INITIAL SIZING FOR A FAMILY OF HYBRID-ELECTRIC VTOL GENERAL AVIATION AIRCRAFT

D. F. Finger, F. Götten, C. Braun
FH-Aachen, Institute of Aircraft Engineering
Hohenstaufenallee 6, 52064 Aachen, Germany

C. Bil
RMIT University, School of Engineering
Plenty Rd, Bundoora, VIC 3083, Australia

Abstract

For vertical take-off and landing (VTOL) aircraft, the power needed for vertical take-off is much greater than the power needed for cruise. This power-matching problem can be solved with a balanced hybrid-electric propulsion system. However, there is a trade-off between take-off weight, wing loading, battery technology and range. This paper applies a new initial sizing algorithm for transitioning VTOL aircraft with hybrid-electric propulsion systems, including serial-hybrid and parallel-hybrid configurations. Exemplarily, a family of transitioning VTOL aircraft, intended for urban air mobility (air taxi) operations is designed. Results indicate that hybrid-electric propulsion systems must be considered for future mid-range VTOL aircraft. Very short missions favor fully electric propulsion systems, as this configuration avoids the complexity of a hybrid.

Nomenclature

AoA = angle of attack
AR = aspect ratio
BSFC = brake specific fuel consumption
C = cruise
c_D = coefficient of drag
c_L = coefficient of lift
c_P = coefficient of pressure
e = Oswald efficiency factor
EM = electric motor
H_E = hybridization of energy
H_P = hybridization of power
ICE = internal combustion engine
k = induced drag factor
L = lift
L/D = lift-to-drag ratio
m = mass
min = minutes
MSL = mean sea-level
MTOM = maximum take-off mass
ODM = on-demand mobility
P/W = power-to-weight ratio
PH = parallel-hybrid
PL = payload
R = range
S = area
SH = serial-hybrid
t/c = thickness-to-chord ratio
TAS = true airspeed
TLAR = top-level aircraft requirement
TRL = technology readiness level
UAM = urban air mobility
VTOL = vertical take-off and landing
W = weight
W/S = wing loading
w_0 = design gross weight

1. INTRODUCTION

The conventional concept of air taxi operations (presented e.g. in [1]) is currently completely overthrown by a new generation of vertical take-off and landing (VTOL) aircraft. With a focus on very low range, electric and hybrid-electric propulsion becomes a suitable option and makes for an interesting business proposition for urban air taxis. The concept of VTOL air taxis was popularized largely by Uber with their 2016 white paper [2]. These air taxi operations are also referred to as urban air mobility (UAM) or on-demand mobility (ODM) [3].

Intra-city air services are proposed mainly for commuting [4]. As a result from urbanization, the extend of urban area has become quite large. For example, the San Francisco bay area or the Los Angeles region require aircraft with a maximum range of about 100 km [4]. Such distances are best served with aircraft that can transition between the inefficient thrust-borne flight and the much more efficient wing-borne flight: i.e. transitioning VTOL aircraft. Some sources call transitioning VTOL aircraft ‘convertiplanes’ or ‘hybrid aircraft’ and many different configurations are used [5] [6]. While rotorcraft are sometimes referred to as “VTOL aircraft” as well, in this paper the abbreviation will be used exclusively for fixed wing aircraft that can switch between hover and wing lift.

For flying very far and very fast, conventional propulsion systems based on hydrocarbon fuels are extremely well suited and there is little to no advantage gained by applying hybrid-electric propulsion systems studies [7].
For short range missions, and for missions that require a lot of excess power for a short period, different results are expected. Examples for such missions are UAM VTOL missions.

While some companies involved in UAM (e.g. Uber) categorically reject hybrid-electric aircraft, some others (e.g. Bell) see a market for such systems.

To operate aircraft in an urban environment, several conditions have to be met: Of course, as for all aviation systems, safety is paramount, but another key priority is to keep the impact on the urban population minimal. Therefore, the key features are low noise and a small footprint. Since the footprint is determined very early in the design process and highly driven by the top level aircraft requirements, this is usually the first parameter to be evaluated and traded against the requirements.
A significant noise reduction can be obtained by low disk-loading propulsors and new propulsion configurations. While the fully electric propulsion system is considered superior to conventional combustion engines, hybrid-electric propulsion systems also offer the potential to reduce noise while offering better flight performance.

The aim of this paper is, therefore, to analyze the design space of urban air taxis and identify the strengths and weaknesses of the different approaches to VTOL propulsion. A new initial sizing methodology will be applied to the design of a family of transitioning VTOL aircraft, intended for urban air taxi operations. Such aircraft will carry 2-6 passengers over distances between 50 km and 500 km.
The new sizing algorithm is suitable for the design of VTOL aircraft and considers general aviation class aircraft with hybrid-electric propulsion systems, including serial-hybrid and parallel-hybrid configurations. This enables sizing studies with respect to a wide range of aircraft attributes. This paper will highlight the impact of the following parameters on aircraft mass and size:

1) Number of passengers (including pilot): 2, 4, 6
2) Design range (without reserves): 100 km, 500 km
3) Propulsion system:
    a. combustion engine
    b. fully electric
    c. parallel-hybrid electric
    d. serial-hybrid electric
4) Technology level: 2020, advanced

This paper is structured the following way: Following this introduction, an overview of the design space is provided and three notional aircraft concepts are presented in Section 2. In Section 3, the methodology for the sizing and technology factors are discussed. Then in Section 4, the sizing results are carefully assessed and the findings are explained. Finally, Section 5 gives a comprehensive conclusion.

2. TRANSITIONING VTOL CONCEPTS FOR URBAN AIR MOBILITY

In this chapter, an overview of the design space will be provided. First, the propulsion configurations for VTOL are discussed and a short summary of hybrid-electric propulsion systems is given (Section 2.1). Then, a typical UAM mission is described in detail (Section 2.2). Finally, the three notional concepts for this sizing study are presented in Section 2.3.

2.1. Propulsion Configurations

2.1.1. Propulsion Configurations for VTOL

The search for the best configurational choice for aircraft with VTOL capabilities has produced a wide variety of different designs [5]. Many readers are familiar with the so-called “Wheel of VTOL” (see e.g. [8], originally prepared by the McDonnell Aircraft Company in 1967). It shows over 60 VTOL concepts that were supposed to radically change the way of air transportation. Today the graphic is often called the “Wheel of Misfortune”, because almost all the concepts failed. Only four VTOL aircraft reached series production: The BAe Harrier, the Yakovlev Yak-38, the Bell-Boeing V-22 and Lockheed Martin’s F-35B. While several new concepts are under development right now, this shows how hard it is to produce VTOL aircraft.

The reason why the design of VTOL aircraft is so challenging is simple physics. This is explained well in [9] and is therefore cited here. “VTOL aircraft require a thrust-to-weight ratio greater than unity for the vertical part of their mission, however, once transition to forward flight is commenced, typically not more than a thrust-to-weight ratio of 0.1 (depending on the achieved L/D – a L/D of 10 is assumed here) is needed to sustain steady flight. Due to this huge gap in required power, a single propulsion system for both hover flight and cruise flight suffers from reduced efficiency, as its primary operation points are very far from each other.” [9]

“Hybrid propulsion options (meaning electric lift motors and combustion engines for endurance flight) are used frequently and minimize the weight impact. Because electric motors have a vastly higher power-to-weight ratio than internal combustion engines (currently about 5 kW/kg vs. 1 kW/kg), they are very much suited for this application. Another benefit of using electric motors for short durations, is their ability to operate in overload conditions for a short time. While this heats up the motors significantly, this can be of benefit in case of an engine failure. This is not possible for a traditional combustion engine.” [9]

While the configuration design of VTOL aircraft is discussed extensively in literature (e.g. [5] or [10]), the basic definitions, as well as pros and cons of certain configurations relevant to this paper will be presented here in an abbreviated form.

There are three “classical” methods to enable VTOL capability for any aircraft:

1) Lift + Cruise (L+C)
   A separate hover system is added to the aircraft. The cruise propulsion system does not contribute to the powered lift. Advantages are the simplicity and the ability to size each propulsion system for its specific constraints. Disadvantages are the added weight and the need for internal volume.
2) Lift = Cruise (L=C)
   In this configuration the aircraft uses the same propulsion system for both cruise and hover. The advantage is, that no additional systems are required. However, the engines are then poorly matched in cruise. This is a problem for combustion engines, as

they cannot be throttled back efficiently. Electric motors only suffer insignificantly from this problem.

3) Lift + Lift/Cruise (L+L/C)
   A lift system is added to the airframe but is supplemented in hover by the cruise propulsion system. This is obviously the most efficient combination of the previous approaches, however, it is also the most complex to design and to operate.

With hybrid-electric propulsion systems, the boundaries between the L=C and the L+L/C configuration diminish. Usually, for aircraft with combustion engines, one of the reasons why the L=C layout is chosen, is to avoid shutting down an engine. This is, of course, much less of an issue if electric motors are used. A shutdown of engines in flight is considered very unconventional for traditional propulsion systems, but perfectly acceptable for electrical machines.
Therefore, if an aircraft like the Ling-Temco-Vought XC-142 was made into a distributed propulsion electric VTOL aircraft, it would probably no longer operated as a L=C but as a L+L/C configuration.
This shows how the design space of VTOL propulsion configurations is transformed by electric systems.

2.1.2. Hybrid-Electric Propulsion Configurations

Just as there are multiple options for the lift and cruise propulsion systems to work together, there are multiple options to join an electric motor (EM) with an internal combustion engine (ICE) [11].

1) Parallel Hybrid
   ICE and EM work in conjunction. They can be coupled to the same propulsor via a gearbox, or operate independently beside ("parallel") each other. In both cases, shaft power is delivered directly to the propulsor. The electric motor is fed by a battery.
2) Serial Hybrid
   An ICE is used to generate electric energy for the EM, which drives the propulsor. The generator is typically supplemented by a battery to allow the electric motor to deliver more than the rated power of the ICE.
   If no battery is used, and EM and ICE are of equal size, the term Turbo-electric propulsion system is used sometimes.

If these hybrid propulsion systems can be analyzed, naturally the fully-electric and fully conventional configurations can be explored, as well. This is done in this paper by using a new sizing methodology, published in [12].

2.2. Mission

For the sizing studies of Section 4, two different missions are considered. Mission 1 has a very low range requirement (100 km), but demands a relatively high cruising speed (150 mi/h / 240 km/h) and is directly based on Uber's sizing mission [13].
To assess the impact of longer flights, mission 2 is introduced. It is similar to mission 1, except for a 5x longer cruise stage. Thus, the range is changed to 500 km (segment 4 in Table 2). Correspondingly, in segment 9), the cruise distance to an alternate landing site is increased to 50 km.
Both missions are flown using standard atmospheric conditions. Take-off is at MSL.
A tabular and graphical overview of the missions is provided in Table 1 and Figure 1, respectively.

Table 1 – Mission Definition

	Segment	Distance [km]	Speed [m/s]	Altitude AGL (ending) [m]
1	Ground Taxi (60 s)	no range credit	2	0
2	Take-off, Hover, Transition (90 s)		0 to 1.2 v_{Stall}	100
3	Accelerate, Climb		v for best climb rate	300
4	Cruise	100 (Mission 1) / 500 (Mission 2)	67	300
5	Decelerate, Descend	no range credit	v for best range	100
6	Transition, Hover (90 s)		1.2 v_{Stall} to 0	0
7	Hover, Transition (90 s)		0 to 1.2 v_{Stall}	100
8	Accelerate, Climb		v for best climb rate	300
9	Cruise	10 (Mission 1) / 50 (Mission 2)	67	300
10	Decelerate, Descend	no range credit	v for best range	100
11	Transition, Hover, Landing (90 s)		1.2 v_{Stall} to 0	0
12	Ground Taxi (60 s)		2	0

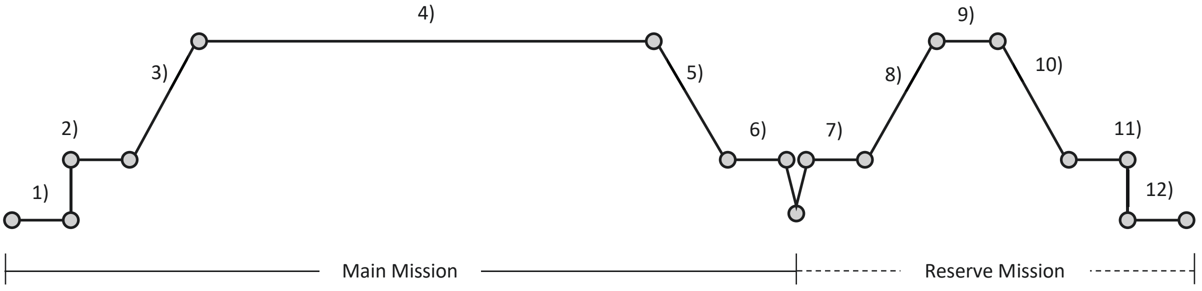


Figure 1 - Mission Definition

The missions consist of the following segments:

Main Mission

1) Ground taxi to take-off position
2) Take-off, hover (out of ground effect) and transition to fixed wing flight
3) Accelerate and climb at best rate speed to altitude
4) Cruise at 240 km/h
5) Decelerate and descend at best range speed
6) Transition and hover (out of ground effect), balked landing

Reserve Mission

7) Hover (out of ground effect) and transition to fixed wing flight
8) Accelerate and climb at best rate speed to altitude
9) Cruise to alternate (10% of mission range) at 240 km/h
10) Decelerate and descend (best range speed)
11) Transition and hover (out of ground effect), landing
12) Ground taxi to parking position

The reserve mission is very short, when compared to existing regulations. For example, 14 CFR 91.151 requires a reserve of 20 min flight time at cruise speed for VFR rotorcraft. In contrast, the 10 km cruise to an alternate landing site used in mission 1 is covered in 2.5 min.
However, in 20 min at cruise speed, the aircraft would cover 80 km, a requirement that can also be considered unreasonable, since this constitutes 80% of the design range. Clearly, new regulations must be put in place for VTOL aircraft with very short ranges. Since Uber is in talks with the FAA, the authors feel confident to use Uber's assumptions, until new regulations are in place.

2.3. Notional UAM VTOL Concepts

For the sizing study, three concept aircraft have been designed. A 2-seat, a 4-seat, and a 6-seat UAM VTOL aircraft. The designs are discussed in the following subsection. All designs are tilt-wings with a L=C (or L+L/C if electric motors are shut down) type VTOL aircraft.
The concepts will be used for all propulsion configurations. Fully-electric and conventional aircraft are, naturally, only equipped with either EMs or ICEs in their nacelles. Serial-hybrid concepts will use an ICE and generator, which are installed in the fuselage to power EMs in the nacelles.
The parallel hybrid concepts could use different arrangements: Either some nacelles are equipped with EMs and some are equipped with ICEs, or a combination of ICE and EM, coupled with a gearbox, could be installed in each nacelle. For sizing purposes, the difference is small. Thus, the only assumption for the parallel-hybrids is, that EMs and ICEs work in conjunction.

2.3.1. 2-Passenger Concept

The 2-passenger (200 kg payload) concept is shown in Figure 2. The configuration is a traditional tilt-wing with four lift motors mounted to the wing, and an additional motor, which provides stability in hover, mounted on top of the highly tapered rear fuselage. Passengers are seated in tandem to reduce frontal area.
A high aspect ratio wing is used for low induced drag. For structural considerations a relatively thick airfoil (NASA LS(1)-0417 - 17% t/c) is used.

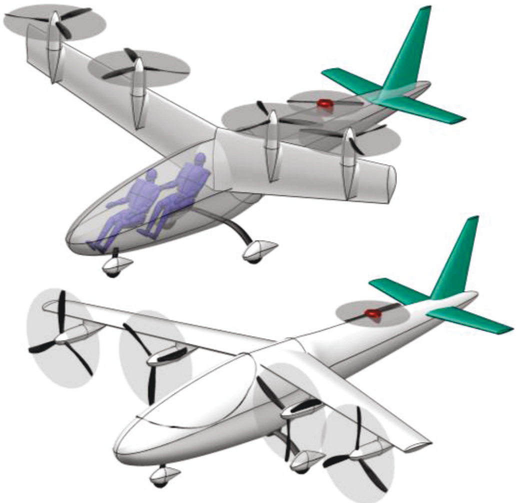


Figure 2 – 2-Passenger Concept – Hover (top) and Flight (bottom)

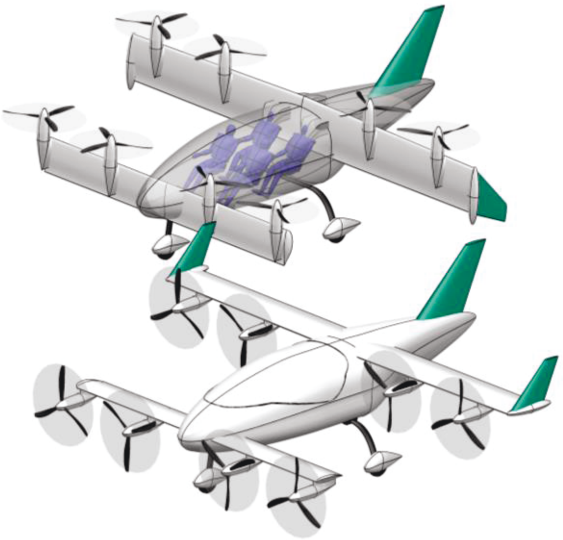


Figure 3 – 4-Passenger Concept – Hover (top) and Flight (bottom)

This helps to limit center of gravity travel due to different payload masses. For stability, a conventional tail is chosen. The aircraft is equipped with a well faired, fixed tricycle gear. The gear allows for easy ground maneuvering and emergency landings if a vertical landing should not be possible. A fixed gear is selected over a retractable gear to minimize weight [14]. For VTOL aircraft a low empty weight is paramount, having more impact on sized weight than an improvement in L/D [9].
The outboard propellers turn against the wingtip vortex. While they are not located at the very tip of the wing, this still might contribute to a slight reduction in induced drag.

2.3.2. 4-Passenger Concept

The 4-passenger (400 kg payload) concept is shown in Figure 3. Like the 2-passenger concept a tilt wing approach is used. The configuration is similar to A³'s Vahana [15]. Tandem tilting wings are used, with the passenger compartment located in between. The 4 passengers are seated in a side-by-side layout, as this keeps the cabin short and reduces the possible center of gravity travel. This is quite important for VTOL aircraft as they need to be balanced in both forward flight and hover. Thus the center of gravity must be close (but forward) to the neutral point in wingborne flight and close to the center of thrust with the wings tilted.

Both wings use the thick LS(1)-0417 airfoils. To provide adequate stall characteristics, the forward wing is heavier loaded than the rear wing. By flying at a higher lift coefficient compared to the rear wing, this lifting surface will stall first, producing a nose-down pitching moment, which alleviates the stalled condition. No winglets are added to the front wing, as these would decrease yaw-stability. 8 propellers provide thrust in hover and forward flight. Four are mounted to the forward wing, and four on the rear wing. Again, the outboard propellers are intended to rotate against the wingtip vortex. The rear wing features winglets to further decrease the induced drag, while keeping the span, and thus the footprint on the ground, small. The winglets contribute to the lateral stability. However, a dedicated vertical tail is required for acceptable stability.

A landing gear similar to that of the 2-passenger concept is used.

2.3.3. 6-Passenger Concept

The 6-passenger (600 kg payload) concept is shown in Figure 4. Once again the tilt wing approach for VTOL is used. The aircraft is quite similar to the 4-passenger concept, therefore only the key differences are highlighted. The same side-by-side passenger compartment is used, but the cabin grows longer. Because the aircraft cannot be expected to always operate at full capacity, a wider center of gravity travel must be designed for as a consequence. To reduce that impact and to improve stability and trim, a third lifting surface is added on top of the vertical stabilizer. This makes this concept effectively a three-surface configuration with a vertical stagger of the wings from low to high. The vertical tail needed to be upsized compared to the 4-passenger concept due to the longer fuselage, however, the required area is reduced by the increased effectiveness of the vertical tail, due to the endplate effect of the top-mounted horizontal stabilizer.

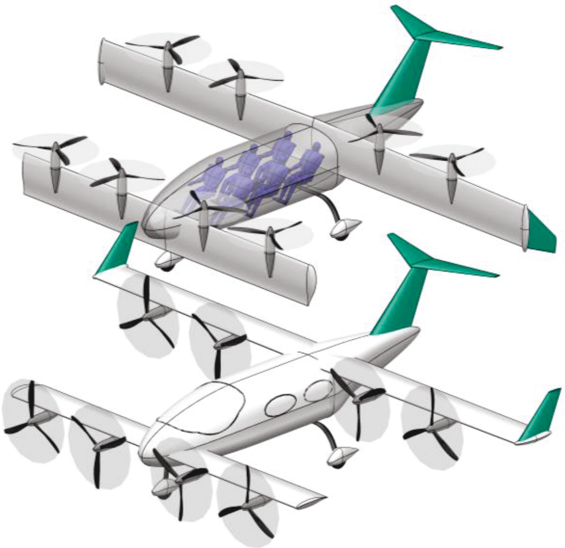


Figure 4 – 6-Passenger Concept – Hover (top) and Flight (bottom)

3. METHODOLOGY

"In aircraft conceptual design, the initial sizing process is used to determine values for maximum take-off weight (MTOM), wing reference area and thrust of a new aircraft concept based on certain top-level aircraft requirements (TLARs). The results from the initial sizing will be used to draw the first design. Then, a more detailed sizing process is started, which leads to a refined design." [7]

At the Institute of Aircraft Engineering at FH Aachen, a tool for the initial sizing of general aviation aircraft has been developed. It allows the sizing of conventional, fully-electric and hybrid-electric aircraft. The methodology of the sizing process is documented in [12].

Good results for conventional take-off and landing general aviation aircraft were achieved, as shown in [7], [16] and [17].

Recently, the tool has been expanded to allow the sizing of VTOL aircraft. The special considerations for the sizing of VTOL vehicles are explained in [9] and [5]. Since these methods are well documented, no further explanation of the tool will be provided here.

3.1. Top Level Aircraft Requirements

The matching of an aircraft's size to its performance requirements is often considered one of the most important calculations in aircraft design [10]. This means, that reasonable requirements and technology assumptions must be used.

The mission that the VTOL air taxis must fly is already specified in section 2.2. This takes care of the mission performance part of sizing. However, this still leaves the point performance [18] to be calculated.

Of course, for VTOL aircraft, the required power is set by the powered lift part of the mission (see next subsection). However, for the assessment of the cruise performance, the calculations are still useful. Since the matching diagram is different for each aircraft concept, only a qualitative example (Figure 5) is provided here.

This figure is constructed only with the basic set of constraints required for VTOL aircraft. Naturally, no take-off distance constraint is used since this limit is replaced with the hover constraint.

The performance requirements used for the sizing study are shown in Table 2.

Please note, that a stall speed constraint is used. This speed is set at half the cruise speed, to allow transition from thrust-borne to wing-borne flight at reasonable forward speed. Also, this speed will still allow an emergency landing in case the hover system should fail. While it might be possible to relax this stall speed constraint, it was elected not to do so for this study due to safety considerations.

Table 2 – Top-Level Aircraft Requirements

Cruise Speed (TAS)	67 m/s
Rate of Climb at MSL	2.5 m/s
Take-Off Ground Roll	not applicable
Stall Speed	33.5 m/s (v_{cruise} * ½)

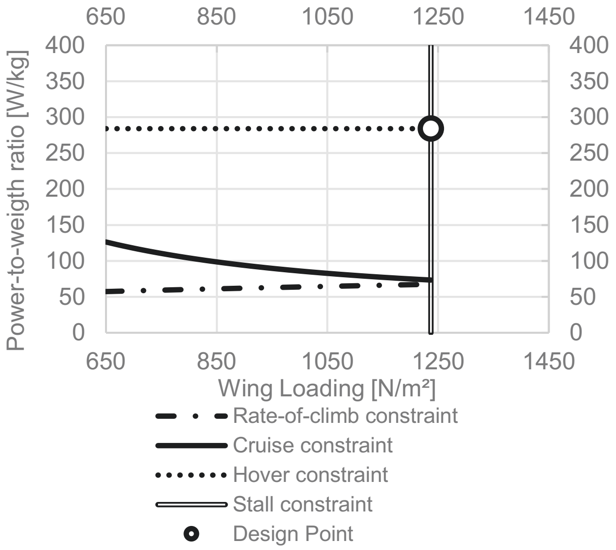


Figure 5 – Matching Diagram (Example)

3.1.1. Surplus Thrust and Disk Loading

For hover, the required power is calculated with a thrust-to-weight ratio (surplus thrust factor) of 1.2. This is about the lowest tolerable factor for VTOL aircraft if hot day conditions are considered [10]. Additionally, the computations assume figure of merit M = 0.8. It is not trivial to achieve such an efficiency for propellers that must operate at hover and fast forward flight. Likely, a variable pitch propeller must be used. Therefore, this technology assumption is quite favorable for the new concepts.

A low disk-loading of 75 kg/m² is used for all concepts. Low disk-loading-propellers can operate efficiently at low tip-speeds. Thus, the noise signature can be significantly lowered [19].

3.1.2. Design Point

The classical logic for selecting the design point is simple: First, the lowest possible P/W is selected (smallest engine) and, as a second priority, the highest possible wing loading is chosen (smallest wing) [20].

For VTOL aircraft, the hover constraint is independent of wing loading, thus the highest possible wing loading is always selected (compare Figure 5).

For conventional take-off and landing aircraft, it was shown in [7], [16] and [17] that the traditional logical cannot be used for hybrid-electric configurations, as the optimal design point can be quite different. This study will show, if this is also the case for VTOL aircraft.

To assess the design point for hybrid-electric aircraft, the degree of hybridization of power (H_P) must be introduced as an additional parameter. H_P is the ratio of the installed propulsion power of all electric motors to the total installed propulsion power at the propeller shaft. It is defined and fixed for any aircraft and propulsion system configuration.

For parallel-hybrid aircraft, $H_{P,PH}$ is defined as in Eq. 1.

$$H_{P,PH} = \frac{P_{EM,max}}{P_{max}} \tag{1}$$

Note that for serial hybrid-electric powertrains, H_P, as it is defined in Eq. 1, is always equal to one, since the EM must be able to solely deliver the total installed power. To differentiate between the all-electric powertrain and to size the range extender, a H_P for serial-hybrids, $HP_{,SH}$, is introduced with Eq. 2. It is always greater than one and thus the two hybrid-electric configurations are easily distinguishable by their H_P value.

$$H_{P,SH} = \frac{P_{EM,max}}{P_{ICE,max}} \tag{2}$$

Another helpful parameter when assessing hybrid-electric aircraft is the degree of hybridization of energy $H_{E.}$ The parameter H_E is specified as the ratio of the required transport energy delivered by batteries (non-consumable - E_{nc}) to the total required transport energy E (Eq. 3). H_E can be calculated for the entire flight or a single flight phase, as required and indicates how much the electric part of the propulsion system is used.

$$H_E = \frac{E_{nc}}{E} \tag{3}$$

For this study, the best design point is always selected under consideration of the optimal combination of wing loading, overall power-to-weight ratio and H_P. Optimization criteria is minimal MTOM. The methodology for selecting this optimum design point is described in [12].

3.2. Technology Levels

Because of constant and rapid improvements in the field of electrical system technologies, it is difficult to assess the level of performance that VTOL air taxis can offer, even if only near term projections are made. Therefore, before the performance of any future VTOL aircraft can be analyzed, a reference for the technological assumptions must be set. For the sizing study, two levels of technology – based on year 2020 projections and an advanced level – are used. They are summarized in Table 3.

Table 3 – Technology Levels

Technology Assumption	Technology Level	
	2020	advanced
Motor Specific Power [kW/kg]	5.0	10.0
Battery Specific Energy [Wh/kg]	250	500
Disk Loading [kg/m²]	75	
Combustion Engine Technology	4-stroke ICE	
ICE Specific Power [kW/kg]	1.0	
ICE BSFC [g/kW/h]	300	
$W_{\text{empty without engines}}$ / W_0 [-]	0.743 $W_0^{-0,06}$	

3.2.1. Batteries

The best battery packs today offer an energy density of about 200 Wh/kg. In an Aviation Week article [21], Uber's goals are quoted as "300 Wh/kg at the pack level by 2023". Batteries with 400-500 Wh/kg at pack level, about twice what is available today, are believed to enable widespread use of electric propulsion systems in aviation.

Accordingly, the specific energies used in this study were selected as 250 Wh/kg for the year 2020 technology level and 500 Wh/kg for the advanced technology level.
The battery is sized with respect to the following considerations:

- The full design mission must be flown at the battery's end of life state. At the end of life a remaining capacity of 80% compared to a new battery is assumed.
- The full design mission must be flown with 80% of the remaining capacity. The bottom 20% capacity are considered unavailable. This prevents the battery from deep discharge, and reduces the voltage drop-off at the end of the mission. This is a measure intended to improve both safety and the battery life.
- Thus, only 64% (80% end of life x 80% discharge protection) of the battery capacity are used for the design mission.
- Missions start with the battery fully charged.

3.2.2. Motors

For electric motors, similar technological assumptions were made. A specific power of 5 kW/kg is already achieved by Siemens with their motor for the electric Extra 300 [22]. While this is still a prototype, its TRL is assumed to improve by 2020. At the advanced level, the same improvement as for batteries is assumed and the specific power is doubled to 10 kW/kg.

3.2.3. Combustion Engines

Because this paper explores the influence of electric systems on the performance of aircraft, the state of technology of the conventional combustion engines is kept constant to avoid too many parameter variations. Combustion engine specific power and fuel consumption are held constant at the values shown in Table 3 . For this study, typical values obtained by traditional four-stroke aviation engines (see e.g. [20]) were selected.

3.3. Drag

All vehicle are sketched in OpenVSP. Due to the unusual configurations the authors decided against a classical drag buildup to determine the drag polar. All concepts have underwing engines, which contribute considerably to interference drag. Also, the 4 and 6 passenger concepts generate their lift with tandem wings, the 6 passenger model even has a third lifting surface for stability on top of the vertical tail. These lifting surfaces interact with each other significantly, but those effects are not captured with regression analysis based drag modeling methods. Götten et al. [23] highlight that drag build-up models can give significantly wrong results, when applied to non-standard aircraft configurations. Therefore, Reynolds Averaged Navier Stokes (RANS) CFD simulations are carried out, to determine the drag polar of the concepts.

Four operating points of each design are calculated using a RANS-based CFD method: -4°, 0°, 4°, and 10° angle of attack (AoA). Then a curve fit is applied to find the lift coefficient at minimum drag $c_{L,minD}$, the minimum drag coefficient $c_{D,min}$, and Oswald's efficiency number e. Those parameter allow the construction of the drag polar in its adjusted form (Eq. 4 and 5):

$$c_D = c_{D,min} + k \cdot (c_L - c_{L,\mathrm{minD}})^2 \qquad (4)$$

$$k = \frac{1}{\pi \cdot AR \cdot e} \qquad (5)$$

Typically, a penalty would need to be applied to drag values found from this CFD modelling, since drag from leakage and protuberance, cooling, propeller interaction and other miscellaneous drag sources are not accounted for. However, since these concepts were not detailed, nor was any optimization performed to improve aerodynamic performance, it is likely that these concepts could be refined to deliver the calculated drag values under real world constraints. Because this study is intended to highlight the sizing implications of using hybrid-electric propulsion systems for the ODM class of aircraft and does not attempt to model a certain existing aircraft as accurately as possible, the obtained accuracy is deemed acceptable.

3.3.1. Simulation Approach

The OpenVSP geometry is transferred to Siemens' simulation package StarCCM+ via the .stl export. Then, the flow field about the models is simulated using a steady-state RANS approach, using the SST k-ω (Menter) turbulence model. Further details on this methodology can be found in Hirsch [24]. The RANS equations are solved using the assumptions of incompressible flow with a Semi Implicit Method for Pressure Linked Equations (SIMPLE) approach.
The cylindrical freestream flow field is divided into finite volumes using StarCCM+'s unstructured Cartesian cut cell mesher with a dedicated prism mesh, which discretizes the boundary layer. Boundary layer thickness is determined using the methods from Schlichting [25] and a low y+ approach is used to obtain y+ values below 1 on the aircraft's surfaces. The surface mesh size was adjusted to give ~100 cells over the wing's chordwise direction.
Lift and drag forces on the models' bodies were obtained by integrating the cells' shear stress tensor and their pressures. Grid independent results are obtained for mesh sizes of about 17 million cells.
Further information on the simulation parameter is presented in Table 4.
The simulation results are presented in the next section, along with the sizing results.

Table 4 – Simulation Parameter

Simulation Parameter	
Free stream velocity	66 m/s
Reference pressure	101325 Pa
Density	1.225 kg/m³
Dynamic viscosity	1.81205 x 10^{-5} Pa s
Turbulence intensity (inlet)	1%
Turbulent viscosity ratio (inlet)	10

4. SIZING STUDIES

In this section the sizing methodology [12] is applied to study the implications that hybrid-electric powertrains have on the UAM class of VTOL aircraft.

The 2 passenger concept will be investigated first, followed by the 4 and 6 passenger concepts.

The aerodynamic data obtained from the CFD analysis is used for the sizing study and the drag coefficients are held constant, regardless of the sizing result. This approach favors aircraft with higher wing loadings, since drag coefficients are referenced to the wing area. However, as the concept aircraft as drawn and as analyzed are reasonably close to the sizing results, this systematical error is not significant in the overall scope of accuracy. Especially for initial sizing, this methodology is industry practice and well established.

The sizing results are presented in tables – e.g. in Table 5. This table – and every subsequent data table – is structured in the following way: The columns contain the sizing results for the different propulsion concepts for the given payload (PL) and range (R). Each propulsion concept (parallel-hybrid, serial-hybrid, and fully-electric) is listed twice. Once for the year 2020 technology level, and once for the advanced technology level, as specified in Section 3.2.

A "conventional" VTOL aircraft, powered by internal combustion engines (ICE) is sized to the same requirements to provide a baseline against the electrified propulsion systems can be compared against. The relative changes in MTOM, total transport energy consumption, and fuel mass, compared to this baseline, are given in the bottom section of the table.

4.1. 2-Passenger Concept

The results of the CFD simulations and the drag polar analysis are shown in Figure 6. The 2-passenger concept reaches a maximum L/D of 14.5 at a c_L of 0.85.

4.1.1. Mission 1 – 100 km Range

This set of requirements results in the smallest aircraft in this sizing study. This is evident by the lowest required range and the lowest payload that needs to be carried. The results are shown in Table 5.

2020 Technology

For the year 2020 technology level, neither a parallel-hybrid powertrain, nor a fully-electric powertrain make sense.

The fully-electric design simply would not close for this set of requirements and technological assumptions. The battery specific energy of 250 Wh/kg is not sufficient to allow the gross weight to converge.

The parallel-hybrid system was optimized with regard to the power-split between ICE and electric machine. The lowest weight solution is reached with a hybridization factor of 0 – a conventional, entirely fuel based propulsion system is optimal for the given set of requirements.

The conventional baseline aircraft converges at ~1533 kg. For this very short mission, it only needs to carry ~55 kg of fuel. This fuel fraction of ~3.5% is very low compared to traditional aircraft. The very short reserve mission enables such a low fuel fraction. In practice, such an aircraft would be designed with a higher fuel fraction to offer more range flexibility at a slight increase in aircraft size.

The serial-hybrid design is ~43% heavier compared to the conventional design. However, it still consumes about 10% less energy than the conventional design. This is due to the higher efficiency of electrical systems, compared to internal combustion engines.

Advanced Technology

For the advanced technology level, the results change completely. The conventional design is now the heaviest solution, while the use of electric propulsion technology results in weight and energy savings.

The parallel-hybrid comes in at the lowest gross weight, offering a 46.6% gross weight reduction. The serial-hybrid and fully electric designs offer a 41.5 and 34.4 reduction, respectively.

The hybrid designs have a very small combustion engine, which can just support the aircraft in cruise flight, for the hover portions, energy is supplied by the battery. The parameter $HE_{average}$ indicates the energy-split between fuel and battery, for both hybrid designs just half of the total energy is provided by fuel.

The fully-electric design profits from the low motor weight and the reduced weight of its energy storage, compared to the 2020 technology level. This design consumes half the energy of the parallel-hybrid and 85.4% less energy than the conventional ICE driven design. This would mean, that six of these 2-passenger VTOL aircraft could be operated and still consume slightly less energy than a single, directly comparable aircraft operating on carbon fuel.

This shows the massive impact that future improvements of the new propulsion technologies can have.

4.1.2. Mission 2 – 500 km Range

For mission 2 the range flexibility is improved considerably. The results are shown in Table 6.

The increase range causes a weight increase of ~922 kg of the conventional design to 2454 kg.

The fully-electric concepts do not converge for this set of requirements, regardless of technology level.

2020 Technology

At the short term technology level, the parallel-hybrid design does converge to a lower weight than the conventional baseline. It weighs 16% less, while using half the fuel. It also gains just half the weight of the conventional design by the five-fold range increase.

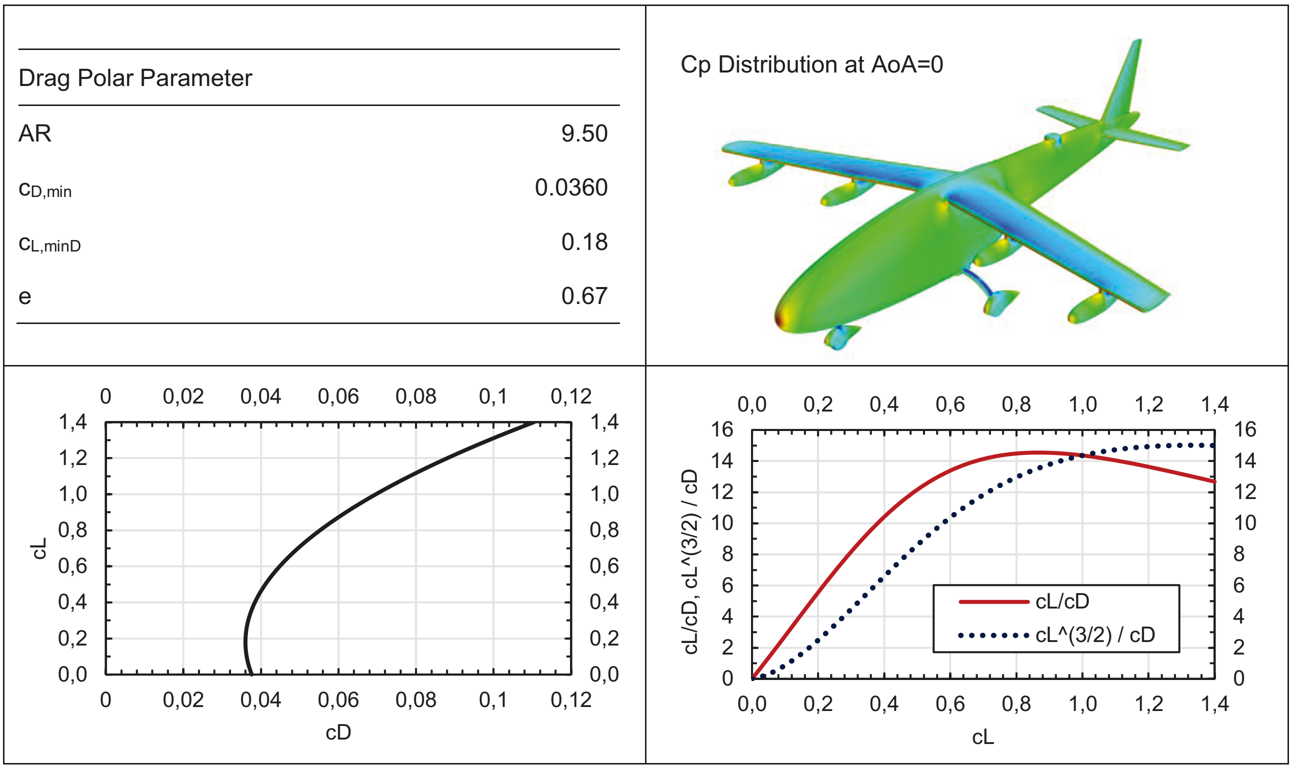
The serial-hybrid design is almost 30% heavier than the baseline and uses about the same amount of energy.

Both hybrid-electric aircraft have about 20% of their total energy supplied by batteries.

Advanced Technology

The hybrid-electric designs are significantly lighter at the advanced technology level compared to the baseline aircraft. The much lighter components allow for a vast improvement in both MTOM and energy consumption. The weight gain from mission 1 to mission 2 is very low, thus a higher range and the according flexibility of operations comes at a much reduced price compared to the conventional design.

Compared to the 2020 results, the weight of the parallel-hybrid is halved, and the serial-hybrid only weights a third.



Drag Polar Parameter	
AR	9.50
$c_{D,min}$	0.0360
$c_{L,minD}$	0.18
e	0.67

Figure 6 – Aerodynamic Data – 2-Passenger Concept

Table 5 – Sizing Results – 2-Passenger Concept – 100 km Mission

Technology	2020			Advanced Technology			Conventional
PL 200 kg R 100 km	Parallel Hybrid	Serial Hybrid	Fully Electric	Parallel Hybrid	Serial Hybrid	Fully Electric	ICE
MTOM [kg]	parallel-hybrid design does not outperform the conv. baseline	2188.98	fully electric design does not converge	817.97	896.89	1005.94	1532.53
W/S [N/m²]		1237		1237	1237	1237	1237
P/W [W/kg]		284.0		284.0	284.0	284.0	284.0
HP [-]		384%		74%	394%	100%	-
$HE_{average}$ [-]		49%		49%	50%	100%	-
Energy [MJ]		1995.20		699.77	817.15	326.82	2232.15
m_{fuel} [kg]		41.45		14.35	16.91	0.00	55.16
$m_{battery}$ [kg]		551.92		103.38	115.24	283.70	-
Relative change compared to conventional baseline							
ΔMTOM		42.8%		-46.6%	-41.5%	-34.4%	
ΔEnergy		-10.6%		-68.7%	-63.4%	-85.4%	
Δm_{fuel}		-24.9%		-74.0%	-69.3%	-100.0%	

Table 6 – Sizing Results – 2-Passenger Concept – 500 km Mission

Technology	2020			Advanced Technology			Conventional
PL 200 kg R 500 km	Parallel Hybrid	Serial Hybrid	Fully Electric	Parallel Hybrid	Serial Hybrid	Fully Electric	ICE
MTOM [kg]	2062.55	3176.19	fully electric design does not converge	959.44	1103.97	fully electric design does not converge	2454.04
W/S [N/m²]	1237	1237		1237	1237		1237
P/W [W/kg]	284.0	284.0		284.0	284.0		284.0
HP [-]	68%	364%		74%	384%		-
$HE_{average}$ [-]	19%	20%		20%	20%		-
Energy [MJ]	5076.00	9621.82		2676.84	3476.85		9766.51
m_{fuel} [kg]	118.90	227.28		62.89	82.22		241.34
$m_{battery}$ [kg]	458.92	736.78		114.34	130.04		-
Relative change compared to conventional baseline							
ΔMTOM	-16.0%	29.4%		-60.9%	-55.0%		
ΔEnergy	-48.0%	-1.5%		-72.6%	-64.4%		
Δm_{fuel}	-50.7%	-5.8%		-73.9%	-65.9%		

4.2. 4-Passenger Concept

For the second concept, the results of the CFD simulations and the drag polar analysis are shown in Figure 7. The 4-passenger concept reaches a maximum L/D of 13.9 at a c_L of 0.65.

Compared to the smaller aircraft, the best L/D is moved to lower lift coefficients, which should benefit the cruise performance of the 4-passenger concepts.

The basic trends observed for the 2-passenger concept also apply for the variant with the double payload. The key differences will be pointed out below.

4.2.1. Mission 1 – 100 km Range

The results for mission 1 are shown in Table 7.

2020 Technology

For the year 2020 technology level, again, fully-electric design does not close. The parallel-hybrid system reaches the lowest weight solution with a hybridization factor of 0. Thus, the conventional baseline aircraft is still an excellent design with today's "off the shelf" technology. It converges at ~2702 kg.

The serial-hybrid design is ~35% heavier compared to the conventional design. The weight increase is slightly less than for the 2-passenger concept. The consequence is that for the heavier payload, it consumes about 20% less energy than the conventional design – twice the energy savings of the smaller aircraft.

Advanced Technology

For the advanced technology level, the results are very similar to the smaller concept. The conventional design is heaviest of the set, while the use of electric propulsion technology results in weight and energy savings.

The parallel-hybrid comes in at the lowest gross weight, followed by the serial-hybrid and fully electric designs.

The fully-electric design is the most energy efficient aircraft again.

4.2.2. Mission 2 – 500 km Range

The results for mission 2 are shown in Table 8. The increased range causes a weight increase of ~1220 kg of the conventional design to 3922 kg.

The fully-electric concepts, again, do not converge for this set of requirements, regardless of the technology level.

2020 Technology

The slightly different aerodynamic properties cause the results to vary slightly from those of the 2-passenger concept. The parallel design is ~11% lighter than the baseline while consuming just 54% of the energy.

The weight increase of the serial-hybrid design is less than for the short mission. While the increase is slightly less than a quarter of the MTOM, a reduction in consumed energy of 10% is achieved. This is quite significant, especially since the serial-hybrid counterpart of the 2-passenger concept could only realize a 1.5% energy reduction.

Advanced Technology

The hybrid-electric designs are significantly lighter at the advanced technology level compared to the baseline aircraft. At just 43% of the conventional aircraft's MTOM the parallel-hybrid design uses ~71% less energy. The serial-hybrid still realizes a ~63% reduction at over 50% MTOM saving.

Compared to the 2020 designs, the doubling of battery specific energy and motor specific power results in a gross weight reduction of 51% for the parallel-hybrid and 60% for the serial hybrid.

4.3. 6 passenger concept

For the largest concept, the results of the CFD simulations and the drag polar analysis are shown in Figure 8. The 6-passenger concept reaches a maximum L/D of 13.7 at a c_L of 0.60.

This concept results in the heaviest aircraft. At 5404 kg, the heaviest conventional design is close to the Part 23 weight limit. Still, compared to the previous concepts, the results are very similar.

4.3.1. Mission 1 – 100 km Range

The results for mission 1 are shown in Table 9.

2020 Technology

For the year 2020 technology level, again, fully-electric design does not close and the parallel-hybrid system does not differ from the conventional baseline, which converges at ~3809 kg.

The serial-hybrid design is ~33% heavier but consumes about 21% less energy than the conventional design.

Advanced Technology

For the advanced technology level, the relative changes are almost identical to those of the 4-passenger concept.

4.3.2. Mission 2 – 500 km Range

The results for mission 2 are shown in Table 10. The increased range causes a weight increase of ~1595 kg of the conventional design to 5404 kg.

The fully-electric concepts, again, do not converge for this set of requirements, regardless of the technology level.

2020 Technology

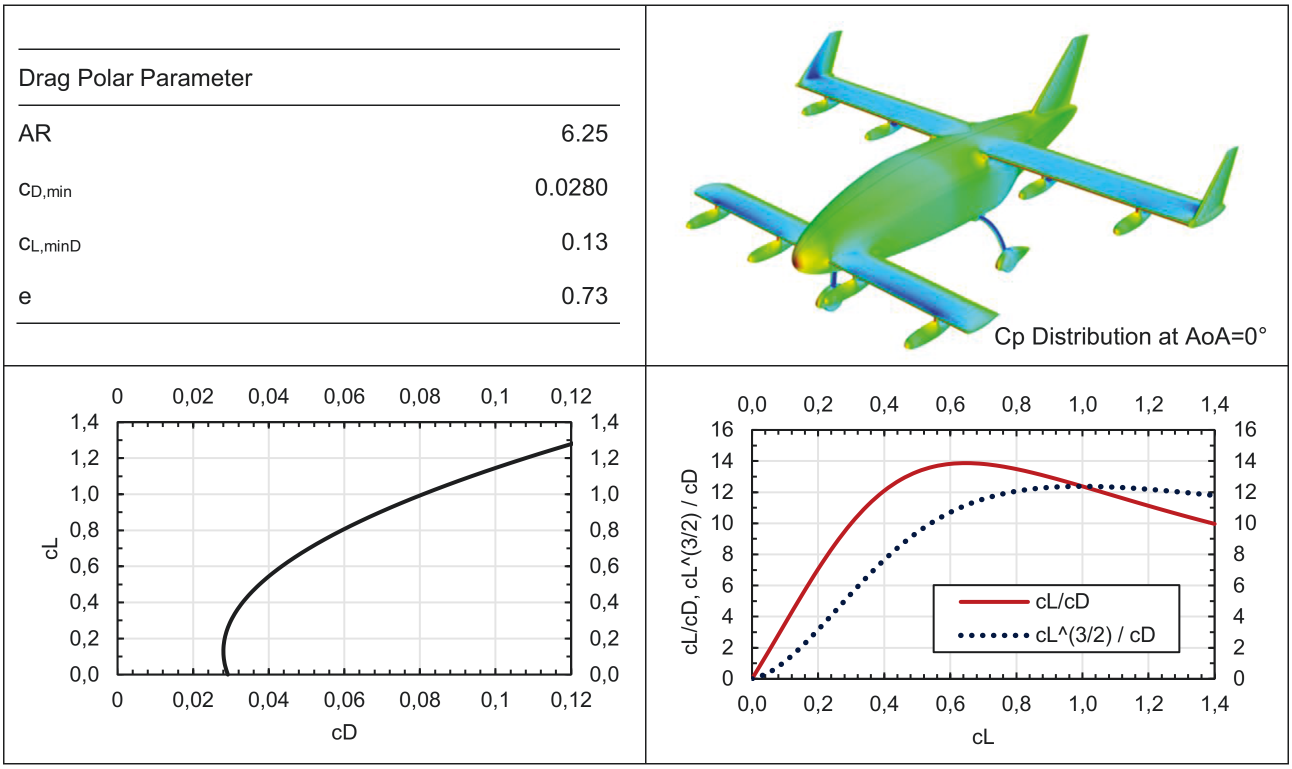
Just as for the short mission, the relative changes are almost identical to those of the 4-passenger concept.

The weight of the serial-hybrid is very high, even beyond the limit of the Part 23 regulations. Thus, even though this design consumes 10% less energy, it is an unfeasible concept.

Advanced Technology

The hybrid-electric designs are significantly lighter at the advanced technology level compared to the baseline aircraft. At just 43% of the conventional aircraft's MTOM the parallel-hybrid design uses ~71% less energy. The serial-hybrid still realizes a ~63% reduction at over 50% MTOM saving.

Compared to the 2020 designs, moving to the advanced technology level results in a gross weight reduction of 50% for the parallel-hybrid and 59% for the serial hybrid.



Drag Polar Parameter	
AR	6.25
$c_{D,min}$	0.0280
$c_{L,minD}$	0.13
e	0.73

Figure 7 – Aerodynamic Data – 4-Passenger Concept

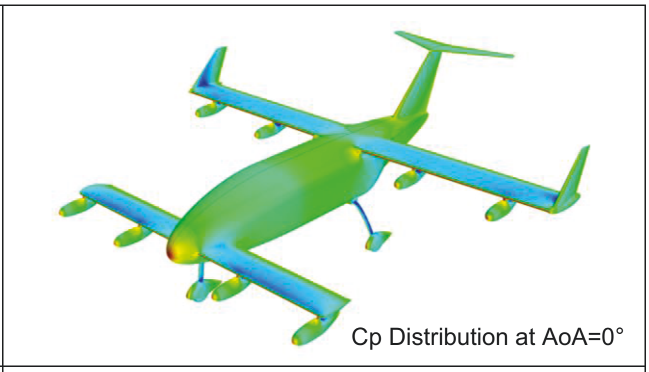
Table 7 – Sizing Results – 4-Passenger Concept – 100 km Mission

Technology	2020			Advanced Technology			Conventional
PL 400 kg R 100 km	Parallel Hybrid	Serial Hybrid	Fully Electric	Parallel Hybrid	Serial Hybrid	Fully Electric	ICE
MTOM [kg]	parallel-hybrid design does not outperform the conv. baseline	3656.68	fully electric design does not converge	1493.06	1610.99	1768.40	2702.30
W/S [N/m²]		1237		1237	1237	1237	1237
P/W [W/kg]		284.0		284.0	284.0	284.0	284.0
HP [-]		430%		77%	444%	100%	-
$HE_{average}$ [-]		53%		53%	54%	100%	-
Energy [MJ]		3055.14		1173.15	1336.38	552.07	3779.52
m_{fuel} [kg]		61.81		23.39	26.85	0.00	93.40
$m_{battery}$ [kg]		961.60		196.81	216.78	479.23	-
Relative change compared to conventional baseline							
ΔMTOM		35.3%		-44.7%	-40.4%	-34.6%	
ΔEnergy		-19.2%		-69.0%	-64.6%	-85.4%	
Δm_{fuel}		-33.8%		-75.0%	-71.2%	-100.0%	

Table 8 – Sizing Results – 4-Passenger Concept – 500 km Mission

Technology	2020			Advanced Technology			Conventional
PL 400 kg R 500 km	Parallel Hybrid	Serial Hybrid	Fully Electric	Parallel Hybrid	Serial Hybrid	Fully Electric	ICE
MTOM [kg]	3487.16	4802.00	fully electric design does not converge	1696.08	1891.65	fully electric design does not converge	3921.79
W/S [N/m²]	1237	1237		1237	1237		1237
P/W [W/kg]	284.0	284.0		284.0	284.0		284.0
HP [-]	72%	406%		77%	430%		-
$HE_{average}$ [-]	21%	22%		23%	23%		-
Energy [MJ]	7712.22	12907.92		4227.63	5303.51		14410.68
m_{fuel} [kg]	178.85	302.29		98.43	124.39		356.11
$m_{battery}$ [kg]	824.20	1172.15		212.30	234.33		-
Relative change compared to conventional baseline							
ΔMTOM	-11.1%	22.4%		-56.8%	-51.8%		
ΔEnergy	-46.5%	-10.4%		-70.7%	-63.2%		
Δm_{fuel}	-49.8%	-15.1%		-72.4%	-65.1%		

Drag Polar Parameter	
AR	6.25
$c_{D,min}$	0.0275
$c_{L,minD}$	0.14
e	0.66



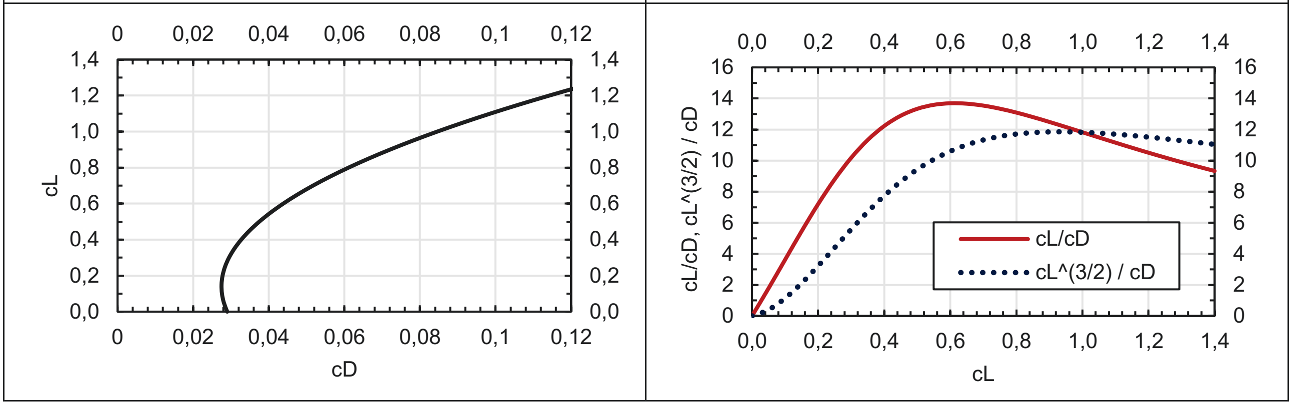


Figure 8 – Aerodynamic Data – 6-Passenger Concept

Table 9 – Sizing Results – 6-Passenger Concept – 100 km Mission

Technology	2020			Advanced Technology			Conventional
PL 600 kg R 100 km	Parallel Hybrid	Serial Hybrid	Fully Electric	Parallel Hybrid	Serial Hybrid	Fully Electric	ICE
MTOM [kg]	parallel-hybrid design does not outperform the conv. baseline	5079.50	fully electric design does not converge	2155.63	2316.97	2534.43	3809.33
W/S [N/m²]		1237		1237	1237	1237	1237
P/W [W/kg]		284.0		284.0	284.0	284.0	284.0
HP [-]		430%		77%	444%	100%	-
$HE_{average}$ [-]		53%		53%	54%	100%	-
Energy [MJ]		4217.90		1684.28	1919.30	790.13	5317.88
m_{fuel} [kg]		85.20		33.52	38.58	0.00	131.41
$m_{battery}$ [kg]		1337.09		284.42	310.99	685.88	-
Relative change compared to conventional baseline							
ΔMTOM		33.3%		-43.4%	-39.2%	-33.5%	
ΔEnergy		-20.7%		-68.3%	-63.9%	-85.1%	
Δm_{fuel}		-35.2%		-74.5%	-70.6%	-100.0%	

Table 10 – Sizing Results – 6-Passenger Concept – 500 km Mission

Technology	2020			Advanced Technology			Conventional
PL 600 kg R 500 km	Parallel Hybrid	Serial Hybrid	Fully Electric	Parallel Hybrid	Serial Hybrid	Fully Electric	ICE
MTOM [kg]	4851.17	6537.66	fully electric design does not converge	2434.23	2702.07	fully electric design does not converge	5404.62
W/S [N/m²]	1237	1237		1237	1237		1237
P/W [W/kg]	284.0	284.0		284.0	284.0		284.0
HP [-]	72%	406%		77%	430%		-
$HE_{average}$ [-]	22%	22%		23%	23%		-
Energy [MJ]	10660.46	17391.29		6005.60	7493.74		19770.03
m_{fuel} [kg]	247.09	407.01		139.72	175.64		488.55
$m_{battery}$ [kg]	1148.08	1598.49		305.18	335.28		-
Relative change compared to conventional baseline							
ΔMTOM	-10.2%	21.0%		-55.0%	-50.0%		
ΔEnergy	-46.1%	-12.0%		-69.6%	-62.1%		
Δm_{fuel}	-49.4%	-16.7%		-71.4%	-64.0%		

4.4. Result Assessment

Year 2020 Technology Level

Data of all concepts shows that for the very short 100 km UAM mission the conventional combustion engine is still the most viable propulsion system, if today's technology is considered. Then why are there no urban air taxis flying right now that use this principle? Apparently, these aircraft do not offer a good enough business case.

As longer missions are considered, the aircraft with conventional propulsion systems experience a very high weight growth. A weight growth of the same scale is also found for serial-hybrid aircraft. The parallel-hybrid configuration, however, is much more efficient. For the 500 km mission, the parallel-hybrid designs are always lighter and use over 45% less energy per flight. Such aircraft offer a clear benefit over a conventional VTOL aircraft.

The serial-hybrid propulsion system, per definition, cannot be as efficient as the parallel-hybrid [7]. However, the system design is simplified and overall complexity is reduced. Additionally, some aircraft configurations (e.g. distributed propulsion) can only be explored with such a system. Therefore, they do have a place in the overall design space.

With the technology assumptions that were made for this study, the fully-electric VTOL aircraft is not yet viable. Only if lighter energy storage becomes available, these concepts will "take off".

Advanced Technology Level

At the advanced technology level, the parallel-hybrid propulsion system might not be the concept of choice, even though it realizes the highest weight reduction.

For short ranges, the weight advantage over the serial-hybrid and the fully-electric configuration could not be high enough to warrant the additional complexity of the parallel-hybrid system. The weight delta is still small, even if longer ranges are considered, which favors the choice of the serial hybrid.

If a family of VTOL aircraft is considered, the serial-hybrid holds another advantage: A low range version of an aircraft can be operated fully-electrically. A longer range version of the same aircraft could replace a part of the battery with a "range extender". Also, this concept makes it easier to replace one part of the system (e.g. the motors) with advanced components as they become available. A carefully designed parallel-hybrid system cannot offer such flexibility.

In the short range market, fully-electric VTOL aircraft will become viable in the near future. They will offer superior efficiency and a reduction in system complexity compared to both conventional and hybrid-electric designs.

However, for flight ranges of 500 km, the electric designs will not close, even with batteries that offer energy densities of 500 Wh/kg. For this segment, hybrid-electric propulsion systems are the next best alternative.

Design Point

The optimization of the design point always returned aircraft with the highest possible wing loading. This is not a true optimum, but rather a boundary optimum, limited by the stall speed constraints.

For the hybrid-electric designs, the combustion engines were always sized to provide the power during cruise. Power requirements above this level were always provided by the electric motors. This shows that the assumptions that were made in [9] are correct. A vertical lift system, which is only used for short periods during take-off and landing, should always be designed with electric motors.

However, if the objective is not the minimization of MTOM, but minimization of the energy consumption, this "rule of thumb" is not true anymore. For those cases, the electric system will also be used in cruise. However, how much it is used, is very much dependent on the technology employed. No general statement can be made.

5. CONCLUSION

This paper has attempted to give an overview of the design space of UAM VTOL aircraft. However, it is in no way complete. While typical concepts were analyzed, there are different ways and criteria that could be used to design and asses this new class of aircraft. Also, the authors are well aware, that due to the wide range of available operational and technological opportunities, the results of this study are not generally applicable. The design of VTOL aircraft is both highly mission critical and very sensitive to technology variations. The same holds true for hybrid-electric aircraft. If both are combined, the sensitivity can only go up.

Nevertheless, the results of this sizing study allow some interesting conclusions:

- Today's technology level is not sufficient to allow short range inter urban air transport. This is evident, because there is no such vehicle currently in series production.
  Fully-electric propulsion systems are still too heavy, and hybrid-electric systems offer no clear benefit over the conventional configurations.

- If medium range missions are considered, hybrid-electric propulsion systems allow an increase in efficiency, even at today's technology level. However, the increased efficiency must be traded-off against the increase in complexity.

- With steady progress in electric motor and battery technology, there are opportunities to design new VTOL aircraft that are far more efficient than aircraft with conventional propulsion systems.
  For short ranges, the very high efficiency of fully-electric system is unbeatable.
  At longer ranges, the hybrid-electric technology is the propulsion system of choice. Even at a battery specific energy of 500 Wh/kg, electric VTOL aircraft will not be able to fly 500 km, even with the lightest payload.

The study also shows, that Uber's mission requirements [13] are challenging, but not impossible to fulfill with just a slight advance in battery technology. The advanced technology level considered here is already too advanced to just enable UAM VTOL aircraft.

Shorter VTOL missions than the ones considered in this paper can obviously be flown today on electric energy alone, as demonstrated by Volocopter [26].

This case study clearly shows that electric and hybrid-electric powertrains must both seriously be considered for new VTOL aircraft. Either concept must be carefully evaluated. The basis for such an evaluation must, of course, be a proper initial sizing.

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