



Mass, primary energy, and cost: the impact of optimization objectives on the initial sizing of hybrid-electric general aviation aircraft

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Abstract

For short take-off and landing (STOL) aircraft, a parallel hybrid-electric propulsion system potentially offers superior performance compared to a conventional propulsion system, because the short-take-off power requirement is much higher than the cruise power requirement. This power-matching problem can be solved with a balanced hybrid propulsion system. However, there is a trade-off between wing loading, power loading, the level of hybridization, as well as range and take-off distance. An optimization method can vary design variables in such a way that a minimum of a particular objective is attained. In this paper, a comparison between the optimization results for minimum mass, minimum consumed primary energy, and minimum cost is conducted. A new initial sizing algorithm for general aviation aircraft with hybrid-electric propulsion systems is applied. This initial sizing methodology covers point performance, mission performance analysis, the weight estimation process, and cost estimation. The methodology is applied to the design of a STOL general aviation aircraft, intended for on-demand air mobility operations. The aircraft is sized to carry eight passengers over a distance of 500 km, while able to take off and land from short airstrips. Results indicate that parallel hybrid-electric propulsion systems must be considered for future STOL aircraft.

Keywords Hybrid-Electric · Aircraft Sizing · Aircraft Design · STOL · Optimization Objectives

Abbreviations

AR	Aspect ratio
BSFC	Brake-specific fuel consumption
c_D	Coefficient of drag
c_L	Coefficient of lift
E	Energy
e	Oswald's efficiency factor
EM	Electric motor
GA	General aviation
H_E	Hybridization of energy
H_P	Hybridization of power
ICE	Internal combustion engine
ISA	International standard atmosphere
k	Induced drag factor
L/D	Lift-to-drag ratio
m	Mass
min	Minutes

MSL	Mean sea level
MTOM	Maximum take-off mass
ODAM	On-demand air mobility
P/W	Power-to-weight ratio
PE	Primary energy
PEF	Primary energy factors
S	Area
STOL	Short take-off and landing
t/c	Thickness-to-chord ratio
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

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1 Introduction

Aircraft design is an optimization task. To find the best aircraft for a set of requirements, different design parameters must be varied in such a way that a minimum of a particular cost function is attained. For example, design trades can be

carried out for P/W and W/S, aspect ratio and taper ratio, wing sweep, airfoil thickness, propulsion parameters, fuselage fineness ratio, even configuration trades and many other parameters [1].

Consequently, a large number of variables must be optimized in such a way that an objective function is minimized while satisfying performance and mission constraints. Such “everything-optimization” would require an extremely large number of data points and is not reasonable, especially in the early stages of design. To make the optimization applicable to the aircraft conceptual design process and limit computational time, the optimization task is carried out with a significantly reduced set of variables. Only variables that have high interdependency are selected for the optimization process.

Initial sizing is typically the very first step in the conceptual design process, and it is already an optimization task. Because it is the first step, it is typically carried out with the lowest number of design variables and design constraints. This reduces accuracy but increases efficiency. This is crucial, as a large number of different designs must be evaluated.

Traditionally, the optimization problem during initial sizing can be stated as minimize MTOM by varying P/W and W/S while satisfying performance and mission constraints. These parameters are selected because the installed power and wing reference area are the main design drivers of conventional aircraft. Hence, P/W and W/S are chosen such that the optimization objective is minimized. Typically, mass is chosen as the measure of merit [2], as it can also be a substitute for cost. For conventional aircraft, the lowest MTOM is usually obtained by the smallest wing and installing the lightest and smallest propulsion system possible. Wing size strongly influences aerodynamics, and the propulsion system is the main driver of fuel mass.

For hybrid-electric aircraft, propulsive power is one of the central design parameters, as well. However, the initial sizing optimization of hybrid-electric aircraft requires a third parameter to determine the size of the propulsion system: the level of hybridization of power H_p . H_p determines the size of the electric system in relation to the combustion engine. Therefore, the optimization problem during the initial sizing for hybrid-electric aircraft must be stated as minimize MTOM by varying P/W, H_p , and W/S while satisfying performance and mission constraints.

However, it is uncertain if the best optimization strategy for hybrid-electric aircraft is the same as for conventional aircraft. Is the “best” aircraft still obtained by minimizing MTOM, or should other measures of merit be used?

To answer these questions, this paper applies an initial sizing algorithm for general aviation aircraft with hybrid-electric propulsion systems, which was developed at FH Aachen. The methodology is exemplarily applied to the design of a STOL (short take-off and landing) general

aviation aircraft, intended for on-demand air mobility operations. In this study, a comparison between optimization results for minimum mass, minimum consumed primary energy, and minimum cost is conducted, with specific focus on the determination of an optimal degree of hybridization, with respect to the particular optimization objective. The impact of the optimization goal on this parameter is carefully investigated.

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

2 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). Results from initial sizing will be used to draw the first design. Then, a more detailed sizing process is started, which leads to a refined design.” [3]

2.1 Matching diagram for parallel-hybrid electric aircraft

At the Institute of Aircraft Engineering at FH Aachen, a tool for the initial sizing of general aviation aircraft has been developed. It allows sizing of conventional, fully electric, and hybrid-electric aircraft. The methodology of the sizing process is documented in [4]. Good results for conventional take-off and landing general aviation aircraft were achieved, as shown in [3, 5, 6]. Recently, the tool has also been expanded to allow sizing of VTOL aircraft [7].

Since these methods are well documented, only a very brief introduction of the tool will be provided here.

The sizing tool’s goal is the identification of an overall optimal design point in terms of power-to-weight ratio (P/W) and wing loading (W/S), as well as the determination of the corresponding degree of hybridization. Analog to the classical method for initial sizing (e.g., [8–10]), the methodology is separated into point performance and mission performance.

The methodology of the point performance part largely conforms to the classical procedure. Top-level aircraft requirements are transformed into performance constraints, and the design point is searched in the conventional design region of the matching diagram with respect to a specified objective function. However, the rule that prescribes the position of the conventional design point cannot be applied

anymore, as the classical procedure does not apply to hybrid-electric aircraft [5]. Consequently, for every considered design point, a complete mission performance analysis has to be performed to evaluate the objective function. Afterward, all considered design points have to be compared concerning the design objective to identify the optimal design point.

In the course of this process, the optimal degree of hybridization of power (H_p) is calculated by gradually dividing the overall power demand arising from each considered design point to the electric motors (EM) and the internal combustion engines (ICE). This subdivision results in so-called split points, as illustrated in the constraint diagram shown in Fig. 1. By evaluating the objective function for multiple design- and split point combinations, the overall optimal result can be determined.

The mission performance analysis is based on the classical iterative process, as presented in [1] or [11]. However, to cover the mix of consumable (carbon-based fuels) and non-consumable (batteries) energy sources on board, the masses are not treated as fractions, as it is usually done in initial sizing, but as absolute values. Therefore, the mission is broken into a large number of short segments and simulated, using a universally valid, energy-based approach.

For each mission segment, the transport energy demand is computed with respect to the current flight attitude. Energy demands can arise from aerodynamic drag, acceleration (kinetic energy), altitude change (potential energy), and ground friction. The transport energy is divided into energy delivered by consumable sources and non-consumable sources by the degree of hybridization of energy (H_E) of the considered mission phase. H_E is defined as the ratio between energy from non-consumable carriers and the transport energy provided in total in a time segment.

While the mission is simulated incrementally, the energy is converted to fuel mass and battery mass using efficiency models. To sum up the MTOM, the mass estimation for the powertrain components is conducted using dedicated models, as well as the computation of the aircraft's empty mass

on the basis of sophisticated empty mass methods [9]. Based on this MTOM, the next iteration step is started. The iteration stops when a certain mass convergence is reached.

2.2 Determination of optimal parameter combinations

To determine the combination of P/W , W/S , H_p , which leads to an optimum for a defined objective function for a specific flight mission, the hybrid-electric design space, limited by performance constraints, must be analyzed. This requires that, for combinations of P/W , W/S , and H_p , the value of the objective function has to be determined. This is done by applying a mission performance analysis to compute parameters which are relevant to calculate the value of the objective function (e.g., MTOM, energy, cost, etc.), using the fast initial sizing analysis, and using the result for the following more detailed design work.

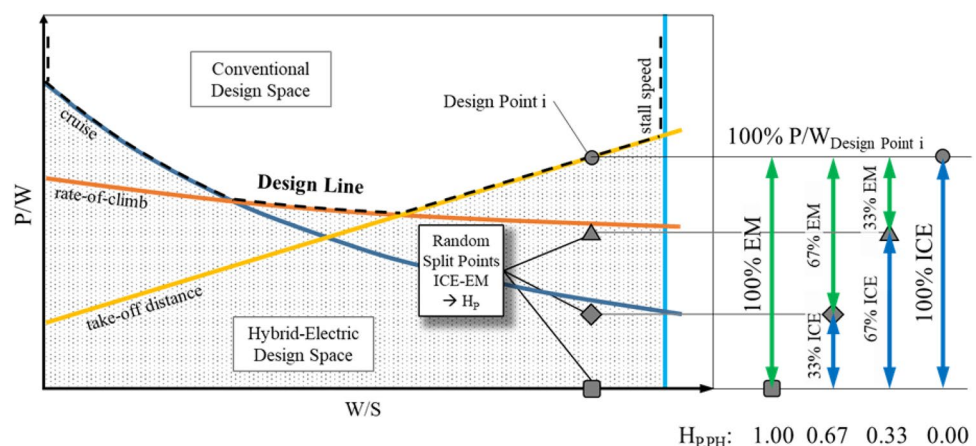
The design optimization can be performed using numerical tools, or by populating the entire design space and plotting the result. The former method gives a fast result, and the latter allows the user to gain further understanding of the design space.

To gain this visual insight, the whole design space must be analyzed for varying values of P/W and W/S , as well as for different values of H_p and H_E . The values of the objective function are then plotted and superimposed with the performance constraints. Such a figure is shown in Fig. 2 as a hybrid-electric initial sizing example. Figure 2 links all performance constraints to the MTOMs of differently sized aircraft—each with a different parameter combination.

Such a plot also exists for classical designs and is sometimes called a “performance thumbprint” [12].

For aircraft without hybrid-electric propulsion, such a thumbprint plot would be the result of unconstrained optimization. Then the designs below the design line would not meet one or more of the performance constraints. As an example, such plots could be used for requirement trades.

Fig. 1 Matching diagram for parallel hybrid electric aircraft [4]



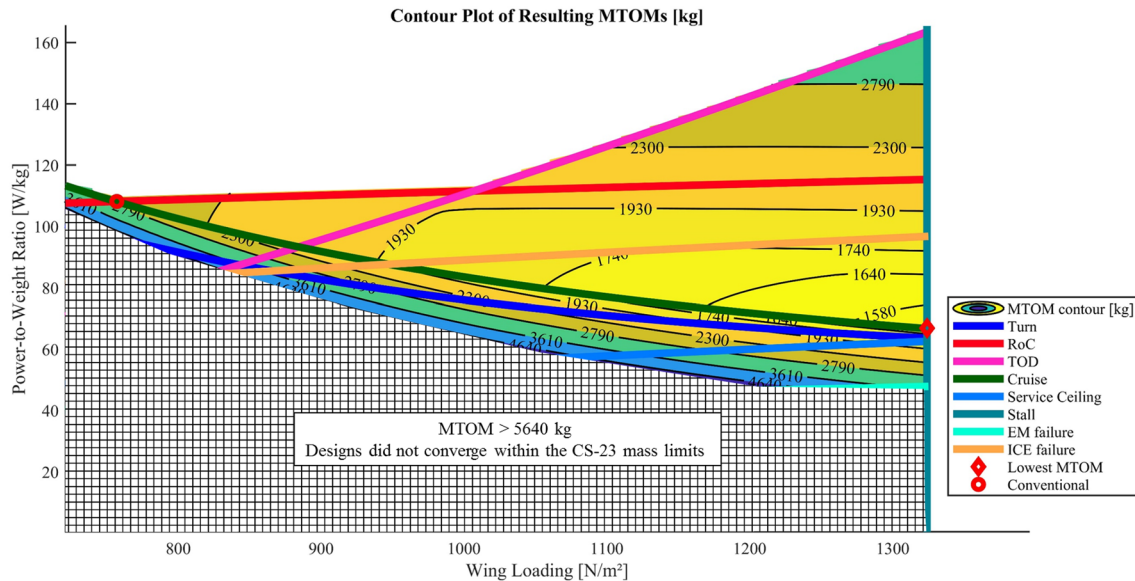


Fig. 2 Thumbprint plot of an exemplary design space exploration [4]

In the context of this new methodology, the thumbprint plot is used differently: Every design on such a plot fulfills all constraints because each P/W is sized up to the design line. Basically, any point on the plot indicates how much of the P/W is provided by the combustion engine.

Any point above the design line is a conventional aircraft, without any hybridization ($H_p=0$). Any point on the x-axis is a fully electric aircraft ($H_p=1$).

2.3 Optimization objectives

2.3.1 Maximum take-off mass

The minimization of MTOM is usually the goal during aircraft design since it is widely acknowledged that “the lightest aircraft that does the job is considered the best” [13]. Boeing engineers found that for a given set of top-level requirements, the lightest aircraft performed best over a range of operating conditions [2]. Besides, designers traditionally use aircraft weight to predict cost, as cost scales almost linearly with aircraft weight [14, 15].

If this reasoning still holds up for hybrid-electric aircraft is debatable. For this reason, this study is conducted.

2.3.2 Primary energy consumption

Another suitable measure for assessing aircraft is their energy consumption. However, if only the energy consumption during flight is assessed, the environmental impact of each flight is not fully captured. The reduction of efficiency that is caused by sourcing energy and delivering it to the

aircraft must be accounted for. This can be done by primary energy factors (PEF).

Primary energy (PE) is a measure for the total energy that was expended to extract energy from natural resources and to provide the extracted energy to the consumer. Gasoline fuel, for example, has to be refined from raw oil, which needs to be extracted from oilfields. The energy to produce the fuel is summed up in the PEF. The factors for Germany are 1.17 for fossil carbon-based fuel and 2.80 for electricity (data from [16], dated 2016). The factor for electricity is that high, because of Germany’s electrical energy mix. Coal-burning and nuclear power plants have a big share, which have a high PEF, as the thermal efficiency of the power stations needs to be accounted for.

Nevertheless, as an EM is over three times as efficient as an ICE, there is still a net benefit in PE consumption that can be obtained by operating electric aircraft.

2.3.3 Production and procurement cost

The estimation of the cost of developing an aircraft is an essential part of any aircraft’s design process [8]. Typically, cost estimation models are used to determine the development and procurement cost of an aircraft already in the early design stages. In this stage, the design can still be changed easily, and different approaches to a set of top-level requirements can be tried and evaluated. When hybrid-electric propulsion systems are assessed, costs are a significant consideration. Thus, the traditional methods need to be updated for hybrid-electric aircraft.

To estimate the development and procurement cost of a new aircraft, Eastlake’s GA DAPCA-IV model [17]

is modified, as explained in [18]. The modified method requires extra adjustment factors that consider the additional effort that the implementation of a hybrid-electric propulsion system requires. Total program costs include

- Engineering labor costs
- Tooling labor costs
- Manufacturing labor costs
- Manufacturing materials costs
- Development support costs
- Flight test costs
- Quality control costs

To determine the selling price, insurance and profit are added.

This optimization goal was selected to analyze whether the old correlation (“the lightest aircraft is the cheapest”) is still valid. The author’s experience shows that the development of hybrid-electric aircraft is significantly more expensive compared to a conventional aircraft. This is due to the additional complexity of such a system, which increases the required time to design and test it. Naturally, this is reflected in the sales price. However, it is assumed that this increase in pricing will be offset by reduced operating costs.

2.3.4 Operating cost

The operator of an aircraft needs to determine his cost to operate a new aircraft. This information is used to determine the price of the service offer.

Total service provision costs comprise of three components: variable direct operating costs (VDOC), fixed direct operating costs (FDOC), and indirect operating costs (IOC).

- VDOC cover energy costs, operating crew costs, landing charges, and maintenance costs.
- FDOC include depreciation of the aircraft (a function of the procurement cost), insurance, annual inspections, and storage costs.
- IOC comprise capital expenditures for the aircraft as well as selling, general, and administration (SG&A) expenses.

When estimating the operating costs, predominantly VDOC components need to be adjusted for hybrid-electric aircraft. The method is explained in detail in [18], where the authors modified the cost estimation approaches from [19] and [20]. Energy and battery costs represent additional components as part of VDOC, and the calculation of maintenance costs differs. Additionally, as the sales price of hybrid-electric aircraft is increased, the fixed operating costs change as well.

Thus, there will have to be a balance between an increase in fixed cost and a decrease in variable cost for

hybrid-electric aircraft to make sense financially. While the reduction of the environmental impact should be a consideration for air service providers, this goal will be much more readily achieved if being eco-friendlier also increases shareholder value by reducing the service provision cost. Therefore, it will be interesting to see if the minimization of operating costs will yield any benefit in terms of PE consumption.

3 A STOL aircraft concept for on-demand air mobility

Interest in the concept of ODAM, or air taxi operations is a recurring theme in aviation. The common notion is to use small aircraft to provide near-on-demand air transportation. Because general aviation (GA) aircraft are used, the service providers can operate from small airfields that are much closer to the origin and destination points. These kinds of operations are conducted either with small propeller aircraft or with light jets [21].

When Uber published their 2016 white paper [22], they took a more aggressive approach towards on-demand air mobility (ODAM). Uber proposes an air service that operates vertical take-off and landing (VTOL) aircraft. With a focus on a very short-range inter-urban mission and a specific focus on electric propulsion, they propose to fly directly within cities that suffer from gridlock and thus minimize travel time. These inner-city air taxi operations are also referred to as urban air mobility (UAM) [23].

The Uber concept of UAM generated a lot of interest and investment from venture capital. However, electric VTOL aircraft are very challenging to design, require an extremely high thrust-to-weight ratio compared to GA aircraft, and present a high certification risk [24].

A less complex alternative to VTOL can be found in short take-off and landing (STOL) aircraft. STOL aircraft take off similarly to conventional aircraft but can do so in a much shorter distance. They also allow much steeper climb-out and glideslope paths, thereby reducing their noise footprint compared to conventional GA aircraft. In addition, STOL aircraft can be hand-flown by a trained pilot. VTOL aircraft cannot be controlled in such a way. Instead, they require a full authority fly-by-wire control system. Therefore, STOL aircraft offer compelling arguments to consider them over VTOL platforms. In this paper, an initial sizing approach is used to analyze the performance of this aircraft class.

To operate any 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. A significant noise reduction can be obtained by low disk-loading

propulsors and new propulsion configurations. These factors will be taken into consideration when designing the aforementioned configurations.

3.1 Design requirements and mission

A new initial sizing methodology will be applied to the design of a STOL aircraft, intended for ODAM operations. The aircraft will carry eight people, covering distances of up to 500 km.

The key design requirements are

1. Number of passengers (including pilot): 8.
2. Design range (without reserves): 500 km.
3. Cruise speed of 66 m/s.
4. Take-off ground roll distance: 150 m.
5. Stall speed: 25 m/s.
6. Propulsion system: parallel-hybrid electric.
7. Battery technology level: 250 Wh/kg, 500 Wh/kg, 1000 Wh/kg. 20C discharge rate.

3.1.1 Payload

The payload requirement is set to 800 kg. If the mass of an average adult male in winter clothing is assumed as 93 kg (as per FAA AC 120-27E [25]), this leaves 7 kg for carryon luggage per passenger. This is deemed acceptable for the ODAM mission. If a higher baggage capacity per person is required, the number of passengers must be reduced. This is typical for small aircraft.

3.1.2 Range and cruise speed

The parameter combination of design range and cruise speed ensures that the typical mission duration does not exceed 2.5 h. This, in turn, leads to passengers not spending excessive time in a small environment without access to a lavatory. It is assumed that the typical mission duration which is flown in service with this kind of aircraft is closer to 1 h.

For ranges beyond 500 km, the advantage of small aircraft is lost in any case, as traditional airline transportation is a lot more competitive.

3.1.3 STOL performance

The take-off ground roll distance is set at 150 m. This is a typical value for STOL aircraft, like the Antonov AN-2 or Dornier's Do-27, and should allow the aircraft to clear a 15 m obstacle within 300 m. According to [26], the chosen stall speed of 25 m/s allows landing within the same distance.

3.1.4 Propulsion system

For any STOL aircraft, a hybrid-electric propulsion system is expected to deliver superior performance compared to a conventional propulsion system, because the power needed for a short take-off is much greater than the power needed for cruise, while this excess power is only required for a fraction of the total flight time. This power-matching problem can be solved with a balanced hybrid propulsion system.

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 limit the weight increase due to high installed power requirements. Arguably, this advantage is offset by a weight increase due to the battery system. With today's battery technology, this forbids the continuous use of battery power. For this reason, hybrid-electric propulsion configurations are used. Because batteries are heavy, it is recommended to bias the operational strategy of the hybrid system towards using the ICE. If the required power can be delivered by the ICE, then the electric system is not used. Only if the required power is higher than the ICE's maximum power (e.g., during take-off and climb), the EM is activated and delivers the necessary additional power. This strategy is also known as peak-load shaving, as the EM "shaves" the peak load off the ICE. Consequently, the battery's energy must be made available over a short portion of the total flight time. As shown in [3], parallel-hybrid systems outperform serial-hybrid systems significantly, if they are compared on equal terms. The serial-hybrid propulsion system, per definition, cannot be as efficient as the parallel-hybrid. 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. Because this technology is not the focus of this study, the serial-hybrid configuration is not considered for this study. More information on hybrid-electric propulsion systems can be found in [27].

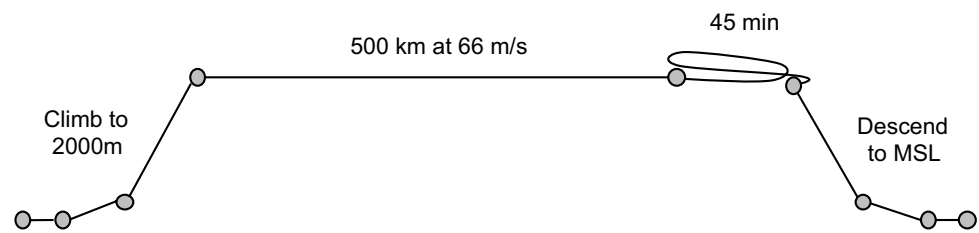
In this paper, a parallel hybrid-electric propulsion configuration is studied. ICE and EM work in conjunction. They are coupled to the same propulsor via a gearbox.

Furthermore, if the parallel-hybrid configuration is analyzed, naturally, fully electric and fully-conventional configurations can be explored as well. These configurations correspond to hybridization ratios of 1 and 0, respectively.

This study will be conducted for three different levels of battery technology. The best battery packs today offer an energy density of about 200 Wh/kg. In an Aviation Week article [28], Uber's goals are quoted as "300 Wh/kg at the pack level by 2023". Batteries with 400–500 Wh/kg at pack level are considered, about twice what is available today, are believed to enable widespread use of electric propulsion systems in aviation.

Table 1 Mission definition

Segment and prescribed time	Distance (km)	Speed (m/s)	Altitude AGL (ending) (m)
1. Ground taxi (5 min)	No range credit	5	0
2. Take-off + reserve (5 min at max power)		0 to $1.2 v_{\text{Stall}}$	100
3. Accelerate, climb		v for best climb rate	2000
4. Cruise	500	66	2000
5. Loiter (45 min)	No range credit	v for best endurance	2000
6. Decelerate, descend		v for best range	100
7. Landing		$1.2 v_{\text{Stall}}$ to 0	0
8. Ground taxi (5 min)		5	0

Fig. 3 Mission definition

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 an advanced technology level. As a “what if” consideration, 1000 Wh/kg batteries are also considered.

3.2 Mission

For the sizing studies of Sect. 4, a simple mission definition is considered. After a brief ground taxi, the aircraft takes off after a 150 m ground roll, then accelerates and climbs to 2000 m altitude. It cruises for a distance of 500 km and then loiters 45 min to fulfill the mandated IFR reserve flight time. Then follows, descend, landing, and another taxi phase. To cover any abnormal situations like go-arounds, the initial take-off is assumed as a 5-min period at maximum power.

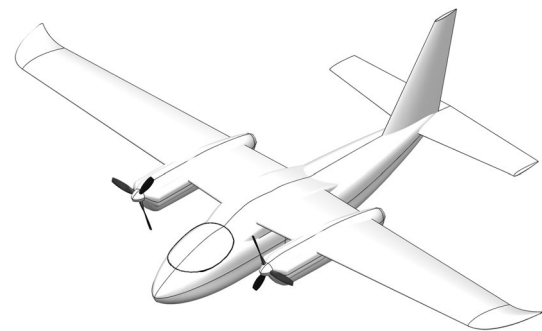
The mission is flown using standard atmospheric conditions, and take-off is at ISA MSL.

A tabular and graphical overview of the missions is provided in Table 1 and Fig. 3, respectively.

3.3 Notional ODAM concept

For this sizing study, a notional air taxi concept aircraft has been designed. The concept is shown in Fig. 4. The configuration is a traditional high-wing twin-prop design somewhat reminiscent of the Aero Commander aircraft family. Eight passengers are seated in 4 rows of two seats.

A high aspect ratio wing is used for low induced drag. For structural considerations, a 15% thick airfoil is used at the wing root. The wing thickness tapers off to 12% at the

**Fig. 4** STOL ODAM concept

wing tip. The wing spar is run over the top of the cabin. This requires a fairing of the wing-fuselage junction but allows for additional headroom in the cabin. It is also a very light solution. A low empty weight is paramount for STOL aircraft, where low-speed performance is a prime consideration. For stability, a conventional tail is chosen.

The propulsion system is mounted in the nacelles. The nacelles are large enough to house the engine-motor-gearbox combination, as well as the batteries and the retractable gear. This way, a significant amount of weight is carried on the wing, reducing the wing root bending moment and contributing to a lighter design. The wing provides more than enough space for fuel, especially because the range is restricted at 500 km. This allows to dedicate a large portion of the wing to high-lift devices and thereby obtain a high maximum lift coefficient.

The aircraft is equipped with retractable tricycle gear.

3.4 Sizing assumptions

Because of constant and rapid improvements in the field of electrical system technologies, it is difficult to accurately predict the level of performance that hybrid-electric air taxis can offer, even if only near term projections are made. Therefore, a reference for the technological assumptions must be set.

For the sizing study, three levels of battery technology are used. All assumptions are summarized in Table 2.

3.4.1 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 is held constant at the values shown in Table 2. For this study, typical values obtained by traditional four-stroke aviation engines (see, e.g., [8]) were selected.

3.4.2 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 [29]. While this is still a prototype, its TRL is assumed to improve by 2020.

3.4.3 Batteries

The battery is sized with respect to the following considerations:

- The full design mission must be flown with 80% of the remaining capacity. The bottom 20% capacity is consid-

ered 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 battery life.

- Missions start with the battery fully charged.
- The battery is not recharged over the course of the flight.
- All specific energy values are given at pack level.

The battery's specific power is determined by considering the same 20C discharge capability for all levels of specific energy. Lithium batteries can already deliver these high C-rates today, but typically at a low specific energy level. Therefore, this must be considered an optimistic assumption. However, as future projections are used for all batteries, this is considered acceptable within the scope of this study.

The timeline for development of such advanced batteries is hard to predict. Today, battery packs with 250 Wh/kg are available, but their low discharge rate and limited cycle life prevents them from widespread use. Battery packs with 500 Wh/kg might be available in the mid-2030s, if the current trend of an 8% increase in specific energy is continued. Still, this will require innovation in cell chemistries and pack design and integration. A timeline for 1000 Wh/kg batteries cannot be predicted at this stage [30].

Further information on the impact of battery performance on the design of hybrid-electric aircraft can be found in Ref. [31].

The operational strategy of the hybrid system is biased to using the ICE. In each flight phase, the required power is compared to the available power. If the required power can be delivered by the ICE, then the electric system is not used. Only if the required power is higher than the ICE's maximum power (e.g., during take-off and climb), the EM is activated and delivers the necessary additional power. This strategy is also known as peak-load shaving, as the EM "shaves" the peak load off the ICE. Therefore, the battery's energy must be made available over a short portion of the total flight time.

3.4.4 Aerodynamic performance

The aerodynamic efficiency of the design is estimated rather conservatively with the help of drag-buildup methods.

A significant allowance is made for trim drag, cooling drag, wheel well gaps, flap tracks, and other undesirable drag. This brings the $CD_{\min\text{Drag}}$ to about 300 counts. This drag coefficient is achieved at the lift coefficient for minimum drag $CL_{\min\text{Drag}} = 0.17$.

Due to the interference effects of the fuselage and large engine pods on the wing, Oswald's aircraft efficiency factor is chosen conservatively, as $e = 0.63$. The aircraft drag polar is described as

Table 2 Technology levels

Technology assumption	Technology level
Combustion engine technology	4-stroke ICE
ICE specific power (kW/kg)	1.0
ICE BSFC (g/kWh)	315
EM specific power (kW/kg)	5.0
Battery specific energy (Wh/kg)	250–500–1000
Battery discharge C-rate	20C
Flap system	Fowler flaps
CL_{\max}	2.5
$W_{\text{empty without engines}}/W_0$ [–]	$0.743 W_0^{-0.06}$

$$CD = CD_{minD} + \frac{(CL - CL_{minD})^2}{\pi \cdot AR \cdot e},$$

$$CD = 0.03 + \frac{(CL - 0.17)^2}{\pi \cdot 9 \cdot 0.63}.$$

The performance is showcased in Fig. 5.

3.5 Matching diagram

These top-level requirements are then translated into the matching diagram, which is shown in Fig. 6.

It should be no surprise that the matching diagram for the notional STOL aircraft is dominated by the take-off-, cruise speed-, and stall speed constraints. The requirement for climb rate is chosen as 4.5 m/s in the all engines operating condition, and 1 m/s in the one-engine inoperative (OEI) condition. These performance levels are easily surpassed because the aircraft must be sized with respect to take-off and cruise constraints.

Secondary constraints like loiter or speed for a constant energy turn are neglected at this design stage.

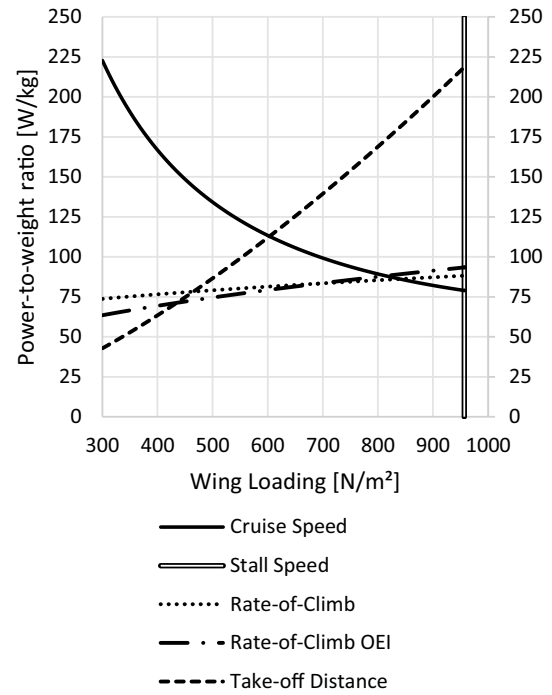


Fig. 6 Matching diagram

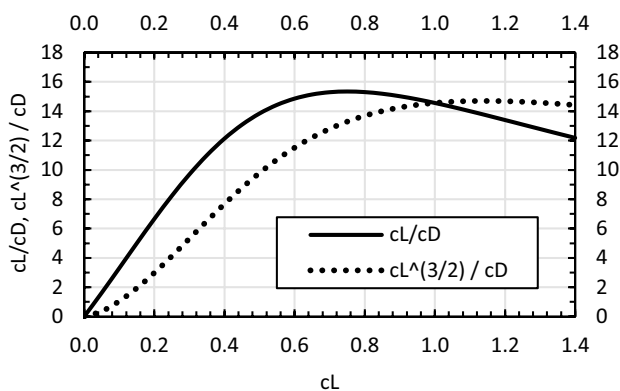
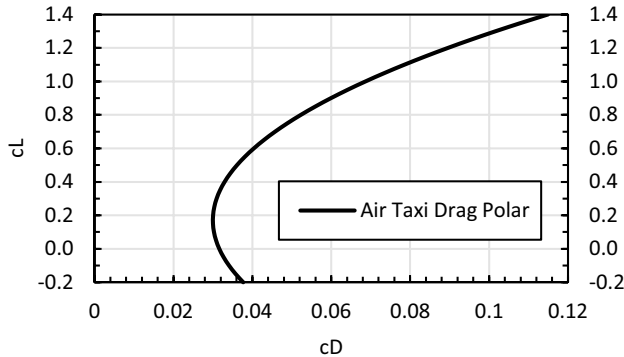


Fig. 5 Aerodynamic performance

3.6 Cost estimation assumptions

The following assumptions were made for the production and procurement cost estimation calculations:

- Certification under CS-23 rules
- Production of 125 aircraft over a 5-year period
- A learning curve of 0.95
- 15% insurance premium on the total production cost
- 10% profit margin on the total production cost

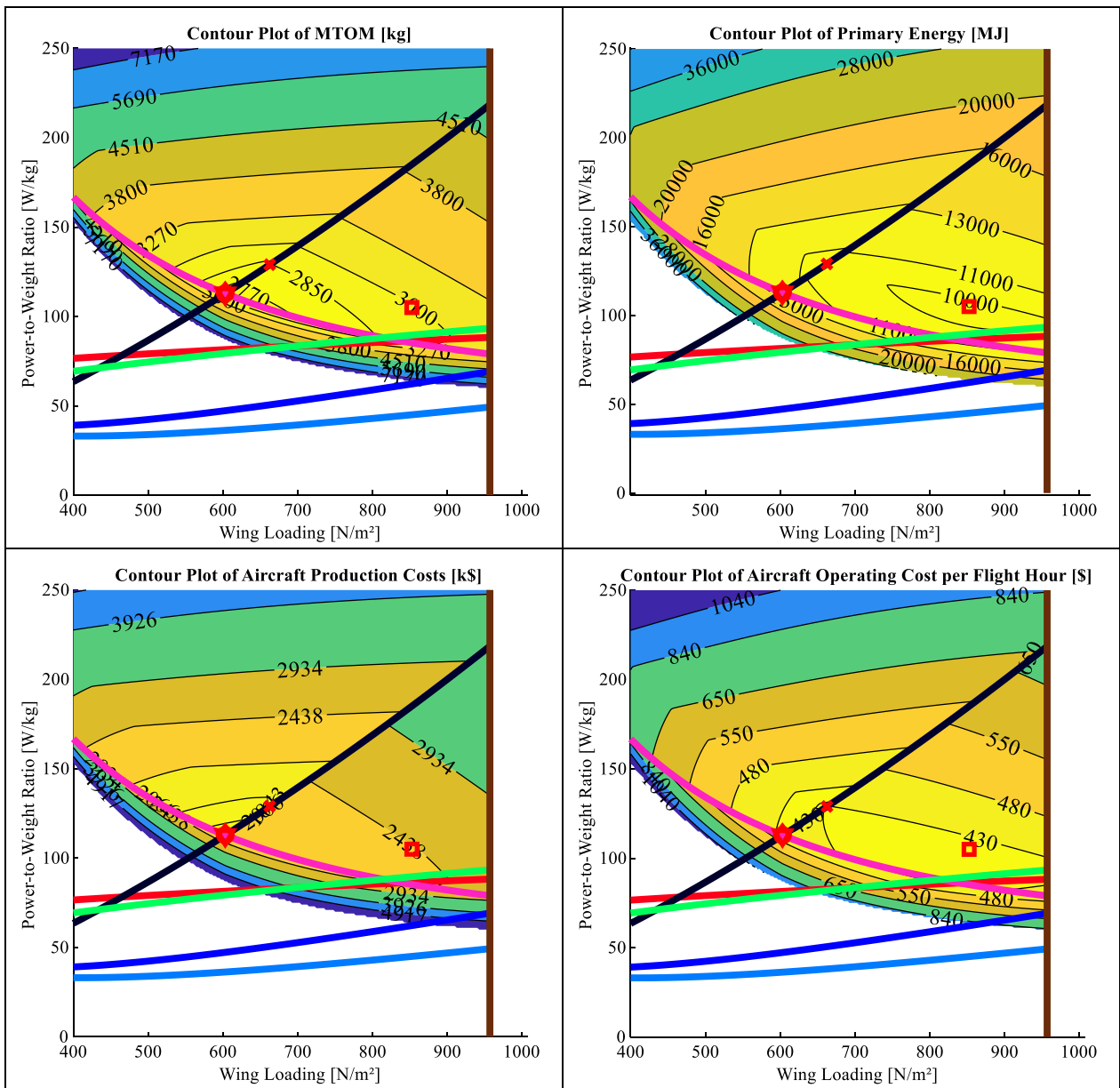
The fixed cost for the propulsion system is defined as follows:

- Combustion engines: 174 \$/hp
- Electric motors: 150 \$/hp
- Power management system: 150 \$/hp
- Batteries: 210 \$/kWh

No attempt is made to model improvements in the price of these systems in the future.

The following assumptions were made for the operating cost estimation calculations:

- Fuel price of 3.3 \$/kg
- Electricity price of 0.4 \$/kWh
- Ratio of flight hours to maintenance hours of 0.3



Design Point	Conventional Design Point	Min MTOM	Min Primary Energy	Min Production Cost	Min Ops Cost
MTOM [kg]	2736	2736	2982	2736	2822
W/S [N/m ²]	603.0	603.0	852.5	603.0	662.5
P/W [W/kg]	112.9	112.9	185.0	112.9	129.0
HP [-]	-	-	43.3%	-	-
HE _{average} [-]	-	-	3.7%	-	-
PE [MJ]	11639	11639	9777	11639	10335
m _{fuel} [kg]	246	246	201	246	218
m _{battery} [kg]	-	-	125	-	-
Production Cost [k\$]	1695	1695	2423	1695	1789
Ops Cost [\$/h]	424	424	416	424	405

Relative change compared to conventional baseline					
ΔMTOM	baseline	0.0%	9.0%	0.0%	3.1%
ΔPrimary Energy		0.0%	-16.0%	0.0%	-11.2%
Δcost		0.0%	42.9%	0.0%	5.5%
Δops Cost		0.0%	-1.9%	0.0%	-4.5%

Fig. 7 Sizing results: 250 Wh/kg batteries

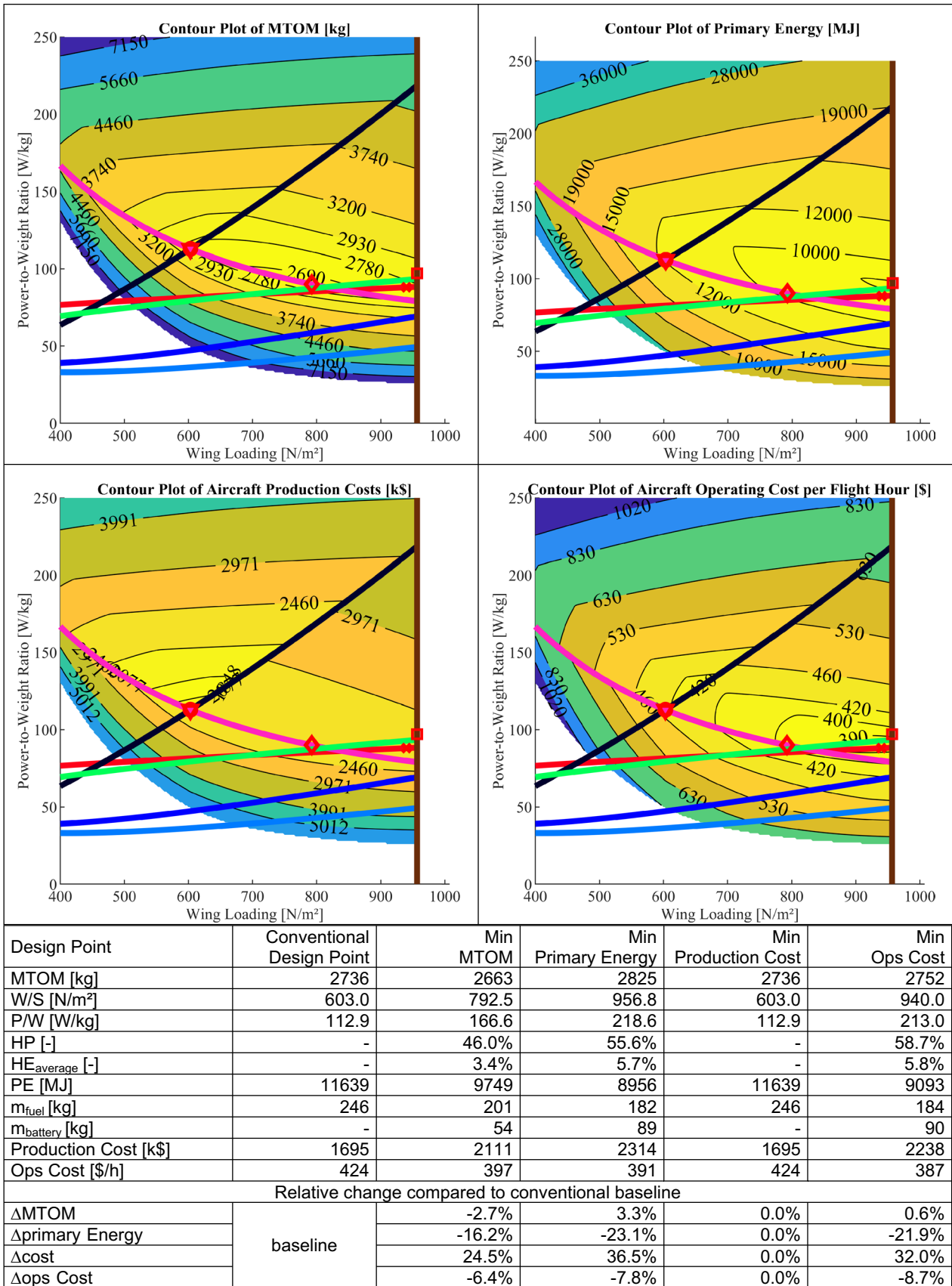
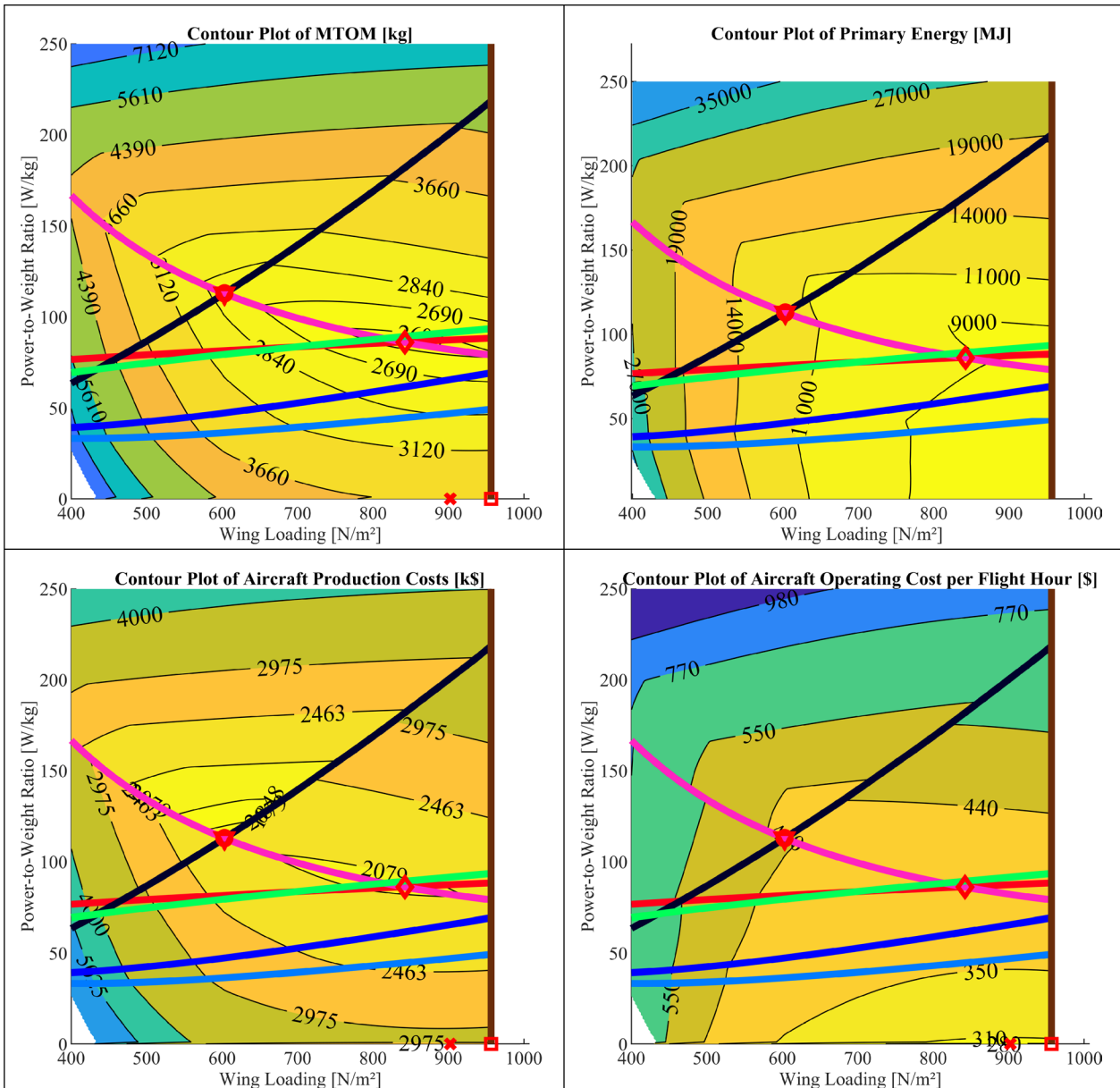


Fig. 8 Sizing results: 500 Wh/kg batteries



Design Point	Conventional Design Point	Min MTOM	Min Primary Energy	Min Production Cost	Min Ops Cost
MTOM [kg]	2736	2572	3566	2736	3566
W/S [N/m²]	603.0	842.5	956.8	603.0	902.5
P/W [W/kg]	112.9	181.9	218.6	112.9	200.9
HP [-]	-	52.7%	100.0%	-	100.0%
HE _{average} [-]	-	4.4%	100.0%	-	100.0%
PE [MJ]	11639	9170	7971	11639	8070
m _{fuel} [kg]	246	188	-	246	-
m _{battery} [kg]	-	33	988	-	1001
Production Cost [k\$]	1695	2043	2514	1695	2500
Ops Cost [\$/h]	424	380	274	424	273
Relative change compared to conventional baseline					
ΔMTOM	baseline	-6.0%	30.3%	0.0%	30.3%
Δprimary Energy		-21.2%	-31.5%	0.0%	-30.7%
Δcost		20.5%	48.3%	0.0%	47.5%
Δops Cost		-10.4%	-35.4%	0.0%	-35.6%

Fig. 9 Sizing results: 1000 Wh/kg batteries

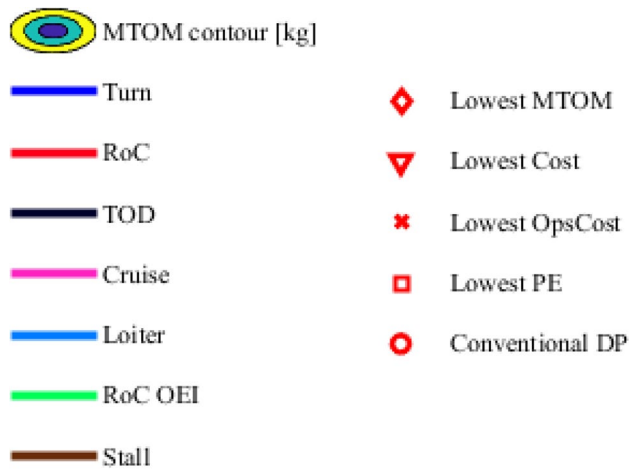


Fig. 10 Legend for Figs. 7, 8 and 9

- Battery is written off over 1000 cycles over a 10-year period
- Aircraft is written off over a 10-year period
- Aircraft is operated 8 h per day with a 25 min turnaround time.

4 Sizing studies

In this section, the sizing methodology is applied to study the implications that hybrid-electric powertrains have on the ODAM class of STOL aircraft.

The aerodynamic data obtained from the drag-build up analysis are 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 is 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 Figs. 7, 8, 9. These figures are structured in the following way: the thumbprint plots for the respective optimization criteria are shown first. They are split into MTOM optimization, PE optimization, production cost (incl. profit) optimization, and operating cost (per flight hour) optimization.

To save space, the legend for Figs. 7, 8, 9 is only given once, in Fig. 10. The best points are indicated by markers in the thumbprint plots. The sizing results for the best points are shown in tabulated form. This allows for easy comparison. A “conventional” ODAM aircraft, powered only by ICEs, is sized to the same requirements to provide a

baseline which the hybridized propulsion versions can compete against. The relative changes in MTOM, PE consumption, cost, and operational cost, compared to this baseline, are given in the bottom section of the table.

A fourth study is presented in Fig. 11. It focuses on assessing the impact of the PE assumptions. This study is explained in detail in Sect. 4.4.

4.1 Sizing results: 250 Wh/kg batteries

When assessing the thumbprint plots of Fig. 7, it is evident that only a fraction of the possible design space is filled with contour lines. In the white-space of the hybrid-electric design space (compare Fig. 1), no aircraft converged within the mass limit of the CS-23’s commuter class (8618 kg). Only conventional and some hybrid-electric designs converged within the mass limit. Other aircraft became too heavy. Because the space of converged designs does not extend down to the x -axis, it is shown that no fully electric aircraft are possible for this set of requirements, if 250 Wh/kg batteries are considered.

The conventional design point gives an MTOM of 2736 kg. This is a reasonable result for an 8-seat STOL aircraft. The conventional design point is also the best point when MTOM or production costs are optimized. No hybrid-electric design improved these measures of merit. This shows why conventional aircraft are typically designed with the smallest possible engine.

For this very short mission, these conventional designs only need to carry 246 kg of fuel. This fuel fraction of $\sim 9.0\%$ is quite low compared to traditional aircraft. The short-range 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.

Another design point, however, still conventional, is best for the lowest cost per flight hour. A slight increase in W/S and P/W results in a 4.5% operating cost improvement. The shift to higher wing loadings allows the L/D in cruise flight to increase while operating the ICE at a slightly reduced power setting, which in turn reduces fuel consumption. This way, 11.2% PE reduction is obtained, even though the aircraft is 5.5% heavier than the conventional and lightest baseline aircraft.

The only hybrid-electric design for the 250 Wh/kg batteries is found when optimizing for minimal PE usage. The design point is shifted to a significantly higher wing loading (41% increase) and, consequently, a higher P/W (64% increase). H_p indicates that just 57% of the installed power is supplied by a combustion engine. For the short period of take-off and climb out, the ICE is boosted by an EM. However, as $H_{E,average}$ shows, this boost phase makes up only

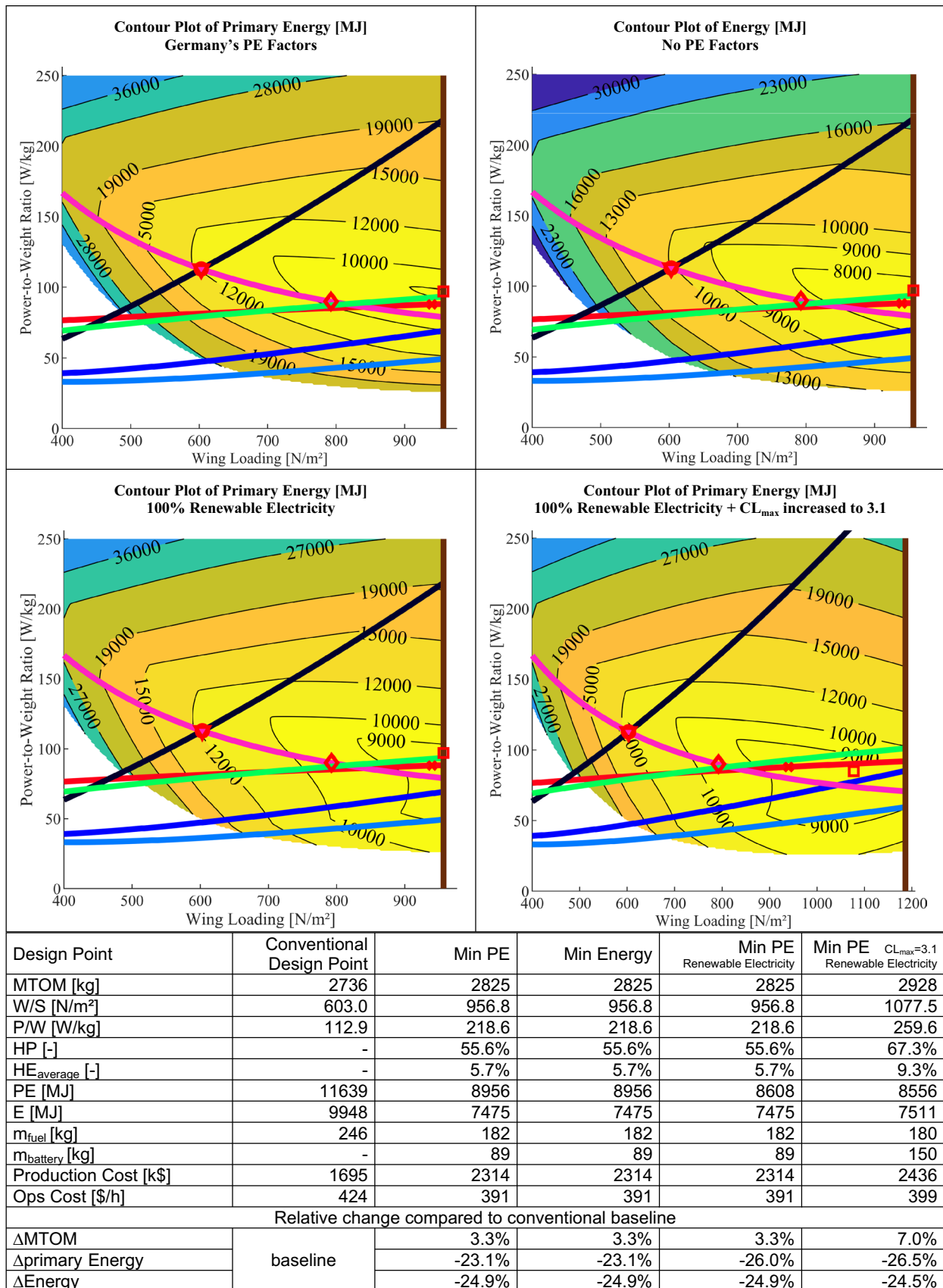


Fig. 11 Sizing results: energy comparison

3.7% of the total consumed energy over the course of the flight. Nevertheless, improving cruise L/D and downsizing the ICE improves PE consumption by 16%. This corresponds to a fuel burn reduction of 45 kg. However, as 125 kg batteries need to be carried, the total mass increases by 9%.

The production costs are increased significantly by 43%. This is caused by the much longer development time that is required by hybrid-electric systems. This sharp increase can be observed as a jump of the iso-contour lines that shows below the take-off constraint. Nevertheless, if the aircraft's price is written off over a period of 10 years, the operating costs per flight hour are very slightly (1.9%) below those of the conventional design. This shows the potential that hybrid-electric aircraft have, once battery technology improves. To quantify the possible improvements, the following studies are carried out.

4.2 Sizing results: 500 Wh/kg batteries

When compared to the 250-Wh/kg battery study, even doubling the battery specific energy to 500 Wh/kg is still not sufficient to allow the entire design space to converge within the CS-23 commuter class mass limit for this set of requirements (see Fig. 8). Nevertheless, reducing battery mass by 50% has a significant impact on the optimization results.

The conventional design point is only optimal when minimum production costs are the main objective. All other objectives are minimized by selecting a hybrid-electric aircraft.

The optimum design points for minimum operational cost and minimum PE consumption are both situated close to the stall speed wing loading constraint. They both feature an ICE sized for cruise power requirements and an EM that can boost the total power to meet the short take-off requirement. However, the ICE is slightly larger when optimizing for minimum energy usage. This can be attributed to the fuel consumption model that is used for this study. The minimum specific consumption is achieved at about 80% of the rated power. Thus, slightly less fuel is consumed by using a larger, heavier, and more expensive engine. Consequently, if the aircraft is designed for minimum energy consumption, it is slightly heavier and slightly more expensive. Still, the absolute difference is quite small, and both energy and cost reduction are just slightly different. A maximum reduction of the cost per flight hour of 8.7% could be realized. This is 0.9% less than when optimizing for minimum consumption of PE. Conversely, a maximum reduction of PE by 23.1% is achieved, 1.1% less than when optimizing for minimum cost per flight hour. The procurement cost of both aircraft is over 30% more expensive. This shows that the reduction in energy consumption is large enough to recover the increased acquisition cost of a hybrid-electric aircraft. Nevertheless, the average hybridization of energy is just slightly less than 6%. Therefore, the power shaving operational strategy shows

a rather large impact while keeping the battery size reasonable. However, this low number is slightly misleading: due to the higher efficiency of electrical systems, compared to ICEs, a lot more work is extracted from this small share of energy.

The minimum mass design point represents somewhat of a middle ground. It shows a small improvement for all measures of merit, but production cost. It, too, has an ICE sized by the cruise conditions, but it does not feature an extreme wing loading as the design for minimum operational cost or for minimum PE consumption do. While the MTOM reduction is a mere 2.7% less than the conventional baseline, it still uses 16.2% less PE and is 6.4% less expensive per flight hour compared to that baseline. Still, it is significantly more expensive, with a 24.5% procurement cost increase.

The reduction in fuel consumption of 43 kg is made up for by a battery mass of 54 kg. The mass reduction is realized by having a smaller, lighter ICE and a significantly lighter, but powerful EM.

4.3 Sizing results: 1000 Wh/Kg batteries

Doubling the battery specific energy again to 1000 Wh/kg finally allows assessing most of the design space within the limits of the CS-23 commuter class. As can be seen in Fig. 9, only for these highly optimistic assumptions, fully electric aircraft become a possibility.

It turns out that—at this technology level—fully electric aircraft are indeed the best choice when the objectives are minimum primary energy consumption or minimum cost per flight hour. The design point for those objectives is not exactly the same. However, the difference in performance is very similar.

These fully electric aircraft are about 30% heavier than the conventional baseline while consuming about 30% less primary energy. Additionally, operational costs are reduced by more than 35%. This means, in simplified terms, that it would be possible to operate four of these aircraft instead of three conventional aircraft while having the same operational cost and roughly the same environmental impact. This shows that cost reduction and efficiency can go hand in hand. At the same time, the reader is reminded that the required technology level for this kind of performance will most likely not be reached in the next few decades. When acquiring these aircraft, at least a 50% premium over conventional aircraft is projected.

The fully electric designs carry about 1000 kg of batteries. This is about four times the fuel mass of the conventional design and shows how restricting the mass increase of batteries really is.

The minimum mass design converged to a hybrid-electric design, which is quite similar to the one obtained for 500 Wh/kg batteries. This time, it is 6% lighter than the

baseline. However, at this level of technology, this design is much inferior to the fully electric aircraft. It is much more complex, requires additional infrastructure to refuel, and the additional maintenance of the ICE is expensive. At the same time, only a 10.4% cost per flight hour saving is obtained while the procurement cost is 20.5% higher than the baseline. The reduction of PE consumption is impressive at 21.2%, but this is still less than what could be obtained by going fully electric.

The lowest production costs are, again, achieved by selecting the conventional design point. It is interesting to see that a secondary local minimum for costs is formed about the location of the design point of the minimum MTOM aircraft. However, production costs are still significantly higher there than for a conventional design.

4.4 Sizing results: energy comparison

To assess the impact of the assumed PE factors, another study is conducted. Using the 500 Wh/kg battery technology assumption, the energy assessment is varied. In Fig. 11, four different contour plots are shown.

1. This is the baseline plot of PE, using Germany's PE factors, as for the previous studies.
2. This is a raw energy plot, assuming no PE multipliers. It still includes the propulsion system's efficiency, which was used to calculate the required raw energy to power the aircraft.
3. Another PE contour plot is shown, but here the PE factor of electricity is reduced to 0, which assumes that spending this energy has no environmental impact whatsoever. Electricity is assumed to be 100% renewable green energy.
4. In this plot, electricity is still assumed to be 100% renewable green energy, but the design space is expanded to higher wing loadings by assuming $CL_{\max} = 3.1$. This is a highly optimistic assumption.

The results show that the sizing outcome does not depend on the way that energy consumption is assessed—at least for this particular set of requirements. The best point for minimum PE, minimum raw energy, and minimum “green” PE are always the same. When looking for the relative energy efficiency improvements over the conventional baseline aircraft, all designs show an improvement of about 25%. However, there are subtle differences.

When hybrid-electric aircraft are compared using the raw energy figure, it will always show a larger improvement over the baseline, than using PE. This is natural, as a part of the electrical systems efficiency is outweighed by the efficiency chain required to produce that energy. Conversely, assuming 100% renewable electrical energy will skew the numbers in

favor of hybrid-electric designs. As can be seen in Fig. 11, the contour lines are extended significantly towards lower split-points and, therefore, higher levels of hybridization. However, the best design point for these objectives does not change. It is always situated right at the maximum wing loading constraint, and the split-point is always slightly above the cruise speed and climb rate constraints.

To check the influence of the stall speed constraint, another “what-if” study is conducted, and the maximum lift coefficient is raised to 3.1. This expands the design space and allows to find an unconstrained optimum. It is interesting to see that none of the other optimization points (MTOM, production cost, and operating cost) change as the design space is expanded. However, the minimum PE point moves to the right in the matching diagram, as expected.

The best PE split-point is now located slightly below the climb rate constraints, but still above the cruise speed constraint. This allows the aircraft to cruise on the ICE, while the higher wing loading results in a higher cruise L/D. Because this optimum is not a constraint optimum, it could be reached with $CL_{\max} = 2.81$, or the stall speed could be reduced to 23.8 m/s. Still, the PE consumption is just very slightly increased (26.5% vs 26.0% for the other green energy example), and the raw energy consumption is actually slightly increased (− 24.5% vs − 24.9%), as is MTOM (7% increase vs. a 3.3% increase for the constrained design point).

Nevertheless, this study shows how easily results can be skewed by making certain assumptions when assessing designs. This is even more true when fully electric aircraft are considered.

5 Conclusion

In this paper, it has been shown that the traditional sizing optimization assumptions should not be used for future hybrid-electric aircraft.

For conventional designs, selecting the design point, which allows the lowest installed P/W does indeed result in the lightest aircraft, which will also be the cheapest design to produce. This design point is also reasonably close to the point for minimum operating costs. However, analysis confirms that this design point should not be used as the default design point for aircraft with parallel-hybrid electric propulsion systems. Once battery technology progresses, the freedom to split the installed power between an ICE and an EM allows for much better solutions. Typically, wing loading is increased for improved cruise performance, while the EM is used to boost the installed power to meet the take-off performance requirements.

Optimizing a STOL ODAM aircraft concept for different measures of merit revealed that unique best points for

minimum MTOM, PE consumption, and operating cost will be found when parallel-hybrid electric powertrains are considered.

The minimum MTOM design point does result in aircraft with minimal production cost. This is true for conventional and hybrid-electric aircraft. However, due to the additional design and testing effort inherent to hybrid-electric aircraft, conventional aircraft will be significantly cheaper to produce, even if the hybrid-electric aircraft might be a few percent lighter.

Nevertheless, even though this increased purchasing price of hybrid-electric aircraft is considered when the operating costs are calculated, the improvement in energy efficiency makes it cheaper to operate hybrid-electric aircraft in the long run. Interestingly, in this study, the ideal design point for minimum operating cost and minimum PE consumption are found very close to each other. This shows that saving energy and reducing cost are not exclusive objectives, but go together rather well.

At the same time, the results indicate that the design space must be analyzed specifically for these measures of merit. The designer must not trust that a minimum mass design will also be optimal from an energy consumption or operating cost standpoint.

This paper has also attempted to give an overview of the design space of STOL aircraft for ODAM applications. The authors are aware that due to the wide range of available operational and technological opportunities, the results of this study might not be generally applicable. The design of hybrid-electric aircraft is both highly mission-critical and very sensitive to technology variations. Nevertheless, the results of this sizing study allow some interesting observations:

- With steady progress in battery technology, there are opportunities to design new STOL aircraft that are more energy and operating cost-efficient than aircraft with conventional propulsion systems.
- Once battery technology progresses to the point that fully electric aircraft become possible, their very high efficiency is unbeatable from both an ecologic and economic standpoint. However, this study shows that a major breakthrough in battery technology is required to get to this stage. A battery with 1000 Wh/kg that allows a 20C discharge rate is unlikely to become a reality in the next few decades.
- In the foreseeable future, parallel-hybrid electric propulsion technology is likely to be the propulsion system of choice. They offer significant benefits over conventional aircraft, even though they will be more expensive to develop.

This case study clearly shows that hybrid-electric powertrains must seriously be considered for new ODAM

aircraft. Still, new concepts must be carefully evaluated and optimized. This basis for such an evaluation must, of course, be a proper initial sizing.

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