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Tuesday, August 23, 2022

Assessment of the feasibility and potential of the Lilium urban air vehicle concept

This report represents a scientific analysis and assessment of the Lilium urban air vehicle concept, which is an electrically driven distributed, impeller (ducted fan) based concept.

The analysis was performed for Iceberg-Research and is based on a Lilium White Paper, [1]. Referring to information of Lilium, the White Paper represents a technical status of end of 2020 and has not yet been updated.

For the analysis presented here, actual Lilium blogs, like [2], [3], [4] have been considered as well as comments provided by Lilium to the previous version.

Concerning the requested analysis the following aspects will be addressed:

- Is the calculated **performance achievable** in terms of **range and speed** with respect to the available **electrical power capacities**?
- Is the **noise assessment** of the Lilium White Paper realistic?
- Do the **conclusions of the White Paper** comply to the state of technology?

Conclusions

In the subsequent sections, following the structure of the Lilium White Paper an analysis of the Lilium methodology for performance assessment has been performed. Generally, the presented calculations reflect state of science and they are valid, but the taken numerical assumptions and estimates of performances and efficiencies are not yet considered as always realistic for the next 3-4 years.

Some of the reviewers of the White Paper, which are personally well known and respected colleagues, have been contacted and interviewed about their reviews and assessments. They confirm that the calculation methodologies are also from their perspective representing state of technology. However, they state, that they do not confirm the assumptions made by Lilium concerning e.g. efficiencies or energy densities.

Questions have to be therefore raised about the estimations and assumptions of various figures especially in chapter 5 for the efficiencies and discharge level, which are considered as being too optimistic.

In particular the following aspects should be carefully checked and discussed by Lilium:

1. The mass breakdown as shown in the White Paper, is roughly performed following a top-down, instead of a well established bottom-up approach, implying a lot of uncertainties about the real empty mass and the net battery mass.
   It is expected, that the available net battery mass for energy storage is significantly lower that 953kg as stated by Lilium, because components like battery power control, housing, wiring, integration losses, etc. for the battery package are not yet considered.
   For the vehicle empty mass system components of high redundancy like electrical systems, fully automated avionics, landing gear, cabin will contribute a significant share. The chosen top down analysis with a maximum takeoff mass of 3175kg given by certification standard at least provides a maximum available mass budget, also for the energy mass storage, [5].

2. The considered battery specific density for short term availability on package level is too optimistic. Very often the author mixes cell and package level performance which is about 30% different, [18], [19]. The assumed cell performances by Lilium is therefore much too optimistic for the next 3-4 years.
   A required specific density of about 400Wh/kg on package level might be achievable in 6 - 7 years from now (2022), if 7% efficiency increase is generally expected per year.
   Concluding, a 400 Wh/kg cell power density on package level, considering all losses and reserves will allow for a range far below 100km for a 5 seater, see table 2 last line.
3. In a feedback from Lilium to this analysis it was confirmed, that the Lilium Jet is designed as a piloted vehicle. Therefore any technologies or mass reductions caused by a fully automated operational flight concept are not considered, yet.
4. Lift estimation based on simple vehicle mass equivalence is not sufficient due to the complex wing – ducted fan flap system, which implies a lot of aerodynamic losses in lift. The remaining clean wing and canard areas seem to be aerodynamically much too small, especially in chord length to allow the development of sufficient pressure distribution for lift.
5. The power estimation for the transition phase is underestimated, because due to the tilt process of about 21 seconds, the initial hover power must be splitted into a horizontal (to create forward speed for lift) and vertical (to keep the vehicle in the air) thrust component. Since this process reduces the initial vertical thrust, more power must be provided until sufficient forward speed is developed to create sufficient aerodynamic lift carrying the vehicle.
6. Setting the minimum de-charging level to 10% is not state of technology. At least for Lithium based batteries a minimum charge level of 20% is required, to prevent the batteries from damage. This mismatch will reduce the overall usable battery capacity by additional 10%.
7. The maximum battery aging loss due to re-charging cycles must be considered, which for Lithium batteries is often set to 80%.
8. Taking into account the consequences of 5. and 6. either a significantly higher battery mass or a clear reduction in mission range will result, which is confirmed by own calculations based on the methodology presented by Lilium, see table 2.
9. From operational point of view the assumed hover time is found to be too short, because during takeoff in vertical climb obstacle clearance has to be achieved first before passing over to aslant climb.
10. Concerning the achievable noise level the authors calculate about 96m/s (351 km/h) exhaust speed, which is as much as 3 times higher than the flow speed of a 3 tons helicopter rotor and also in the same order of magnitude as a A320/B737 short range aircraft at takeoff full power. Therefore, it is not understandable, why Lilium states 60dB perceived noise level being achievable. The a.m. exhaust speed of an aircraft engine is more in the range of 85 dB noise level.
    In the meantime Lilium announced to reduce the amount of ducted fans from 36 to 30, where it is assumed, the duct and massflow diameter respectively will increase for a single ducted fan to reduce the flow speed. This is a significant change compared to the baseline of the White Paper. Following this way Lilium has understood, that a larger crossection per fan will reduce the flow speed and therefore also the noise level.

All these major conclusions extracted from the entire analysis below lead to the final assessment, that the entire Lilium jet concept is **technically feasible**, but essential mission requirements especially regarding **range and noise will not yet be met**. The noise mainly driven by the exhaust speed will be significantly higher, than e.g. for a rotorcraft in hover, [13].

The real operational range will be clearly below 150km, see table 2, because of additional power consumption in hover and transition, but also due to an overestimation of the short term battery package capacities and available battery net mass.

Further detailed aerodynamic analysis is mandatory to calculate the real achievable lift of this wing/canard configuration with tilting duct fans acting as lifting flaps. The key uncertainty here is the very small chord length of the clean wing/canard, which is expected not to provide sufficient lift.

Analysis of the Lilium White Paper (Status: End of 2020, not yet updated)

The Lilium Jet is defined in the White Paper either as a 4 and 6 seater passenger air vehicle with an additional pilot seat each. Also, a cargo version is under conceptual planning, [2]. The overall vehicle concept is a duck-wing thrust-vectored distributed propulsion configuration.
The operational specification is for 40 – 200 km range at up to 300 km/h, which roughly results in 40 minutes flight time at maximum, excluding additional time for takeoff, landing and transition phases, [2].

In the following, chapterwise observations and findings about the analysis, calculations and assumptions of Lilium are described.

1. Analysis of the architectural design space for e-VTOL aircraft

In this chapter various configurations of air vehicles are compared concluding, that for regional range air vehicle a tilt thrust configuration is the best choice, if VTOL characteristics as well as fast cruise capabilities are required.
Concerning the operation of the envisaged vehicle on heliport sized landing areas an air vehicle box size of less than 14x14m^2 is derived. This is a reasonable but not mandatory requirement.
Further the author introduces the ducted fan as an appropriate technology to reduce propeller engine noise by shielding the propeller with a duct and acoustic liners. This conclusion is correct, if only the propeller is considered.
In a next step it is stated that the ducted fans will stabilize the flow over the wing, when they are homogeneously distributed over the wing. Indeed, there are studies especially from NASA, where distributed propeller based propulsors, placed in front of the leading edge of a wing as puller improve the aerodynamic efficiency of the wing.
However, a lot of research is ongoing to understand the aerodynamic phenomena of the pulling and pushing principle of the propulsor and there is no clear view about the potential of this concept. In particular it is a significant difference, whether a propeller pulls and let the accelerated flow over a wing or an unaccelerated flow will be sucked in at the end of a wing surface, as for the proposed ducted fan concept.
Such distributed propulsion concepts can only be realized using electrical engines driving the propulsors.
The author also concludes that ducted fans installed at the trailing edge of a wing can act as thrust vectors, which can replace further control surfaces. This conceptual idea is very interesting and justifies further investigations.
The competitive Joby Air Vehicle is designed with a reduced set of highly efficient open propellers of larger size, which comprise highly efficient propulsive efficiency, less mass flow speed and lower noise level.

2. Design of a DVTC e-VTOL aircraft

The second chapter describes the design definition of the Lilium vehicle. Since a specified take off mass breakdown cannot be found neither in the White Paper nor on the homepage, [1], [3], Lilium considers the maximum category takeoff mass of 3175kg, specified by EASA, [5]. The real takeoff mass for both intended versions is essential to know for the entire performance calculation. Flight test videos like https://www.youtube.com/watch?v=QNl0DDUnp0E indicate a much lower vehicle mass, otherwise the noticeable exhaust noise would be much higher, see below.

Assuming 100kg per person as done by Lillium is state of technology and realistic, [1]. It leads to 500kg (4 seater) and 700kg (6 seater) payload including a pilot.

In a backward calculation a battery mass share of 30% or 953kg out of 3175kg maximum certifiable takeoff mass is derived, since the aforementioned payload is subtracted; and the empty mass of about 1524kg is estimated from a literature based percentage value (48%). Within this vehicle empty mass, systems masses of the distributed propulsors (all ducted fans and power supply), avionics for full automated flight, landing gear, further electrical consumers, movables and also the entire structure and cabin must be considered. Comparing the empty mass to similar configurations like Velocity TXL, the overall share of 48% approximately is realistic, [15]. Nevertheless, those vehicles are conventionally driven and contain one centralized propulsor, which is more compact and less heavy. Therefore, a more substantial mass breakdown approach bottom up should be presented, e.g. following Raymer, [16], with more detailed cabin, avionics, power control breakdown, etc..

Within the 953kg battery mass housing, cooling, power control, wiring, etc. of the battery package must be also considered. Further according to [18] mass and power penalties reasonably must be considered for the installation of safety systems and power reserves. Here, about 15% of the overall battery package mass must be provided for these measures, [18], which are not operationally available for power calculation. This will reduce the available maximum battery power mass to be considered for the overall power storage. It is very hard to say how much it is?

Therefore, the resulting and estimated stored power of 305 kWh is actually assumed to be too optimistic. Considering an increase in power density up to 400Wh/kg within the next 10 years instead of 320Wh/kg and a net battery mass of e.g. 800kg instead of 953kg (i.e appr. 15% loss for battery control, safety measures, etc.) one could achieve 320 kWh (800kg x 400Wh/kg) stored power, which is slightly higher than 305 kWh. Assuming 7% density increase per year of technology improvement in 10 years the stored power could be nearly doubled (factor 1,96). That means in fact 400 Wh/kg, required for a realistic power calculation would available in 6-7 years from now.

Further Lilium has commented on a previous version of this analysis, that the vehicles will be all defined with a pilot on board. Therefore, more details about the cockpit systems and pilot station should be provided to assess the overall mass breakdown. It can be realistically expected that the pilot station and cockpit systems will be of the same size as in an advanced general aviation aircraft like e.g. a Diamond DA42/65, Pilatus or Cessna.

Coming back to the vehicle characteristics, at first the general configuration is considered. Here, the use of canards is from energy perspective a good design choice, since canards, due to their allocation in front of the main wing, create positive lift, when the aircraft is climbing.

For the lift generation in cruise Lilium states, that the canards will produce about 20% of the entire lift (equals takeoff mass) or 1246N (635kg), [3]. Assuming the overall takeoff mass of 3175kg (6229 N) the canards should provide a wing area of at least 5m^2 at design speed and a typical cruise lift coefficient of C_L=0,3. For such a canard wing area, with a given canard wing span of 6.3 m the resulting canard wing chord will be around 0.8m. Looking at figure 2 of the White Paper [1] and considering a given duct length of 0.7m as stated by Lilium, only 0.1m canard chord length or 0.63 m^2 wing area will remain for the 20% lift generation. Here, a lift contribution of the ducted fan

surface is not yet considered, because the detailed aerodynamics of the ducted fan are not clear.
This is definitively too small for 20% lift generation, because there are only 10cm to generate the negative pressure peak curve, although the ducted fan is increasing the flow speed to generate the negative pressure.
Looking at the main wing with 60% lift contribution [3], and 13.9m span according to [1], the resulting wing chord will be around 1m, which is also confirmed by [8]. Again, substracting 0.7m duct length, only 0.3m aerodynamic chord length will remain for lift generation. This value seems to be inappropriate to generate the required lift, [1]. Further, during the transition, when the ducted fans are tilted, they do not provide all thrust for lifting the vehicle and the remaining chord length is too short to substitute the reduced thrust by aerodynamic lift. Looking again at the video https://www.youtube.com/watch?v=QNl0DDUnp0E, it can be seen, that the flow above the ducted fans is completely stalled in these phases and contribute no lift. That means, in the transition actually the vehicle is kept in the air only by the vertical thrust vector portion and the vehicle must be much lighter that 3175kg as considered in the White Paper. Other investigators describe similar conclusions, [20].
While the ducted fan, and therefore the thrust split is as much as twice splitted between the canards and the main wing (1:2) as stated in [1], page 7, equivalence between canards ducted fans performance and main wing ducted fans performance must be well balanced by the relative position of the canards to the c.g, which is not known yet. If it is leveled 2:1 forward to the main wing 100% power of the canards will correspond to100% of the main wing fans in stabilized hover condition. There will be no control reserves.

For the overall mass assessment Lilium states a maximum battery mass of 953kg equivalent to a 30% portion of the maximum takeoff mass, [1] page 6. So, the next analysis is dedicated to the associated achievable gravimetric energy density, i.e. the power per kilogram. For this exercise 320Wh/kg energy density is assumed by Lilium. Resulting in an energy storage of 305kWh this is a realistic forecast of the near term (4 years) potential. Therefore, the first guess of 320 Wh/kg is ok, although it is not yet available. That means the Lilium assumption of installed power is seen as too optimistic for the next 2-3 years.

3. Performance analysis method

Regarding the performance calculation in chapter 3 the general approach follows a state of technology logic.
Here the various flight states hover, transition hover to cruise and back, cruise, climb and descent are discussed. It is becoming obvious, that the vertical climb and vertical descent as early and final flight states are not considered, although they are mandatory to achieve obstacle clearance. In addition, close to the ground the power saving in ground hover effect is not considered, which can be about 10% power saving in this phase.
For all phases the efficiency of the power provision is chosen as the starting point. From aircraft design perspective it would preferrable to start first with a calculation of the required power from vehicle mass and speed point of view.
A cruise altitude of 3000 m chosen for the mission profile definition is reasonable as an upper and from air density point of view conservative upper limit.

Referring to the various flight states in **hover thrust** is defined in **section 3.1** as $T = m \cdot g = \rho \cdot A_d \cdot v_i \cdot n$. Taking into account a maximum weight of $3175kg \cdot 9.81 \frac{m}{s^2} = 31146\,N$ this would be the required thrust in hover.

Here, a thrust reserve of about 20% for vertical climb out of obstacle area must be considered for safety reasons, which either will increase the need for power or reduce the cruise range.

The related exhaust speed v_i calculated by Lilium will result in nearly 351 km/h (97,5 m/s), which is pretty high and noisy. In comparison a typical exhaust speed of aircraft jet engines at full power (takeoff condition) is about 480 km/h directly behind the engine and Airbus indicates for a 3 tons class H135 helicopter (similar to the Lilium vehicle weight) 86km/h, [12], [13].

	Lilium [1]	Boeing [13]	Airbus Helicopters [14]
Flow speed	97,5 m/s	133,3 m/s (480km/h)	23,9 m/s (86km/h)

Table 1: Comparison of ducted fan, turbo fan, rotor flow speed

In both cases the exhaust diameter of the engine fan and the rotor is much larger by orders, than the exhaust diameter of a single ducted fan. The estimated very high exhaust speed of the Lilium ducted fans compared to typical aircraft and rotorcraft exhaust speeds raises severe concerns about the noise impact and general ground operations, because the high speed will create a lot of turbulence close to the ground. For jet VTOL systems like VJ101, VAK191 or DO 31 ground erosion and heating became a critical issue, because the ground could be destroyed.

In this context it must be mentioned, that thrust generated by massflow can be generated either by a large area where the air mass flows through or by a high flow speed. If the area is small like for the ducted fan of the Lilium Jet the flow speed has to be high. If the flow speed shall be low and quiet, the area must be large.
The efficiency chain, describing the influence of the fan, the duct, the motor, the battery, in equation 3 is logical, while it would have been expected to learn more about the background and justification of the assumed values in equation 4.

$$\eta_O = \eta_F \cdot \eta_D \cdot \eta_{PE} \cdot \eta_M \cdot \eta_B$$

In any case the chain shows, that the overall efficiency is very sensitive to single changes of one specific efficiency. For example, taking the value of section 5.2 for hover and changing only the electric motor efficiency $\eta_{M,h}$from 95% to 93%, the entire efficiency $\eta_{O,h}$ will change from

$$\eta_O = 0{,}88 \cdot 0{,}964 \cdot 0{,}95 \cdot 0{,}92 \cdot 0{,}80 = 0{,}59$$

to 0,57 or 2% change of the overall chain. If further the efficiency e.g. of the fan or duct come out as being lower, than estimated, the entire power balance may directly decrease. Here the reviewers of the White Paper being well experienced in electric flight systems state, that the efficiency values are too high and optimistic for a realization within the new 3-4 years.

In **section 3.2** the power estimation for **cruise** is presented. Since the power is depending on the vehicle drag and cruise speed, these parameters will be determined in chapter 4. Once again, the efficiency chain is the same as discussed for hover, but with different figures.
In the cruise condition the vehicle will be carried in the air by lift. Here it is important to understand how much lift will be generated not only by the wing/canard area but also by the ducted fan upper area. Since lift is generated by high negative pressure above the surface and medium positive pressure below (where the fan is) it must be shown, that the high speed above is significantly higher than the sucked speed below. Otherwise, the difference in speed does not create sufficient pressure difference and therefore lift. This aspect must be considered in the power calculation.
For the **transition phase** in **section 3.3** the situation is discussed. The transition phase is a crucial flight state at low speed between 0 to x kts forward speed, where the wing is taking over a measurable portion of the lift force, which is driven by the squared horizontal speed portion V_{hor}^2.

At 45° tilt of the fan, 0,707 of the vertical thrust is available only and must be compensated by the aerodynamic lift. That means, in this state the aerodynamic lift and the associated forward speed must contribute at least 30% of the vertical lift at canards and wing, if the flight path shall remain horizontal. The more the ducted fans are tilting, the more the related thrust vector is contributing to forward speed and therefore lift. It is not visible in the paper at which tilting position the wing and the canards will contribute to the lift. As mentioned above in this state the flow above the tilted ducted fans is completely stalled due to the high tilt angle (corresponding to a high local angle of attack at the ducted fan surface) as shown in the video.

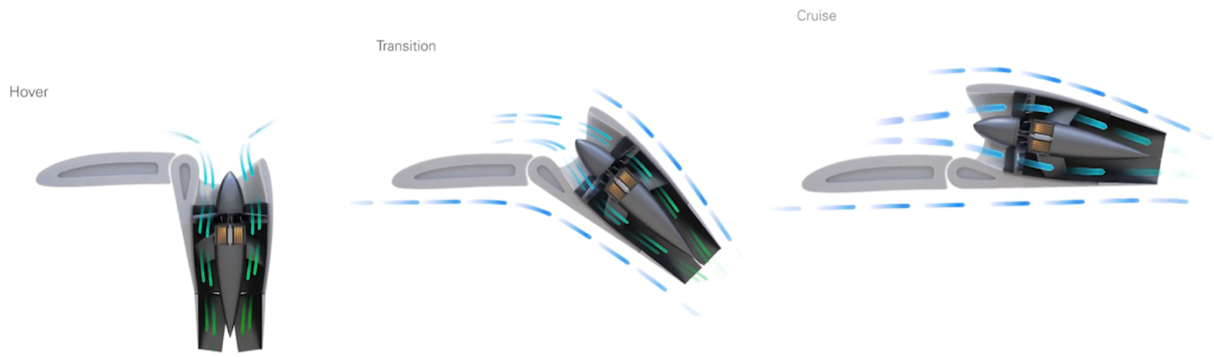

Figure 1: ducted fan orientation in hover, transition, cruise, [20]

The author of the White Paper calculates the required power in transition as an average value between beginning and end of the transition

$$P_{avg} = \frac{1}{2} \cdot \left(P_h + \frac{P_h}{\kappa}\right)$$

with a reduction factor κ=10. It describes the required average power is about 0,55 (=0,5*(1+0,1)) of the required power in hover. At the beginning of the transition the thrust vector is slightly tilting and at small tilt angles the thrust is deflected being reduced in the vertical axes. This reduction must be substituted by additional power to compensate the mass at the same flight level. On the other hand, the resulting small forward speed is too low to create significant lift.
Consequently, at the beginning of the transition more rather than less power of stable hover power is required. Further in cruise condition conventional aircraft require approximately 30-40% of the take off power to overcome the aerodynamic drag and to create forward speed. Therefore, a decrease of power by 90% down to 10% in cruise as performed in the averaged calculation seems to be not logical. It must be proven, that the resulting forward speed generates sufficient lift in this condition, due to the short chord length at canard and main wing.
The aslant **climb and descent** is discussed in **section 3.4.** While the power calculation sounds reasonable, it is questionable why the climb speed is set to 275km/h. This figure is not the climb speed, but the geometrical mix of forward and vertical speed resulting from thrust vectoring split. Also, setting the descent power level to 20% (equation 11) of the cruise power is hard to understand. Since the entire propulsion and climb/descent control are based on thrust vectoring, the related speed must be splitted into a vertical and horizontal component, where the vertical component contributes to the climb rate, while the horizontal one is driving the aerodynamic lift. Therefore, it is recommended to recalculate the climb phase.
Section 3.5 is dedicated to the calculation of the **flight range** based on a power consumption approach as described in equation 13. Setting the minimum de-charging level SOC to 10% is not

state of technology. At least for Lithium based batteries a minimum charge level of 20% is recommended in practice, to prevent them from damage. This mismatch will reduce the overall usable battery package capacity by 10%. Another question, not yet answered, is about the aging of the battery due to various charging cycles, which decreases the remaining power capacity of time. In this context, it must be defined, down to which capacity level a battery shall ensure a complete mission duration. E.g. if the lowest level is assumed to be 80%, at which the battery has to provide power for a complete mission, only 60% of a nominal battery can be considered for the performance and power calculation, because 20% minimum de-charge level and 20% maximum aging loss have to be substracted. This consideration is fundamental and will increase the require battery mass and density significantly (see last line of table 2), or reduces the achievable mission range. Those aspects have not yet been addressed by Lilium also in the actual blog, [4]

4. Performance of the DVTC e-VTOL aircraft

In chapter 4 drag, efficiencies and battery power are determined.

While most of the drag calculations in section 4.1 are straightforward and reasonable in most cases, for the calculation of the **wing drag** in **section 4.1.2** the wing area is determined by the clean area only, i.e. the area of the ducted fans is calculated separately, see below. This approach makes sense and enforces the statement above, that the aerodynamically efficient area is pretty small.

Special attention should be paid to the **flap drag** estimation in **section 4.1.3**. It is stated, that the flap, i.e. the entire ducted fan, is a lifting component. Typically lift of a surface is created by negative pressure above the surface and positive pressure below. The surface area below is completely covered by the fan and it needs to be investigated by Computational Fluid Dynamics (CFD) how much negative pressure will contribute to lift. The drag derivative is set to 0,017, but the justification for this value is not clear, neither by aerodynamic calculation nor by statistics or empirics.

For the **lift induced drag** in **section 4.1.4** only the canard contribution is mentioned, considering an Oswald-factor of 0.83, which is pretty high for this ducted fan concept, since interference losses must be more considered. This well known factor reflects aerodynamic inefficiencies, which occur at surface edges. While the canard area is relatively small a lower factor would be expected in the range of 0.75 to 0.8. Unfortunately, an equivalent factor for the main wing with the ducted fan is missing, which would be expected in the range of 0.7 due to inefficiency of the wing area and fan interaction.

This leads to the point, that in **section 4.1.5** the **overall drag** is calculated from the glide number of 18.26. This is indeed a good aerodynamic performance. However, it is based on the simple, but correct assumption, that lift equals weight. Due to the aerodynamically very specific and demanding configuration of a thrust vectored canard and wing configuration with a significant aerodynamic loss caused by the ducted fan flap system, a detailed CFD based lift calculation is ultimately required to determine the achievable aerodynamic lift.

In **section 4.2 various efficiencies** are determined as fixed values. For the **fan efficiency** $\eta_{F,h}$ in hover 0.88 is "estimated" in **section 4.2.1**, the basis for this figure as well as for the cruise condition is not clear. For the **propulsive efficiency** in **section 4.2.2** no remarks have to be made, except, that the exhaust speed is pretty high, see above. For the **duct efficiency** in **section 4.2.3** the losses in cruise are calculated 5 times less than in hover. The boundary losses $T \cdot \dot{S}_{d,iirev}$ derivation is hard to understand, where the related drag count is set to 0.002. This needs much more explanation. While it is expected, that in both flight states the inflow direction is in the same direction as the duct fan, it is not understandable, why higher losses in horizontal cruise are calculated. The resulting

efficiencies interestingly differ only by 0.03 related to $\eta_{D,cr}$= 0,923, which is far below a factor of 5. The **power electronics efficiency** discussed in **section 4.2.4** just states 2 figures, which in general are realistic but very optimistic state of technology. Also, when the **battery efficiency** in **section 4.2.6** is very briefly discussed, one can argue, whether these figures are right or wrong. At least, the high efficiency loss of 18% for hover power delivery compared to cruise is remarkable and considered to be too much. It will increase credibility, if substantial scientific analysis can be provided. Actually, the description sounds not justified.
The next **section 4.3** discusses the **power extraction of the battery** starting with an assumption of 8 kW constantly required for onboard power. It is not clear, which consumers are considered for this figure, i.e., overall avionics, flap and ducted fan kinematics, simple air condition, etc.? Without any bottom-up power breakdown, it is hard to believe in this figure. Remarks about the realism of the assumptions in section 4.3.1-4.3.4 have been made in chapter 3.
However, the assumed times for the different mission phases of the entire **flight range** in **section 4.4** in table 3 raise concerns. First, when taking off, the vehicle has to perform a vertical climb out of obstacle area before reaching its initial hover position and passing off to the aslant climb or horizontal flight. Therefore, the take-off hover time is too short and must be as similar as the landing hover, which is also confirmed by [9]. With practical flight experience from rotorcraft an overall hover flight time of approximately 2-3 minutes is more realistic for one mission.
Consequently, the calculated overall range of 261km is very optimistic due to the not yet achievable energy density, a very short hover time, and too low de-charging level. Reflecting the observations and remarks explained here, the White Paper honestly states, that the entire methodology is a simplified one, and many operational aspects are not yet considered.
At last, in **section 4.5** a **first order noise assessment** is introduced. Unfortunately, the reference of the key equation (58) cannot be found under the given link.
Also, the detailed calculation of the frequency correction cannot be checked. The Lilium assumption, that a fan blade design can reduce the current pressure level is in general correct. Nevertheless, one must bear in mind, that thrust is created by mass flow through a cross section, which has the variables diameter A and flow speed v_1, as also mentioned above.

$$F = \dot{m} \cdot v_j = \rho \cdot A \cdot v_j \cdot v_j$$

As shown in the formula a given thrust can be achieved either by a large diameter or by high flow speeds. The smaller the diameter the higher the flow speed has to be. That means in fact, that for the given fan design a high flow speed is mandatory. Therefor the presented statements about the noise assessment require a detailed and transparent description and explanation. The current given figures are not reliable.

5. Technology Assessment

The chapter provides some literature analysis about the expected battery capacity and power train and electric motor efficiencies. Since this is only a list of cited figures an assessment is not really useful. Nevertheless, based on 270 Wh/kg today, the Lilium assumption of 320Wh/kg (4 years) and 400Wh/kg (7 years) in the future is realistic, if 7% improvement per year is considered.
As mentioned before, the minimum discharge level of 10% is considered as too low, while 20% is recommended.
At last referring to recent publications about this topic, integration losses in terms of cell packaging (-30%), safety reserves like cold temperature losses, power reserve, etc. will further request significant more net power, than estimated under theoretical conditions in the White Paper, [17], [18].

6. Parameter Variation Analysis

At last, some parameter variations are performed to demonstrate the impact of hover time, energy density and battery mass on range.

An own recalculation has been performed here following equation 57 of the White Paper [1]. Doing the same calculations for different combinations of parameters the following results are achieved for the 7 and 5 seater configuration, taking all other parameters as constant from the paper, v_{cr}=300km/h, m_{TOM}=3175kg; m_{bat}=953kg; $|_{h}$=59; $|_{cr}$=0,65:

		Power density [Wh/kg]	Hover time [sec}	Minimum de-charge [%}	Minimum max-charge due operat. reserves [%]	Resulting Range [km]
(1)	Lilium DVTC-2 (Reference)	250 (7 Seater)	60	0.1	0	181
(2)	Lilium DVTC-2 with 90 sec Hover	250 (7 Seater)	90	0.1	0	153
(3)	Lilium DVTC-2 with 180 sec Hover	250 (7 Seater)	180	0.1	0	67
(4)	Lilium DVTC-2 with increased hover time, decharge level and power reserve	250 (7 Seater)	90	0.2	0.2	57
(5)	Configuration with current energy density	270 (7 Seater)	60	0.1	0	205
(6)	Increased hover time	270 (7 Seater)	120	0.1	0	147
(7)	Increased decharge level	270 (7 Seater)	60	0.2	0	170
(8)	Increased decharge level and additional power reserve	270 (7 Seater)	60	0.2	0.2	101
(9)	Increased hover time	270 (7 Seater)	90	0,1	0	176
(10)	Increased hover time and decharge level	270 (7 Seater)	90	0.2	0	142
(11)	Lilium DVTC-2 with increased hover time and decharge level	270 (7 Seater)	120	0.2	0	113
(12)	Lilium DVTC-2 (7 Seater) with current energy density	270 (7 Seater)	120	0.2	0.2	44
(13)	Lilium DVTC-5 (5 Seater) with	270 (m_{Bat} 1153kg, 5 Seater)	60	0.1	0	270

	current energy density and extended battery mass					
(14)	Lilium DVTC-5 with packaging losses and reduced battery mass due to battery power management electronics	196 (330x0,7x0,85) (m_{Bat} 1153kg, 5 Seater)	60	0.1	0	167
(15)	Lilium DVTC-5 (5 Seater) with 3 years improved energy density extended battery mass	196 (330x0,7x0,85) (m_{Bat} 1153kg, 5 Seater)	120	0.2	0.2	19
(16)	Lilium DVTC-5 with packaging losses and reduced battery mass due to battery integration losses	224 (400x0,7x0,85) (m_{Bat} 1153kg, 5 Seater)	120	0.2	0.2	58

Table 2: Recalculation of different configurations

The parameter variations of Lilium have been extended by

- Increase in hover time from 60 up to 180 seconds
- Increase of minimum de-charge level from 10% to 20%
- Increase of battery mass from 953kg to 1135 due to passenger reduction (5 seater)
- Introduction of 20% battery capacity loss over time

It´s becoming obvious, that an increase of hover time by 30 seconds (60 to 90) reduces the range by 25 km (table 2 (2)). The more realistic 120 seconds hover time results in 147 km range (table 2 (6)). Setting the de-charge level to 20%, which is much more realistic from operational safety perspective leads to a minor decrease of 10km range, (table 2 (7)).

If the more realistic combination of 120 seconds hover and 20% minimum de-charging is taken into account, the overall range is reduced to 113 km instead of 181 km (table 2 (11). This significant reduction in range can be compensated by an increase of battery mass, as done by Lilium with the reduction from 7 to 5 seats, leading to an increase in available battery mass of 1153kg instead of 953kg (table 2 (13)).

In the last line of table 2 (16), considering the previously discussed capacity reductions due to packaging (30%), integration losses (15%) and safety power reserves (20%) a 5 seater with future 400 Wh/kg (6 years from 2022) installed cell density will end up with 58 km range. This parameter setting shows, that more realistic power installation, decharge level and power reserve will result in significant shorter flight distance than announced by Lilium.

Resuming all these aspects for a today´s battery capacity of 270 Wh/kg an operational range of much less than 150 km must be considered as more realistic.

Table 2 (1) – (4) show that an increase in hover time reduces the range most. A change from 7 to 5 seater provides more battery mass and recovers the previous range losses (table 2 (13) – (16). However, if packaging and integration losses are considered too, the with 3 years efficiency improvement of 7% per year (i.e. 330 Wh/kg) a range of only 19 km may be achieved.
All these variations conclude in the expectation, that depending on the assumptions for packaging losses, integration losses, hover time, decharge level and power reserve a 5 seater may achieve a range between 19 and 58 km, which is far below 100 km and the most realistic expectation with todays technologies. It also is in the same range like the volocopter vehicle with about 27km with todays technologies.
Finally, from certification point of view a reduction in range or cruise speed will not inhibit a certification but reduce the mission performance for the operator.
Lilium has responded to these considerations stating, that they will be compliant to the new EASA regulation, [8]. This would be achievable. However, this new regulation requires from the developer and operator, that they set parameters in such a way, that the requirements will be fulfilled. At the end Lilium has to adapt the parameter settings to more realistic and lower values, e.g. as it is described here.

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