Maximum total range of eVTOL under consideration of realistic operational scenarios

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Abstract— **The growing scientific and economic interest in electric vertical take-off and landing vehicles (eVTOLs) has led to a large variety of different technological configurations with partly very different information on the maximum flying range promoted by manufacturers. But as physical equations regarding the potential performance are discussed in literature already, it remains unclear to what scale realistic operational scenarios impact total range and which battery capacities are needed in the future to conduct safe and efficient flights for commercial purposes. Therefore, we use a novel evaluation approach that combines the results from model-specific energy-consumption equations with operational and external constraints, such as hover time due to traffic management procedures and regional weather conditions. Our calculations are based on publicly available information and expert reviewed assumptions on key parameter for the efficiency of multicopter, lift & cruise, tilt-rotors and vectored thrust eVTOL architectures, and the utilization of the extended Breguet's range equation. Furthermore, a sensitivity analysis is performed to determine the most influential factors in realistic scenarios. With a 10 min. hover phase e.g., a contingency procedure, the range can be reduced by up to 75% depending on the eVTOL configuration. Moreover, strong headwind conditions of 20 m/s reduced the final range by 71% as well. But also, we can predict, that with the anticipated development of batteries in the next three decades the ranges can be increased by up to 110%. In consequence we conclude that effective operation of eVTOL is not only dependent on further technological development, but also an adaptive and individual approach to regulation and traffic management as the capabilities differ significantly based on the vehicle type. In order to depict realistic scenarios, the environmental variables, airspace characteristics and mission-related parameters are representative for the area of the Frankfurt Airport.**

Keywords-component: eVTOL, Performance; Energy; Demand and Capacity; Maximum total range; Battery

NOMENCLATURE

A_r	Rotor aera	R	Range
BM	Battery weight	r_N	Hub radius
b	Span wide	r_P	Propeller radius
c_A	Coefficient of lift	U	Blade tip speed
c_W	Drag coefficient	v	Speed
c_{W0}	total drag of the aircraft	W	Resistive polar
c_{Wi}	lift induced drag coefficient	W_I	induced drag polar
c_{Ws}	harmful drag coefficient	W_P	profile drag polar
c_{Wp}	profile drag coefficient	W_S	damaging resistance polar
E_A	provided energy of the battery	α_w	Trailing contraction parameter
E_R	energy demand during cruise flight	ε_R	lift-to-drag ratio
E_S	energy demand during hovering flight	η_R	Travel efficiency
e	Oswald factor	η_S	Hovering efficiency
e_A	effective energy density	μ	Airfoil progress ratio
f_S	damaging surface	μ_A	Weight ratio between BM and MTOW
g	acceleration due to gravity	μ_P	Passenger mass ratio
P_R	Power requirement for cruise flight	ρ	Air density
P_S	power requirement for hovering flight	σ	Areal density
q	Air pressure	Λ	Aspect ratio

I. INTRODUCTION

The aviation industry, be it airport, airlines, manufacturers or any stakeholder in the industry has experienced a significant growth throughout the past decades. [1] We have seen new passenger volume records year by year. Although, the industry is significantly hit by the Covid pandemic and its measures, it is foreseen that the growth will come back. [2] Usually airport capacity gets increased in order to satisfy growing demand. Unfortunately, airports only are naturally limited by their area – above all in Europe. In order to stay competitive, airport operators are continuously looking for new business opportunities. [3] A promising area with emerging technologies and various business models are eVTOL aircraft (electrical vertical take-off and land) - commonly referred to as airtaxis.

Airtaxi manufacturers' value preposition and their aircraft concepts are publicly discussed. Billions of dollars and euros have been invested over the past few years in those companies. At the same time, aviation authorities around the world develop regulations for this new format of mobility. The disruptive technology and its effects (i.e. development of new airspace structures) are foreseen to become reality in the mid of 2020. [4] One main driver of this new technology is the prolonging growth of cities, such as London, Sao Paulo and Singapore. Evermore people live in mega cities and need to get from A to B in a safe, fast and ideally economical way. [5, 6] For some experts airtaxis seem to be a countermeasure for gridlocks in the world's megacities. [7] Even if airtaxis will not solve megacities traffic problems, they could be an additional transport mode, that benefits intermodality. Besides, they are a strategic first step towards electrification of air traffic [8] and they could become a sustainable way of travelling if the energy for the electric-driven aircraft engines will be provided by renewable energies. [9]

To cope with the technical and operational challenges of integrating these aircraft into urban und sub-urban environments, several research projects are being carried out in Europe under the SESAR program umbrella[1]. One of the main challenges is the consideration of a mixed traffic in low airspace levels and the heterogeneity of the concept of operations. [10]

Airport operators and other aviation stakeholders actively observe these developments and assess how to participate in future Urban Air Mobility (UAM) operations models. One possible option is the deployment of shuttles between airports and their surrounding cities. Amongst others there are two essential aspects from an airport operator's perspective which contribute to the success of the airtaxi technology:

1) *How successful will be the underlying business model, public acceptance and the consequent willingness to pay?* [6]
2) *Are the promised key data, e.g., operating range and performance realistic and achievable in the middle-term?*

Recently, the second question gained momentum in different scientific and public articles, as optimistic promises of manufacturers and a bullish mood in the investment sector attracted several critical examinations from a technical point of view. [11]

A. Aim

In a joint project, researchers from the Technical University of Darmstadt and Fraport AG have now collaborated in order to assess the dependency of the currently popular airtaxi architectures in terms of energy consumption and realistic operational scenarios. This allows for a more precise rating of UAM business cases in terms of their aeronautical and technical feasibility, as well as it allows to emphasize the need for adaptive and target-oriented regulative approaches when it comes to eVTOL.

This paper summarizes the comparative evaluation of the electric flights' energy demand, based on the current technical developments. Considering the current not finalized but expected regulations and standards, the energy requirement is to be determined depending on operational and external factors, such as reserve for emergency procedures and weather influences. Furthermore, this study gives an answer to the question if typical flight scenarios, as expected by major stakeholders, can be conducted. Furthermore, potential flight missions will be introduced and the potential of the implementation of UAM under the current legal and operational aspects will be elaborated. Airports are expected to play an essential role in UAM concepts since they will be the natural provider of intermodal connections to traditional aviation services and legally anchored to provide public services. It is essential for investors and business partners to get a neutral evaluation of eVTOL concepts and their performance capabilities, since they are crucial for efficient UAM business models and business-related decisions.

II. STATE-OF-THE-ART

UAM is a new concept of air transportation that transports people and cargo, between locations in urban and regional areas. This involves revolutionary new passenger aircraft with electric propulsion and vertical take-off and landing capabilities. Although this new aviation technology is known as Urban Air Mobility, reflects its intended uses in a congested urban environment, it is becoming increasingly clear that their benefits will not be limited to cities; eVTOLs can be deployed anywhere to reach geographically distant, underserved communities and bridge infrastructure gaps. UAM integrates use cases such as cargo delivery, short-range but also long-range commercial air operations, public service, and private/recreational use. It will consist of an ecosystem that considers aircraft development and safety, operational framework, airspace access, infrastructure development, and community engagement. [12]

UAM stakeholders have different visions about future mobility and its impact on the society. Some see novel business concepts such as ridesharing, which makes an air taxi trip affordable for everyone. Passengers could book flights via mobile app technologies and have the nearest air taxi sent directly to a convenient pickup location. This will also integrate airports and train stations. [13] This business model competes with existing modes of transportation. Therefore, the focus is the so-called airport shuttle - a transport service between the airport/vertiports - to surrounding cities. In this context, low altitude flight operations in both controlled and uncontrolled airspace are envisaged. [14]

A. eVTOL architecture and performance

There are currently over 500 eVTOL concepts with a large variety of technological maturity and different architectures.[2] Most of these concepts propelled by electric motors supplied with battery system, though some of them follow a hybrid-electric approach where combustion engines act as generators. Essentially, the architectures used for these various concepts can

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[1] https://www.sesarju.eu/U-space

[2] https://evtol.news/aircraft

be classified using the categories Wingless (Multicopter, Quadcopter), Lift & Cruise, Tilt Rotor and Vectored Thrust. [15, 16]

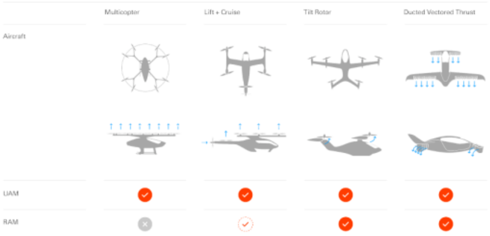

Figure 1: Comparison of different e-VTOL concepts [17]

In Fig. 1, the four most common types of eVTOL aircraft architectures are shown and compared against their predicted application in the UAM market. The choice of architecture already suggests the tradeoff between the different cruise and hover efficiencies.

The first category of eVTOL is the wingless architecture, which with its multiple propellers provides only the lift - Wingless. This eVTOLs configuration can be further distinguished in two types of models. One is the quadcopters, which require only four propellers for lift, or multicopter, which need several propellers for lift. The layout of propellers can also vary based on a coaxial arrangement. Multicopter has a high degree of hovering efficiency, as the arrangement of the propellers mostly resembles a helicopter from the perspective of the rotor area. As a consequence, this configuration can be very efficient during vertical take-off, landing, and hovering, due to low disc-loading. However, without wings, multicopter lack cruise efficiency, which limits their application to the UAM market. [18]

The second category of eVTOL is the Lift & Cruise architecture and use completely independent thrusters (engines or propellers) for lift and cruise flight. This feature allows the eVTOL to achieve high efficiency levels during the hover phase and cruise phase. Depending on the aerodynamic parameter, higher ranges than the multicopter can be achieved in this case, as usually the lift-to-drag ratio is higher.

The third category of eVTOL is the Tilt Rotor architecture, which are pivoted over the transverse axis to change the direction of thrust and thus used for lift and cruise flight. Thereby the wing and propellers, or the propellers alone, tilting through 90 degrees during the transition phase from hover to forward fight. The resulting flight dynamics of this layout exhibits a high technical complexity of the pitch and control mechanism. For hover flight, the propellers must be large, have a low tip speed, and have a low disc loading. This means that either the motors must be large and heavy to produce the low-speed torque, or a gearbox is required, which can impact the structure and cost-efficiency. Other challenges may arise in the design of flight dynamics during the flight transition process. [17]

The fourth category of eVTOL is the Vectored Thrust configuration. In principle, this involves fixed-wing aircraft, which uses its engines with shrouded propellers, means where the propellers are shrouded with a sleeve, for the lift and cruise phase.

B. *Lithium-ion Batteries (LIB)*

The battery acts as the core element in the electrification of eVTOLs. It does not only determine performance and consequently the possible range, but also the lifetime and significantly influences the weight and cost of an eVTOL. Thus, the' battery plays a key role in the electrification of the drive train of eVTOLs. [19]

Two important performance parameters of a battery are the specific (also called gravimetric) energy density (Wh/kg) and the volumetric energy density (Wh/l). In the last ten years, the specific energy density of LIB has doubled to date [20]. In 2020, typical specific energy density for LIB is between 160 - 260 Wh/kg at the cell level and between 150 - 200 Wh/kg at the battery level, since a loss of about 8 - 18% from the cell to the battery has to be taken into account. [20, 21] In terms of volumetric energy density, a loss of between 20 - 50% is to be expected during the transition from the cell level to the module level. In addition, a reduction in performance must likewise be considered during the transition to the system level. [22]

In the course of the further development of LIB, it is assumed that the specific energy, power density, life cycles, charging time, temperature behavior (in ranges from -20 to +40°C), cost point, safety, but also environmental compatibility will increase. [20] However, the performance and lifetime of LIBs cannot be increased indefinitely, as the full maturity of LIBs may be developed in the next 10 to 30 years. [22] By 2030, the volumetric energy density can double again, provided that the major research and development challenges are successfully implemented. An increase of the specific energy density by lithium metal anodes to ~ 400 Wh/kg might be conceivable. [20, 23] From today's perspective and trends, higher figures from the literature appear speculative and are rather unlikely.

TABLE I. LIB PERFORMANCE DATA - 2020, 2030 and 2050 [20, 22]

LIB	**Year**			
	2021	***2025***	***2030***	***2050***
Energy density – Modul [Wh/kg]	200	250	300	400

C. *Power requirements of VTOL*

For the calculation of the energy demand of a hover or cruise flight for eVTOLs there is no general approach yet. However, since eVTOLs take off and land vertically like helicopters, the flight mechanics for helicopters and the basic principles of power accounting can also be assumed for eVTOLs during hover phase. Bernoulli's momentum theory is the method to calculate the thrust of propellers and rotors based on the momentum and energy theorems. [24]

Similarly to [24], the following effects are neglected in this study: Finite number of blades, Profile drag of the rotor blades, Twist in the wake, Non-uniform pressure distribution across the rotor, Non-uniform flow through the rotor, Hub displacement, Blade tip losses, Non-profiled blade necks and Re-number.

For the determination of the thrust, the beam theory is not sufficient, because profile losses and other diverse losses are not considered. Therefore, the blade element method, also called blade element theory, is used for a closer examination of the real rotor. In addition, real rotors cause power losses in hover flight based on the following factors [24]:

- Profile drags 20 - 30 %
- Non-uniform flow 5 - 7 %
- Residual twist in the airflow approx. 2 %
- Blade tip losses 2 - 4 %

D. *Design Parameter of eVTOL*

For the determination of the efficiency in hovering flight, the simple jet theory is also not sufficient. [25] A sufficiently accurate calculation can only be made using the blade element theory. It determines the quality of the rotor blades, which depends on the blade surface, twist, restriction, slenderness, taper and fillet, but also on the gap to the shroud. In addition, the inflow due to the blade pitch angle, rotational speed and airspeed play a major role. This consideration has been used in different studies [24, 26, 27]. The transition from hover to cruise or forward flight is a complicated process in terms of aerodynamics and mechanics. Therefore, the rotor is simplified as a disk, rather than the aerodynamic forces on the individual rotor blade. As with all aircraft, the power requirement for helicopter cruise flight must be determined using the power polar, also called the drag polar (W). As a first approximation [24], the propulsive power (N_{Ro}) in cruise flight is calculated over the speed (v) and the efficiency of the cruise flight (η_R) with the induced (index I), damaging (index S), and airfoil power or drag (index P), resulting in [24]:

$$\begin{aligned} N_{Ro} &= \frac{W * v}{\eta_R} = \frac{v}{\eta_R} * (W_I + W_S + W_P) \\ &= \frac{G * v}{\eta_R} * (\frac{W_I}{S} + \frac{W_S}{S} + \frac{W_P}{S}) \end{aligned} \tag{1}$$

With the help of these equations the design parameters of the evaluated eVTOLs can be determined as the following:

$$c_{Wi} = \frac{c_A^2}{\pi * \Lambda * \mathrm{e}} \text{ with } \Lambda = \frac{b^2}{A_r} = \frac{4}{\pi} \tag{2}$$

The Oswald factor e is also called wing efficiency or span efficiency. Its optimal value would be 1, but usually, it lies in the range between 0.6 and 0.9.

$$c_A = \frac{F_A}{q * A_r} = \frac{2 * MTOW * g}{\rho * (A_r) * v^2} \tag{3}$$

$$\begin{aligned} \mathrm{A_r} &= b * l \\ \mathrm{S_w} &= \mathrm{b * l} \end{aligned} \tag{4}$$

$$\frac{W_I}{S} = \frac{c_A}{4} \text{ and } \frac{W_S}{S} = \frac{f_S}{c_A * \pi * R^2} \tag{5}$$

$$c_{WS} = \frac{f_S}{\pi * R^2} \tag{6}$$

With flight mass (TOW), helicopters statistically have a damaging surface area (f_S), with coefficients ranging from 0.84 to 1.74 m² for A and from 0.33 to 1.07 m² for B as aerodynamic quality decreases:

$$f_S = A * \ln(TOW) + B \tag{7}$$

$$\frac{W_P}{S} = \frac{c_{Wp}}{c_A} * \frac{\sigma}{4} * (\frac{1}{\mu^3} + \frac{3}{\mu}) \tag{8}$$

$$\mu = \frac{v * \cos(\alpha_{Ro})}{U} \approx \frac{v}{U} \tag{9}$$

$$c_{w0} = c_{WS} + c_{Wp} \tag{10}$$

The drag ratio in cruise flight is an important parameter of the aerodynamic quality and describes the ratio of the aerodynamic lift and the air resistance for the entire aircraft.

$$\varepsilon_R = \frac{F_A}{F_W} = \frac{c_A}{c_W} = \frac{c_A}{c_{W0} + c_{Wi}} \tag{11}$$

These above presented equations are used for the calculation of the energy demand.

E. *Energy demand*

The general power and energy requirement during hover flight can be determined by the thrust calculation. The factor α_w is crucial in addition to the conventional power demand equations. Based on the shroud design, the area of slipstream flow at the exit, and the velocity at the duct exit, the factor α_w serves as a wake contraction parameter. For open propellers this factor is 2 and for shrouded fans it is nearly 4. Thus, based on the jet theory, the following equations are derived for thrust calculation [28]:

$$E_S = P_S * t_s = MTOW * \mathrm{g} * \sqrt{\frac{MTOW * g}{\alpha_w * \rho * A_r}} * \frac{1}{\eta_s} * t_s \tag{12}$$

The total rotor area for shrouded fans with hub (index SF) and open propellers (index OP) can be calculated as follows:

$$\begin{aligned} A_{r,SF} &= x_p * \pi * (r_P^2 - r_N^2) \\ A_{r,OP} &= x_p * \pi * r_P^2 \end{aligned} \tag{13}$$

For cruise flight, the required power demand for all flight types can be calculated with (14). The equation for the required propulsion net power in cruise flight differs from hover flight because the glide ratio is included as an important factor:

$$E_R = P_R * t_R = MTOW * \mathrm{g} * \frac{1}{\varepsilon_R} * v_{real} * \frac{1}{\eta_R} * t_R \tag{14}$$

The provided energy of the battery results from the multiplication of the effective energy density and the total mass of the accumulator unit:

$$E_A = e_A * BM \text{ with } \mu_A = \frac{BM}{MTOW} \tag{15}$$

Considering the different thrust calculations between shrouded propellers and open rotors, the range of eVTOLs can be calculated using the following two equations for the different types:

$$R = v_{real} * t = \varepsilon_R * \eta_R * \left(\frac{\mu_A * e_A}{g} - \frac{t_s}{\eta_s} * \sqrt{\frac{MTOW * g}{\alpha_w * \rho * A_r}}\right) \tag{16}$$

From the range equation it is evident that the expression of the brackets must always be positive in order to achieve a positive range. If the term in the bracket result to zero and the equation is resolved according to the total hover duration, the maximum possible hover duration is obtained. At the point where the maximum possible hover duration is exceeded, cruise flight is no longer possible because the energy provided is only limited:

$$t_{s,max} = \frac{e_A * \eta_s * \mu_A}{\sqrt{\frac{MTOW * g^3}{\alpha_w * \rho * A_r}}} \tag{17}$$

These equations illustrate that Breguet's range equation (18) is not sufficient for determining the realistic range of eVTOLs.

$$R = E * \frac{1}{g} * \eta_{total} * \frac{L}{D} * \frac{W_{battery}}{W_{total}} \tag{18}$$

III. METHODOLOGY

In order to achieve the realistic ranges, flight scenarios for an UAM operation are carried out using the environment of the Frankfurt Airport (FRA) as an example to demonstrate possible flight routes in theory. Furthermore, the realization of the UAM integration will be discussed on the basis of these flight scenarios from a regulatory and operational point of view, so that resulting challenges and opportunities can be identified. In this deductive work, the electrical range of the treated eVTOLs is investigated considering realistic operational conditions. Due to the scarce published literature for the new concepts, the literature review for this work is based on existing literature on helicopters, where VTOL design and procedures are similar. In addition, other literature, such as white papers and published documents from eVTOL manufacturers or institutes, were used. The research performed is further based on attendance and participation at various technical conferences [29] and workshops to obtain the most up-to-date information from eVTOL manufacturers, companies, institutes, and experts in the field.

As a first step, the energy demand for different eVTOLs has been derived. In order to include characteristics of various eVTOLs in the calculations, the necessary data were either researched, in literature, technical conferences, workshops or in data portals, such as TransportUP (https://transportup) and Electric VTOL News (https://evtol.news), or requested directly from the eVTOL manufacturers. Gaps in the data were determined using extrapolations with the help of calculations and finally, educated assumptions.

A. Validation Scenarios

To determine the range of eVTOLs, a flight scenario is mainly divided into a hover (vertical takeoff and landing) and cruise phase. Acceleration and deceleration phases are not considered due to the different eVTOL configurations. Climb and descent phases are of less importance in terms of total flight time, since the required excess energy is compensated by the reduced energy in the descent phase. [27] Therefore, the climb and descent phases are considered in the calculation as hover phases. The start-up of the propellers or engines is also disregarded. In the energy balance, no electrical consumers were included in the calculations. During vertical takeoff and landing for hovering flight, the ground effects, due to the velocities close to 0, are negligible. The Coandă effects, i.e., unrelated phenomena of the air currents, are difficult to estimate without practical empirical values, thus not considered.

In the following, influences on the battery and thus on the range are described. In particular, the thermal load on the battery is key. A study on electric vehicles from the automotive industry [30] and expert assessments from the field of battery technology were used to take into account the influence of the outside temperature on the battery:

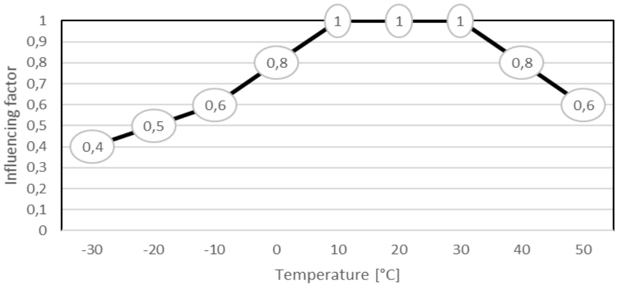

Figure 2: Temperature dependent range

The calculations of the realistic ranges are based on the previous findings and the integration of all equations and data in the macro calculation tool set up in Excel. In the calculation tool for the range calculation, it is possible to select between different eVTOL configurations, and the different annual scenarios for a flight altitude of 500 m above sea level with the stored air density. Thus, a sensitivity analysis can be performed using different options and scenarios. With the properties selection for different cases with different conditions (Table 2) were calculated and analyzed to evaluate the absolute range of the eVTOLs selected. The choice of air temperature is based on the averages of the last 10 years in the Frankfurt region and the 5% coldest and 5% warmest days. The choice of wind speed is based on the best case, i.e., none, but also the worst case of max 20 m/s. In addition, the mean value of the last 10 years and the 5% windiest days in the Frankfurt region are used for the calculation. The weather data were taken from the CDC-OpenData of the Deutscher Wetterdienst at the station Frankfurt.

TABLE II. SELECTED CONDITIONS FOR REALISTIC OPERATIONAL SCENARIOS

Parameter	**Selected conditions**			
Hover time	1 min	2 min	5 min	10 min
Air Temperature	10,4 °C	-9,1 °C	39,4 °C	
Headwind speed	0 m/s	4,9 m/s	10,1 m/s	20 m/s
Year	2021	2025	2030	2050

B. *eVTOL Performance Data*

TABLE shows an overview of the specifications of the seven eVTOLs designs. In this paper, all eVTOL architectures are computed with open propellers, except the Vectored Thrust model with the computation as shrouded fans. Thus, the different configurations with different design parameters can be compared in terms of performance.

TABLE III. eVTOL ARCHITECTURE AND SPECIFICATION

eVTOL architecture	**eVTOL Specification**		
	PAX	***MTOW [kg]***	***Speed [km/h]***
Multicopter	2	900	100
Multicopter – koaxial	2	600	100
Quadcopter	4	2200	120
Lift & Cruise 1	2	800	180
Lift & Cruise 2	2	1442	180
Vectored Thrust (SF)	5	3500	300
Tilt Rotor	5	1815	322

As further shown in TABLE IV, the key factors for calculation of energy demand are the efficiency values for hover η_S and cruise flight η_R as well as the specific drag ratio ε_R.

TABLE IV. eVTOL ARCHITECTURE AND DESIGN PARAMETER

eVTOL architecture	**eVTOL Design Parameter**			
	Battery mass BM [kg]	***Hover efficiency*** η_S	***Cruise efficiency*** η_R	***Drag ratio*** ε_R
Multicopter	180	0,70	0,50	4
Multicopter – koaxial	100	0,55	0,48	4
Quadcopter	800	0,55	0,40	2
Lift & Cruise 1	200	0,70	0,50	9
Lift & Cruise 2	400	0,70	0,50	11
Vectored Thrust (SF)	900	0,60	0,60	17
Tilt Rotor	400	0,70	0,46	15

However, since few reliable data has been published by manufacturers or validated in experiments, estimates and approximations were used for these studies. These were discussed with 6 experts from the departments of flight mechanics and aerodynamics at various universities and confirmed as plausible. Thus, the baseline of this study is a hypothetical description of similar existing design concepts, and not an evaluation of available products from specific companies.

IV. RESULTS

A. *Energy demand*

For the analysis of the technical value, the energy demand (kWh) for hovering between 0 and 10 minutes for each of the seven eVTOLs is calculated using a best-case scenario where the hover time is 1 min. Similarly, the energy demand for a cruise flight between 0 and 60 minutes was calculated which represents a best-case scenario as well. The following figure shows the normalized energy demand in hover against cruise flight per eVTOL type:

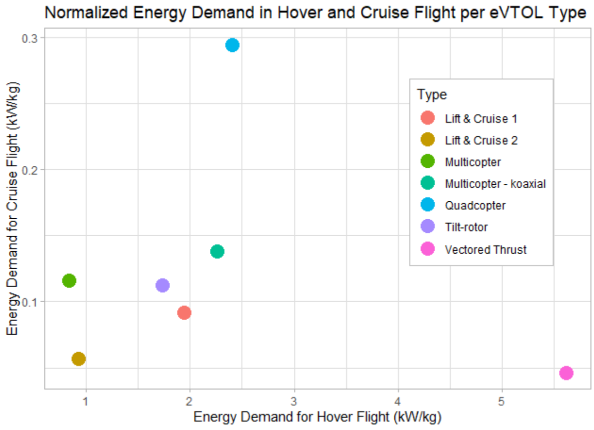

Figure 3: Normalized Energy Demand in Hover and Cruise flight

It is clear that the Vectored Thrust model has the highest energy demand during the hovering phase due to the weight and hovering efficiency. The Quadcopter has the highest energy demand during the cruise phase due to the weight and cruising efficiency. The lowest energy demand during hover and cruise phase has eVTOL type Lift & Cruise 2. This results from the efficient parameters during hover and cruise phase.

Figure 4 shows the results as per operational scenario simulated. Fig. 4.A shows the hover time scenarios per flight minute per eVTOL type. The higher the hover time the lower the range, because the energy consumption during the hover phase is considerably higher than during the cruise phase. On average, the range is reduced by just under 10% during a two-minute hover phase. With a 5 min hover phase, the range is reduced by up to 30% depending on the eVTOL type. In this phase, the Vectored Thrust model cannot provide any range due to the high energy consumption. In a 10 min. hover phase scenario (e.g., in case of emergency procedure), the range is reduced by up to 75% depending on the eVTOL type.

In Fig. 4.B it can be seen that the optimal operating temperature of the electric battery ranges between 10°C and 30°C. At a temperature of around -9,1°C, the battery drops ca. 40%. The colder the outdoor temperature, the higher the loss of the battery's capacity. Similarly, at a high temperature of 39,4°C, the battery only has an average of 20% of its capacity left. This means that the temperature has a considerable influence on the total range.

Fig. 4.C shows the range for four headwind scenarios. Depending on the eVTOL type, the range is reduced by 18% at a headwind speed of 4,9 m/s. On windy days (10,1 m/s), the range can be reduced by 22%. In worst-case conditions (20 m/s), the range can be reduced by up to 55%. Based on the forecasted battery development, Fig. 4.D, it is assumed that maximum range of eVTOLs will increase over time as the development in the field of battery technology continues. According to the current forecasts of the research institutes [20], an increase in the range by an average of 48% in the next 10 years and by about 110% in the next 30 years can be expected.

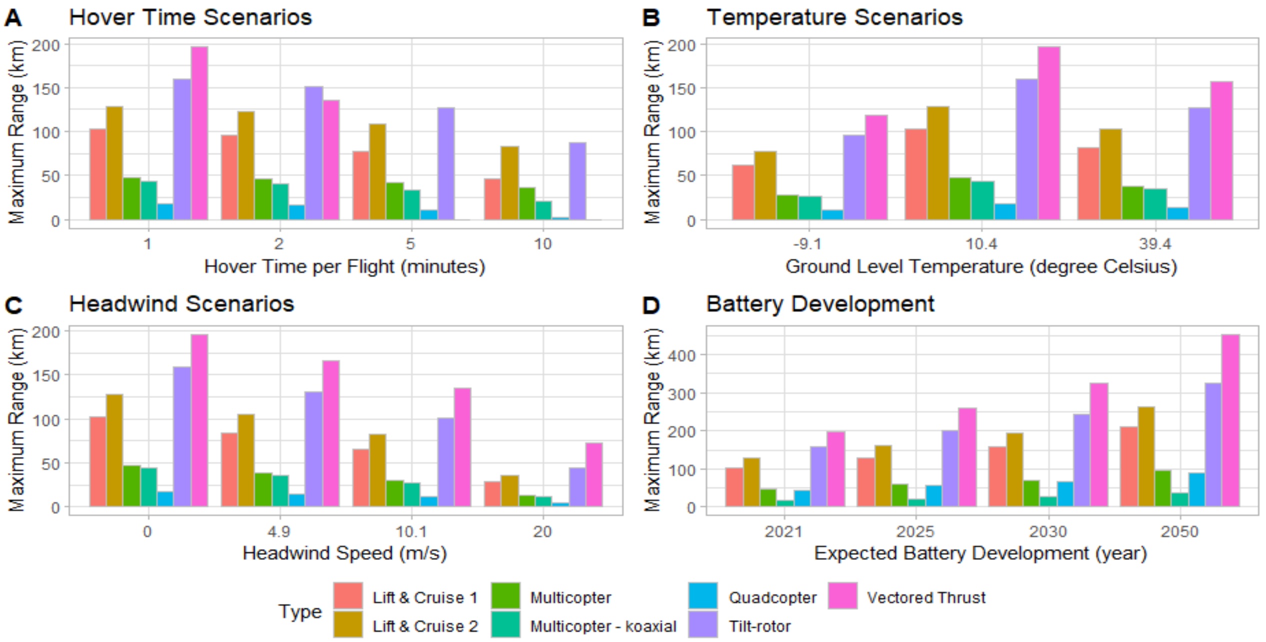

Figure 4: (A) Hover Time Scenarios (B) Temperature Scenarios (C) Headwind Scenarios (D) Battery Development

V. CONCLUSIONS

We developed a calculation method for the realistic range of eVTOLs by considering operational key influence factors. This enables the demonstration of exemplary scenarios and the different levels of impact on the ranges of currently discussed architectures. At the same time, it allows to evaluate economic use cases and traffic management principles based on current and future battery capacity. In doing so, it became clear that the proportional division of the flight into hover and cruise phases has a strong influence depending on the model.

To this effect, it has been ascertained that the larger the rotors of an eVTOL, the less thrust energy is required. Furthermore, it can be deduced from the equations that the larger the area *Ar*, the lower power is required. In general, hovering flight requires more energy than forward flight. Air density also plays a role in the performance. The denser the air, the less propulsive power is required, and the more weight can be carried. As the air density decreases with increasing altitude, the smaller the performance of the eVTOL. Based on the range equation, key qualitative conclusion can be made regarding to the maximum range. On the one hand, the range of all eVTOLs increases linearly if the glide ratio or the efficiency in cruise flight increases linearly. On the other hand, the range increases linearly as well as soon as either the battery mass ratio, the energy density or the efficiency in hovering flight increases linearly. The higher the hover duration or the maximum takeoff mass, the lower the maximum range.

Based on the calculations of the realistic range, it can be concluded that the results of the most optimal conditions matched with the specified range of the eVTOL manufacturers. In real operational scenarios such as low temperatures (winter conditions) and long hover phases, the manufacturers' specified ranges cannot be met. In the case of a 10 min hover phase, i.e., an extended holding procedure, no significant cruise flight is possible anymore for most eVTOLs - since most energy stored in the batteries is consumed already. Anyhow, the influence factors that predominantly affected the standard range are drag ratio, efficiency of hover and cruise phase as well as the overall system, energy density and weight. From an operations and traffic management design perspective influence of hovering phases, temperature and wind level should be given special attention.

In fact, only in the scenario with a 30 second hovering time, which can be considered as a minimum for takeoff and landing, the specified ranges of the eVTOL manufacturers appear feasible. Punctually, the higher the hover time, the higher the energy demand in hover flight, leading to a remarkably reduction of the total range. Another influence factor is the temperature at flight altitude. In cold conditions of about 0°C, the range of an eVTOL is reduced by 20% on average.

During the research performed, only high-level range calculations of electric aircraft have been found. At the time of completion of this study, there was no study evaluating the electric range of eVTOLs from a realistic and operational point of view. However, it shall be pointed out that manufacturer Lilium has published a paper recently, in which a range calculation for hover times with 60 and 90 seconds are performed with different energy densities as in our study. [17]

VI. NEXT STEPS

Our conclusion lead to two major issues of UAM that will need to be addressed in future research. First, the limitation of current battery technology. Even though testing with battery technologies is extensive and promising, two other types of technology could become more relevant in the meantime and neglect limited flight ranges and long recharging cycles between flights: fuel cells and hybrid electric technology. One the one hand fuel cells are expected to enable long distance travelling due to the high potential energy density of hydrogen (up to 1000 Wh/kg). On the other hand this technology is both, cost-intensive and infrastructure intensive. [19, 22] Instead, hybrid electric technology (a system with internal combustion engine and at least one electric motor) could become a new standard. The advantage of energy density could increase the total range. However, the high vibrations and resulting noise of the combustion engine could bring new challenges for operators and users. Future research on sound cancellation for both hybrid and all-electric propulsion systems can address these issues.

Second, the rapidly increasing developments on air mobility concepts in terms of eVTOL energy capacity and architecture. As it was remarked in this paper, there is wide range of configurations and concepts growing in maturity. It is certainly important that there is a diversity of solutions to promote the competition of the market, but this also raises challenges for all stakeholders of the UAM undertaking. Airport/Vertiport operators will be directed to develop risk management concepts and ensure the availability of potentially various fuel types at the take-off and landing sites. Airspace service providers will need to ensure rules' applicability and potentially restructure the low-level airspace. Air traffic control will need to consider this diverse battery capacities in the management mechanisms. Regulators will have to work hand in hand with manufactures to avoid a slowing down in the advancements in the concepts, and lastly, all operational stakeholders will have to integrate the concerns of the society to make UAM a viable solution. Further research into these topics should reveal the technical, operational and economic feasibility of the promising concepts existing today.

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