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Air taxi flight performance modeling and application

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***Abstract*—Urban air mobility encompasses the idea of extending urban transportation to the airspace. For this purpose, several aircraft manufacturers and start-up companies have developed aircraft concepts for flying completely electrical. Electric aircraft have different behavior concerning flight performance, which mostly depends on battery characteristics. Due to this, electric vertical take-off and landing aircraft (eVTOL) are more limited in their flight performance concerning range and endurance than conventional aircraft. Nowadays data on that topic are mostly published by eVTOL manufacturers and seem to be quite ambitious concerning the current state of battery technology. This paper aims at determining flight performance by considering state-of-the-art battery characteristics. Each flight segment has a different influence on battery discharge, due to different power requirements. Based on an application case, the range capabilities of three eVTOLs are estimated. Therefore, the results reveal a range of around 115 km for vectored thrust eVTOL, around 70 km for lift & cruise eVTOL, and around 50 km for multicopter eVTOL.**

***Keywords*—eVTOL, flight performance, battery characteristics, energy consumption, range estimation**

I. Introduction

A. State of the Art

The development of electric vertical take-off and landing aircraft (eVTOL) innovates the whole aviation sector by challenging it at the same time in terms of safe and secure integration. Lots of different applications are considered to be useful in the future. This consideration also includes the passenger transport performed by eVTOLs, which are bigger than today's small electric unmanned aircraft systems (UAS). The eVTOLs considered in this paper are intended to provide passenger air taxi services from an origin to a destination instead of transporting freight. Therefore, lots of manufacturers have created eVTOLs for passenger transport, which have reached different stages of maturity. The operational parameters range, flight speed, and passenger capacity (incl. hand luggage) are the most relevant ones [1]. Since there are only prototypes, there is a lack of detailed information about network operation capabilities of these new passenger aircraft. This paper delivers a framework to estimate the power requirements for three different eVTOL types in each of the mission flight segments. For each type (vectored thrust, lift & cruise, and multicopter), the total energy consumption is derived from the power requirements per flight segment and transferred into an estimated range. Based on this, specific flight routes in an urban area can be designed in the future for recharging requirements to be considered in network planning exercises.

B. Focus and Structure of the document

As stated before, there is a need to get an overview of the power requirement to create a realistic picture of UAM passenger operation in an urban environment. Therefore, section II introduces a general flight mission profile for eVTOLs before giving a short overview of existing eVTOL types. This section closes with state-of-the-art on characteristics of batteries, which are used for electric propulsion of eVTOLs. Within section III, the methodology of performance modeling is presented. Therefore, this section is divided into the before-mentioned flight segments, which deliver the equations to determine the required power to perform each of them. In section IV, the methodology is applied to the different eVTOLs to show first results on required power per flight segment. At the end of this section, the required power per segment and eVTOL is transferred into energy consumption to compare with predefined values for today's battery characteristics and corresponding flight range of each eVTOL type. Within section V, findings of our power modeling are presented before we give a short outlook on the usage of our results in future research within section VI.

II. Operational Background

A. General UAM flight mission

In the literature, there are different approaches to sketch a general UAM mission profile. According to [2], the flight mission is divided into five segments, namely: take-off, climb, cruise, descent, and landing. As mentioned by the authors, this mission profile is simplified because it does not consider any forward flight during climb and descent, such that there is potential for further investigation in the future. Within [3] and [4], the UAM flight mission is extended by taxi segments before take-off and after landing, as well as transition segments in order to change eVTOL configuration from vertical (take-off and landing) to horizontal flight (cruise flight) and vice versa (see section II-B). The general flight mission is shown in figure 1, which is adapted from [3] and [4]. In the following, the segments are explained in more detail:

Fig. 1: General UAM mission profile

The way from point A to B describes the taxiing from the eVTOL aircraft stand to the touchdown and lift-off (TLOF) at the departure vertiport. There are different ways how eVTOLs can perform this segment: hovering flight, rolling on installed wheels at its landing gear, or via special ground-based infrastructure that can move the eVTOL across the taxiways on a skid undercarriage [4].

After the eVTOL reaches the TLOF, the take-off begins and the eVTOL climbs vertically to a predefined altitude (B to C), where a first transition/conversion is performed (C to D). This segment is needed for a configuration change of the eVTOL. At this point, the eVTOL changes from vertical to horizontal flight configuration. It is important to note that only the vectored thrust and lift & cruise eVTOLs do a transition - multicopters do not (for more details, see section II-B) [4].

From point D to E, the climb segment follows until the desired cruise altitude is achieved. The cruise flight (E to F) within an UAM mission is comparable to the cruise segment of conventional aircraft. In this segment, the altitude should not change, except potential airspace characteristics or clearances by local air traffic control (ATC) require such a change [4].

The segment from F to G describes the descent. In [2], [4] it is assumed that this is done vertically. However, in [3] the descent is not shown as a vertical descent. The descent stops at a certain altitude to perform again a transition (G to H) back from horizontal to vertical flight configuration (if it is assumed like shown in figure 1). Possibly, a short hover holding could be necessary next to get final clearances for landing [4] before a vertical landing (H to I) is performed. After that, again a taxi segment is assumed to get from the TLOF pad at arrival vertiport (I) and/or to the corresponding eVTOL aircraft stand (J).

B. *eVTOL aircraft concepts*

There are more than 400 aircraft concepts that intend to take-off and land vertically with pure electric propulsion, but not every eVTOL listed in [5] is considered as an air taxi (e.g., hover bikes). The basic assumption is that taxi services should consider at least a capacity of two passengers (two seats), well knowing that one of them is occupied by a pilot on board at the beginning of operation due to VFR. The classification of eVTOLs by [5] is focused on the propulsion system and specifies the one made in [1], which is based on lift production especially during cruise flight. According to both of them, the following eVTOL categories can be summarized (see table I).

Propulsion system [5]	**Cruise lift production [1]**
vectored thrust	fixed-wing
lift & cruise	fixed-wing
multicoper	rotary-wing

TABLE I: eVTOL aircraft classification

The used electric propulsion system for eVTOL is called distributed electric propulsion (DEP) technology, where multiple electrical units are distributed along the eVTOL and powered by several electric motors directly, which get their power from one or more battery packs [6].

eVTOLs with vectored thrust propulsion use any of their electric engines for both take-off and cruise. Such eVTOLs have tilting elements (wings or only propulsion units) to adjust the propulsion vector to the desired direction (vertical for VTOL and horizontal for cruise). The difference between the two configurations is shown in figures 2 (vertical configuration) and 3 (cruise configuration).

Fig. 2: Vectored thrust vertical configuration [7]

Fig. 3: Vectored thrust cruise configuration [8]

In comparison to vectored thrust configurations, lift and cruise eVTOLs have independent propulsion units (one each for VTOL and cruise) without any vectoring. An example is given by figure 4:

- the first propulsion unit for the fixed propellers along the wings, which are responsible for lift generation during vertical segments, and
- a second one for the pusher propeller in the rear of the eVTOL, which is for cruise flight.

Due to that, the vertical behavior is expected to be more efficient in comparison to the vectored thrust concepts. In the end, both concepts behave like fixed-wing aircraft during cruise and rely on aerodynamic lift.

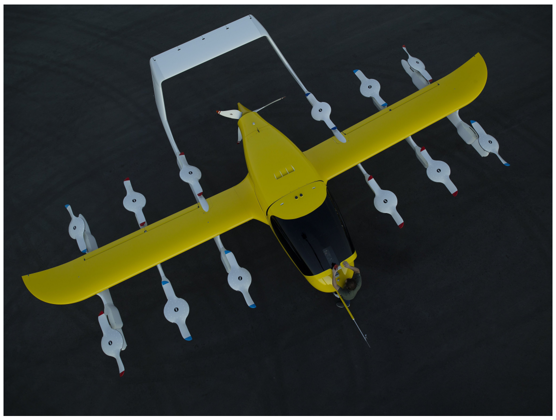

Fig. 4: Lift and cruise air taxi [9]

The last eVTOL class mentioned in table I is the multicopter. This eVTOL class is comparable to conventional helicopters in terms of flight behavior, except for the missing tail rotor and multiple horizontally mounted rotors hampering lower aerodynamic efficiency for the sake of safety and maneuverability (see figure 5). This is resulting in a high drag such as flight efficiency during vertical segments, but in a consequently very limited range when cruise.

Fig. 5: Multicopter air taxi [10]

C. Battery characteristics

Battery technology has already been implemented in other transport segments. The car industry has presented various electric cars over the last years which are limited in their range between 120 km and 500 km (depending on the type of car) due to lower specific energy (amount of energy per unit weight) compared to fossil fuels [11]. For electric aviation and especially for UAM, the operational parameter range is one of the most relevant ones [1], relying on current battery technology. Especially energy density is a crucial factor; lithium-ion batteries reach a value of up to 260 Wh/kg [12].

III. Power Requirements

Within this section, the methodology for the power modeling of eVTOLs is presented. The focus of our work concentrates on unducted lift propellers as it is the case for the previous presented eVTOLs in section II-B. Therefore, the equations are delivered per flight segment.

A. Taxi

As mentioned in section II-A, there are several possibilities to perform taxiing with eVTOLs. In this section, the equations to perform a ground taxi (P_{gt}) segment on own wheels and as a hovering flight (P_{ht}) are formulated. According to [4], the ground taxi on own wheels requires around 10% of cruise flight power P_{cruise} (1).

$$P_{gt} = 0.1 \cdot P_{\text{cruise}} \tag{1}$$

The requested power to hover taxi P_{ht} is assumed to be equal to the power to hover P_h, well knowing that this is a simplification since there is no forward flight in a nominal hovering flight. P_h is the product of thrust T and the velocity v_h at the rotor disc according to [13]. In hovering flight, the thrust T is equal to the eVTOL's weight W. Besides, the power for hovering flight also depends on the disc loading (DL (2)), which is an important parameter for comparing eVTOLs. It is defined as the ratio between eVTOL weight and its total disc area (A). n_{rotor} describes the number of rotors and r_{rotor} is the radius of every rotor.

$$DL = \frac{W}{A} = \frac{m \cdot g}{n_{\text{rotor}} \cdot 2\pi r_{\text{rotor}}^2} \tag{2}$$

With the DL, the air density ρ, and the eVTOL's weight W the equation for a hovering flight can be written as (3):

$$P_{ht} = P_h = T \cdot v_h = T \cdot \sqrt{\frac{T}{2\rho A}} = W \cdot \sqrt{\frac{DL}{2\rho}} \tag{3}$$

(3) does not consider the loss of power due to profile drag of the rotor blades. Therefore, a hover efficiency term η_h is introduced and the required power P_{ht} finally becomes:

$$P_{ht} = \frac{W}{\eta_{\text{hover}}} \cdot \sqrt{\frac{DL}{2\rho}} \tag{4}$$

The air density ρ is considered at mean sea level (MSL).

B. Vertical climb (take-off)

After reaching the TLOF, the following take-off is performed as a vertical climb to the transition altitude. The required power P_{to} for this segment is estimated from helicopters theory [13] (5).

$$P_{to} = P_h \cdot \left[\frac{RoC_{to}}{v_h} + \frac{v_i}{v_h}\right] \tag{5}$$

The required power for take-off depends on the power to hover P_h, the RoC for the vertical climb, the hover velocity v_h, and the induced velocity v_i in the climb at the rotor disk plane. During hovering flight, the velocity terms are equal [14]. According to [13], it is possible to define a ratio between them during the vertical climb (6).

$$\frac{v_i}{v_h} = -\left(\frac{RoC_{to}}{2v_h}\right) + \sqrt{\left(\frac{RoC_{to}}{2v_h}\right)^2 + 1} \tag{6}$$

Substituting (6) into (5) the required power for vertical take-off P_{to} is finally delivered in (7).

$$P_{to} = P_h \cdot \left[\frac{RoC_{to}}{2v_h} + \sqrt{\left(\frac{RoC_{to}}{2v_h}\right)^2 + 1}\right] \tag{7}$$

C. Transition

The next segment is the transition, which is only performed by vectored thrust and lift & cruise eVTOLs due to their configuration change from vertical to horizontal flight. Within this segment, stability has to be preserved while avoiding any loss of altitude [15]. Generally, the power required for the transition segment is the sum of several power terms, which are defined in (8).

$$P_{trans} = P_{\text{induced}} + P_{\text{drag, rotor}} + P_{\text{drag, aircraft}} \tag{8}$$

The first power term is the induced power P_{induced} during the transition, which considers the tilt configuration by its tilt angle (Θ_{tilt}), propulsive efficiency (η_{trans}, and the induced velocity at rotor disc plane ((9) according to [15]).

$$\begin{aligned} P_{induced} &= \frac{W}{\eta_{\text{trans}} \cdot sin(\Theta_{\text{tilt}})} \\ &\cdot \sqrt{-\frac{V_\infty^2}{2} + \sqrt{\left(\frac{V_\infty^2}{2}\right)^2 + \left(\frac{W}{sin(\Theta_{\text{tilt}}) \cdot 2\rho A}\right)^2}} \end{aligned} \tag{9}$$

The second power term $P_{\text{drag, rotor}}$ describes the power required to overcome the rotor profile drag, which depends on rotor geometry (solidity σ), rotor blade drag (C_d) and blade tip speed (V_{tip}). The solidity parameter σ is defined as ratio between blade area and rotor disc area (10), with chord c, N number of blades per rotor and r_{rotor} radius of a single rotor. σ is the value for one rotor. To get the total value (necessary for calculating $P_{\text{drag, rotor}}$), it has to be multiplied by the number of rotors n of the eVTOL, which are used for vertical lift production.

$$\sigma = \frac{\text{blade area}}{\text{rotor disc area}} = \frac{N \cdot c \cdot r_{\text{rotor}}}{\pi \cdot r_{\text{rotor}}^2} \cdot n = \frac{N \cdot c}{\pi \cdot r_{\text{rotor}}} \cdot n \tag{10}$$

The parameter μ is the non-dimensional velocity at rotor disc plane and defined by equation 11, where V_∞ corresponds to the velocity the eVTOL is expected to gain after transition (V_{climb}, climb out speed; see section III-D). The angle used in equation 11 describes the angle between the free stream velocity and the velocity at the rotor disc V_{tip}. Because of the tilt mechanism of the rotors at the vectored thrust eVTOL, the angle is corresponds to the tilt angle Θ_{tilt}.

$$\mu = \frac{V_\infty \cdot cos(\Theta_{\text{tilt}})}{V_{\text{tip}}} \tag{11}$$

Finally, the power required to overcome the rotor profile drag is delivered in (12) according to [15].

$$P_{\text{drag, rotor}} = \rho A V_{\text{tip}}^3 \cdot \left(\frac{\sigma C_d}{8} \cdot (1 + 4.6\mu^2)\right) \tag{12}$$

The last power term of (8) is the power to overcome the aircraft drag ($P_{\text{drag, aircraft}}$) as it gains speed during the transition phase. It is defined in (13) by multiplication of aerodynamic drag and the expected velocity after transition V_∞ (which also corresponds to later climb out speed V_{climb}).

$$P_{drag,aircraft} = 0.5 \rho V_\infty^3 C_D S \tag{13}$$

For lift & cruise eVTOL, no tilt angle can be defined due to two different propulsion systems - one for vertical and one for horizontal flight segments (no tilting mechanism). Following this, Θ_{tilt} is not considered in (9) and the ratio between free stream velocity V_∞ and velocity at rotor disc V_{tip} (μ, (11)) cannot be computed because the propulsion system for the horizontal flight starts to push the eVTOL during the transition while the vertical lift propulsion system reduces its contribution. However, for simplification reason and to use (12) also for required transition power of lift & cruise eVTOL, μ is set to zero.

The multicopter does not have this flight segment, such that an instant passage between both flight segments (take-off to climb) is assumed, similar to helicopter operations.

D. Climb to cruise altitude

The transition is followed by the climb segment, which ends after reaching the cruise altitude. We assume that the eVTOLs perform this segment with a constant RoC. It is the product of climb angle γ_{climb} and the climb out speed V_{climb} (horizontal climb speed), shown in (14).

$$RoC_{cl} = V_{\text{climb}} \cdot sin(\gamma_{\text{climb}}) \tag{14}$$

The required power within this segment can be simplified by (15).

$$\begin{aligned} P_{climb} = \frac{T \cdot V_{\text{climb}}}{\eta_{\text{climb}}} &= \frac{V_{\text{climb}}}{\eta_{\text{climb}}} \cdot (m \cdot g \cdot sin(\gamma) + D) \\ &= \frac{W}{\eta_{\text{climb}}}\left(RoC_{cl} + \frac{V_{\text{climb}}}{\left(\frac{L}{D}\right)_{\text{climb}}}\right) \end{aligned} \tag{15}$$

In general, it is the product of thrust produced by the eVTOL and the climb out speed, divided by the propulsive efficiency (η_{climb}). Thrust is approximately resolved into opposing drag force and eVTOL weight, dependent on the climb angle γ_{climb}. By assuming a small climb angle, the weight is considered to be approximately equal to lift. Then, drag force can be found by dividing weight by $(L/D)_{\text{climb}}$.

E. Cruise and descent

After reaching the cruise altitude, the cruise segment begins. It is expected to be the longest segment in terms of time spent and achieved range/ distance. The required power in this segment P_{cruise} is estimated by using a force balance between lift and eVTOL weight, where the drag is considered equal to thrust provided by the propulsion system (16).

$$P_{\text{cruise}} = \frac{T \cdot V_{\text{cruise}}}{\eta_{\text{cruise}}} = \frac{W \cdot V_{\text{cruise}}}{\left(\frac{L}{D}\right)_{\text{cruise}} \cdot \eta_{\text{cruise}}} \tag{16}$$

Within this segment, the aerodynamic efficiency of fixed-wing eVTOLs is higher than for multicopter. This leads to minor power consumption.

For simplification reasons, we consider that the cruise segment also includes the descent phase until the second transition starts. This is for reasons that there are no precise data available about the descent segment. Therefore, following [15], the cruise segment is extended and the cruise performance is assumed for the whole duration.

F. Second Transition and Holding

For the second transition, the same approach is used as in section III-C. We assume that the eVTOL reduces its speed to the end of the cruise segment, starting the descent segment with the same characteristics as the climb. Therefore, the deceleration phase is neglected and this segment is performed as the previous one (8), with v_∞ equal to descent velocity V_{d}. This results in the equation to estimate the required power for the second transition ($P_{\text{trans,2}}$):

$$\begin{aligned} P_{\text{trans,2}} = {} & \frac{W}{\eta_{\text{trans}} \cdot sin(\Theta_{\text{tilt}})} \\ & \cdot \sqrt{-\frac{V_d^2}{2} + \sqrt{\left(\frac{V_d^2}{2}\right)^2 + \left(\frac{W}{sin(\Theta_{\text{tilt}}) \cdot 2\rho A}\right)^2}} \\ & + \rho A V_{\text{tip}}^3 \cdot \left(\frac{\sigma C_d}{8} \cdot (1 + 4.6\mu^2)\right) \\ & + 0.5 \rho V_d^3 C_D S \end{aligned} \tag{17}$$

For lift & cruise, the same assumption is used as in section III-C while multicopters do not have to perform this second transition. As mentioned in subsection II-A, the second transition could be followed by a holding phase, which is performed by hovering flight (4).

G. Vertical Descent and landing

After the eVTOL is cleared for landing, the vertical descent can start. Therefore, the eVTOLs use their lift propulsion system, where the estimated power for vertical descent (P_{vd}) has the same definition as the one for the vertical climb (see equation 18), where instead of the RoC the rate of descent (RoD) is used.

$$P_{\text{vd}} = P_h \cdot \left[\frac{RoD_{\text{ld}}}{v_h} + \frac{v_i}{v_h}\right] \tag{18}$$

The only numerical difference is that RoD is negative because of the downward moving of the eVTOL while thrust is orientated upwards. Another difference is the definition of the ratio between induced and hover velocity (19) [16].

$$\frac{v_i}{v_h} = -\left(\frac{RoD_{\text{ld}}}{2v_h}\right) - \sqrt{\left(\frac{RoD_{\text{ld}}}{2v_h}\right)^2 - 1} \tag{19}$$

It is noted that the argument under the square root must not be negative. Following this, (19) only is valid when:

$$|RoD_{ld}| \geq 2v_h \tag{20}$$

The flight region of $-2 \leq RoD \leq 0$ describes the vortex ring state, where the flow is turbulent having upward and downward velocities [16]. To overcome this issue, it is used an experimental approach by [17]. The corresponding approximation of the velocity is shown in (21):

$$\frac{v_i}{v_h} = k + \sum_{i=1}^{4} k_i \left(\frac{RoD}{v_h}\right)^i \tag{21}$$

with $k = 0.974, k_1 = -1.125, k_2 = -1.372, k_3 = -1.718,$ and $k_4 = -0.655$.

H. Energy consumption and range estimation

After defining the power demand for each flight segment, it is possible to obtain the demand for energy from the battery pack in each flight segment. Therefore, it is necessary to know how much time the eVTOLs spend in these segments because the energy demand of each segment E_i is defined as the product of corresponding power P_i and time t_i (22).

$$E_i = P_i \cdot t_i \tag{22}$$

If n is the number of segments, the total energy consumed E_{tot} is the sum of all energy terms (shown in (23)). Finally, it must be checked that the total energy consumed is less than the total battery energy (see section IV-A).

$$E_{\text{tot}} = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} P_i \cdot t_i \tag{23}$$

When the energy demand for each segment is calculated, it is possible to estimate a corresponding flight range according to [18]. In general, the range R can be defined as the product of horizontal flight speed v_∞ and flight time t (24):

$$R = v_\infty \cdot t \tag{24}$$

For electric aircraft, the flight time is equal to the time to drain the battery, which depends on energy density E^*, the mass of the battery m_{battery}, and the power supplied by it P_{battery} (25).

$$t = \frac{m_{\text{battery}} \cdot E^*}{P_{\text{battery}}} \tag{25}$$

Substituting (25) into (24) yields:

$$R = v_\infty \cdot \frac{m_{\text{battery}} \cdot E^*}{P_{\text{battery}}}. \tag{26}$$

The released power of the battery depends on the required propulsive power of the eVTOL P_{aircraft} in cruise flight (forward flight):

$$P_{\text{battery}} = \frac{P_{\text{aircraft}}}{\eta_{\text{tot}}}, \tag{27}$$

where the P_{aircraft} is linked to its weight, lift over drag ratio and horizontal flight speed:

$$P_{\text{aircraft}} = D_{\text{aircraft}} \cdot v_\infty = \frac{m \cdot g}{\left(\frac{L}{D}\right)} \cdot v_\infty \tag{28}$$

By substituting (28) into (27), P_{battery} becomes:

$$P_{\text{battery}} = \frac{m \cdot g}{\left(\frac{L}{D}\right) \cdot \eta_{tot}} \cdot v_\infty \tag{29}$$

and can be inserted into (26):

$$R = v_\infty \cdot \frac{m_{\text{battery}} \cdot E^*}{\frac{m \cdot g}{\left(\frac{L}{D}\right) \cdot \eta_{tot}} \cdot v_\infty}. \tag{30}$$

The simplification of (30) delivers the range equation for electric flight of battery powered aircraft (31):

$$R = E^* \cdot \eta_{\text{tot}} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{\text{battery}}}{m_{\text{aircraft}}}. \tag{31}$$

IV. Model Application

In this section, the previously presented equations are used to obtain appropriate results for the required power per flight mission segment. Therefore, parameters and values are assumed for the presented eVTOL types. For vectored thrust eVTOL Joby S4 (see figures 2 and 3) is considered, for lift & cruise the Wisk Cora (former Kitty Hawk, see figure 4), and, finally, the VoloCity for multicopters (see figure 5). Besides, appropriate data about battery characteristics are chosen in accordance to section II-C. The corresponding values are summarised in table II based on scientific literature or made by assumptions (see section IV-A).

A. Initial assumptions

The maximum take-off mass ($MTOM$) of the presented eVTOLs is adopted from manufacturers data [7] [10] [19]. The corresponding battery mass is measured in accordance with [20], where a battery mass ratio of 0.33 is suggested. This value is confirmed by [21]. The payload corresponds to the passenger capacity (number of seats). Therefore, it assumed by 100 kg per seat (passenger incl. hand luggage).

Finding suitable values for both specific energy and specific power is quite challenging due to various lithium batteries for different applications. The battery characteristics should consider the expected higher peak power demand during vertical segments of vectored thrust eVTOLs, whereas lift & cruise and multicopter are expected to require more power during horizontal segments. Following this, the corresponding values of specific energy (E^*) and specific power (P^*) are chosen according to [2] and [22] by considering state-of-the-art battery characteristics (mentioned in section II-C). The total values for energy and power are found by multiplying corresponding specific values with battery mass. It should be noted that the usable power (P_{use}) and energy (E_{use}) are lower compared to total values (P and E) because of the battery efficiency $\eta_{battery}$ (due to heating losses; estimated by 0.95) and the depth of discharge (DoD), necessary to preserve a certain lifetime of the battery [23]. Especially for longevity, the DoD represents a key factor, namely the part of the battery capacity which has been removed from the fully charged battery. To preserve a certain lifetime, the DoD for current Li-ion batteries is suggested by 80% [24], so that there is a remaining battery capacity (state of charge, SoC) of 20%. Due to safety reasons, UBER [3] defines the minimum reserve by a remaining SoC of 30%, as it is shown in figure 6 (line 3). In nominal operating conditions, this minimum reserve SoC should not drop below this level, whereas it is only allowed to operate in this condition during a contingency mission. However, also in contingency missions, the SoC of the battery has to remain above the battery floor (line 4 in figure 6) as it is a very unsafe battery condition due to suddenly occurring loss of battery capacity [3]. To complete figure 6, Line 2 describes a minimum SoC for an additional take-off/flight and line 1 is the maximum SoC of the battery, which is decreasing during operation.

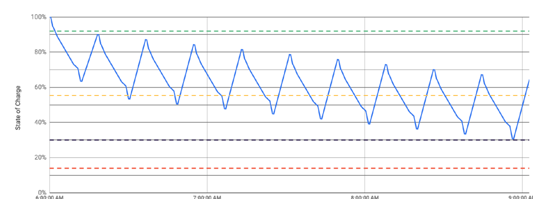

Fig. 6: State of charge overview

For our application, we choose the DoD according to [24] by 80%. To conclude, the P_{use} and E_{use} is then computed by using (32) and (33).

$$P_{\text{use}} = P^* \cdot m_{\text{battery}} \cdot \eta_{\text{battery}} \cdot DoD \tag{32}$$

$$E_{\text{use}} = E^* \cdot m_{\text{battery}} \cdot \eta_{\text{battery}} \cdot DoD \tag{33}$$

As already shown in section III, there are several efficiency values per flight segment. These values represent additional power requirements due to losses of the propulsion system of the eVTOLs compared to ideal conditions. During hovering flight, the multicopter has the best efficiency (η_{hover}) due to its helicopter-like configuration (assumed at 0.80) [2]. Contrary to this, the efficiency during the cruise (η_{cruise}) is the lowest one compared to the other eVTOLs (assumed at 0.60). The reason for this is the lift production during the cruise segment (see table I) and therefore the associated higher performance effort for multicopters. η_{hover} for lift & cruise eVTOL is assumed higher (0.75) than for vectored thrust eVTOL (0.70) because of its independent propulsion system for vertical segments (DEP, see section II-B). It is the same reason for a better transition efficiency (η_{trans}) value of the lift & cruise eVTOL (0.70) in comparison to vectored thrust (0.65). During the cruise, the vectored thrust eVTOL is assumed to be most efficient with η_{cruise} at 0.80. The last one describes the efficiency during the climb (η_{climb}) and is considered to be the mean value between η_{hover} and η_{cruise}.

Concerning the aerodynamic parameters, the values for lift-drag-ratios during cruise and climb ($(L/D)_{\text{climb}}$ and $(L/D)_{\text{cruise}}$) are taken from [2] and [24], in which calculations based on geometric characteristics of eVTOLs were performed in order to estimate the drag coefficient C_D of the eVTOLs. The blade drag coefficient C_d is considered equal for all eVTOLs and a typical one for helicopters according to [13].

The blade tip speed M_{tip} has an influence on the acoustic footprint of the eVTOLs induced by the rotors. In [25], a maximum value of 0.60 is mentioned, such that we assume a slightly smaller one. The cruise speed v_{cruise} is based on manufacturers data [7] [10] [19]. Therefore, it is chosen at 80% of the proposed maximum cruise speed as a kind of econ reference speed.

The parameters linked to the vertical segments are chosen as follows: the rate of climb during climb segment (RoC_{cl}) corresponds to typical values in general aviation [25] and are also expected for the rate of descent in the descent segment (RoD_{desc}), only with a negative sign. The vertical RoC and RoD during take-off and landing (ROC_{to} and RoD_{ld}) are chosen according to user comfort [4]. The tilt angle Θ_{tilt} is defined as the rotation of lift propellers to pass from vertical to climb configuration. It is only considered for those eVTOLs which have to perform the transition segment.

Finally, there are reported parameters related to rotor geometry and corresponding lift area [24]. From the DL, it is observable which eVTOL is more efficient in hovering flight due to low values. For higher DL values, it is required more power for hovering and vertical segments.

Within the next subsections, the previously described approach (see section III) to define the power required from the batteries in each flight segment is presented. The results are shown in table III and V. It is noted that the presented equation concerning power consumption is only valid for unducted rotors, as it is the case for the previously described eVTOL in section II-B.

Parameter	Vect. Thrust	Lift & Cruise	Multicopter
$MTOM$ [kg]	2,200	1,200	900
$Payload$ [kg]	400	200	200
m_{battery} [kg]	730	400	300
$\frac{m_{\text{battery}}}{MTOM}$ [-]	0.33	0.33	0.33
E^* [Wh/kg]	150	180	180
E [kWh]	109	72	54
P^* [W/kg]	2,100	1,600	1,100
P [kW]	1,533	640	330
η_{battery} [-]	0.95	0.95	0.95
DoD [-]	0.8	0.8	0.8
E_{use} [kWh]	83	55	41
P_{use} [kW]	1,165	486	251
η_{hover} [-]	0.70	0.75	0.80
η_{cruise} [-]	0.80	0.70	0.60
η_{trans} [-]	0.65	0.70	-
η_{climb} [-]	0.75	0.73	0.70
$(\frac{L}{D})_{\text{climb}}$ [-]	15	12	3
$(\frac{L}{D})_{\text{cruise}}$ [-]	16	13	4
C_D [-]	0.039	0.061	0.098
C_d [-]	0.015	0.015	0.015
M_{tip} [-]	0.55	0.55	0.55
v_{cruise} [m/s]	72	40	24
γ_{climb} [°]	8	8	8
α [°]	8	8	8
RoC_{to} [m/s]	0.5	0.5	0.5
RoC_{cl} [m/s]	4.5	4.5	4.5
RoD_{ld} [m/s]	-0.5	-0.5	-0.5
RoD_{desc} [m/s]	-4.5	-4.5	-4.5
θ_{tilt} [°]	82	-	-
n [-]	6	12	18
d_{rotor} [m]	1.3	1.0	2.3
A [m²]	8.0	9.4	74.8
S [m²]	11	11	-
N [-]	5	2	2
c [m]	0.3	0.2	0.1

TABLE II: Listed parameters for calculation

B. Power calculation

As described in subsection III-A, the taxiing could be performed differently by each eVTOL. To make it more comparable, we assume that the first taxi segment is performed by a hovering flight (4) and the second one on a potential installed landing gear (1). Due to the high DL of the vectored thrust and lift & cruise eVTOLs, the required power for a hovering taxi flight is much higher than for multicopters.

The required power for the vertical take-off is computed by using (7). It is depending on the previous calculated P_{ht} (which is assumed equal to the power for hovering flight P_h), the RoC, and the corresponding v_h. v_h is taken out of (3).

The results for the first transition are based on (8). It is noted that only vectored thrust and lift & cruise eVTOLs have to perform the transition before the climb to cruise altitude may start. As mentioned in section III-F, the same approach is used for the second transition. Therefore, the values are equal and we do not consider an additional holding.

The power required to perform the climb to cruise altitude is determined by using (15).

As stated in subsection III-E, we assume that the descent segment is included until the second transition begins. Therefore, the values are obtained by using (16).

The results of vertical descent and landing are based on (18) and (21), because RoD_{ld} is assumed at -0.5 and therefore in between the region of vortex ring state ($-2 \leq RoD \leq 0$).

C. Calculation of energy consumption

To compute the energy consumption per flight segment, it is necessary to define the period each eVTOL spends in each segment (22). These times t_i are assumed and listed in table IV. Altogether, the whole flight mission is assumed by 1,800 seconds. This results in an energy consumption per flight segment and total energy for the whole mission as presented in table V.

Segment	Vect. Thrust	Lift & Cruise	Multicopter
1st taxi	725.07	250.60	54.17
Take-off	732.82	254.55	57.00
1st transition	1,431.09	688.71	-
Climb	191.51	116.01	192.68
Cruise & descent	121.40	51.75	88.29
2nd transition	1,431.09	688.71	-
Landing	708.43	248.48	52.78
2nd taxi	12.14	5.18	8.83

TABLE III: Calculated required power per flight segment [kW]

Segment	time t_i
1st taxi	30
Take-off	45
1st transition	45
Climb	60
Cruise & descent	1500
2nd transition	45
Landing	45
2nd taxi	30
$\sum$	1,800

TABLE IV: Time spent in each flight segment [s]

Considering that multicopters do not perform the transition segment, the following assumptions are made:

- The time for the first transition is included in the climb segment. Therefore, the climb segment for the multicopter has a duration of 105 seconds.
- The time for the second transition is included in the cruise and descent segment, which results in a duration of 1,545 seconds.

Segment	Vect. Thrust	Lift & Cruise	Multicopter
1st taxi	6.02	2.08	0.45
Take-off	9.16	3.18	0.71
1st transition	17.89	8.61	-
Climb	3.20	1.94	5.63
Cruise & descent	50.59	21.56	37.89
2nd transition	17.89	8.61	-
Landing	8.86	3.11	0.66
2nd taxi	0.10	0.04	0.07
$\sum$	113.71	49.13	45.41

TABLE V: Energy consumption per flight segment [kWh]

D. Range estimation

In this subsection, (31) is used to estimate the range R of each eVTOL. According to [18], the total efficiency η_{total} is expressed as the product of several efficiency terms (batteries, electric motors, electronic controllers, gearbox, and propellers). In nominal conditions, η_{total} could reach a value of about 0.7 [18]. To make it more realistic, in our application η_{total} is considered by 0.65.

To estimate the range dependent on the calculated energy consumption, it is necessary to get a corresponding energy density value for the cruise and descent segment (E^*_{cruise}). This is done by modifying (33) with E_{use} taken from table V for cruise and descent energy consumption, m_{battery} listed in table II, $\eta_{\text{battery}} = 0.95$, and $DoD = 0.8$. The results for energy density based on the results of the energy consumption (see section IV-C) are shown in table VI.

	Vect. Thrust	Lift & Cruise	Multicopter
E^*_{cruise}	91.19	70.92	166.18
R	114.85	72.57	52.32

TABLE VI: Energy densities corresponding to computed cruise and descent energy consumption [Wh/kg] and corresponding range [km]

V. Findings

A. Power calculation

Compared to vectored thrust and lift & cruise eVTOLs, it is noted that the multicopter has the lowest power requirement for a hovering taxi flight due to its helicopter-like configuration. For the following take-off, the required power increases of about one to 1.5% (vectored thrust and lift & cruise), whereas the multicopters required take-off power P_{to} has an increase of around 5.2%. Within the transition segment, the required power for vectored thrust and lift & cruise eVTOLs is higher than the assumed usable power value P_{use} provided by the battery. For lift & cruise eVTOL, the required transition power P_{trans} is also higher than the corresponding maximum power value P, whereas at least this value would fit for vectored thrust eVTOL resulting in a higher DoD (more than 80%) by falling below the SoC for reserve (see table VII).

These results show that assumed specific power P^* for vectored thrust and lift & cruise eVTOLs is chosen too low. Therefore, both eVTOLs would not be able to perform the transition (peak power demanding segment) with E_{use} in our application. The required power for vectored thrust eVTOL in transition is 22.8% higher than the usable power from the battery. For lift & cruise eVTOL, it is even 41.7% higher in this segment. At least this expresses the assumption that this segment is the most power-consuming one for eVTOLs, which have to perform this. Contrary to that, the assumed specific power for the multicopter has a remaining power potential in the climb segment (peak power demanding for multicopter) of about 23% (see table VII).

For the climb, the calculation results show that the vectored thrust eVTOL requires the lowest power from its battery. In cruise and descent, the multicopter requires about one-third of its usable power, whereas the other two eVTOLs only need 10%. This is due to their fixed wings and the corresponding behavior like a normal passenger aircraft (resulting in a much better lift to drag ratio compared to multicopter). The required power for vertical landing is quite similar to those of vertical take-off.

The last segments are the taxi segments. In our application case, there are two different possibilities to perform these. The first taxi segment is modeled by hovering flight, which is close to the values of vertical take-off as already mentioned at the beginning of this subsection. Then, the second taxi segment is assumed to be performed on the eVTOLs own landing gear (wheels), which requires significantly less power.

At this point, it has to be noted that normally, the influence of the altitude is given by the air density ρ within the presented equations in section III. For our application, the influence of

Segment	Vect. Thrust	Lift & Cruise	Multicopter
1st taxi	62.2	51.6	21.6
Take-off	62.9	52.4	22.7
1st transition	122.8	141.7	-
Climb	16.4	23.9	76.8
Cruise & descent	10.4	10.6	35.2
2nd transition	122.8	141.7	-
Landing	60.8	51.1	21.1
2nd taxi	1.0	1.1	3.5

TABLE VII: Required power per segment compared to P_{use} [%]

the altitude is fully neglected by calculating with ρ equal to ISA conditions on MSL. Determining the altitude for UAM passenger operations is challenging due to other existing air traffic (e.g. arrivals and departures from conventional aircraft, general aviation, helicopters, gliders) and also depending on the prospected topography concerning obstacles.

B. Energy consumption

From table V, the results of the energy consumption for our assumed mission can be obtained. These values have to be compared to the usable energy E_{use} (see table II). From an energetic point of view, the lift & cruise eVTOL is the only one that could perform the assumed mission. It is noted that there is a remaining energy capacity of 11% (see table VIII). Both other eVTOLs would not be able to perform this mission: the vectored thrust eVTOL requires 37% more energy in comparison to its E_{use} and even 4.3% more when compared to its maximum energy E provided by the battery. The multicopter also requires 11% more energy for the whole mission by comparing to E_{use}. However, at least it would be able to perform the assumed flight mission with maximum energy E provided by its battery. For this case, the multicopter would have a remaining energy capacity of around 16%.

	Vect. Thrust	Lift & Cruise	Multicopter
E_{use} [kWh]	83	55	41
$E_{mission}$ [kWh]	113.71	49.13	45.41
Perc. difference	+37%	-11%	+11%

TABLE VIII: Required energy for flight mission compared to E_{use}

C. Range estimation

The calculated range R to the assumed flight mission is based on the corresponding energy density E^*_{cruise}. It has to be noted that this corresponds only to a theoretical range since there are issues concerning the assumed values for specific power and energy density of each eVTOL. That is the reason why none of the presented eVTOLs would be able to reach this range. Besides, the results in table VI also include the descent phase in our application. When the range is only to be considered for the cruise phase, the range would be decreasing.

Based on (31), it can be observed that the range is almost independent of horizontal flight speed v_∞ (affects the range only indirectly via lift to drag ratio). For reaching a higher range, the following parameters should be maximized:

- battery mass ratio (corresponds to an increasing battery mass while not increasing the MTOM of the eVTOL),
- energy density (also depending on battery mass),
- lift over drag ratio (for better aerodynamic resulting in less power/energy consumption), and
- total system efficiency (from the battery to propulsive power).

Besides, it has to be mentioned that the influence of the temperature on the range is not considered within our application, but we assume that there should be an influence on it by temperature because it is affecting the battery.

VI. Conclusion

Within this paper, we presented a simplified approach to determine the flight performance of three different eVTOLs, which are considered to be suitable for air taxi operations in urban areas. Based on this, we used a set of parameters to demonstrate the methodology using state-of-the-art battery parameters. The application shows that these battery parameters (specific power and energy density) are not sufficient in any case due to the limited battery mass. That is the reason why there is a need of higher energy densities especially for aviation application by keeping the mass of the battery constant. In [26] it is predicted that rechargeable Lithium batteries with an energy density up to 450 Wh/kg will be produced by around 2025 (shown in figure 7).

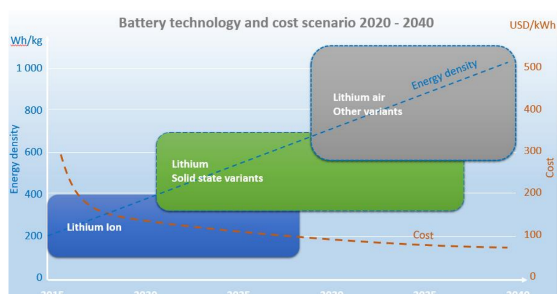

Fig. 7: Battery Development [26]

When these values can be used for aviation applications, usable energy values will be more than doubled (by assuming a constant battery mass; see table IX). The predicted range capabilities are calculated based on $E_{\text{use, 2025}}$ values in 2025. The required energy demand is estimated by the ratio of today's energy consumption in cruise flight and the total energy consumption of the whole flight mission for each eVTOL (see table V). The resulting values have been converted into energy densities by using (33) and finally inserted into (31) for delivering the predicted range capabilities in 2025 (by assuming constant battery masses and efficiency values). Therefore, higher ranges or/and increased flight frequencies (more flights on a single battery charge) are assumed in the future. Based on our values concerning battery technology, it can be stated that the value of specific power affects and limits the vertical segments performing capability because these are

	Vect. Thrust	Lift & Cruise	Multicopter
$E_{\text{use, today}}$ [kWh]	83	55	41
R_{today} [km]	115	73	52
$E_{\text{use,2025}}$ [kWh]	250	137	103
R_{2025} [km]	261	194	118

TABLE IX: Usable energy today and in the future and corresponding ranges

the peak power demanding phases (see table III), while energy density will influence the achievable range (31).

For today, the obtained results will be used in further research concerning network design for UAM operation. The results of the range estimation for vectored thrust eVTOL seem to be more realistic than the corresponding manufacturer's data (see [7]). The lift & cruise eVTOL and the multicopter have higher ranges in our application than the corresponding value published by manufacturer (see [10] and [19]). Nevertheless, from an operational point of view, the results can contribute to an improved image of passenger air taxi services in urban areas within the framework of UAM due to the shown dependency on battery characteristics.

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