Temperature feasibility.

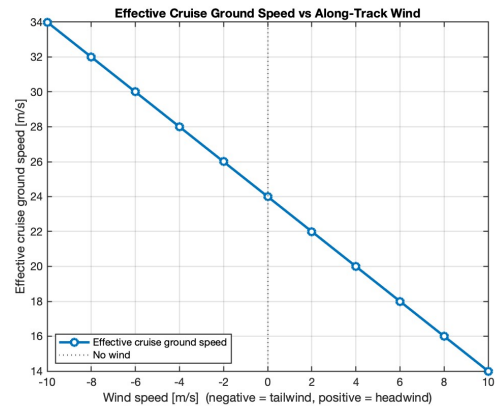


(b) Wind feasibility.

Figure A.8: Additional feasibility plots for temperature and wind sweeps.



(a) Wind sweep: final usable SOC.

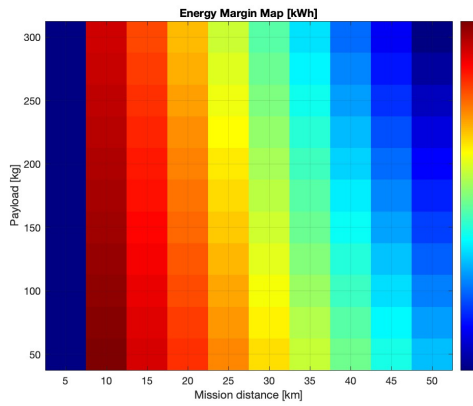


(b) Wind sweep: effective cruise ground speed.

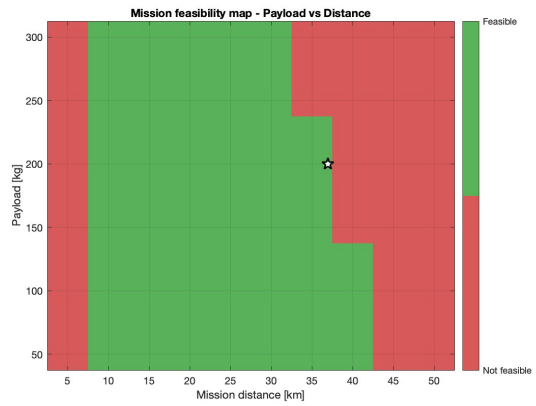
Figure A.9: Additional wind sweep results for the Milazzo–Vulcano mission.

A.3. Additional Combined Parametric Maps

The following maps complement the combined parametric analysis performed for the Milazzo–Vulcano reference mission. They provide alternative views of the operational envelope using energy margin, final usable SOC and feasibility metrics.

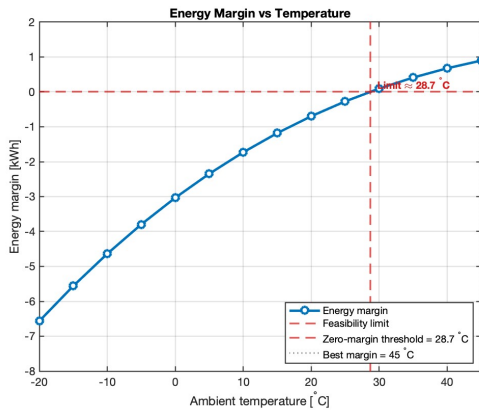


(a) Payload–distance energy margin.

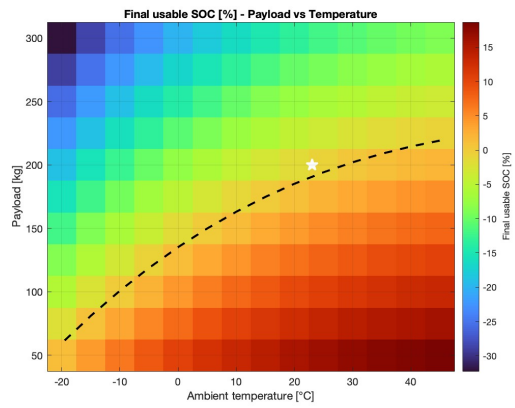


(b) Payload–distance feasibility.

Figure A.10: Additional payload–distance maps for the Milazzo–Vulcano mission model.

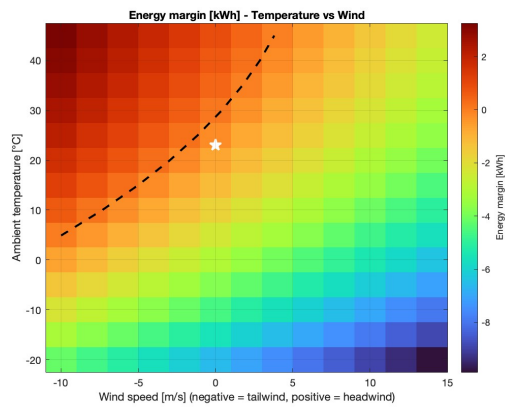


(a) Payload–temperature energy margin.

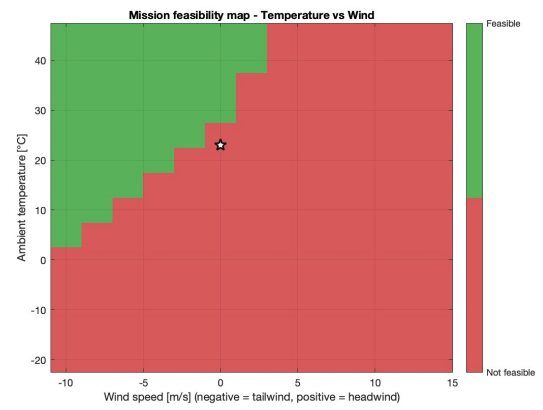


(b) Payload–temperature final usable SOC.

Figure A.11: Additional payload–temperature maps for the Milazzo–Vulcano mission model.



(a) Temperature–wind energy margin.



(b) Temperature–wind feasibility.

Figure A.12: Additional temperature–wind maps for the Milazzo–Vulcano mission model.

B | Equations Summary

This chapter reports a compact summary of the main governing equations used in the mission-energy model. The objective is not to repeat the full methodology, but to provide a quick reference for the quantities implemented in the MATLAB code and used in the subsequent analyses.

B.1. Aircraft Mass and Weight

The total take-off mass is computed as:

$$m_{\text{TO}} = m_{\text{empty}} + m_{\text{payload}} + M_{\text{batt}} \quad (\text{B.1})$$

The corresponding aircraft weight is:

$$W = m_{\text{TO}}g \quad (\text{B.2})$$

where g is the gravitational acceleration.

B.2. Rotor Geometry and Disc Loading

The area of a single rotor disc is:

$$A_{\text{rotor}} = \frac{\pi D_R^2}{4} \quad (\text{B.3})$$

The total rotor disc area is:

$$A_R = n_{\text{rotor}} A_{\text{rotor}} \quad (\text{B.4})$$

The disc loading is:

$$DL = \frac{W}{A_R} \quad (\text{B.5})$$

B.3. Hover-Induced Velocity and Hover Power

The ideal hover-induced velocity is estimated from momentum theory as:

$$v_h = \sqrt{\frac{W}{2\rho A_R}} \quad (\text{B.6})$$

The hover power is:

$$P_{\text{hover}} = \frac{k_{\text{ind}} W v_h}{\eta_{\text{prop}}} \quad (\text{B.7})$$

where k_{ind} is the induced-power correction factor and η_{prop} is the propulsive efficiency.

B.4. Battery Energy and Power

The nominal installed battery energy is:

$$E_{\text{batt,nom}} = E^* M_{\text{batt}} \quad (\text{B.8})$$

The usable battery energy is:

$$E_{\text{batt,use}} = E^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (\text{B.9})$$

The effective physical battery energy after efficiency is:

$$E_{\text{batt,phys}} = E^* M_{\text{batt}} \eta_{\text{batt}} \quad (\text{B.10})$$

The maximum available battery power is:

$$P_{\text{batt,max}} = P^* M_{\text{batt}} \eta_{\text{batt}} DoD \quad (\text{B.11})$$

B.5. Mission Segment Energy

For each mission segment, the energy is computed as:

$$E_i = \frac{P_i t_i}{3600} \quad (\text{B.12})$$

where P_i is expressed in watts and t_i in seconds, so that E_i is obtained in watt-hours.

The total mission energy is:

$$E_{\text{mission}} = \sum_{i=1}^N E_i \quad (\text{B.13})$$

The maximum mission power is:

$$P_{\text{max}} = \max(P_1, P_2, \dots, P_N) \quad (\text{B.14})$$

B.6. Cruise Distance and Time

For a fixed-distance mission, the cruise distance is obtained by subtracting the horizontal climb and descent distances from the imposed mission distance:

$$d_{\text{cruise}} = d_{\text{mission}} - d_{\text{climb}} - d_{\text{desc}} \quad (\text{B.15})$$

The mission is geometrically compatible with the prescribed climb and descent profile only if:

$$d_{\text{cruise}} > 0 \quad (\text{B.16})$$

The cruise time is:

$$t_{\text{cruise}} = \frac{d_{\text{cruise}}}{V_{\text{cruise}}} \quad (\text{B.17})$$

B.7. Forward Climb and Descent Distances

The horizontal distance covered during forward climb is:

$$d_{\text{climb}} = V_{\text{climb}} \frac{h_{\text{cruise}} - h_{\text{VTO}}}{RoC} \quad (\text{B.18})$$

The horizontal distance covered during forward descent is:

$$d_{\text{desc}} = V_{\text{desc}} \frac{h_{\text{cruise}} - h_{\text{VLAND}}}{RoD} \quad (\text{B.19})$$

The minimum mission distance required to include a positive cruise segment is:

$$d_{\text{min}} = d_{\text{climb}} + d_{\text{desc}} \quad (\text{B.20})$$

B.8. Paper-Consistent Cruise Power

In the paper-consistent cruise model, the cruise power is expressed as:

$$P_{\text{cruise}} = \frac{WV_{\text{cruise}}}{(L/D)_{\text{eq}} \eta_{\text{cruise}}} \quad (\text{B.21})$$

The cruise energy is:

$$E_{\text{cruise}} = \frac{P_{\text{cruise}} t_{\text{cruise}}}{3600} \quad (\text{B.22})$$

B.9. Speed-Dependent Cruise Power

For the cruise-speed sensitivity analysis, cruise power is decomposed into induced, profile and parasite contributions:

$$P_{\text{cruise}}(V) = P_{\text{ind}}(V) + P_{\text{profile}}(V) + P_{\text{parasite}}(V) \quad (\text{B.23})$$

The induced power is:

$$P_{\text{ind}}(V) = \frac{\kappa W v_i(V)}{\eta_{\text{ind}}} \quad (\text{B.24})$$

The profile power is modelled as:

$$P_{\text{profile}}(V) = P_{\text{profile},0} \left[1 + k_{\text{prof}} \left(\frac{V}{V_{\text{tip}}} \right)^2 \right] \quad (\text{B.25})$$

The parasite power is:

$$P_{\text{parasite}}(V) = \frac{\frac{1}{2}\rho V^3 f_{\text{eq}}}{\eta_{\text{cruise}}} \quad (\text{B.26})$$

where:

$$f_{\text{eq}} = C_D S_{\text{ref}} \quad (\text{B.27})$$

and:

$$S_{\text{ref}} = k_{\text{geom}} \frac{\pi}{4} b_{\text{cab}} h_{\text{cab}} \quad (\text{B.28})$$

B.10. Battery State of Charge and Margins

The final usable state of charge is:

$$SOC_{\text{final,use}} = 100 \left(\frac{E_{\text{batt,use}} - E_{\text{mission}}}{E_{\text{batt,use}}} \right) \quad (\text{B.29})$$

The final physical state of charge is:

$$SOC_{\text{final,phys}} = 100 \left(\frac{E_{\text{batt,phys}} - E_{\text{mission}}}{E_{\text{batt,phys}}} \right) \quad (\text{B.30})$$

The energy margin is:

$$\Delta E = E_{\text{batt,use}} - E_{\text{mission}} \quad (\text{B.31})$$

The power margin is:

$$\Delta P = P_{\text{batt,max}} - P_{\text{max}} \quad (\text{B.32})$$

B.11. Mission Feasibility Conditions

The mission is energy-feasible if:

$$E_{\text{mission}} \leq E_{\text{batt,use}} \quad (\text{B.33})$$

It is power-feasible if:

$$P_{\text{max}} \leq P_{\text{batt,max}} \quad (\text{B.34})$$

The complete mission-feasibility flag is:

$$\text{Mission Feasible} = \text{Energy Feasible} \cap \text{Power Feasible} \cap \text{Geometry Feasible} \quad (\text{B.35})$$

B.12. Temperature Correction

The temperature-dependent battery capacity is expressed as:

$$Q(T) = Q_{\text{ref}} \exp \left[A_1 \left(\frac{1}{T} - \frac{1}{T_{\text{ref}}} \right) + A_2 \left(\frac{1}{T} - \frac{1}{T_{\text{ref}}} \right)^2 \right] \quad (\text{B.36})$$

The normalised capacity correction factor is:

$$k_Q(T) = \frac{Q(T)}{Q_{\text{ref}}} \quad (\text{B.37})$$

The corrected usable battery energy is:

$$E_{\text{batt,use}}(T) = E_{\text{batt,use,ref}} k_Q(T) \quad (\text{B.38})$$

B.13. Wind Correction

For the wind sensitivity analysis, only the along-track wind component is considered. The adopted sign convention is:

$$V_{\text{wind}} > 0 \quad \text{headwind} \quad (\text{B.39})$$

$$V_{\text{wind}} < 0 \quad \text{tailwind} \quad (\text{B.40})$$

The effective ground speed is:

$$V_g = V_{\text{air}} - V_{\text{wind}} \quad (\text{B.41})$$

where the aircraft airspeed is kept equal to the nominal value.

B.14. Operating Cost, Emission and Time Comparison

The grid energy required to recharge the eVTOL battery is:

$$E_{\text{grid}} = \frac{E_{\text{mission}}}{\eta_{\text{charger}}} \quad (\text{B.42})$$

The eVTOL electricity cost is:

$$C_{\text{eVTOL}} = E_{\text{grid}} c_{\text{el}} \quad (\text{B.43})$$

The indirect grid-related CO₂ emissions are:

$$m_{\text{CO}_2, \text{eVTOL}, \text{grid}} = E_{\text{grid}} E F_{\text{grid}} \quad (\text{B.44})$$

The direct operational emissions of the eVTOL are:

$$m_{\text{CO}_2, \text{eVTOL}, \text{direct}} = 0 \quad (\text{B.45})$$

The eVTOL mission time is computed as the sum of segment durations:

$$t_{\text{eVTOL}} = \sum_i t_i \quad (\text{B.46})$$

For maritime transport, the kinematic crossing time is:

$$t_{\text{sea,kin}} = \frac{d_{\text{route}}}{V_{\text{sea}}} \quad (\text{B.47})$$

The conversion between knots and kilometres per hour is:

$$V_{\text{sea}}[\text{km/h}] = 1.852V_{\text{sea}}[\text{kn}] \quad (\text{B.48})$$

The maritime fuel mass is estimated as:

$$m_f = P_{\text{inst}} L F t_{\text{sea,kin}} SFC \quad (\text{B.49})$$

The fuel volume is:

$$V_f = \frac{m_f}{\rho_f} \quad (\text{B.50})$$

The maritime fuel cost is:

$$C_{\text{sea}} = V_f c_{\text{diesel}} \quad (\text{B.51})$$

The maritime CO₂ emissions are:

$$m_{\text{CO}_2,\text{sea}} = V_f EF_{\text{diesel}} \quad (\text{B.52})$$

B.15. Normalised Cost and Emission Indicators

For the eVTOL mission, the cost per unit payload is:

$$I_{C,\text{payload}} = \frac{C_{\text{eVTOL}}}{m_{\text{payload}}} \quad (\text{B.53})$$

The grid-related CO₂ emissions per unit payload are:

$$I_{\text{CO}_2,\text{payload}} = \frac{m_{\text{CO}_2,\text{eVTOL,grid}}}{m_{\text{payload}}} \quad (\text{B.54})$$

For the maritime reference case, the passenger-equivalent capacity mass is:

$$m_{\text{cap,sea}} = N_{\text{pax}} m_{\text{pax,ref}} \quad (\text{B.55})$$

The maritime cost per unit passenger-equivalent capacity is:

$$I_{C,\text{cap,sea}} = \frac{C_{\text{sea}}}{m_{\text{cap,sea}}} \quad (\text{B.56})$$

The maritime CO₂ emissions per unit passenger-equivalent capacity are:

$$I_{\text{CO}_2,\text{cap,sea}} = \frac{m_{\text{CO}_2,\text{sea}}}{m_{\text{cap,sea}}} \quad (\text{B.57})$$

C | Code Structure

This chapter briefly describes the numerical implementation adopted in the thesis. The MATLAB code was organised with a modular structure in order to separate input definition, derived-parameter calculation, mission simulation, post-processing and sensitivity analysis. This approach improves readability, makes the model easier to modify and allows each mission segment to be checked independently.

C.1. General Workflow

The general workflow followed by the MATLAB implementation is summarised as follows:

1. definition of the aircraft, battery, mission and environmental inputs;
2. computation of derived parameters such as weight, rotor area, disc loading, hover power and usable battery energy;
3. execution of the mission model through a sequence of flight segments;
4. collection of segment-level energy, power and time results;
5. computation of mission-level outputs, including total energy, maximum power, final SOC and feasibility flags;
6. generation of plots, tables and sensitivity-analysis results.

The main scripts are used to run complete mission cases, while dedicated functions are used to compute each segment and post-process the results. A typical execution sequence is:

```
p = inputs_mission_milazzo_vulcano();

p = compute_derived_parameters_mission(p);

[segments, summary, p] = run_mission_milazzo_vulcano_case(p);
```

```
batteryProfile = compute_battery_profile(segments, p);
```

where `p` is the main parameter structure, `segments` contains the results of each mission phase, and `summary` stores the overall mission outputs.

C.2. Input Files

The input files define the reference aircraft, battery and mission assumptions. They include quantities such as aircraft mass, payload, battery mass, battery specific energy, rotor count, rotor diameter, cruise speed, climb rate, descent rate, mission altitude and route distance.

The main input file used for the Milazzo–Vulcano case is:

```
inputs_mission_milazzo_vulcano.m
```

This file provides a single location where the nominal mission parameters can be modified. For sensitivity analyses, the same baseline input structure is loaded and then selected variables are changed inside the sweep scripts.

C.3. Derived Parameter Calculation

After loading the input file, the model computes derived quantities required by the mission simulation. This step is performed by:

```
compute_derived_parameters_mission.m
```

Typical derived parameters include:

- total take-off mass and aircraft weight;
- single-rotor and total rotor disc area;
- disc loading;
- hover-induced velocity;
- hover power;
- usable battery energy;
- maximum available battery power.

Keeping these calculations in a separate function avoids duplicating equations inside the main mission scripts and ensures that all mission cases use consistent derived parameters.

C.4. Mission Segment Functions

The mission is implemented as a sequence of segments. Each segment function receives the parameter structure as input and returns the duration, energy consumption and power demand of that specific phase. The mission architecture includes:

```
initial taxi  
take-off hover  
vertical take-off  
forward climb  
cruise  
forward descent  
vertical landing  
landing hover  
final taxi
```

The segment-based structure allows the contribution of each phase to be identified separately. This is useful both for validation and for interpreting the results, because hover, climb, cruise and descent do not affect the mission energy in the same way.

C.5. Mission Runner

The complete mission is executed by the mission runner:

```
run_mission_milazzo_vulcano_case.m
```

This function calls the segment functions in the prescribed order, stores the segment results and computes the final mission summary. The main outputs are:

- total mission time;
- total mission energy;
- maximum mission power;
- climb, cruise and descent distances;
- energy margin;
- final usable SOC;
- final physical SOC;
- energy, power and mission feasibility flags.

The feasibility logic is based on three main checks:

```
energy_feasible = E_mission <= E_batt_use;  
power_feasible  = P_max <= P_batt_max;  
mission_feasible = energy_feasible && power_feasible;
```

For fixed-distance missions, a geometric pre-check is also introduced to ensure that the imposed route distance is sufficient to include forward climb and descent while retaining a positive cruise segment.

C.6. Battery Post-Processing

Battery evolution during the mission is computed after the segment results are obtained. The main post-processing function is:

```
compute_battery_profile.m
```

This function reconstructs the cumulative energy consumption and the battery state of charge along the mission. The post-processing outputs are used to generate plots of remaining battery energy, usable SOC and physical SOC.

C.7. Sensitivity and Parametric Scripts

The sensitivity analyses are implemented through dedicated MATLAB scripts. Each script starts from the baseline input file, modifies one or more parameters and reruns the mission model. The main sweep scripts include:

```
run_cruise_speed_sweep.m  
run_payload_sweep.m  
run_distance_sweep_milazzo_vulcano.m  
run_rotor_count_sweep_milazzo_vulcano.m  
run_climb_distance_RoC_sweep.m  
run_temperature_sweep_milazzo_vulcano.m  
run_wind_sweep_milazzo_vulcano.m  
run_combined_parametric_effects_milazzo_vulcano.m
```

The outputs of these scripts are stored in arrays or result structures and then used to generate the figures discussed in the thesis. This organisation makes it possible to repeat the same mission model under different assumptions without modifying the core functions.

C.8. Plotting and Output Generation

Plots are generated either by dedicated plotting functions or directly inside the sensitivity scripts. The main output figures include:

- segment energy and power breakdowns;
- battery energy and SOC profiles;
- sensitivity curves;
- feasibility maps;
- combined parametric heat maps.

The plotting routines were kept separate from the mission calculations whenever possible. This separation ensures that the numerical model and the visual representation of the results remain independent.

C.9. Summary

The MATLAB implementation follows a modular workflow based on input files, derived-parameter functions, segment models, mission runners, post-processing functions and sensitivity scripts. This structure allows the model to be extended without rewriting the full codebase. New routes, aircraft assumptions, environmental conditions or sensitivity analyses can be introduced by modifying the input structure or by creating additional sweep scripts while preserving the same mission-simulation core.

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List of Symbols

Symbol	Description	Unit
A_1	first coefficient of the temperature-capacity correction model	K
A_2	second coefficient of the temperature-capacity correction model	K ²
A_R	total rotor disc area	m ²
A_{rotor}	single-rotor disc area	m ²
b_{cab}	representative cabin width used for frontal-area estimation	m
C_D	equivalent aerodynamic drag coefficient	–
C_{eVTOL}	electricity cost of the eVTOL mission	€
C_{sea}	fuel cost of the maritime reference mission	€
c_{diesel}	diesel fuel price	€/L
c_{el}	electricity price	€/kWh
D_R	rotor diameter	m
d_{climb}	horizontal distance covered during forward climb	m
d_{cruise}	cruise distance	m
d_{desc}	horizontal distance covered during forward descent	m
d_{mission}	imposed mission distance	m
d_{min}	minimum distance required by climb and descent segments	m
d_{route}	route distance	m or km
DL	disc loading	N/m ²
DoD	usable depth of discharge	–
E^*	battery specific energy	Wh/kg
$E_{\text{batt,nom}}$	nominal installed battery energy	Wh or kWh
$E_{\text{batt,phys}}$	effective physical battery energy after efficiency	Wh or kWh
$E_{\text{batt,use}}$	usable battery energy	Wh or kWh
$E_{\text{batt,use,ref}}$	reference usable battery energy before temperature correction	Wh or kWh
E_{cruise}	cruise energy consumption	Wh or kWh
E_{fixed}	energy contribution of the non-cruise mission segments	Wh or kWh
E_{grid}	electrical energy drawn from the grid for battery recharge	kWh
E_i	energy consumption of mission segment i	Wh or kWh
E_{mission}	total mission energy	Wh or kWh
EF_{diesel}	diesel emission factor	kgCO ₂ e/L
EF_{grid}	electricity grid emission factor	kgCO ₂ /kWh
f_{eq}	equivalent flat-plate area	m ²
f_{usable}	usable battery-energy fraction	–
g	gravitational acceleration	m/s ²
h_{cab}	representative cabin height used for frontal-area estimation	m
h_{cruise}	cruise altitude	m
h_{VLAND}	altitude at the beginning of vertical landing	m
h_{VTO}	altitude reached after vertical take-off	m
i	mission-segment index	–
$I_{C,\text{payload}}$	eVTOL operating cost per unit payload mass	€/kg

Symbol	Description	Unit
$I_{C,\text{cap,sea}}$	maritime operating cost per unit passenger-equivalent capacity	€/kg
$I_{\text{CO}_2,\text{payload}}$	eVTOL grid-related CO ₂ emissions per unit payload mass	kgCO ₂ /kg
$I_{\text{CO}_2,\text{cap,sea}}$	maritime CO ₂ emissions per unit passenger-equivalent capacity	kgCO ₂ e/kg
k_{geom}	geometric correction factor for reference frontal area	–
k_{ind}	induced-power correction factor	–
k_{prof}	profile-power correction coefficient	–
$k_Q(T)$	temperature-dependent battery-capacity correction factor	–
L/D	lift-to-drag ratio	–
$(L/D)_{\text{eq}}$	equivalent lift-to-drag ratio used in the cruise model	–
LF	average engine load factor for maritime propulsion	–
m	aircraft mass	kg
$m_{\text{cap,sea}}$	passenger-equivalent capacity mass of the maritime reference vessel	kg
$m_{\text{CO}_2,\text{eVTOL}}$	indirect grid-related eVTOL CO ₂ emissions	kgCO ₂
$m_{\text{CO}_2,\text{eVTOL,grid}}$	grid-related eVTOL CO ₂ emissions	kgCO ₂
$m_{\text{CO}_2,\text{eVTOL,direct}}$	direct eVTOL operational CO ₂ emissions	kgCO ₂
$m_{\text{CO}_2,\text{sea}}$	maritime CO ₂ emissions	kgCO ₂ e
m_{empty}	aircraft empty mass	kg
m_f	fuel mass consumed during the maritime crossing	kg
m_{payload}	payload mass	kg
$m_{\text{pax,ref}}$	passenger-equivalent reference mass	kg
m_{TO}	total take-off mass	kg
M_{batt}	battery mass	kg
$MTOM$	maximum take-off mass	kg
N	total number of mission segments	–
N_{pax}	passenger capacity of the maritime reference vessel	–
n_{rotor}	number of rotors	–
P^*	battery specific power	W/kg
$P_{\text{batt,max}}$	maximum available battery power	W or kW
P_{cruise}	cruise power	W or kW
P_{hover}	hover power	W or kW
P_i	power demand of mission segment i	W or kW
P_{ind}	induced power contribution	W or kW
P_{inst}	installed propulsion power of the maritime vessel	kW
P_{margin}	available power margin	W or kW
P_{max}	maximum mission power	W or kW
P_{parasite}	parasite power contribution	W or kW
P_{profile}	rotor profile power contribution	W or kW
$P_{\text{profile,0}}$	reference rotor profile power	W or kW
$Q(T)$	battery capacity as a function of temperature	Ah
Q_{ref}	reference battery capacity	Ah
R	mission range or route distance	km
RoC	rate of climb	m/s
RoD	rate of descent	m/s
SFC	specific fuel consumption of the maritime diesel engine	kg/kWh
S_{ref}	reference frontal area	m ²
SOC	state of charge	%
$SOC_{\text{final,phys}}$	final physical state of charge	%
$SOC_{\text{final,use}}$	final usable state of charge	%
T	absolute temperature	K
T_C	ambient temperature	°C
T_{ref}	reference absolute temperature	K

Symbol	Description	Unit
t_i	duration of mission segment i	s
t_{climb}	forward-climb time	s
t_{cruise}	cruise time	s
t_{desc}	forward-descent time	s
t_{eVTOL}	total eVTOL mission time	s or min
t_{mission}	total mission time	s or min
t_{sea}	maritime crossing time	h
$t_{\text{sea,kin}}$	kinematic maritime crossing time	h or min
V	generic forward speed	m/s
V_{air}	aircraft airspeed	m/s
V_{climb}	forward climb speed	m/s
V_{cruise}	cruise speed	m/s
V_{desc}	forward descent speed	m/s
V_f	fuel volume consumed during the maritime crossing	L
V_g	effective ground speed	m/s
V_{headwind}	headwind component along the route	m/s
V_{sea}	maritime vessel speed	kn or km/h
V_{tailwind}	tailwind component along the route	m/s
V_{tip}	representative rotor tip speed	m/s
V_{wind}	along-track wind speed	m/s
v_h	ideal hover-induced velocity	m/s
v_i	induced velocity in forward flight	m/s
W	aircraft weight	N
ΔE	usable battery energy margin	Wh or kWh
ΔP	battery power margin	W or kW
η_{batt}	battery efficiency	–
η_{charger}	charger efficiency	–
η_{cruise}	cruise efficiency	–
η_{ind}	induced-power efficiency	–
η_{prop}	propulsive efficiency	–
κ	induced-power correction factor in the speed-dependent cruise model	–
ρ	air density	kg/m ³
ρ_f	diesel fuel density	kg/L
<i>AAM</i>	Advanced Air Mobility	–
<i>BVLOS</i>	beyond visual line of sight	–
<i>CSFL</i>	continued safe flight and landing	–
<i>eVTOL</i>	electric vertical take-off and landing	–
<i>FATO</i>	final approach and take-off area	–
<i>HSC</i>	high-speed craft	–
<i>MOC</i>	means of compliance	–
<i>SC-VTOL</i>	Special Condition for VTOL-capable aircraft	–
<i>TLOF</i>	touchdown and lift-off area	–
<i>UAS</i>	unmanned aircraft system	–
<i>VTOL</i>	vertical take-off and landing	–

Acknowledgements

Ricordo ancora quel giorno, avevo sostenuto la maturità da un paio di mesi, era appena trascorsa l'estate più bella della mia vita, un'estate segnata dalla spensieratezza, dalla consapevolezza di aver chiuso un capitolo fondamentale della mia vita nel migliore dei modi e dalla voglia di iniziarne uno nuovo altrettanto entusiasmante. Mi trovavo a casa di mia zia, volevo salutare i parenti prima di partire alla volta della città che da lì a poco avrebbe cambiato totalmente la mia vita. Quella sera, per la prima volta nella mia vita, nonostante la sicurezza che ha sempre contraddistinto il mio essere, mi sono sentito perso, confuso, poco sicuro di ciò che avrei potuto trovare in un luogo così lontano da casa mia, un luogo che con milazzo condivide solo la M, la i, la L, la A e la O. Piansi, e non poco, ma ciò non mi fermò davanti alle scelte fatte e partii alla volta della grande città, la quale mi ha accolto e fatto sentire meno solo in questi anni lontano dal tetto che mi aveva visto crescere. Colgo l'occasione per leggere queste parole di fronte a tutti voi e trasmettervi parte di quelli che sono stati i pensieri che ho maturato durante questi lunghi anni della mia nuova vita, anni in cui sono state tante le persone che mi hanno dimostrato vicinanza, affetto e stima per il coraggio di aver cambiato radicalmente la mia vita per inseguire le mie ambizioni.

A mia madre, il demiurgo di questa tempesta. A te devo tutto, hai creduto in me sin da quando ero un bambino che sognava di diventare un calciatore professionista. Non ti sei mai persa una mia partita, sempre lì a tifare per me, sei stata la forza di cui avevo bisogno per non fermarmi davanti agli ostacoli che la vita mi ha posto davanti. Non basterebbero altre 300 pagine per ringraziarti per tutto quello che hai fatto per me. Questo traguardo è anche tuo, hai messo al mondo tre figli mettendo da parte la tua stessa vita, regalandoci la possibilità di poterci formare lontani da casa nonostante le difficoltà che insieme a papà avete affrontato durante la nostra crescita. Noi siamo il risultato dei vostri sacrifici e i nostri traguardi vi appartengono tanto quanto appartengano a noi che li abbiamo raggiunti. Molte volte ho provato rabbia per alcune scelte avvenute durante la mia gioventù, mi sentivo diverso dagli altri, ad oggi invece ti ringrazio per quelle volte in cui mi hai detto "No", parola che tanto mi ha fatto piangere e che oggi più che mai mi ha fatto capire come dovrò comportarmi con i miei futuri figli per farli diventare uomini

e donne pieni di valori e rispetto per i tempi, le esperienze, le persone e le circostanze. Sei stata, sei e rimarrai per sempre l'unica donna della mia vita. Ps. A big shout out for the name, love u.

A mio padre, il motivo dei miei studi. A te devo tutta la passione che coltivo da quando ero solo un bambino per il mondo dei motori. Come dico sempre, il primo ricordo che conservo con cura della mia giovane età sono le domeniche in cui mi svegliavo a ridosso dell'ora di pranzo e dalla cucina riuscivo a sentire vivido dentro le narici un misto tra l'odore della pasta al forno di mia madre e l'odore della sigaretta di mio padre, seduto a capo tavola mentre guarda la di formula 1 con Gianfranco Mazzoni in telecronaca. Tu, come gli idoli di tanti ragazzi, hai corso tante gare nella tua vita, e nonostante non fossi a livello di Ayrton Senna, per me, sei sempre stato un supereroe sopra quel kart (ti avrei battuto in pista). Ti ringrazio per tutto quello che hai fatto per me, per i sacrifici, per le notti in cui io tornavo dalla discoteca e tu uscivi di casa per andare a lavoro, per tutto ciò che non ti sei mai potuto godere e che in cuor tuo hai sempre voluto potessero vivere i tuoi figli al posto tuo. Sappi che è grazie a te se conosco il valore delle cose, è grazie a te se ad oggi riconosco quali siano le priorità nella vita e riesco a scindere tra ciò che vorrei e ciò che devo. Mi hai insegnato ad essere sempre ligio al mio dovere, a non sottavultare nessuno, motivo per cui in questi lunghi anni ho sempre messo al primo posto il mio lavoro, rinunciando spesso a tanti divertimenti pur di portare a termine questo percorso nel rispetto della fiducia che hai riposto in me e nelle mie sorelle, ripagandoti con traguardi come questo. Il mio sogno è riuscire in parte a realizzare il tuo un giorno, rendendoti fiero di me e della passione che mi hai trasmesso con i tuoi racconti infiniti sulle mille battaglie tra Senna e Prost, sull'importanza dei kart 100 per un pilota che si rispetti.

A Mary, mia sorella maggiore. Se ad oggi riesco a cucinare dei primi piatti fantastici il merito è tutto tuo. Mi hai insegnato come si vive lontano da casa, come si gestisce in modo ottimale il proprio tempo e come essere autosufficienti al cento per cento. Sei sempre stata e continuerai ad essere il punto di riferimento per i tuoi fratelli minori. Ti ringrazio per avermi influenzato positivamente con la tua curiosità verso il mondo e discipline spesso lontane dal consueto, ad oggi è grazie a questo se non mi accontento mai di ciò che so e proietto me stesso verso nuove scoperte all'insegna del mio arricchimento culturale.

A Desy, aa sorella de Roma. Se ripensassi a tutti i dispetti che mi hai fatto probabilmente finirei con il terminare qui questi ringraziamenti (il pianerottolo di Maria ti ricorda qualcosa???). Sorvolando questi dettagli volevo ringraziarti per essere sempre stata al mio fianco, nel torto e nella ragione, supportandomi in ogni mia scelta e facendomi sentire parte integrante della tua vita (anche perchè se no chi te le faceva le foto?). Mentre ti truccavi cantavi sempre le canzoni di Post Malone, ed è grazie a questo se ad oggi non solo

sono innamorato di questo cantante ma ho anche deciso di percorrere un cammino di studi in lingua, affascinato dalla tua incredibile pronuncia e capacità di switchare dall'italiano al più complesso degli accenti londinesi.

A Elena, la mia parrucchiera, psicologa, cuoca, tabaccaia e soprattutto migliore amica. Non fai parte di quelle persone che conosco da decine di anni, ci siamo conosciuti solo qualche anno fa, eppure sei riuscita ad entrare a gamba tesa nelle mie giornate riuscendo a conoscere parti di me che in pochi riuscirebbero mai a vedere. Una volta mi hai tirato un bicchiere per aver tolto una canzone su spotify, gesto folle per alcuni, per me invece è la rappresentazione del rapporto che abbiamo creato, un rapporto vero e fatto di un reciproco ed immenso bene. Grazie per tutto ciò che hai fatto per me in questi anni in termini di presenza, compagnia, supporto e sostegno, ma soprattutto per avermi sopportato senza mai allontanarti.

A Piero, il fratello che non ho mai avuto. A te devo più di quello che immagini. Spesso mi ritrovo in determinate circostanze in cui il mio comportamento verso queste e verso le persone è estremamente figlio della nostra amicizia, del tuo essere e della tua personalità. Ti ringrazio per avermi fatto crescere in questi anni come persona, a volte anche inconsapevolmente. Grazie per tutte le volte in cui ti sei messo di traverso contro gli altri pur di difendermi, qualora anche questo significasse poi sgridarmi in privato. Definirti amico è riduttivo, potrai sempre contare su di me e sono certo che in qualsiasi momento basterebbe una chiamata per farti scappare (è già successo, ops). Per il resto dei nostri giorni ricorda, casa mia è casa tua. Ps. Oggettivamente sei bellissima...

A Marcolino, fratello da una vita. Abbiamo condiviso tutto, dai campi di calcio quando eravamo bambini, passando per i bagni delle discoteche da ragazzi, finendo al tavolo della mia casa milanese tra una tappa di lavoro e l'altra. Grazie per avermi dimostrato che la distanza non è importante quando l'amicizia è forte e radicata. Sono fiero della persona che sei diventata e ti auguro ogni bene possibile, ti voglio bene.

A Gabriele, o meglio, a Zazzarè! Grazie per aver reso meno malinconiche e noiose le mie lunghissime giornate chiuso tra le quattro mura milanesi. La tua risata, spesso, è stata terapeutica, anche se in quel momento non lo sapevi nemmeno. Insieme abbiamo quasi rischiato di farci seppellire nel deserto degli Emirati, passando una delle notti più insonni della nostra vita: una notte conclusa con la celebre frase: "Ndi spettunu o passu, fra". Quando ti sentirai perso, potrai sempre contare su di me. E ricorda: "L'ultima è sempre da mutanda".

A Peppe, il mio compagno di arrocchi. La nostra amicizia è nata contro ogni aspettativa e, probabilmente, all'inizio provavamo persino una certa antipatia reciproca. Eppure eccoci

qui: ti ho riservato uno spazio nel lavoro più importante della mia vita, un posto destinato a quelle persone che mi hanno davvero dimostrato vicinanza e affetto. Abbiamo trascorso centinaia di notti al telefono, a parlare di tutto e di nulla, a sfidarci a scacchi, a raccontarci le nostre zuccherate e a gossippare come se fossimo due zie di Santa Marina, affacciate alle persiane di casa loro con lo sguardo rivolto direttamente sulla strada del paese. Averti conosciuto più a fondo mi ha dato la possibilità di scoprire una persona speciale. E dopo questa forchetta reale, fratello, questa è da abbandono

Ai miei colleghi: Luca, Ermal, Gianmarco, Antonio, Luigi, Federico, Giuseppe, Davide, Marco, Edoardo, Giacomo, Giovanni, Andrea, Cosimo e a tutto il gruppo “Marco è libero”. Grazie per aver rappresentato la mia famiglia in questi cinque anni. Siete una delle cose più preziose che la vita mi abbia regalato. Senza di voi, questo lavoro non esisterebbe. Grazie per tutte quelle volte in cui avete teso la vostra mano laddove la mia non sarebbe mai arrivata. Grazie per essere stati molto più che semplici compagni di viaggio: in voi ho trovato i miei simili, persone con cui poter discutere, confrontarmi ed elucubrare su tematiche che solo dei fulminati come noi potevano affrontare. Anche se il nostro percorso universitario è giunto al termine, sarò sempre a un passo da voi e vi custodirò a un centimetro dal cuore. Vi amo.

A Ermal e Lidio, i miei fratelli maggiori. Mi avete visto crescere e siete stati un punto di riferimento per me. Grazie a voi sono maturato tanto. Vi ringrazio per avermi fatto sentire parte di voi nonostante la differenza di età, coccolandomi e trattandomi come fossi addirittura un vostro familiare. Sarò per sempre grato della vostra amicizia, una di quelle che si contano sulle dita di una mano per quanto totalizzanti e vere.

Alle Spice Girls, le mie stupende vicine di casa. Grazie per aver ricreato, in questi anni, quel clima familiare tipico della mia adolescenza, accogliendomi nella vostra quotidianità e facendomi sentire amato e coccolato come facevano le mie sorelle quando ero solo un bambino. Anche quando le nostre strade si separeranno, non dimenticherò mai ciò che avete fatto per me: dalle sorprese per i compleanni alle mille bracioline scongelate nel vostro microonde. Love u.

A Salvatore, il capitano. Ci incrociavamo di sfuggita quando eravamo solo due bambini che accompagnavano le proprie sorelle alle lezioni di danza, siamo diventati due uomini che si rispettano e condividono la tavola in famiglia. Grazie per essere così autentico e vero. A coppa da 38 comu semu? Ti voglio bene!

A Simone, amico da una vita. Col passare degli anni non sei mai cambiato nei miei confronti, incarnando la figura di amico che più si avvicina a quella che inseguo da sempre, un amico presente, disponibile e sempre pronto a spendere una parola di elogio nei miei

confronti, senza mai sfociare nella competitività e invidia. Ti voglio bene, per sempre Side e Wayne.

A Lorenzino, il drago. Sei la dimostrazione che nella vita a volte è più importante la qualità della quantità. Insieme abbiamo trascorso meno di un anno, nonostante ciò sei stato l'unico con cui sono riuscito ad instaurare un rapporto molto più profondo di una semplice convivenza. Ti ringrazio per avermi sopportato imparando a conoscermi, per aver condiviso la stessa tavola ogni giorno, a pranzo e a cena, ricreando la routine familiare che spesso si perde quando si vive lontani, in cui ognuno pensa al proprio orticello non curandosi dei legami con le persone che vivono sotto lo stesso tetto. Lo so, vivere con me non è stato facile, è stato "Teeeeerrrrribileeeee".

Ad Aurora, senza di te non avrei trovato il coraggio di affrontare l'ultimo scoglio del nostro percorso. Grazie per avermi accompagnato nella fase finale di questo rush verso la gloria, rendendolo più leggero, divertente e saporito (con tutte quelle pizzette che mi hai fatto mangiare...). Grazie a me oggi riesci a capire come torce un'ala e come sono orientate le forze aerodinamiche che agiscono su una typical section, nonostante ciò, come dice Giorgia, rimani una zingara! Ti voglio bene.

Grazie a tutti coloro che per una volta nella loro vita sono stati orgogliosi di me, coloro che anche solo per un attimo hanno sentito dentro al cuore il desiderio di sapere come stavo dall'altra parte dell'Italia, alle amicizie durature, a quelle che sono terminate, ai miei sostenitori, agli invidiosi, a coloro che a differenza di altri hanno sperato che potessi fallire, grazie a tutti. Senza tutti voi oggi non sarei qui, nel bene e nel male siete stati la forza che mi ha spinto a continuare ad ineguire i miei obiettivi. Grazie a coloro che hanno deciso di farsi da parte lungo il cammino, avete fatto spazio a nuove energie, energie positive che spero possano rimanere a lungo accanto a me.

Un ringraziamento speciale va al relatore di questa tesi, il Professor Alberto Servienti. Lei non è soltanto un professore, ma una risorsa preziosa per il nostro Ateneo. L'ambiente accademico ha profondamente bisogno di persone come Lei: gentili, disponibili, preparate e sempre attente al futuro degli studenti, che troppo spesso affrontano il proprio percorso senza un adeguato accompagnamento e sostegno. Il Suo interesse verso coloro che un giorno entreranno nel mondo del lavoro è davvero ammirevole. La ringrazio per la fiducia accordatami nello svolgimento di questa tesi e per l'empatia con cui mi ha permesso di trasformare questo lavoro in qualcosa di estremamente personale, legato alla città in cui sono nato e alle isole che tanto amo, e che per vent'anni della mia vita ho osservato affacciandomi dal mio balcone. Grazie.

