공학석사학위논문

eVTOL 항공기 사이징을 위한 중량 분율 추정

Weight Fraction Estimation for eVTOL Vehicle Sizing

2023 년 8 월

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Weight Fraction Estimation for eVTOL Vehicle Sizing

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In recent years, eVTOL aircraft have emerged as environmentally friendly new transportation vehicles, garnering a significant attention in their design. Here, an approach that preserves the characteristics of an electric propulsion while staying within the realm of the conventional aircraft design method is required.

One of the primary challenges resulting from the initial lack of the design results is encountered during its sizing stage. This thesis proposes a method for battery weight estimation in initial sizing stage. Due to the nature of the electric propulsion, estimation of the required battery energy will be deployed. To achieve it, the required power estimation formulas for each mission segment and prescribed flight duration formula for each mission segment of the profile will be used for eVTOL battery weight estimation. the battery weight ratio will be estimated and compared against that of the designed eVTOLs accordingly. Before comparing the obtained results, The weight information for the designed eVTOLs (SNU baseline eVTOL, four existing eVTOL, eVTOL demonstrator) will be given first.

To construct each design battery weight result, the requirements, or targets, mission configuration aircraft configuration will be utilized. The battery and empty weight are estimated by supplying the maximum takeoff weight (MTOW) and payload for SNU baseline eVTOL and four existing eVTOL configurations. The maximum difference of 25% in the battery weight estimation for SNU baseline eVTOL is observed. Similarly, for the four existing eVTOL configurations, the maximum difference of approximately 15% in the battery weight is observed. Finally, the same method of this thesis will be applied to an eVTOL technology demonstrator for estimating battery weight. Except for the twin tilt-rotor whose payload is smaller the present of the battery weight shows a discrepancy within 20%.

The proposed method applies to SNU baseline eVTOL and four existing eVTOL, and eVTOL demonstrator. From the comparison, it is confirmed that meaningful estimation of the battery weight is possible. For future work, by investigating empty weight formula of eVTOL, the initial battery sizing method could be constructed with it.

Keywords: eVTOL Aircraft Sizing, Conceptual Design, Weight Estimation

Student Number: 2020-24601

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Nomenclature

E [s]: Prescribed flight-duration

E_{sb} [W/kg]: Specific energy of the battery

η_{b2s}: Battery to motor efficiency

η_p: Propeller efficiency

η_{mech}: Transmission efficiency

P_{used} [W]: Used power

W [N]: Maximum take-off weight

W_b [N]: Battery weight

W_e [N]: Empty weight

$W_{payload}$ [N]: Payload

W_{crew} [N]: Weight of the crews

m [kg]: Maximum take-off mass

m_b[kg]: Battery mass

A: Empty weight empirical parameter

C: Empty weight empirical parameter

f: Downwash on the fuselage

M: Figure of merit

S_{disk}[m^2]: disk area

e: Oswald's efficiency

q [Pa]: Dynamic pressure

L [N]: Lift

D [N]: Drag

L/D: Lift-to-drag ratio

D/q [m^2]: Drag area

V [m/s]: cruise speed

V_{climb} [m/s]: Rate of climb

γ [deg]: Flight path angle

R [m]: Range

W_b/W: Battery weight fraction (BWF)

W_e/W: Empty weight fraction

m_b/m: Battery mass fraction (BMF)

ρ [kg/m^3]: Atmospheric density

g [m/s^2]: gravity acceleration

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Preface

본 학위논문은 2023 년 4 월 21 일 한국항공우주학회 춘계학술대회에서 발표한 “임무형상 재구성을 통한 네 가지 AAM 의 목표 성능 검토”과 2023 년 6 월 14 일 AIAA Aviation Forum 의 “Weight Fraction Estimation for eVTOL Vehicle Sizing” 제목의 발표 내용을 기초하여 작성하였습니다.

This thesis is based on studies first presented at the spring conference of Korean Society for Aeronautical and Space Sciences (KSAS) on April 21st, 2023, with a title of “Examination of target performance of four AAM concepts through reconstruction of mission profile” and American Institute of Aeronautics and Astronautics (AIAA) Aviation forum on June 14th, 2023, with a title of “Weight Fraction Estimation for eVTOL Vehicle Sizing”.

Chapter 1

Introduction

1.1 Advanced Air Mobility (AAM) Overview

In recent years, advanced air mobility (AAM), including Urban Air Mobility (UAM), has emerged as a prominent concept for future air transportation [1]. With the increasing urban population density and the growing number of car owners, commuting to densely populated areas has become a challenge for many individuals. This has led to significant time wastage and increased air pollution due to the emissions from internal combustion engines. For instance, in metropolitan areas like Los Angeles, the average commute time to work is around 90 minutes [2]. Consequently, greenhouse gas emissions are generated, and commuters experience stress due to congested roads. Moreover, traffic congestion in New York Manhattan alone costs over $20 billion, primarily attributed to wasted fuel and time [3]. To address these challenges, the concept of urban air mobility (UAM) has emerged, and numerous developers of electric vertical take-off and landing (eVTOL) aircraft are actively designing their own concepts to seize opportunities in this new market.

eVTOL is expected to serve as a rapid transportation solution for passengers and cargos, connecting key areas within urban centers. However, there are several considerations that need to be addressed for eVTOL development in urban operations. Safety, electric propulsion, noise reduction, vertical take-off and landing (VTOL), autonomous flight, and infrastructure are among the various factors that need to be taken into account. Particularly, the emphasis on safety revolves around the certification authorities such as the Federal Aviation Administration (FAA) [4] and the European Union Aviation Safety Agency (EASA) [5], as well as the concept of operation (ConOps) by developers [6, 7].

With advancements in electric propulsion technology, eVTOL has become a viable environmentally friendly transportation option. Recent developments in Siemens motors with a power-to-weight ratio of 5,000W/kg [8] and lithium-ion battery cells with an energy density of 250Wh/kg [9] have paved the way for commercial operations.

To facilitate the commercialization of eVTOL within urban environments, efforts are being made to incorporate vertical landing capabilities while targeting significantly reduced noise levels, aiming for a maximum of 65dB [10-13] during low-altitude operations.

Cost reduction, both in terms of acquisition and operational expenses, is crucial for commercial viability. While the elimination of pilots has been considered to reduce operational costs [7], the FAA currently includes the presence of a pilot on eVTOLs as a requirement [3, 6].

Infrastructure plays a vital role in the eVTOL ecosystem, serving not only as landing sites but also as facilities for electric charging, maintenance, and transferring to other transportation.

The aforementioned development requirements play a crucial role in the successful introduction and widespread adoption of AAM in the mobility market. However, meeting these requirements poses a significant technological challenge in the current landscape. Furthermore, the limited availability of design configurations for eVTOL aircraft presents a hurdle in accurately estimating their initial weight. In order to address this challenge, numerous researchers have undertaken studies focusing on the conceptual design of eVTOL aircraft.

1.2 Literature Review

Estimating the empty weight of eVTOL aircraft is not easy due to the limited number of eVTOL development cases available. To address this challenge, researchers in the field of eVTOL utilize weight estimation formulas for electric propulsion devices, such as motors, developed by Kim, Kadhiresan [14, 15], or employ weight estimation formulas derived from the components of conventional aircraft. However, these weight estimation formulas, which are empirically derived based on geometric parameters, are complex to use. Even for similar configurations, discrepancy in weight can arise when estimating eVTOL weight that utilize turbine engines instead of electric propulsion with motors and batteries. These empirical formulas typically require specified values for geometric parameters to estimate weight, imposing constraints on exploring various initial configurations of eVTOL designs.

The weight estimation formulas utilized by NDARC were developed by Aero Flight Dynamics Directorate (AFDD). Those formulas were created based on the weight of turbine-powered tilt-rotor and compound rotorcraft. However, when comparing the results of those formulas to the actual weight of aircraft, it is commonly found that differences exceeding 20% are frequently observed [16].

Due to the lack of established methodologies for eVTOL design, several conceptual design approaches have been proposed. In the study by Kim [14], a comparable eVTOL to the Hyundai S-A1 was developed using reverse engineering techniques based on the design specifications of the S-A1. Through that study, a conceptual design of an eVTOL with a weight class of 3,125 kg, a range of 100 km, and a speed of 240 km/h was achieved. However, the usage of computer-aided design (CAD) software for aerodynamic analysis is required to effectively employ reverse engineering approach, making it challenging to apply to alternative configurations.

Regarding the literature on aircraft design, Raymer [17] provides a comprehensive coverage of conventional fixed-wing aircraft design. Although it has recently incorporated content on the design of electric fixed-wing aircraft and briefly touches on VTOL aircraft design, it lacks specific information on electric propulsion rotary-wing aircraft, limiting its applicability to eVTOL design. On the other hand, Leishman [18] is a prominent source for rotorcraft aerodynamics, encompassing various configurations ranging from basic helicopters to side-by-side, tandem, and coaxial designs. It serves as a valuable design reference for these concepts. However, similar to Raymer, it does not specifically address electric propulsion, making it inadequate for eVTOL design purposes.

1.3 Research Objective and Thesis Outline

This study introduces a method for estimating the battery weight ratio of eVTOL aircraft using conventional aircraft design approaches. Furthermore, it validates a battery weight estimation method by applying it to the SNU baseline eVTOL, four existing eVTOL aircraft, and an eVTOL demonstrator. The remaining chapters are outlined as follows:

Chapter 2 provides a brief introduction to the classification of eVTOL aircraft and presents examples. Subsequently, equations derived from fixed-wing and rotary-wing flight laws are proposed to estimate the required power for eVTOL missions. The method for estimating battery weight using these equations is then introduced.

In Chapter 3, the method described in Chapter 2 is applied to the SNU baseline eVTOL, four existing eVTOL aircraft, and the eVTOL demonstrator in sequence. The battery weight is estimated based on the design requirements, targets, and mission configurations for each aircraft. The estimated results are discussed in comparison with the existing design outcomes.

Chapter 4 summarizes the findings from Chapter 3 and highlights the key contributions. And lastly, introduce the future work of this thesis.

Chapter 2

Methodology

2.1 Classification of eVTOL

The examples of eVTOL configurations that are expected to meet the mentioned requirements briefly in Chapter 1 are presented in Figure 2.1 (a)-(d). eVTOL aircraft can be broadly classified into three types, as summarized in Table 2.1. The classification of eVTOLs can be further differentiated based on the presence of wings, the type of propulsion system, and the type of moving components.

The Wingless type, as shown in Figure 2.1 (a) Volocity, generates lift solely using rotors without wings. Such type is also referred to as Multi-copter or Multi-rotor and operates similarly to conventional helicopters.

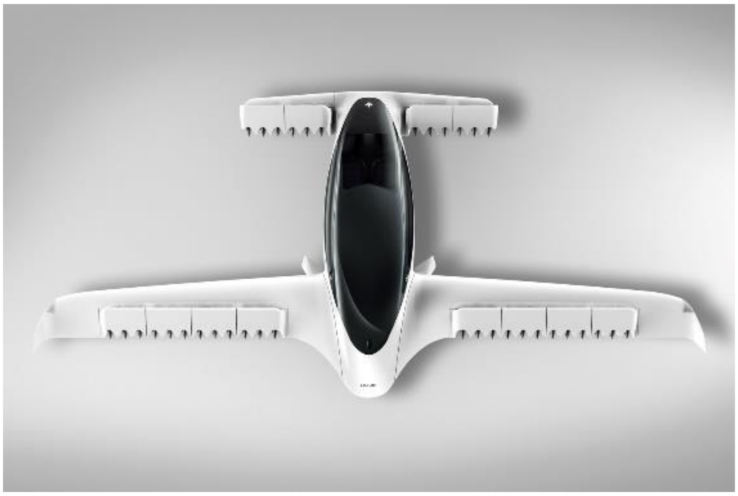
In contrast, the eVTOLs with wings are categorized as the Winged type and can be further differentiated into two subtypes based on the type of propulsion system: Vectored thrust or Lift+cruise. The Vectored thrust type includes examples such as Lilium Jet in Figure 2.1 (b) and S4 of Joby in Figure 2.1 (c). Such aircrafts have propulsion systems that provide both lift and thrust simultaneously. During take-off, the propulsion system generates lift using thrust, and during cruise, it primarily provides thrust. Depending on the specific component responsible for such functions, Vectored thrust can be further classified into subtypes. For example, when the rotor tilts, it is referred to as a tilt-rotor, and when the duct tilts, it is called a tilt-duct. The prefix "tilt" is included to indicate the tilting movement of a component.

In contrast, the Lift+Cruise type refers to aircraft where separate propulsion systems are responsible for lift and thrust. In other words, it has both a lift rotor and a propeller. An example of such type is Cora in Figure 2.1 (d). it takes-off using the lift rotor and then transition to cruising flight using the propeller after reaching a sufficient altitude.

Table 2.1 Types of eVTOL

<table>
<tr><th>Category</th><th>Winged or wingless</th><th>Propulsion Type</th><th>Moving component</th></tr>
<tr><td rowspan="3">eVTOL concepts</td><td>Wingless</td><td colspan="2">Multi-rotor (Multi-copter)</td></tr>
<tr><td rowspan="2">Winged</td><td>Vectored thrust</td><td>Tilt-wing
Tilt-rotor
Tilt-duct</td></tr>
<tr><td colspan="2">Lift+cruise</td></tr>
</table>

(a) Volocotper Inc., Volocity (multi-rotor)



(b) Lilium Inc., Lilium Jet (vectored thrust)

(c) Joby Aviation, S4 (tilt-rotor)

(d) Wisk inc., Cora (lift+cruise)

Fig 2.1 eVTOL configuration examples

2.2 Battery Weight Estimation

Previously as summarized in Table 2.1, it is difficult to follow the classification for eVTOL of the conventional aircraft. It is due to that it is neither fixed-wing nor rotary-wing aircraft. It has both properties of them, and it uses electricity as an energy source rather than the fossil fuel. Thus, eVTOL battery weight estimation method need to be updated from its original one. Next section will propose a method of estimation of the battery weight of eVTOL, considering an electric propulsion.

2.2.1 Required Power Estimation Formulas

Before determining the battery weight required for eVTOL mission, the required power for rotary-wing and fixed-wing flight segment need to be estimated. The power estimation formulas for each flight mode are presented in Eqs. (1) to (6), which are derived from flight laws.

For the axial flight segment, Eq. (2.1) [17] can be derived by considering the vertical climb or descent in the momentum equation. Eq. (2.1) will be used to obtain the required power for hovering, vertical climb, or descent flight. As a design parameter, the disk loading is included in the formula, while the rate-of-climb (ROC) is specified by the mission. By utilizing the targeted Figure of Merit (FM) set during the design process, the required power for rotary-wing flight can be determined, and from it, the battery weight can be estimated. The fuselage download factor f, which accounts for the influence of rotor downwash on the airframe, will be typically set to 1.03. Due to this downwash effect, an eVTOL requires additional power generation. The mechanical efficiency, η_{mech} , representing the power transmission efficiency from the motor to the rotor, will be is set to 0.97 [17] typically.

$$P_{used} = \frac{W}{\eta_{mech}} \left(\frac{f}{M} \sqrt{\frac{f(W/S_{disk})}{2\rho}} + \frac{V_{climb}}{2} \right) \tag{2.1}$$

During the edgewise flight in a rotary-wing mode, the required power will be estimated by treating the rotor disk as an equivalent wing and accounting for parasite power with drag area of an eVTOL. This, combined with the required power for climb and descent flight, yields Eq. (2.2) [17]. This formula is primarily applicable to multi-copter configuration. The flight speed and flight path angle will be specified based on the mission. In Chapter 3, for the case of Volocity, the estimated drag area based on the configuration will be utilized. The parameter *e* represents the Oswald efficiency factor, which typically ranges from 0.5 to 0.8 for rotorcraft. The propeller efficiency, η_p, is generally assumed to be between 0.6 and 0.85 [17].

$$P_{used} = \frac{V}{\eta_p \eta_{mech}} \left(q \left(\frac{D}{q} \right) + \frac{W^2}{4eqS_{disk}} + W \sin\gamma \right) \tag{2.2}$$

Eq. (2.3) is used to estimate the required power during fixed-wing mode cruise-climb or cruise-descent flight. it can be derived by considering the equilibrium equation for fixed-wing climb flight and assuming a constant ROC and a small flight path angle. When an eVTOL climbs or descends in a fixed-wing mode, the flight speed and ROC are specified based on its mission, and the required power and battery weight during such segments can be estimated using the lift-to-drag ratio (L/D) as a design target.

$$P_{used} = \frac{W}{\eta_p}\left(V_{climb} + \frac{V}{L/D}\right) \tag{2.3}$$

Eq. (2.4) can be used to obtain the required power during fixed-wing cruise flight. When an eVTOL is in such segment, Eq. (2.4) is derived based on the relationship between the thrust generated by the propeller and the power consumed by the motor. Similarly, as the flight speed and the lift-to-drag ratio are specified from the mission, the power required during cruise flight can be estimated using Eq. (2.4).

$$P_{used} = \frac{1}{\eta_p}\frac{W}{(L/D)}V \tag{2.4}$$

By utilizing the relationship between the required energy and battery mass of an eVTOL in steady fixed-wing mode, the battery weight fraction (BWF) required for cruise flight can be estimated directly using Eq. (2.5).

$$BWF = \frac{W_b}{W} = \frac{Rg}{E_{sb}\eta_{b2s}\eta_p(L/D)} \tag{2.5}$$

For other mission segments, the BWF of them can be estimated using Eq. (2.6). Eq. (2.6) is derived by relationship between the required power and the battery mass of the eVTOL. Since Eq. (2.6) simply relates such fact, it can be applied to any segments such as vertical takeoff, ascent, and descent. η_{b2s} represents a battery to motor shaft efficiency of an eVTOL, Usually, a value of 0.95 is recommended [17].

$$BWF(BMF) = \frac{E}{E_{sb}\eta_{b2s}}\frac{P_{used}}{m} \tag{2.6}$$

Above formulas are summarized in Table 2.2, and there is a short explanation of the used parameters and corresponding mission segment of the formula.

If MTOW is obtained, the battery weight will be determined from the total battery weight fraction from the mission profile. From each mission segment, the required power will be obtained from Eqs. (2.1) to (2.4). The cruise required power is directly estimated by Eq. (2.5). Otherwise, Eq. (2.6) is used to estimate BWF from required power and duration. Finally, the battery weight will be estimated from the total sum of the fraction and by multiplying MTOW. This is represented in Eq. (2.7)

$$\frac{W_b}{W} = \sum \left(\frac{W_b}{W}\right)_{segment} \tag{2.7}$$

Parameters needed for estimating the required power are the inherent properties of eVTOL configuration or mission profile. Configuration of eVTOL has information such as the motor, battery, propeller efficiency, download effect. Mission profile contains the flight speed, climb angle, and segment duration.

Table 2.2 Power and BWF estimation formula

Flight principle	Mission Segment	Formula	Nomenclature
All [17]	Vertical take-off, landing Acceleration, maneuver	$BWF(BMF) = \frac{E}{E_{sb}\eta_{b2s}} \frac{P_{used}}{m}$	E [s]: Prescribed flight-duration E_{sb} [W/kg]: Specific energy of the battery η_{b2s}: Battery to motor efficiency η_p: Prop efficiency η_{mech}: Transmission efficiency P_{used} [W]: Used power f : Downwash on the fuselage M : Figure of merit W [N]: Maximum take-off weight m [kg]: Maximum take-off mass S_{disk} [m^2]: disk area e: Oswald's efficiency q [Pa]: Dynamic pressure V [m/s]: cruise speed V_{climb} [m/s]: Rate of climb g [m/s^2]: gravity acceleration R [m]: Range
Rotary-Wing [17]	Hover, Climb, Descent	$P_{used} = \frac{W}{\eta_{mech}} \left(\frac{f}{M} \sqrt{\frac{f(W/S_{disk})}{2\rho}} + \frac{V_{climb}}{2} \right)$	
	Cruise, forward climb/descent	$P_{used} = \frac{V}{\eta_p \eta_{mech}} \left(q\left(\frac{D}{q}\right) + \frac{W^2}{4eqS_{disk}} + W\sin\gamma \right)$	
Fixed-Wing [17]	Climb, Descent	$P_{used} = \frac{W}{\eta_p} \left(V_{climb} + \frac{V}{L/D} \right)$	
	Cruise	$BWF = \frac{Rg}{E_{sb}\eta_{b2s}\eta_p(L/D)}$	

2.3 Battery Weight Estimation Process

In this section, the validation procedure for appropriately estimating the battery weight of designed eVTOLs is described. The battery weight of eVTOLs is estimated following the process shown in Fig. 2.2 and compared to the existing results. First, based on the requirements and mission configuration of the eVTOL, the BWF for each mission segment is estimated using Eqs. (2.1) to (2.6). The total BWF is obtained by summing all the estimated BWFs according to Eq. (2.7). The battery weight is then estimated by multiplying the total BWF by the Maximum Takeoff Weight (MTOW). The estimated battery weight is compared to the actual battery weight of the designed eVTOL.

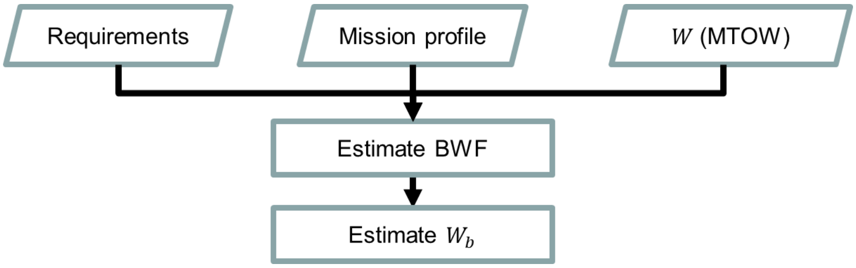


Fig 2.2 Estimating battery weight with the prescribed MTOW

Chapter 3

Validation

3.1 Seoul National University (SNU) Baseline eVTOL

The Seoul National University (SNU) baseline eVTOL [19-21] consists of four configurations: tilt-rotor, tilt-wing, lift+cruise, and quadrotor. In this thesis, they will be referred to as the SNU tilt-rotor, SNU tilt-wing, SNU lift+cruise, and SNU quadrotor, respectively. These configurations were designed using the NASA reference configurations [22-23]. The programs utilized for the SNU baseline eVTOL include NDARC [24], MATLAB, and DATCOM. NDARC was used for conceptual design and generating reference battery weight, required power, and energy, DATCOM for higher fidelity aerodynamic coefficients, and MATLAB for airframe visualization. In the future, MATLAB will be employed for the automation and optimization of the SNU baseline design.

(a) NASA tiltrotor

(b) NASA tiltwing

(c) NASA lift+cruise

(d) NASA quadrotor

Fig 3.1 NASA reference configurations [21]

3.1.1 Mission Profile for SNU Baseline eVTOL

SNU baseline eVTOL [19-21] are designed to have a range 37.5nm, which is the half-length of the mission profile suggested by Johnson [23]. The MTOW of them is unified to have 6,500lb for a useful comparison of the weight breakdown of each vehicle. While NASA reference configurations are designed assuming the battery technology advancement in the year of 2040 up to 520Wh/kg [23], SNU baseline eVTOL are designed deploying the current state-of-art battery technology of 250Wh/kg. 20-minute reserve mission are included like NASA reference configurations.

The mission profile of SNU baseline eVTOL is shown in Fig. 3.2. In it, it contains taxi, landing, hover, transition, climb, descend, cruise segment. Its total range is 37.5nm. Details of each mission segment is summarized in Table 3.1. Transition segment is replaced with hovering for a specified duration when estimating required power for that segment. In the table, the segment type, altitude, duration, distance, speed, rate-of-climb (ROC) are listed for each segment.

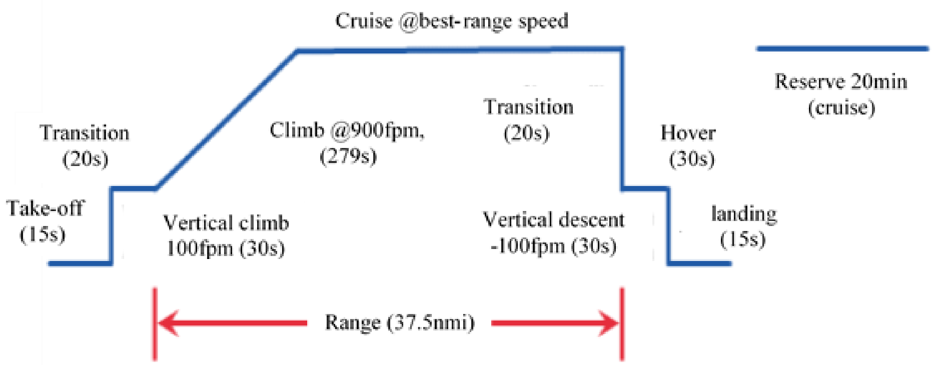


Fig 3.2 SNU baseline eVTOL mission profile [19]

Details of the mission profile is as follows. After taxing and take-off are completed, eVTOL will climb at 100fpm. With an enough height is obtained, a transition flight will be performed from the rotary-wing to fixed-wing mode. Then, climb up to the cruise altitude at 900fpm will be executed. Cruise will follow to the destination at an altitude of 10,000ft with the best range speed. After 37.5nm flight is reached, eVTOL will perform a transition back to the rotary-wing mode and wait at hover. After the landing place is open, eVTOL will descend until the ground at 100fpm and will finally land. 20-mintue energy reserve will be included in battery for safety. The designed configuration of SNU baseline eVTOL by NDARC [24] and MATLAB are shown in Fig. 3.3.

In this thesis, the assumptions for estimating the weight of SNU baseline are as follows. This thesis does not consider required power during take-off or landing segment, because it rarely affects the result of energy estimation, the present required power in this segment will be assumed as the result of SNU baseline eVTOL. In addition, for reserve segment, it was assumed that the eVTOL would fly at the same best-range speed as in the cruise flight to ensure a safe landing. Target values for estimating the required power are summarized in Table 3.2, and those are brought from SNU baseline eVTOL design [22-24]. Types of the target values are as follows: figure of merit (FM), lift-to-drag ratio.

As shown in Table 3.2, the SNU baseline eVTOL exhibits relatively high values of Figure of Merit and Lift-to-Drag ratio, with values of 0.78 and 10.8, respectively, for the tilt-wing configuration. This indicates that the mission profile of the SNU baseline eVTOL, as illustrated in Fig. 3.2, represents a challenging task to achieve with the current battery technology.

In NDARC, the Figure of Merit is obtained through definition of figure of merit Tv/P [25], where the user should provide information about the drag to calculate the actual power. Here, T represents rotor thrust, v represents induced velocity, and P refers to actual power. Similarly, the parasitic drag used to calculate the lift-to-drag ratio (L/D) is also obtained from user-provided information.

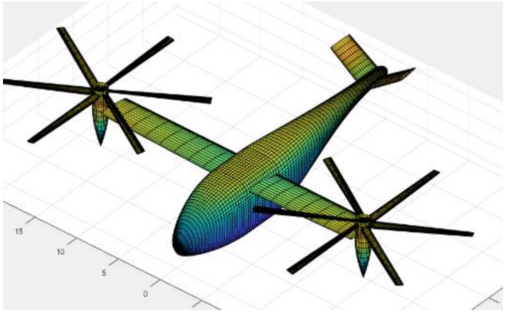
Taking this into consideration, the approach of setting target values for calculation helps eliminate ambiguity and assumptions regarding uncertain drag coefficients. It facilitates a rapid estimation of the battery weight for an eVTOL that achieves the design objectives, without relying on uncertain assumptions about drag coefficients.

Table 3.1 SNU baseline mission

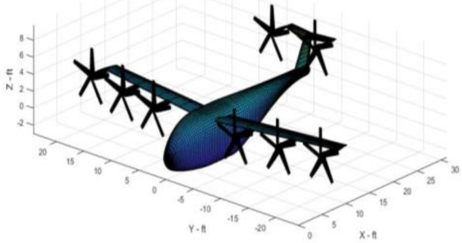
	1	2	3	4	5	6	7	8	9	10
Segment Type	Taxi	Hover	Transition	Climb	Cruise	Transition	Hover	Descend	Taxi	Reserve
Initial Altitude	6,000	6,000	6,050	6,050	10,000	6,050	6,050	6,050	6,000	10,000
Final Altitude	6,000	6,050	6,050	10,000	10,000	6,050	6,050	6,000	6,000	10,000
Time (sec)	15	30	10	t_{climb}	t_{cruise}	10	30	30	15	1,200
Distance (nm)	-	0	0	D_{climb}	$37.5\text{-}D_{climb}$	0	0	0	0	-
Speed	-	-	0	V_y	V_{br}	0	0	-	-	V_{br}
ROC (ft/min)	0	100	0	900	0	0	0	-100	0	0

Table 3.2 Used values for comparison

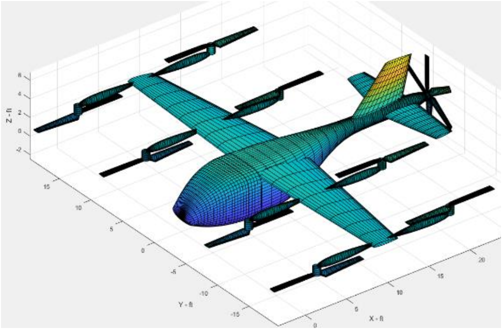
	SNU tilt-rotor	SNU tilt-wing	SNU lift+cruise	SNU quadrotor
Figure of merit	0.7	0.8	0.6	0.7
L/D climb	5.9	5.8	4.5	-
Climb angle (deg)	2.8	4.6	3.7	4.0
L/D cruise	9.1	10.8	7.5	-
Cruise speed (km/h)	314.7	248.2	254.7	198.1
Cruise range (km)	46.4	55.9	52.2	53.7
Rotor for lift (#)	2	8	8	4
Rotor radius (m)	3.1	1.1	1.6	3.7



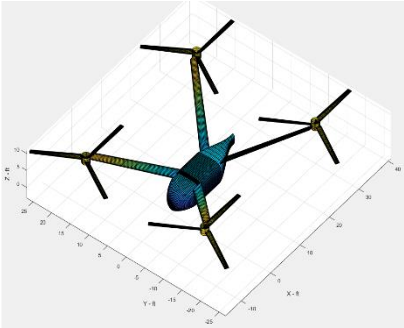
(a) SNU tiltrotor



(b) SNU tiltwing



(c) SNU lift+cruise



(d) SNU quadrotor

Fig 3.3 SNU baseline eVTOL [22-24]

3.2 Result Comparison Against SNU Baseline eVTOL

Using MTOW and payload as an input from SNU baseline result, battery weight will be estimated first for the mission profile in Fig. 3.2. Then, empty weight will be obtained by subtracting the battery weight and payload from MTOW as in Fig 2.3.

Present and SNU baseline eVTOL result are summarized in Table 3.3. In it, the largest discrepancy is observed in the quadrotor configuration as large as 25% in battery weight. And the tilt-wing shows 20% discrepancy. Lift+cruise and tilt-rotor shows 10% and 2.5% discrepancy, respectively.

The discrepancy observed in the Table 3.3 fall within the range of 25% mentioned as an appropriate level in the methodology, because the variance between the estimated weight from conceptual design and the measured weight after manufacturing typically has similar range. specifically, it is known that the discrepancy between the estimated component weight derived from Aero Flight Dynamics Directorate (AFDD) and the actual weight also falls within a similar range [25]. Therefore, considering that such discrepancy occurs during the initial sizing stage, it can be concluded that the formulas used for battery weight and power estimation perform adequately in providing the present results within an appropriate range.

Table 3.3 SNU baseline eVTOL weight estimation and comparison

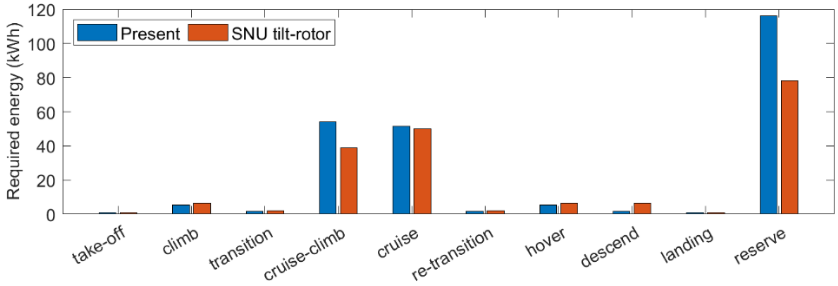
	MTOW (kg) (Input)	Payload (kg) (Input)		Battery Weight (kg) (Output)	Empty Weight (kg) (Output)
Tilt-rotor	2,948.1	198.3	Present	1,030.4	1,719.7
			SNU Tilt-rotor	1,004.8	1,745.0
			Discrepancy (%)	-2.5	1.4
Tilt-wing	2,947.8	219.7	Present	823.8	1,904.3
			SNU Tilt-wing	1,027.0	1,701.1
			Discrepancy (%)	19.8	-11.9
lift+cruise	2,948.0	167.3	Present	842.0	1938.6
			SNU Lift+cruise	938.9	1841.7
			Discrepancy (%)	10.3	-5.3
Quadrotor	2,947.8	144.7	Present	1,012.3	1,790.9
			SNU Quadrotor	1,345.3	1,457.9
			Discrepancy (%)	24.8	-22.8

Figure 3.4 shows required energy for each mission segment. From the figure, it is found that the present required energy is generally similar to the results of SNU baseline eVTOL. And Fig 3.4 also shows most of energy is consumed during cruise-climb, cruise, reserve segments. Regarding those segments which constitute most of the mission, it is also found that present required energy is well following the results of SNU baseline eVTOL less than discrepancy of 10% except for SNU tilt-rotor.

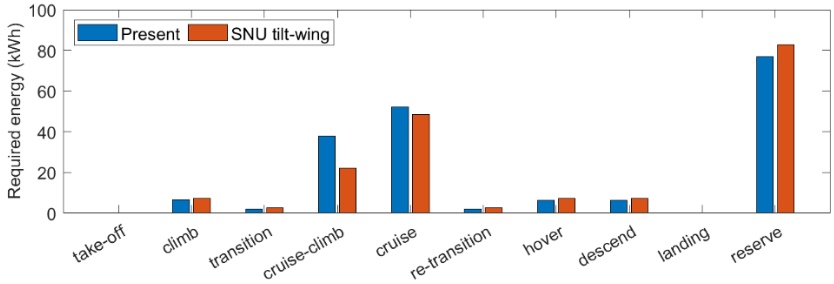
The discrepancy of battery energy of SNU tilt-rotor is due to the assumption made for the reserve mission during the battery energy estimation process. In obtaining the present result, the assumption is made that the speed during the reserve segment is the same as the cruise speed, resulting in equal power requirements for both segments, as shown in Figure 3.5. As a result, there are discrepancy in the require power between the cruise and reserve segments.

Table 3.4 Total energy consumption of SNU baseline eVTOL

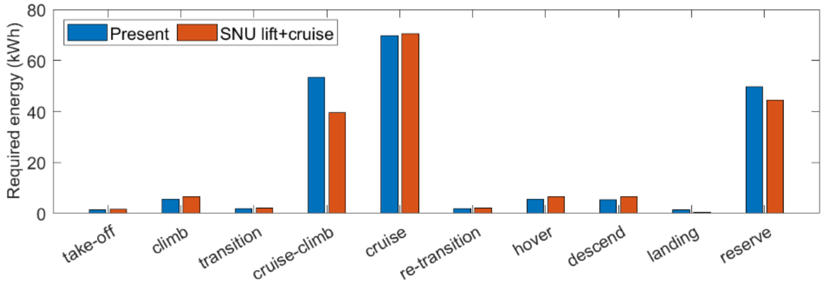
Total required energy(kWh)	Tilt-rotor	Tilt-wing	lift+cruise	quadrotor
Present (kWh)	239.6	191.5	195.8	235.3
SNU baseline (kWh)	193.6	180.5	180.8	258.1
discrepancy (%)	-23.7	-6.1	-8.3	8.8



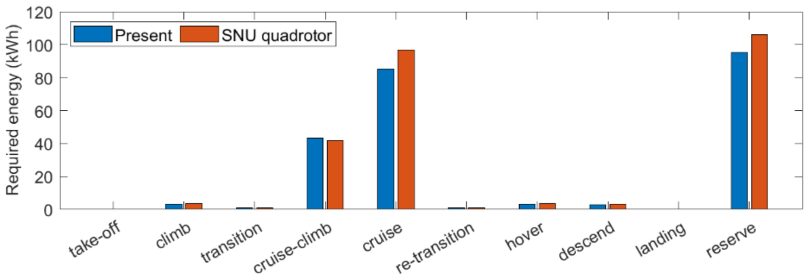
(a) SNU baseline tilt-rotor required energy



(b) SNU baseline tilt-wing required energy



(c) SNU baseline lift+cruise required energy

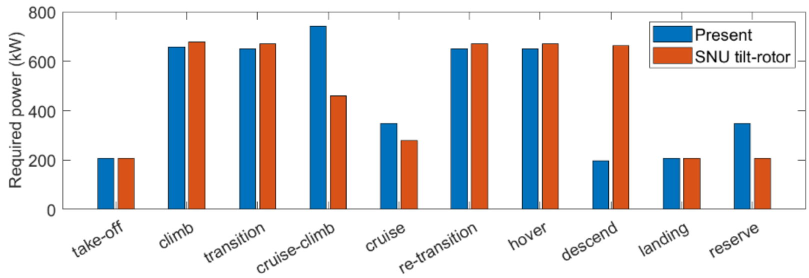


(d) SNU baseline quadrotor required energy

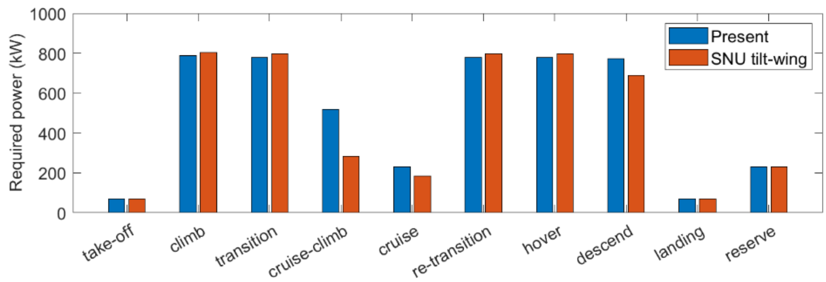
Fig 3.4 SNU baseline eVTOL required energy

In Fig. 3.5, it is observed that the estimated required power obtained by applying the proposed method align well with the results of the SNU Baseline eVTOL [19-21], excluding the cruise-climb segment. From such result, it has been confirmed that most of the formulas used for estimating the battery weight provide accurate estimations, with a maximum difference of up to 20% in the battery weight estimation.

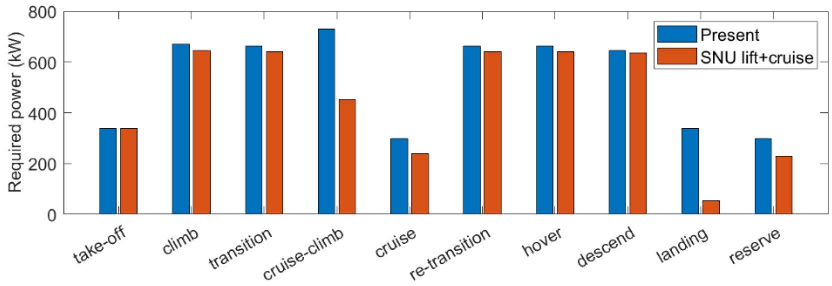
NDARC utilizes the Blade Element Momentum Theory (BEMT) to solve for the forces acting on the rotor in a linear flow field. However, when calculating the aerodynamic drag, coefficients of empirical formula are used, where the user inputs values or experimental data is interpolated linearly from tables. However, in the early design stages where there is limited specific study on the rotor, it is not straightforward to employ such method. Instead, this thesis simplifies the complexity and enables a rapid estimation of the battery weight, focusing on the design objectives of the eVTOL.



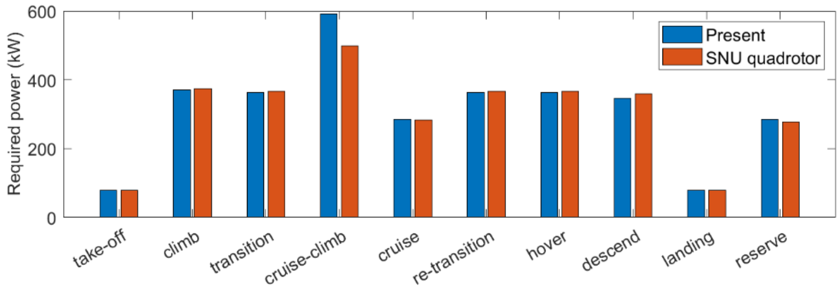
(a) SNU baseline tilt-rotor required power



(b) SNU baseline tilt-wing required power



(c) SNU baseline lift+cruise required power



(d) SNU baseline quadrotor required power

Fig 3.5 SNU baseline required power

3.3 Result Comparison for Four Existing eVTOLs

3.3.1 Overview of Four eVTOLs

Tilt-rotor eVTOL S4 is developed by Joby Aviation. It is equipped with 6 rotors on the main wing and V-tail. Its configuration aims to transport the four passengers and one pilot during the operation. Its target performance during the cruise includes 150 mile-range and a cruise speed of 200mph. Additionally, their advanced packaging technology has capability to achieve 235Wh/kg specific energy. According to Bogaisky [26], information such as MTOW, empty weight, battery weight, and payload is publicly available, while the geometry parameters such as the rotor radius and wing area are estimated based on its configuration.

Volocity represents a multi-copter configuration, and it is developed by Volcopter in Germany. It features18 rotors positioned above the fuselage, distributed across a complex rim structure. Distributed electric propulsion (DEP) ensures a high level of safety. This configuration is expected to have lower development cost compared against the other vehicles due to its similarity to the multi-copter configuration. However, the characteristics also pose a disadvantage that it is not well-suited for long-distance and high-speed flight. Considering the current battery technology of 250Wh/kg, Volocity is projected to have 22 mile-range and cruise speed 56mph during operation [27]. It is designed to transport one passenger and a pilot.

Lilium Jet belongs to a vectored-thrust type like S4. It incorporates a total of 36 ducted fans with DEP on the trailing edge of its main wing and canard wing, enabling vertical take-off and landing capabilities. However, due to its small, ducted fan size, it has a high disk loading, which requires significant power during take-off and landing. It is aerodynamically efficient for the cruise flight, consuming a less power while achieving a high speed of 186mph and 162 mile-range. Currently, Lilium plans to develop a 7-seater configuration, including one pilot. During the conceptual design stage, it is assumed that the battery pack will have a specific energy of 320 Wh/kg, considering the time of commercialization. Weight and geometry information can be utilized from the conceptual design results published by Nathen [28] about the 7-seater design.

Cora is a prominent example of the lift+cruise configuration before the 6th generation appears. It stands out with its intuitive design featuring 12 distributed lift rotors on its main-wing and rear-mounted pusher propeller. In terms of performance, Cora falls between the multi-copter and vectored thrust types. It offers 62 mile-range and a cruise speed of 110mph. However, until autonomous technology reaches maturity, a pilot is included. Weight information of this eVTOL was estimated by Bacchini [29].

3.3.2 Target Design Goal of Four eVTOLs

S4, Volocity, Lilium Jet, and Cora weight data: payload, the number of passengers, the maximum take-off weight and empty weight, battery weight are investigated from the previous research or public domain reports [26-32]. MTOW, payload is summarized in Table 3.5, and those are used as input values for estimating an empty and battery weight.

In Table 3.5, it is observed that the payload plus crew weight ratio of the eVTOL to be investigated was in the range of 15 to 22% without a significant variation depending on the aircraft shape. The vectored thrust type of S4 and Lilium Jet eVTOL has an empty weight ratio of about 40~48%, a battery weight ratio of 30~40%, and a payload and crew weight ratio of 22%. The empty weight ratio has the lowest level of ratio compared against other eVTOL. On the contrary, it has the highest level of battery weight ratio.

On the other hand, the multi-rotor type eVTOL such as Volocity has an empty weight ratio of 56% compared against the maximum take-off weight, which is the highest compared to other eVTOL. The battery weight ratio is 22%, showing the smallest ratio compared to other eVTOL. The reason for it is the achievable requirement with the current technology. The payload and crew weight ratio are also estimated to be 22%.

Cora, a type of lift and cruise, was estimated to have an empty weight ratio of about 52%, which is a value larger than that for S4 and Lilium Jet and smaller than Volocity. Because of the incorporation of the lift and thrust propulsion units on the eVTOL, those characteristics were reflected in the empty weight. Cora is analyzed to be 15% in payload ratio, while S4, Volocity, and Lilium Jet are 21~22%.

Table 3.5 Weight fraction of four eVTOLs

Unit (kg)	S4 [26]	Volocity [27]	Lilium Jet [28]	Cora [29]
payload	453.6	200	700	181
Battery weight	848.2	200	953	400
Empty weight	875.5	500	1,524	643
Maximum take-off weight	2,177	900	3,175	1,224

For the validation of the procedure, comparison will be attempted against the present battery weight against the previously obtain values of four eVTOLs. Range, speed, passenger, batter specific energy of the four eVTOLs are summarized in Table 3.6.

Table 3.6 Target Performance of four eVTOLs

	S4 [30]	Volocity [31]	Lilium Jet [28]	Cora [32]
Range (mi)	150	22	162	62
Cruise speed (mph)	200	56	186	110
Payload (#)	5	2	7	2
Battery Specific energy (Wh/kg)	235	250	320	230

The results included in Table 3.6 are used to assume the mission profile of each eVTOL, and it is utilized for estimating battery weight of the four eVTOLs. Unless noticed, the passenger weight is assumed that each passenger weigh 100kg including the luggage. In case of S4, the investigated passenger weight are used [26].

In Table 3.6, most of eVTOL developers are planning to use higher battery specific energy than the current state-of-art of Li-ion technology. For Lilium Jet, battery specific energy is greater than 300Wh/kg. eVTOL developers usually prefers to present the target performance in US customary unit, but it is herein converted to SI unit for computation.

To estimate the required power of eVTOL, recommended values will be used on those values: the efficiency of the propeller, battery, motor shaft as well as downwash effect. It will be obtained by further aerodynamics analysis in the preliminary design stage. Instead, those values are the recommended ones in an aircraft design textbook, as stated in Raymer [17] otherwise notified. Since the propeller efficiency of Lilium Jet is given by Nathen [28], that value will be used. Meanwhile, the geometric data like the rotor radius and wing area are estimated from the configuration of the corresponding eVTOL. Those are summarized in Table 3.7.

The Figure of Merit (FM) for each configuration is estimated using the relationship between power loading and disk loading presented by Leishman [18]. The power loading and disk loading values used for estimating the Figure of Merit are referred to Turcksin [33]. As for the Lift-to-Drag ratio, Cora, a compound coaxial rotorcraft, used a value of 5.0 [34]. The Lilium Jet, a tilt ducted fan configuration, specifies a value of 6.5 based on wind tunnel test results of a similar configuration [35]. The S4 configuration, a tilt-rotor, has a Lift-to-Drag ratio of 4.5

according to Johnson [34], but considering the difference in the number of rotors and the current technological level, it is set to 5.0.

Table 3.7 Either assumed or estimated parameters of four eVTOLs

	S4	Volocity	Lilium Jet	Cora
Propeller efficiency	0.8 [17]	0.8 [17]	0.85[28]	0.8 [17]
Motor to Shaft efficiency		0.97 [17]		
Battery to Motor efficiency		0.93 [17]		
Download factor		1.03 [17]		
Figure of Merit	0.67	0.70	0.50	0.65
Disk area [m^2]	21.3	74.7	2.5	13.6 [32]
Wing area [m^2]	12.8	-	8.5 [28]	11 [32]

3.3.3 Assumed Mission Profile of Four eVTOLs

The assumed mission profile for the four eVTOLs based on the target performance is shown in Fig. 3.6. The mission profile is referred to those published by Uber Elevate. [36] The mission profile consists of the following eight segments: take-off, vertical climb, cruise-climb, cruise, cruise-descent, vertical descent, and landing. The mission is symmetric to the cruise segment. Hence, the flight conditions are only stated about the first five segments. The detailed flight conditions required for estimating the battery weight are summarized in Table 3.8.

Except for Lilium Jet, a transition segment is excluded, due to the increased computation complexity and little influence on the result. However, since Nathen [29] provides enough information about that segment, it will be possible to include such segment. Though most of eVTOL developing companies do not mention the reserve segment, 10-minute cruise mission will be specified as a reserve mission considering the contingency or emergency. During the reserve mission, the required power for that segment will be assumed as a required power for cruise.

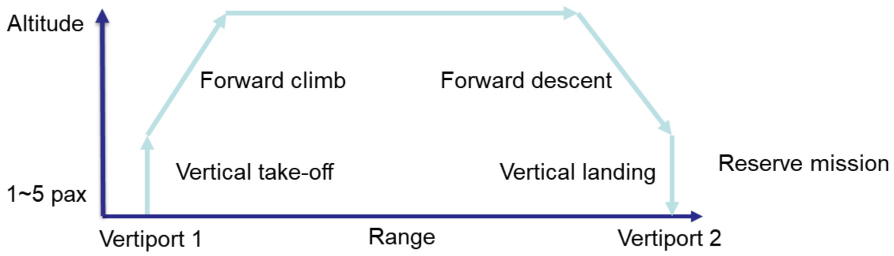


Fig 3.6 Assumed mission profile of four eVTOLs

S4 is assumed to spend 60s for the take-off and vertical climb with a rate-of-climb (ROC) of 2.5m/s (500ft/min). After an enough altitude are secured, a cruise-climb segment will be performed in a fixed-wing mode. During such segment, speed of S4 will be accelerated and flight 241km/h (150mph) average for 300s. Flight path angle of that segment will be obtained by applying an arcsine function to ratio of ROC to the flight speed. For that segment, ROC will still be maintained of 2.5m/s. For the cruise flight, flight condition for S4 is stated in Table 3.8.

For Volocity, both take-off and vertical climb are supposed to spend 30s at a ROC 2.5m/s. For the cruise-climb segment, unlike to other eVTOLs, it will climb to a cruise altitude in the edgewise flight mode. During it, it will also be accelerated and operated in an average flight speed of 75km/h during 300s. At the cruise altitude, Volocity will fly as described in Table 3.8.

As it is previously mentioned, Lilium Jet 7-seater includes the transition within its mission. The motivation of including such segment is that it only requires to assume the maximum lift coefficient for estimating the deficit of the wing lift. Detailed flight condition is specified. As stated by Nathen [28], in the segment, the flight speed of Lilium Jet is in average 150km/h and will last for 20s. To improve its long-range flight capability, Lilium Jet attempts to minimize the duration from the take-off to transition segments during less than 1 minute. And it is reflected as 30-second take-off and climb duration. Duration of the cruise-climb segment are specified to 451s for the cruise efficiency.

Regarding Cora, it is supposed to spend 60s during the take-off and vertical climb at 2.5m/s ROC. After an initial climb is completed, it will climb to a cruise altitude at ROC of 7.25m/s with an average speed of 165km/h for 60s. During its cruise flight, the flight condition is described in Table 3.8.

Table 3.8 Flight condition of four eVTOLs

		S4	Volocity	Lilium Jet	Cora
Take-off and climb	Time (s)	60	60	30	60
	ROC (m/s)	2.5	2.5	2.5	2.5
Transition	Time (s)	-	-	20	-
	Speed (km/h)	-	-	150	-
Cruise-climb	Time (s)	300	300	451	60
	Speed (km/h)	241	75	275	165
	ROC (m/s)	2.5	2.5	2.5	7.25
Cruise	Speed (km/h)	241	90	300	180
	Distance (km)	241	35	261	100
	Lift-to-drag	5.0	5.0	6.5	6.4

3.4 Result Comparison of Four eVTOLs

Based on the assumed mission profile, target performance, eVTOL configuration, and relevant parameters for obtaining BWF, the battery weight of the selected eVTOL is estimated. It is done by using the aforementioned methodology incorporating the obtained values for the maximum take-off weight, crew, and payload. The weight estimation proposed in this thesis demonstrates its validity by the results presented in Table 3.9. The good agreement between the estimated weights and the values reported in Refs. [26-32], except for Lilium Jet which exhibits a 15% difference in the battery weight. The weight estimations for Joby, Volocity, and Cora configurations displayed the differences within 3%. This indicates that the weight estimation is accurately accomplished. The summarized results are presented in Table 3.9, providing the weight estimation for the four eVTOL configurations. By Table 3.9, it is evident that the proposed weight estimation method is valid.

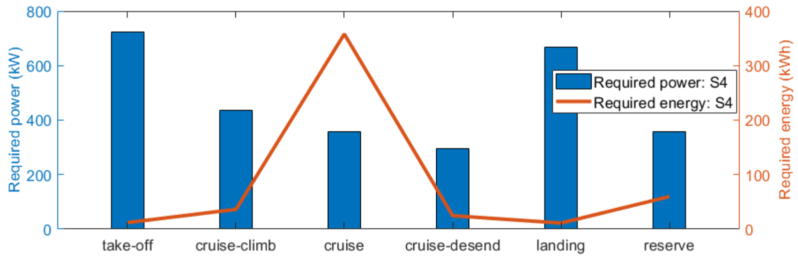
The reason behind the 15% discrepancy in battery weight estimation is attributed to Lilium Jet's tilt-ducted configuration, which induces practicality and delayed flow separation effects, as well as the utilization of variable exhaust nozzles, resulting in relatively lower required power compared against the present.

Table 3.9 Weight result for four eVTOLs

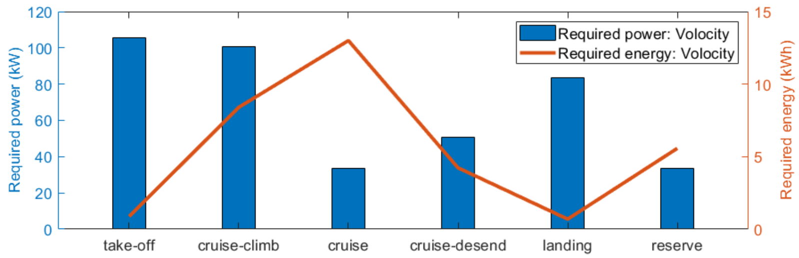
	MTOW (kg, Input)	Payload (kg, Input)		Empty weight (kg, Output)	Battery weight (kg, Output)
S4 [26]	2,177	453.6	Present	898.6	824.8
			Ref. 26	875.5	848.2
			Discrepancy (%)	2.64	-2.76
Volocity [27]	900	200	Present	504.2	195.76
			Ref. 27	500	200
			Discrepancy (%)	0.84	-2.1
Lilium Jet [28]	3,175	700	Present	1,381.8	1,093.2
			Ref. 28	1,524	953
			Discrepancy (%)	-9.33	14.71
Cora [29]	1,224	181	Present	643.2	399.9
			Ref. 29	643	400
			Discrepancy (%)	0.03	0.00

The required power and energy comparison during the mission are shown in Fig. 3.7. The maximum required power takes place during the take-off and vertical climb. Such required power is decreased as the forward flight speed is increased. Volocity also decreases the required power within the transition from axial flight to edgewise flight segment, but its magnitude is smaller when compared against the other winged eVTOLs. The winged eVTOL may share lift with its wings as the speed is increased. The required energy for a segment is obtained by multiplying the required power by the duration. Since the duration for the take-off, climb, and transition is small, the required energy will also be small. On the contrary, most of the energy is required during the cruise flight segment.

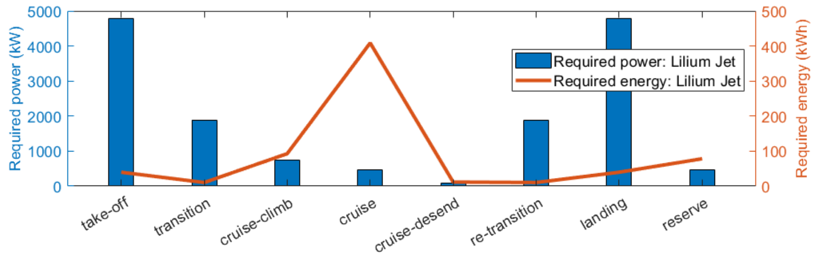
As the rotor disk area is smaller and MTOW of eVTOL is larger, the required power of eVTOL will be larger. In other words, eVTOL has a large disk loading, and the required power of it will also be high. Specifically, for Lilium Jet, it has the largest disk loading among the four eVTOLs, and it also has the largest required power during the take-off stage, as it found in Fig. 3.7 (c). For comparison, the required power of Lilium Jet during take-off is 48 times larger than that for Volocity. S4 and Cora show that 5-6 times larger power is required when compared against Volocity for the same segment. S4 and Lilium Jet, designed for the high-speed long-range flight, demonstrate a demand for the battery energy level within the range of 400-500 kWh. Volocity, designed for urban commuting purposes, appears to be sufficient with a demand for energy below 50 kWh. Cora, which exhibits an intermediate performance level as a lift+cruise configuration, shows a demand for energy that falls between those two categories.



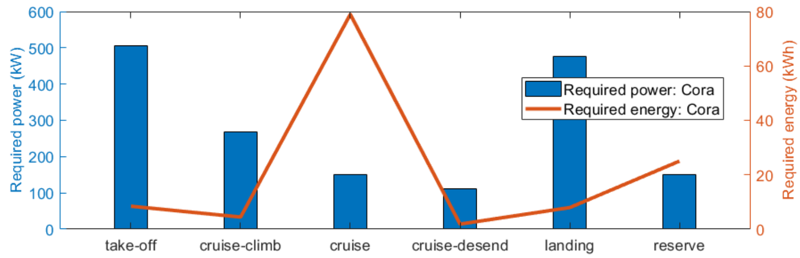
(a) S4 required power and energy



(b) Volocity Required power and energy



(c) Lilium Jet Required power and energy



(d) Cora Required power and energy

Fig 3.7 Required power and energy of four eVTOL

The estimated state of charge (SOC) during the mission of each eVTOL is shown in Fig. 3.8. As shown in Fig. 3.8, large, required power of the take-off segment causes SOC to decrease rapidly. Beyond the take-off, SOC of Lilium Jet and Cora will drop as much as 10%. On the contrary, Volocity and S4 will drop slowly than the Lilium Jet and Cora. 80-90% of SOC is consumed during the cruise-climb, cruise, and descent flights. Last 10-20% of SOC is remained as the reserve energy, in case of either contingency or emergency.

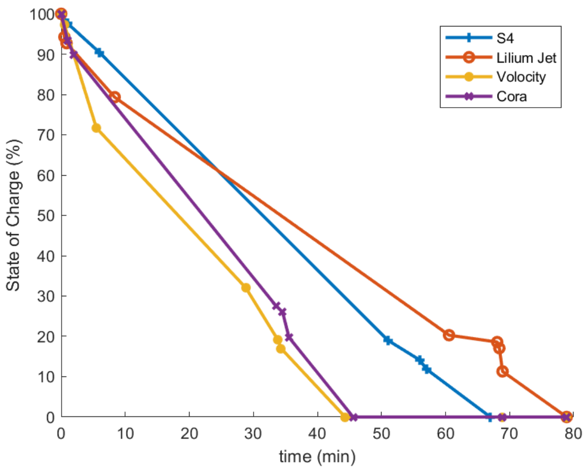


Fig 3.8 Estimated state of charge (SOC) for four eVTOLs

3.5 Sizing of an eVTOL Demonstrator

3.5.1 Overview of the Demonstrator and Design Status

In 2023, currently, 1/5 scale of a 6,500lb demonstrator is to be designed for the purpose of the verification of eVTOL technology. For that, an eVTOL, which has total MTOW 50kg and 25km range along with 3kg payload, will be designed. Tilt-rotor configuration is selected since it shows excellence in terms of the long-range and high-speed flight capability.

Flight condition during the mission for sizing of a tilt-rotor demonstrator is summarized in Table 3.10. The mission of the demonstrator is selected found in Hwang [37], and such profile is deployed to size a demonstrator. And its mission is plotted in Fig. 3.9.

Table 3.10 Flight condition of the demonstrator

	Take-off	Climb	Cruise climb	Cruise	reserve
Duration (min)	0.1	0.4	0.5	t_{cruise}	1.0
ROC (m/s)	0	2.5	2.5	0	0
Speed (km/h)	0	0	90	V_{br}	110
Altitude (start)	0	0	20	100	100
Altitude (end)	0	20	100	100	100
Distance (km)	-	-	-	25	-

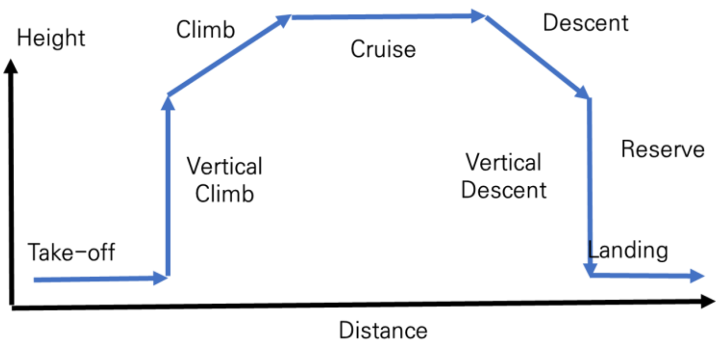


Fig 3.9 Mission profile of the demonstrator

Figure 3.9 represents a transport mission between two waypoints, which closely resembles the expected AAM mission. It includes a 1-minute short reserve segment in the mission for either emergency or contingency situation. The primary reason for this segment is to prevent overestimating the battery weight. For full-scale eVTOL, a normal reserve mission typically requires the minimum of at least 20 minutes as specified in 14 CFR 91.151. But such requirement is excessively stringent for the demonstrator and may cause iterative computation to diverge. The demonstrator is in a flight at a low altitude of 100m, which is enough time to address emergency landing for ground pilot.

The mission profile exhibits symmetry about cruise segment. During the take-off, the demonstrator will climb vertically at a ROC of 2.5m/s and obtain 20m altitude. And then it will transit from the rotary-wing to fixed-wing mode and will climb up to a cruise altitude of 100m. In the cruise segment, the demonstrator will fly at the best-range speed.

The demonstrator has two configuration candidates: a twin tilt-rotor and quad tilt-rotor. They have two and four tilting rotors, respectively. It is designed by using

NDARC. To reduce MTOW of an eVTOL while keeping the performance, trade study will be conducted for the two variables such as the payload and rotor tip speed. From the trade study, a lightweight aircraft configuration that allows the lower rotor tip speed during hover will be selected. It is supposed to carry a payload of 3kg and achieve a range of 25km. For a quad tilt-rotor, rotor tip speed of 110m/s and 3kg payload give the lowest MTOW of 35kg. The twin tilt-rotor has 45.6kg MTOW at the rotor tip speed of 97m/s with the 3kg payload. Thus, those two configurations are selected as three-dimensional CAD drawings for the further investigation. The used CAD program is OpenVSP. It is a parametric three-dimensional CAD program. Those drawings are shown in Fig. 3.10. Since both configurations are smaller than 50kg in MTOW, 5kg-payload for twin tilt-rotor will be included in the results. Their geometric properties and weight breakdown are summarized in Tables 3.11 and 3.12, respectively.

Table 3.11 Geometric properties of the demonstrators

(a) Quad tilt-rotor

Rotor	Number of the Rotors (#)	4
	Number of the Blades (#)	2
	Rotor radius (m)	0.47
Main Wing	Wingspan (m)	2.5
	Aspect ratio	13.66
Tail Wing	Span (m)	2.2
	Dihedral (deg)	30
	Sweep angle (deg)	0
	Taper ratio	0.52
	Aspect ratio	10.58
Fuselage	Length (m)	2.03
	Height (m)	0.4
	Width (m)	0.4

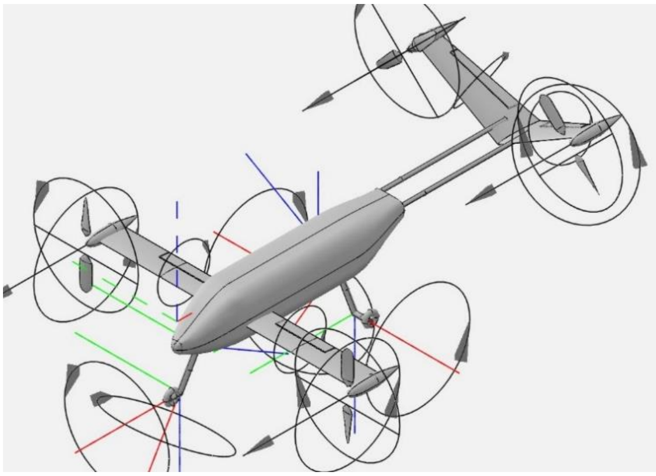
(b) Twin tilt-rotor

		Twin tilt-rotor 3kg payload	Twin tilt-rotor 5kg payload
Rotor	Rotor radius (m)	0.758	0.810
Main Wing	Wingspan (m)	2.5	2.5
	Aspect ratio	10.48	9.18
Tail Wing (Horizontal)	Span (m)	1.74	1.74
	Dihedral (deg)	0	0
	Sweep angle (deg)	0	0
	Taper ratio	0.52	0.52
	Aspect ratio	3.03	3.03
Tail Wing (Vertical)	Span (m)	0.65	0.65
	Sweep angle (deg)	15	15
	Taper ratio	0.52	0.52
	Aspect ratio	2.11	2.11
Fuselage	Length (m)	2.03	2.03
	Height (m)	0.4	0.4

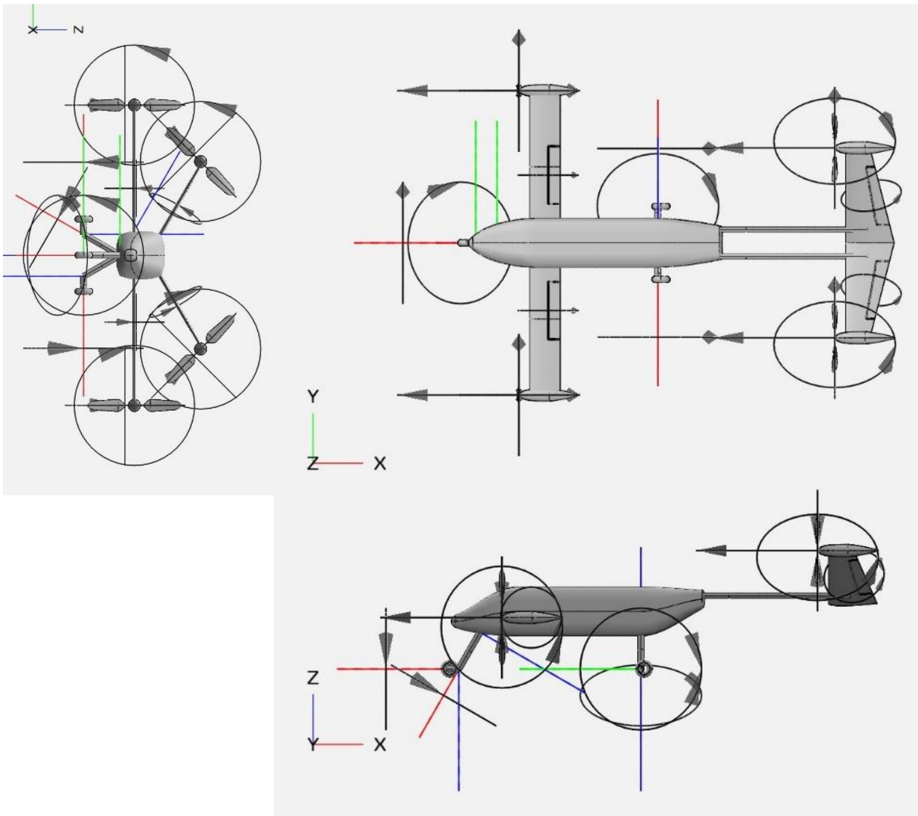
	Width (m)	0.4	0.4

Table 3.12 Weight breakdown of the demonstrator candidate

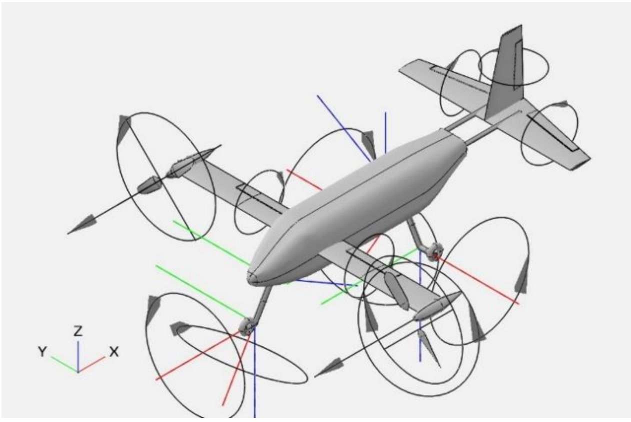
Weight Unit (kg)	Component	Quad tilt-rotor	Twin tilt-rotor 3kg payload	Twin tilt-rotor 5kg payload
Structure	Wing	4.4	3.6	3.7
	Rotor	1.5	2.7	3.2
	fuselage	8.2	9.9	1.6
	Empennage	-	1.6	10.8
	Alighting gear	7.1	8.5	9.2
	Engine nacelle	1.9	2.5	2.7
Propulsion System	Motor	2.7	3.5	3.9
	Battery	2.2	5.0	5.8
	Drive system	0.9	1.8	2.0
System and Equipment	Flight controls	2.9	3.6	3.9
Payload		3.0	3.0	5.0
MTOW		34.9	45.6	51.9



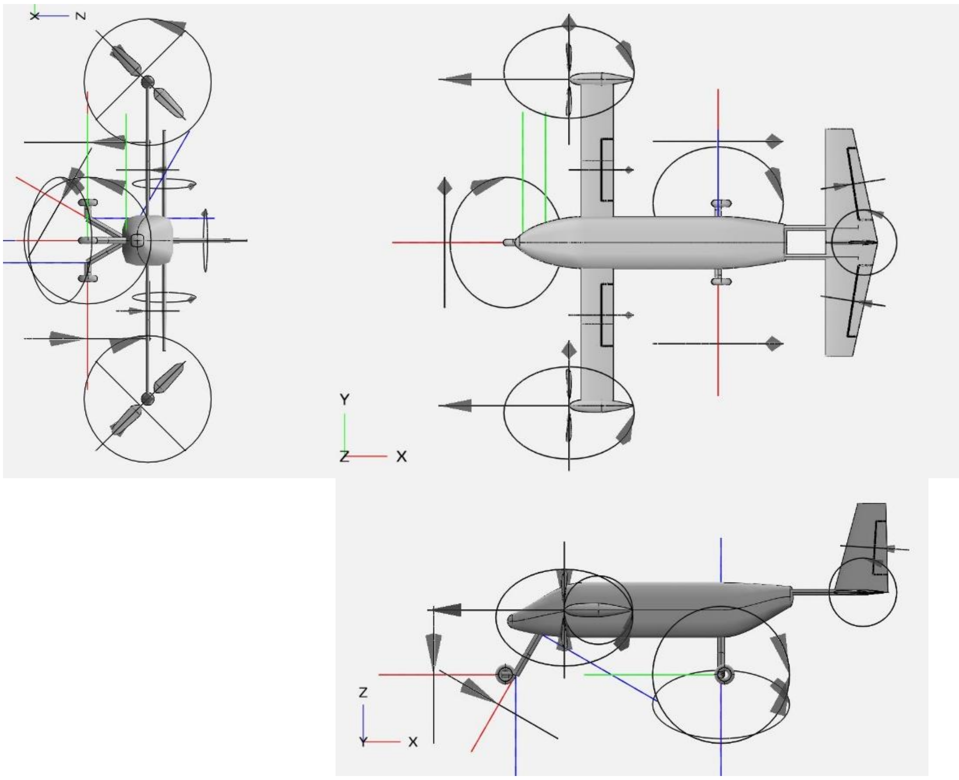
(a) Quad tilt-rotor left isometric view



(b) Quad tilt-rotor three view



(c) Twin tilt-rotor left isometric view



(d) Twin tilt-rotor three view

Fig 3.10 Demonstrator candidate CAD drawings

Disk loading, rotor tip speed, and blade loading are used as the rotor design variable for both twin tilt-rotor and quad tilt-rotor. Wing loading and wingspan are used as the wing design variable of both configurations. Disk loading, wing loading and wing span are referred to the existing design result of QTP-UAV electric version [38] by Korea Aerospace Research Institute (KARI). From that, both configurations have common values of 12.6kg/m^2 disk loading, 76.3kg/m^2 wing loading, and 2.5m wingspan. The geometry of the wing and fuselage is obtained as the simplest as possible considering manufacture.

Aerodynamic properties of the demonstrator candidates are summarized in Table 3.13. In it, lift-to-drag ratio, drag area, figure of merit, cruise speed, and the maximum speed are presented. Lift-to-drag ratio represents a cruise efficiency of eVTOL. In Table 3.13, the quad tilt-rotor is 9.7, and twin tilt-rotor with the payload 3kg is 5.7. The maximum speed of the quad tilt-rotor is 128.7km/h and it is 10km/h faster than the twin tilt-rotor with the payload 3kg. The maximum speed of the twin tilt-rotor with the payload 3kg is 116.8km/h. The figure of merit is the representative hover performance index. The figure of merit for the quad tilt-rotor is 0.8 and the twin tilt-rotor with the payload 3kg is 0.76.

The twin tilt-rotor configuration exhibited values within the range of tilt-rotor lift-to-drag ratios reported by Johnson [34]. However, for the quad tilt-rotor configuration, the lift-to-drag ratio around 10, and the Figure of Merit was 0.80. This indicates that the quad tilt-rotor configuration imposes higher requirements in fulfilling the same mission compared to other candidate configurations. In the context of this technology demonstration, the size is relatively small, which suggests the possibility of Reynolds number values falling below the transitional flow regime. Thus, Reynolds number effects can lead to change in flow separation characteristic and drag prediction.

Table 3.13 Aerodynamic properties of the demonstrators

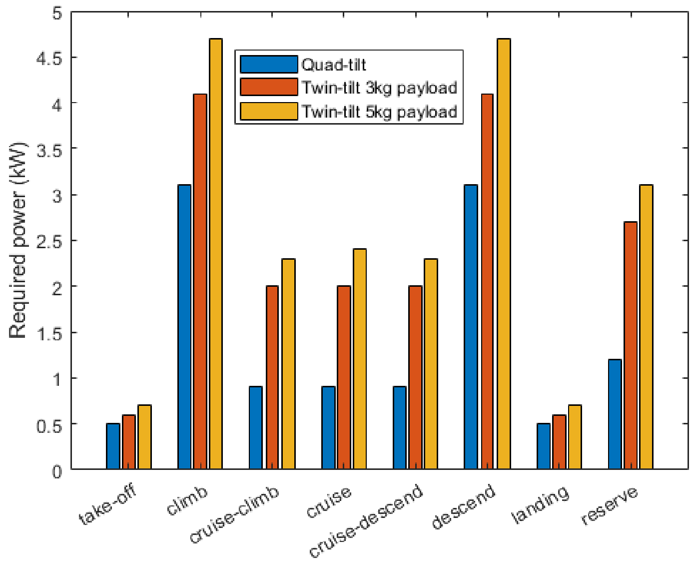
	Quad tilt-rotor	Twin tilt-rotor 3kg payload	Twin tilt-rotor 5kg payload
Figure of Merit	0.80	0.76	0.77
Drag area (m^2)	0.03	0.07	0.09
L/D @ cruise	9.73	5.71	5.63
Best range speed (km/h)	94.49	94.29	94.44
Maximum speed (km/h)	128.73	116.77	115.52

The required power and energy for each mission segment are presented in Fig. 3.11. It is found that the required power during the rotary-wing mode is greater than that for the fixed-wing mode. Regarding the required energy of the demonstrator, the cruise flight occupies most of the energy of the mission.

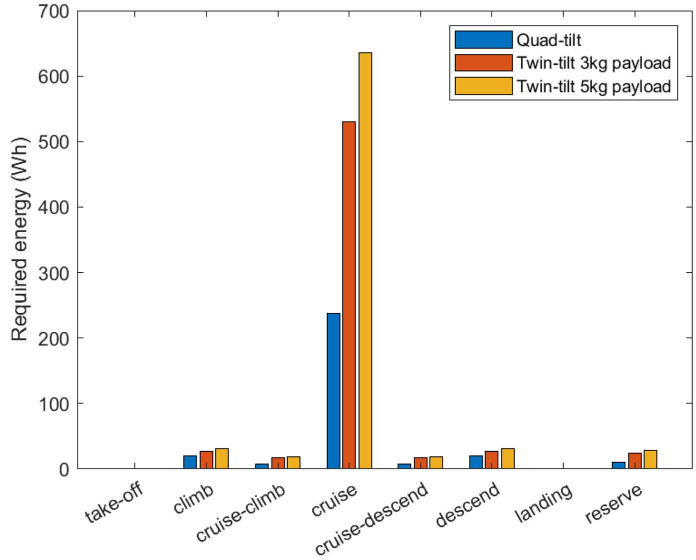
Figure 3.11 (a) shows the comparison of the required power between the quad tilt-rotor and twin tilt-rotor configurations. During the climb segment, the quad tilt-rotor requires 3.1kW and twin tilt-rotor with the 3kg payload requires 4.1kW. During the cruise segment, quad tilt-rotor requires 0.9kW, and twin tilt-rotor with 3kg payload does 2.0kW. Cruise required power of 0.9kW is the lowest power of the quad tilt-rotor.

Figure 3.11 (b) shows the comparison of the required energy between the quad tilt-rotor and twin tilt-rotor. The required energy of the twin tilt-rotor with 3kg payload of the cruise segment is 2.2 times larger than that for the quad tilt-rotor. It is since the twin tilt-rotor with 3kg payload has 2.2 times greater power than the quad tilt-rotor does. The other mission segments have a minor effect on the total required energy, and thus it may be negligible.

The lift-to-drag ratio of the technology demonstrator is calculated as *WV/P*, as defined by NDARC [25]. Here, *W* represents the total takeoff weight, *V* denotes the velocity, and *P* represents the required power. In the case of cruise flight, the values of *W* and *V* for the two candidate configurations are similar. However, the required power for the twin tilt-rotor with a 3kg payload is twice as much as that for the quad tilt-rotor. As a result, the quad tilt-rotor configuration exhibits a lift-to-drag ratio of 9.7. The reason for the lower required power in quad tilt-rotor is that when estimating the drag, the negative drag area of the wing reduces the total drag area of quad tilt-rotor, due to interference effects between the wing and the rotor. For tilt-rotor, the interference coefficient between the rotor and wing is typically assumed to be -0.06, which affects to reduce the drag.



(a) Required power of the demonstrators



(b) Required energy of the demonstrators

Fig 3.11 Required power and energy of the demonstrators

3.5.2 Application to Sizing of the Demonstrator

Using the weight estimation procedure proposed in Section 2.4 and following Fig. 2.2, MTOW will be estimated. In this procedure, the summarized weight breakdown shown in Section 3.5.1 will be used for the mission profile. Fig 3.9 and its flight condition in Table 3.10 are used for eVTOL geometry. Table 3.11 is used, and the aerodynamic properties are deployed based on Table 3.13. Table 3.14 shows the comparison of the weight of the demonstrators.

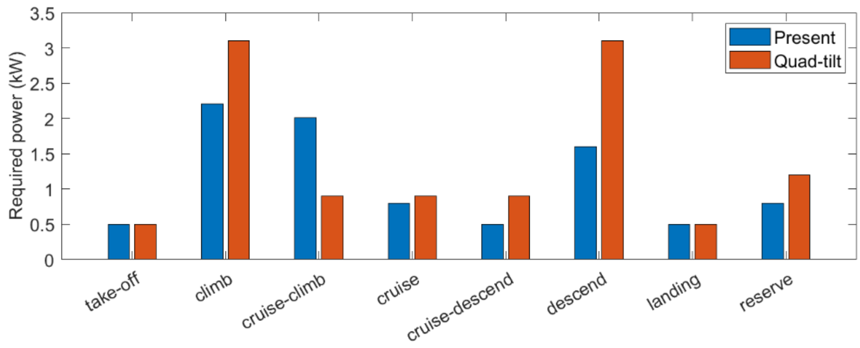
Table 3.14 Weight of demonstrator comparison

	Payload (kg)		MTOW (kg)	Battery (kg)	Empty weight (kg)
Quad tilt-rotor	3	Present	24.3	1.8	19.5
		NDARC	35.0	2.2	29.7
		Discrepancy (%)	31	18	34
Twin tilt-rotor 3kg payload	3	Present	30.8	3.6	24.2
		NDARC	45.5	5.0	37.5
		Discrepancy (%)	32	28	35
Twin tilt-rotor 5kg payload	5	Present	42.5	5.1	32.5
		NDARC	51.9	5.8	41.1
		Discrepancy (%)	18	12	21

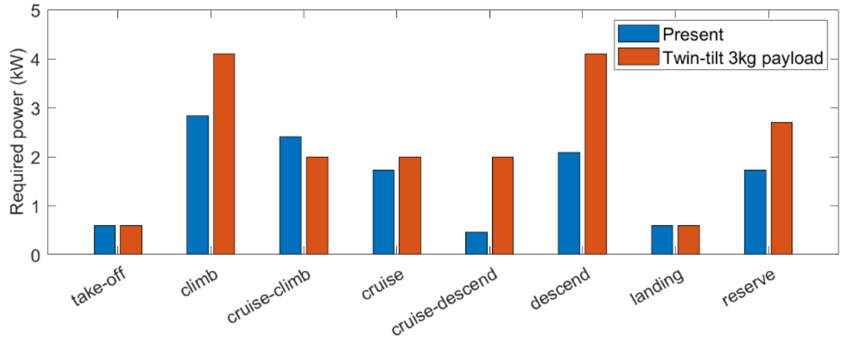
The estimation of the battery weight shows a reduced difference of within 20%, except for the twin tilt-rotor with the 3kg payload. This indicates that the utilized battery weight estimation formulas Eqs. (2.5) and (2.6) provide reasonable results and will be applicable for estimating the battery weight of the demonstrators.

As depicted in Fig. 3.12, it is observed that the present required power generally correlates well with those by NDARC. Particularly, the demonstrator exhibits a similar required power during the cruise segment, which represents a significant portion of the mission.

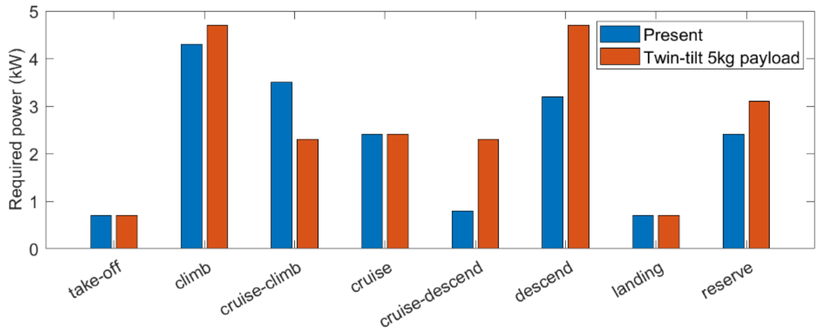
The battery weight discrepancy falls within the range of errors in Aero Flight Dynamics and Directorate (AFDD) weight estimation formula, making it an acceptable range. According to NDARC Theory Manual [25], when comparing the weight estimated using the AFDD empirical formula with the actual weight of aircraft, it is common to encounter component weight differences exceeding 20%, and in severe cases, even exceeding 30%. Furthermore, AFDD empirical formula is designed for turbine-powered compound rotorcraft or tilt-rotor configurations rather than eVTOLs, which could potentially affect the estimation of battery weight in eVTOL technology demonstrators.



(a) Quad tilt-rotor required power comparison

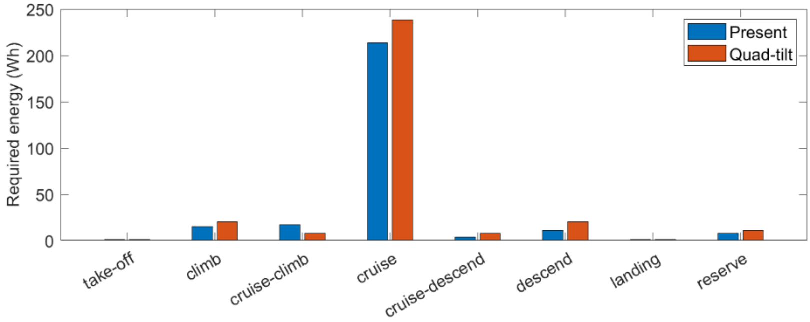


(b) Twin tilt-rotor with 3kg payload required power comparison

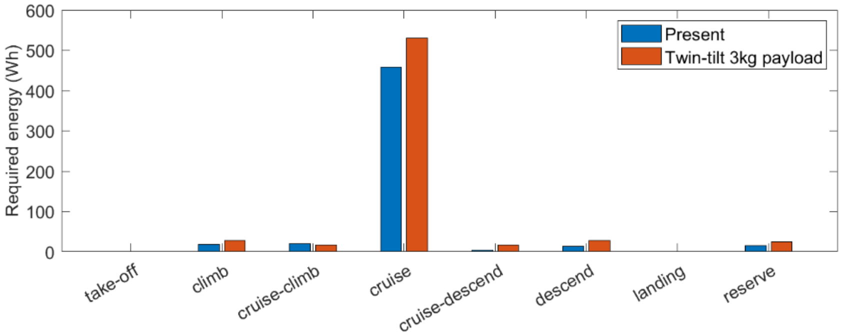


(c) Twin tilt-rotor with 3kg payload required power comparison

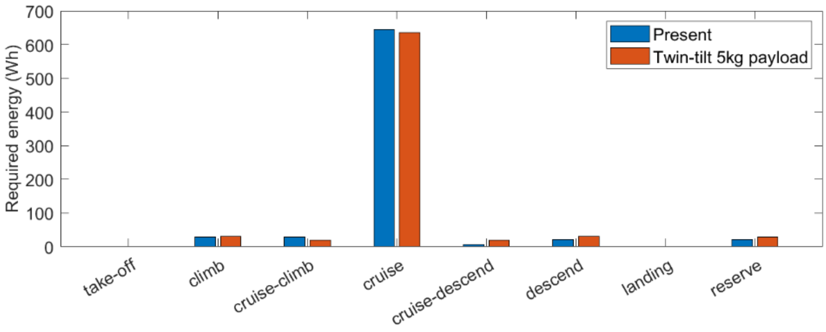
Fig 3.12 Required power of the demonstrators



(a) Quad tilt-rotor required energy comparison



(b) Twin tilt-rotor with 3kg payload required energy comparison



(c) Twin tilt-rotor with 5kg payload required energy comparison

Fig 3.13 Required energy of the demonstrator

Chapter 4

Conclusion

4.1 Summary

This thesis presents an initial sizing method for eVTOL with the requirements, mission profile, and aircraft configuration. The method of estimating the battery weight within the limited available design results is proposed. SNU baseline eVTOLs, S4, Volocity, Lilium Jet, Cora, and eVTOL demonstrator are selected as an object to estimate the battery weight.

When comparing between present weight and SNU baseline eVTOL, the maximum of 25% discrepancy is found in the battery weight for a quadrotor. From this result, deployed formulas for battery weight fraction are valid. When comparing the required energy, which is directly related to the battery weight, the difference is within 10%, except for a tilt-rotor. It is an accurate prediction even in the early conceptual design stage. In estimating the required power, except for the cruise-climb segment, present required power is well matched with that on SNU baseline eVTOL.

The weight of the four eVTOLs are compared against the present estimation. The present weight estimation is shown within the maximum of 15% discrepancy. And S4, Volocity, Cora discrepancy of 3% or less is estimated. Those results highlight the accuracy of the weight estimation.

By NDARC, a 1/5 scale technology demonstrator is designed, and the weight, energy, and power are examined. The demonstrator is being designed for two tilt-rotor configurations, one with 2 rotors and the other with 4 rotors. To find a design that minimizes MTOW (Maximum Takeoff Weight) while maintaining performance, a trade study is conducted regarding the disk load and rotor tip speed. As a result, two configurations: quad tilt-rotor, and twin tilt-rotor, which is capable of performing the mission with a 3kg payload, are obtained. The selected designs are synthesized into CAD drawings for visual representation.

Then, the battery weight estimation is attempted. Present weight breakdown, power and energy estimations are acquired, and those results are compared against NDARC results. The battery weight shows difference within 20% except for the twin tilt-rotor with the payload 3kg.

4.2 Future Work

In future work, the empty weight ratio empirical formula will be investigated and integrated with the battery weight estimation method for eVTOL sizing. It can also be utilized for initial weight estimation of eVTOLs. The process of solving Eq. (4.1) for the initial estimation of MTOW is illustrated in Fig 4.1.

$$W = \frac{W_{crew} + W_{payload}}{1 - \frac{W_b}{W} - \frac{W_e}{W}} \tag{4.1}$$

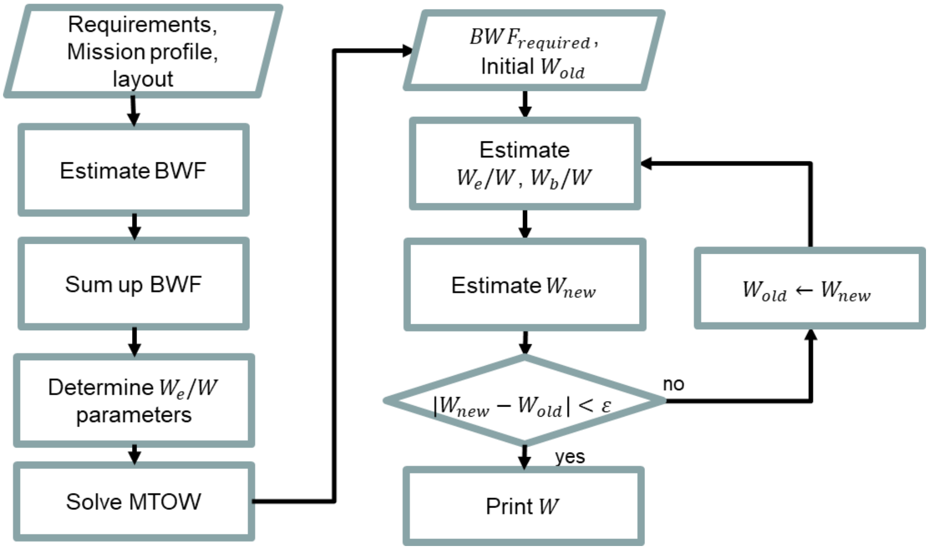


Fig 4.1 Maximum take-off weight estimating procedure

References

[1] Chiland, E., "Number of LA residents dealing with commute times over 90 minutes surges," August 15 2010., Los Angeles Curbed, URL: https://la.curbed.com/2019/8/15/20807275/los-angeles-commute-times-traffic [retrieved 28 Apr 2023].

[2] Moretti, R., and Kelly, C., "News Release: New York State Motorists Lose $28 Billion Annually – Up to $3,200 Per Driver – On Roads that are Deteriorated, Congested and Lack Some Desirable Safety Features," January 12 2022., A National Transportation Research, URL: https://tripnet.org/reports/news-release-new-york-state-motorists-lose-28-billion-annually-up-to-3200-per-driver-on-roads-that-are-deteriorated-congested-lack-some-desirable-safety-features/ [retrieved 28 Apr 2023].

[3] Patterson, M., "Advanced Air Mobility (AAM): Overview and Integration Considerations," August 19 2021., National Aeronautics and Space Administration, URL: https://ntrs.nasa.gov/api/citations/20210020125/downloads/2021-08-19%20VA%20Aviation%20Conf%20AAM%20Presentation%20v1.pdf [retrieved 16 May 2023].

[4] Anonymous, "Advanced Air Mobility | Air Taxis," Federal Aviation Administration, URL: https://www.faa.gov/air-taxis [retrieved 16 May 2023].

[5] Anonymous, “Special Condition for small-category VTOL aircraft,” European Union Aviation Safety Agency, SC-VTOL-01, 1, July 2 2019., URL: https://www.easa.europa.eu/sites/default/files/dfu/SC-VTOL-01.pdf [retrieved 16 May 2023].

[6] Anonymous, “Urban Air Mobility (UAM) Concept of Operations v2.0,” Federal Aviation Administration, April 26 2023., URL: https://www.faa.gov/sites/faa.gov/files/Urban%20Air%20Mobility%20%28UAM%29%20Concept%20of%20Operations%202.0_0.pdf [retrieved 16 May 2023].

[7] Anonymous, “Concept of Operations for Uncrewed Urban Air Mobility,” Boeing Inc., September 22 2022., URL: https://www.boeing.com/resources/boeingdotcom/innovation/con-ops/docs/Concept-of-Operations-for-Uncrewed-Urban-Air-Mobility.pdf [retrieved 16 May 2023].

[8] Wang, J., “Short Course on Electric VTOL Design”, Vertical Flight Society, February 9-10 2021.

[9] Quinn, J. B., Waldmann, T., Richter, K., Kasper, M., and Wohlfahrt-Mehrens, M., “Energy Density of Cylindrical Li-Ion Cells: A Comparison of Commercial 18650 to the 21700 Cells," Journal of The Electrochemical Society, vol. 165, pp. 3284-3291. doi:10.1149/2.0281814jes.

[10] Mikic, G., Bevirt, J., Bain, J., and Stoll, A., "ROTARY AIRFOIL AND DESIGN THEREFORE," US11407510B2, filed October 28 2020, issued Aug 9 2022.

[11] Ingraham, D., "Low-Noise Propeller Design with the Vortex Lattice Method and Gradient-Based Optimization," AIAA SCITECH 2023, American Institution of Aeronautics and Astronautics, December 2 2022, https://doi.org/10.2514/6.2023-2039.

[12] Brinkmann, P., "Joby: Results of noise tests show aircraft would be quiet enough for cities," Aerospace America, May 10 2022., URL: https://aerospaceamerica.aiaa.org/joby-noise-test-results-show-aircraft-would-be-quiet-enough-for-cities/ [retrieved May 16 2023].

[13] McIntosh, A., "Technology Blog," Lilium, August 04 2021., URL: https://lilium.com/newsroom-detail/technology-behind-the-lilium-jet [retrieved May 16 2023].

[14] Kim, D., Lee, J., and Hwang, H., "Aerodynamic Analysis, Required Power and Weight Estimation of a Compound (Tilt Rotor + Lift +Cruise) Type EVTOL for Urban Air Mobility Using Reverse Engineering Techniques," Journal of Advanced Navigation Technology, vol. 25, no. 1, Journal of Advanced Navigation Technology, February 2021, pp. 17–28, doi:10.12673/JANT.2021.25.1.17.

[15] Kadhiresan, A., and Duffy, M., "Conceptual design and mission analysis for eVTOL urban air mobility flight vehicle configurations," American Institute of Aeronautics and Astronautics Aviation 2019 Forum, 2019.

[16] Johnson, W., “NDARC NASA Design and Analysis of Rotorcraft Theory,” NASA Ames Research Center, Moffett Field CA, January 2022.

[17] Raymer, D., “Aircraft Design: A Conceptual Approach," 6th ed., American Institute of Aeronautics and Astronautics, 2021.

[18] Leishman, G., "Principles of Helicopter Aerodynamics," New York: Cambridge University Press, 2006.

[19] Cha, W., Park, S., Hwang, M., Chang, Y., Ahn, C., and Shin, S., “Design of a Lift+Cruise eVTOL Aircraft reflecting the Geometry and Structural Details regarding Battery Locations,” Vertical Flight Society’ 79th Annual Forum, West Palm Beach, FL, May 16-18, 2023.

[20] Ahn, C., Park, S., Hwang, M., Chang, Y., Cha, W., and Shin, S., “Comparison and Analysis of a Tiltrotor UAM Configuration by Using NDARC,” Vertical Flight Society’ 79th Annual Forum, West Palm Beach, FL, May 16-18, 2023.

[21] Chang, Y., Park, S., Kim, Y., Ahn, C., Cha, W., Hwang, M., and Shin, S., “Optimization Framework of a Tiltwing eVTOL Aircraft including Geometry Consideration,” Vertical Flight Society, Mesa, AZ, January 24-26, 2023.

[22] Radotich, M., “Conceptual Design of Tiltrotor Aircraft for Urban Air Mobility,” The VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, January 25-27, 2022.

[23] Silva, C., Johnson, W., Antcliff, K., and Patterson, M., “VTOL Urban Air Mobility Concept Vehicles for Technology Development,” National Aerospace and Space Administration, June 25 2018.

[24] Johnson, W., “NDARC - NASA Design and Analysis of RotorCraft,” 2009.

[25] Johnson, W., "NDARC NASA Design and Analysis of Rotorcraft Theory," 2022.

[26] Bogaisky, J., “Your flying car is finally here,” February 13 2021., URL: https://www.forbesindia.com/article/cross-border/your-flying-car-is-finally-here/66437/1. [retrieved 8 November 2022]

[27] Anonymous, “The roadmap to scalable urban air mobility White paper 2.0,” Volocopter, March 24 2021. [retrieved 8 November 2022]

[28] Nathen, P., “Architectural performance assessment of an electric vertical take-off and landing (e-VTOL) aircraft based on a ducted vectored thrust concept,” April 7 2021. [retrieved 8 November 2022]

[29] Bacchini, A., “Electric VTOL Configurations Comparison,” aerospace, June 26 2019.

[30] Anonymous, “Joby Aviation S4,” eVTOL News, URL: https://evtol.news/joby-s4 [retrieved 8 November 2022]

[31] Anonymous, “Volocopter VoloCity,” eVTOL News, URL: https://evtol.news/volocopter-volocity/ [retrieved 8 November 2022]

[32] Anonymous, “Wisk Aero Cora (Generation 5),” eVTOL News, URL: https://evtol.news/kitty-hawk-cora/ [retrieved 8 November 2022]

[33] Turcksin, T., Bossche, P., Hendrick, P., “Battery weight optimization for hovering aircraft”, EUROPEAN CONFERENCE FOR AERONAUTICS AND AEROSPACE SCIENCES 8th, 2019, doi: 10.13009/EUCASS2019-880.

[34] Johnson, W., “*Rotorcraft Aeromechanics* (Cambridge Aerospace Series),” Cambridge: Cambridge University Press, 2013, doi:10.1017/CBO9781139235655

[35] Choi, S., Kim, J., “Analysis on Aerodynamic Characteristics of the CRW Air-Vehicle,” Korean Society of Computatuonal Fluids Engineering, vol.8, no.4, pp. 26-33, 2003.

[36] Anonymous, “UberAir Vehicle Requirements and Missions,” UberAir, Uber Elevate Summit 2018, May 2018. [retrieved 28 Apr 2023]

[37] Hwang, C., Koo, S., and Choi, S., ”Investigation on a Mission Profile of eVTOL for Urban Air Mobility,” The Korean Society of Aeronautics and Space Science Conference Proceedings, (), 578-579, 2018.

[38] Choi, S., Chang, S., Lee, M., Kim, Y., Koo, S., Kim, J., Kim, D., Oh, S., Kim, S., Ahn, O., Kim, S., Park, M., Kim, J., and Park, J., “Research for Next Generation Aircraft Technology Integration,” Korea Aerospace Research Institute, January 2018. DOI: https://doi.org/10.23000/TRKO201900001616

국문초록

eVTOL 항공기 사이징을 위한 중량 분율 추정

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최근 전기추진 수직이착륙 (eVTOL) 항공기는 친환경적인 새로운 교통수단으로서 가능성이 부각됨과 동시에 그 설계에 대한 많은 관심을 불러일으키고 있다. 본 학위 논문에서는 전기추진 항공기의 특성을 고려하면서도 되도록 기존의 항공기 설계 방법에서 크게 벗어나지 않는 방식이 필요하다.

초기 설계 자료 부족으로 인하여 가장 먼저 겪는 어려움은 크기 설계(sizing) 단계이다. 본 학위 논문은 이 단계에서 배터리 중량 추정을 위한 방법을 제시한다. 한편, 전기추진 특성상 전력 요구량을 추정하는 것이 필요하므로 이를 임무형상에 대하여 각 임무구간 별 요구 마력을 계산하고 이로부터 배터리의 중량을 추정하는 방식을 구성하였다. 이때 요구 마력을 계산하는 방식은 eVTOL 의 비행모드에 식을 달리하여 추정하였다.

이로부터 SNU baseline eVTOL, 네 가지 실존 eVTOL 의 형상, eVTOL 기술실증기에 대하여 본 논문에서 제시하는 방법을 적용하여 추정값과 기존 결과를 비교 및 분석하였다. 각각의 설계 결과를 구성하기 위해서 요구조건 혹은 목표값, 임무형상, 항공기 형상들을 활용하였으며 SNU baseline eVTOL 과 네 가지 실제 eVTOL 형상에 대해 이륙 총중량과 유상하중을 입력으로 하여 배터리와 공허중량을 추정하였다. 이로부터 SNU baseline eVTOL 의 중량추정에 대해서 배터리 중량에 대해 최대 25%의 차이가 발생하는 것을 발견하였다. 마찬가지로 실제 네 가지 eVTOL 형상에 대해서도 최대 약 15%의 배터리 중량 차이가 발생하는 것을 관찰하였다. 같은 방법을 eVTOL 기술실증기에 대해 적용해 배터리 중량을 추정하였다. 배터리 중량을 추정할 때 유상하중이 작은 트윈 틸트로터를 제외하고 20% 이내의 오차가 발생하였다.

이 세 가지 결과를 토대로 SNU baseline eVTOL 및 4 가지 실제 eVTOL 형상, eVTOL 기술실증기에 대해 위의 방법을 적용하였을 때 배터리 중량 추정에 합리적인 추정 결과를 제시함을 확인하였다. 따라서 제안한 방법이 eVTOL 의 배터리 중량을 추정하는데 도움이 될 수 있으며 향후 eVTOL 의 공허중량 경험식을 조사하여 초기 eVTOL 의 사이징 방법 구축하는 데 활용될 수 있다.

핵심어: eVTOL 항공기 사이징, 개념 설계, 중량 추정

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감사의 글

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