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Wolleswinkel, Rob E. ; de Vries, R.; Hoogreef, M.F.M.; Vos, Roelof

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A New Perspective on Battery-Electric Aviation, Part I: Reassessment of Achievable Range

Rob E. Wolleswinkel*, Reynard de Vries†,
Elysian Aircraft, Rendementsweg 2, 3641SK Mijdrecht, The Netherlands

Maurice F. M. Hoogreef‡ and Roelof Vos§
Delft University of Technology, Kluyverweg 1, 2629HS Delft, The Netherlands

Thus far, battery-electric propulsion has not been considered a promising pathway to climate-neutral aviation. Given current and expected battery technology, in most literature battery-electric aircraft are only considered feasible for short ranges (< 400 km) and small payloads (< 19 pax). As a result, battery-electric aircraft development focuses on new aviation segments such as regional and urban air mobility. However, little effort has been made to develop battery-electric aircraft that can replace existing larger aircraft. This paper re-examines the assumptions that lead to the conclusion of limited applicability of battery-electric aircraft. Starting from the range equation, this paper assesses the drivers of two key parameters: the ratio between energy mass and maximum take-off mass, and the maximum lift-to-drag ratio. This assessment, based on Class-I mass and aerodynamic-efficiency estimates, shows that there is a design space where these two parameters can reach significantly higher values than often assumed in the open literature. Based on this finding, several parametric aircraft designs are evaluated, relying on Class-II mass and aerodynamics methods. These parametric studies validate the conclusion from the Class-I assessment. This implies that battery-electric passenger aircraft can play a larger role in climate-neutral aviation than was previously envisioned.

Nomenclature

DEP	=	Distributed electric propulsion
EM	=	Energy mass at maximum payload
ERF	=	Electric range factor
IFR	=	Instrument flight rules
MTOM	=	Maximum take-off mass
MTOW	=	Maximum take-off weight
MPLM	=	Maximum payload mass
OEM	=	Operating empty mass
SAF	=	Sustainable aviation fuel
TLAR	=	Top-level aircraft requirements
TOFL	=	Take-off field length (balanced field length)
TRL	=	Technology-readiness level
EM/MTOM	=	Energy mass fraction
OEM/MTOM	=	Empty mass fraction
PLM/MTOM	=	Payload mass fraction
A	=	Wing aspect ratio [-]
b	=	Wing span [m]
c_{mac}	=	Mean aerodynamic chord [m]
c_{HT}	=	Horizontal-tail volume coeff. [-]
C_{D0}	=	Zero-lift drag coefficient [-]
$C_{L,\max}$	=	Maximum lift coefficient [-]
e_{bat}	=	Usable battery energy density [J/kg]
g	=	Gravitational constant [m/s²]
l_{HT}	=	Horizontal-tail moment arm [m]
$(L/D)_{\max}$	=	Maximum lift-to-drag ratio [-]
$R_{\max}$	=	Max. cruise range in still air [km]
S_{HT}	=	Horizontal tail planform area [m²]
S_{ref}	=	Wing planform area [m²]
S_{wet}	=	aircraft wetted area [m²]
η_{elec}	=	Electric powertrain efficiency [-]
η_{p}	=	Propulsor efficiency [-]

*Co-CEO and CTO, rob@elysianaircraft.com, AIAA member.
†Head of Design & Engineering, reynard@elysianaircraft.com, AIAA member.
‡Assistant Professor, Faculty of Aerospace Engineering, m.f.m.hoogreef@tudelft.nl, AIAA member.
§Associate Professor, Faculty of Aerospace Engineering, r.vos@tudelft.nl, Associate Fellow AIAA.

I. Introduction

In order to meet the stringent sustainability goals established by, amongst others, the European Commission [1], significant advancements of a broad range of technologies will be needed [2]. For research on this topic, several new propulsion technologies are investigated, such as hydrogen propulsion, hybrid-electric propulsion, or the use of sustainable aviation fuel (SAF). In this process, battery-electric propulsion is generally considered as an unrealistic pathway for sustainable aviation. While hybrid architectures with a low or zero degree of hybridization have received ample attention [3–5], large battery-electric aircraft have been considered infeasible when relying on current and near-future expected battery performance [6–8]. Small battery-electric aircraft have been developed and are in operation (see e.g. the Pipistrel Velis Electro). However, more than 95% of all CO_2 emissions is produced by aircraft in the CS-25 class [9]. While there is some literature on electric aircraft in this space [10], research on large battery-electric aircraft is scarce. However, in this two-part paper series, we argue that large battery-electric aircraft are technically feasible *and* also have a large potential to reduce the climate impact of the aviation sector as a whole.

The objective of this paper is to reassess the range limitations of battery-electric aircraft. The key research question is: what maximum cruise range is feasible for battery-electric transport aircraft in the 40−120 seat class? This paper consists of four sections, including this introduction. Section II reviews the perceived range limitations of battery-electric aircraft. Section II.A reviews the cruise-range formula for battery-electric aircraft, states the assumptions of several key parameters and introduces the Electric Range Factor (ERF). Section II.B offers a review of existing literature. Section III then discusses the main arguments brought forward in the literature: (1) a maximum energy fraction of ~25%, (2) a maximum lift-to-drag ratio of 14−18, (3) battery energy required for reserves and (4) negative scale effects, favoring smaller aircraft. Sections III.A through III.D discuss each of these four perceived limitations and concludes that all are misconceptions. Subsequently, Sec. IV offers a revised range estimate for battery-electric aircraft, based on Class II parametric design studies, incorporating the lessons learned from Sec. III. Section IV.A describes the assumptions and parametric design approach for this analysis. Finally, Sec, IV.B shows the result for twelve different parametric designs for a 40-seat, 80-seat, and 120-seat aircraft, and V finishes with the conclusions.

Given the results presented in this paper, we advocate that research on all facets of battery-electric large transport aircraft deserves a higher priority. Many questions remain unanswered, e.g., regarding the actual city-to-city range that can be achieved, the "well-to-wake" energy efficiency, and the ecological footprint and economic viability of these type of aircraft. Also, many technological issues still require a solution. For a first exploration of these questions and issues we refer to our second paper [11].

II. Perceived Range Limitations of Battery-Electric Aircraft

A. Maximum Cruise Range of Battery-Electric Aircraft

The maximum still-air cruise range of a battery-electric aircraft is the maximum range that can be flown in level flight at cruise speed and altitude, and without wind. This is maximum cruise range is determined without considering energy required for take-off, climb and descent, for non-propulsive systems, or to cover reserves. For battery-electric aircraft, the formula for this maximum cruise range (R_{max}), derived from the well-known Breguet range equation, is [3, 12]:

$$R_{\text{max}} = \eta_{\text{elec}}\eta_{\text{p}}e_{\text{bat}}\frac{1}{g}\left(\frac{L}{D}\right)_{\text{max}}\left(\frac{\text{EM}}{\text{MTOM}}\right) \tag{1}$$

In this equation, η_{elec} and η_{p} are the efficiency of the electric powertrain and the propeller, respectively. g is the gravitational acceleration, e_{bat} is the mass-specific energy of the battery, $(L/D)_{\text{max}}$ is the maximum lift-to-drag ratio, EM is the energy mass, and MTOM is the maximum take-off mass. The ratio of energy mass to maximum take-off mass is referred to as the energy mass fraction, EM/MTOM. e_{bat} is determined by the available battery technology and therefore (in first approximation) independent of the aircraft design. η_{elec}, η_{p}, $(L/D)_{\text{max}}$ and EM/MTOM are performance parameters, which depend on the design of the aircraft and its propulsion system. However, the first two are already close to their theoretical maximum with current technology. Therefore, the two key variables that can be varied in the design process and that have a large impact on range are $(L/D)_{\text{max}}$ and EM/MTOM. This paper focuses on these two parameters: $(L/D)_{\text{max}}$ and EM/MTOM. As will be shown later, these parameters have a strong correlation and therefore we introduce a new, combined, parameter: the Electric Range Factor (ERF). This is the product of $(L/D)_{\text{max}}$ and EM/MTOM.

For the other parameters, we assume the following: an electric powertrain efficiency of 91%, a propulsor efficiency of 87%, and usable battery energy density of 300 Wh/kg. A detailed assessment of these assumptions is outside the scope of this paper. Ref. [2] shows realistic estimates of the assumed powertrain and propulsor efficiencies. The "usable battery energy density" employed here refers to the energy density at pack level at the end of life, accounting for maximum state of charge and minimum depth of discharge. Ref. [13] provides further insight regarding estimations of usable battery energy density, considering cell energy density, cell/pack ratio, maximum state of charge, maximum depth of discharge, C-rates and cell degradation.

Given these assumptions, the maximum cruise range equation can be rewritten as ($R_{\max}$ is expressed in kilometers):

$$R_{\max} \approx 87 \times \mathrm{ERF} \tag{2}$$

B. Review of Prior Studies on Battery-Electric Aircraft

Many publications in recent years have underlined the range limitations for battery-electric aircraft. For example,

- Epstein and O'Flarity [6] conclude that electric propulsion is not a promising path to significant reduction of aviation's CO_2 in the first half of the 21st century. Supporting this conclusion, the authors state that ninety-two percent of aviation's CO_2 is produced by single- and twin-aisle aircraft requiring 15,000 to 200,000 kW of shaft power and 150,000 to 2,250,000 kWh of energy at take-off and that no known battery technology can power such aircraft at the ranges flown today.
- Staack et al. [7] conclude that a 19-seat aircraft with a system specific energy of 300 Wh/kg would yield a maximum still-air range of 427 km. This calculation takes taxi, take-off, climb and descent into account; however, it considers neither the energy required for non-propulsive systems nor any reserves. The authors also point out that reference aircraft have empty mass fractions over 50% and that their assumed empty mass ratio of 42% is chosen "for the sake of optimism", assuming a non-pressurized cabin (limiting commercial operations to FL80 and below) and the extensive use of composites (manufacturing cost not considered). The authors assume an $(L/D)_{\max}$ of 20.6 (17.9 in cruise) with a wing aspect ratio of 14.8. They consider these values as optimistic and "aim to represent an upper boundary of what could be technically achieved with a modern clean-sheet design with no stringent cost constraints."
- Mukhopadhaya and Graver [8] point out that the reserve requirements further limit the range. They assume that the legally required reserves (5% contingency reserve, 30 minutes loiter reserve and alternate reserve, assuming an alternate 100 km from the destination airfield) is covered by battery energy. Assuming a 27% EM/MTOM fraction and a battery energy density of 250 Wh/kg for a hypothetical 90 seater (90Bolt), they estimate an operational cruise range of 9 km. This would grow to 281 km when usable battery energy density grows to 500 Wh/kg. For smaller aircraft, the authors assume slightly higher EM/MTOM fractions and lower loiter speeds (requiring less loiter energy), leading to somewhat higher operational cruise ranges.
- Viswanathan et al. [14] state that a pack-level specific energy of 1200˜2000 Wh/kg is required for small commuter aircraft. But these performance levels require a fundamental reassessment of battery chemistry. With adequate levels of support, they conclude that pack-level specific energies in excess of 600 Wh/kg may be feasible by 2030.
- Hall et al. [15] conclude that all electric designs are not feasible at any scale (from thin haul to long haul) because the required battery mass is larger than the airframe parameters can support. This paper argues that even with optimistic estimates of battery capacities available in 2035, batteries alone are unlikely to power aircraft at current design missions for thin haul, regional haul, medium haul, and long haul aircraft.
- Schafer et al. [16] predict that electric aircraft with 10−30% battery mass fraction will only be feasible for regional or short haul flights when battery specific energies increase to much greater values than are currently available.
- Webber and Job [17] consider that a purely battery-powered aircraft is suitable for only short-range applications and therefore out of scope for FlyZero. In supporting this conclusion, the authors consider that a typical empty operating mass fraction is 55%, a typical fuel mass fraction is 20%, and that a battery-powered aircraft with this energy fraction could manage only a very short range of less than 250 nautical miles. The authors also conclude that the range for battery-powered aircraft would only increase to 450 nautical miles at the cost of decreasing the payload mass fraction to zero (thereby ruling out the use of the aircraft to carry any passengers).
- The Air Transport Action Group [18] concludes: "For the 51−100 seat segment several technical challenges remain. For example, for a 70-seat turboprop aircraft operated on a 200 nautical mile segment (around an hour's flight), the energy needed would be roughly 2.6 MWh (two motors developing 1.3 MW average power output during flight mission for an hour). Assuming an optimistic 300 Wh/kg battery energy density, the required

mass of the battery would reach 8,700 kg which is greater than the design payload of the aircraft (approximately 7400 kg). Given the design challenges for a 200 nmi mission, battery energy density would have to increase substantially—around seven times greater than today's highest density batteries—to enable such a scenario. The specific energy is in the range of 200 watt-hours per kilogramme, which is 60 times lower than jet fuel. Another important constraint is the need to have specific power for a high discharge rate of the battery during certain flight phases such as take-off. It was further assessed that while all electric and hybrid-electric battery-based aircraft are likely to become technologically feasible for aircraft with an increasing number of passengers and/or growing flight range as the specific energy of batteries increases, the introduction of these technologies for the largest aircraft and longest ranges is not expected before 2050."

III. Perceived Range Limitations Based on Four Misconceptions

Summarizing the existing publications regarding maximum range of battery-electric aircraft, four statements underpin the infeasibility of battery-electric aircraft:

1) A realistic EM/MTOM fraction for 50−100 pax aircraft is ±25%. This claim is supported by the fact that 40+ seat turboprop aircraft have empty mass fractions (OEM/MTOM) of 55%−65% and payload mass fractions of 20%−25%, and therefore the energy fraction (EM/MTOM) has a maximum of 20%−25%. A meaningfully higher battery fraction without significant payload reduction requires a lower empty mass fraction and often the argument is "if that was possible, aircraft manufacturers would have done so already for fossil fuel aircraft".
2) A realistic cruise L/D is around 14−18, as achieved by current turboprop or regional aircraft. Higher L/D would require low-TRL aerodynamic technologies.
3) The required reserves reduce the battery-electric maximum cruise range by 250−400 km. Given statement 1 and 2, the battery-electric maximum cruise range would be around 300˘400 km, with earlier stated assumptions for usable battery energy density and efficiencies. Subtracting the energy required for reserves would imply a maximum range approaching zero.
4) Negative scaling effects create an inverse relationship between maximum range and aircraft size. Therefore short-range commuter aircraft (up to 19 pax) may be feasible but larger aircraft would have an even lower range.

The authors of this paper have also endorsed such views in previous work [3, 4]. However, in the following sections we challenge these statements.

A. Misconception 1: EM/MTOM Realistically Cannot Exceed 20% – 25%

Several studies [19–21] suggest a causal relationship between aircraft size and empty mass fraction, suggesting that typical 50−100 seat aircraft will have a relatively high OEM/MTOM fraction of 55%−65%, and larger aircraft, thanks to positive scale effects, have lower empty mass fractions. For example, Fig. 1 shows the empty-mass fraction as function of number of passenger seats as a proxy for aircraft size, indicating that in the 50−100 pax class, one can expect an empty mass fraction of 55%−65%.

However, analyses by Obert [22] and Torenbeek [23] lead to a different conclusion. Both Obert and Torenbeek identified a negative linear correlation between empty-mass fraction and fuel fraction, as indicated in Fig. 2. Obert concludes: "For a certain aircraft category, the empty-mass fraction is more or less constant and *almost independent of aircraft size* but is *dependent on range*. For a long-range aircraft, the empty mass fraction would be 45% and the fuel fraction about 45%, leaving 10% for the payload. Short haul aircraft have a fuel fraction of about 20−25%, empty mass fractions of 50%−60% and payload fraction of 25%−30%".

Torenbeek observed a similar correlation and concludes: "the empty mass fraction is more closely related to the fuel fraction than to any other characteristic". Torenbeek further states that if an aircraft has a low empty mass fraction, this is *not necessarily due to a very light structure*. Instead, a large range requirement leads to a high fuel load and high MTOM; hence, the empty mass fraction will consequently be low. In other words, OEM/MTOM is largely *driven by* EM/MTOM.

This relationship between OEM/MTOM and EM/MTOM can be quantified. Based on the observed relations between the various masses, Torenbeek proposes a formula for Class I empty (operating) mass estimation for fossil-fuel aircraft [23]:

$$\mathrm{OEM} = c_1 \cdot \mathrm{MPLM} + c_2 \cdot \mathrm{MTOM} + c_3 \tag{3}$$

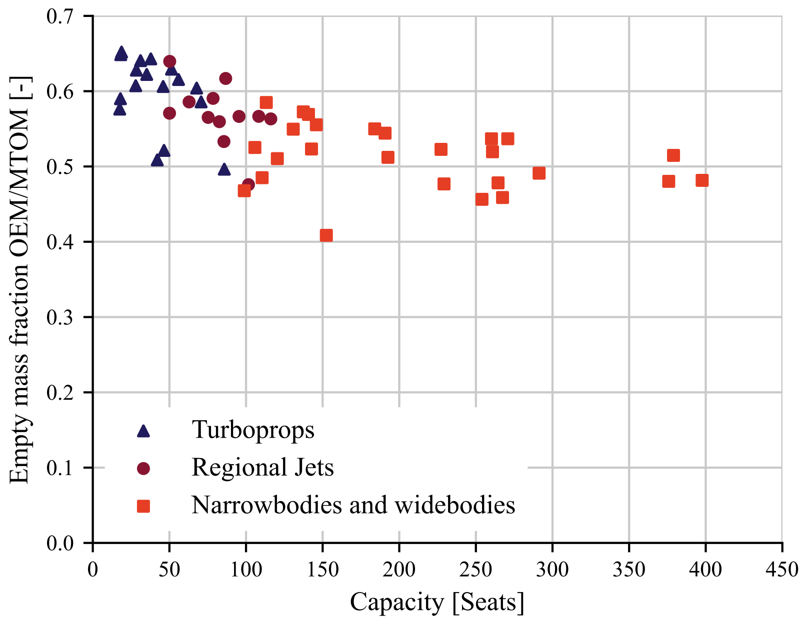


Fig. 1 Correlation between empty mass fraction and aircraft size (seats), adapted from Ref. [21].

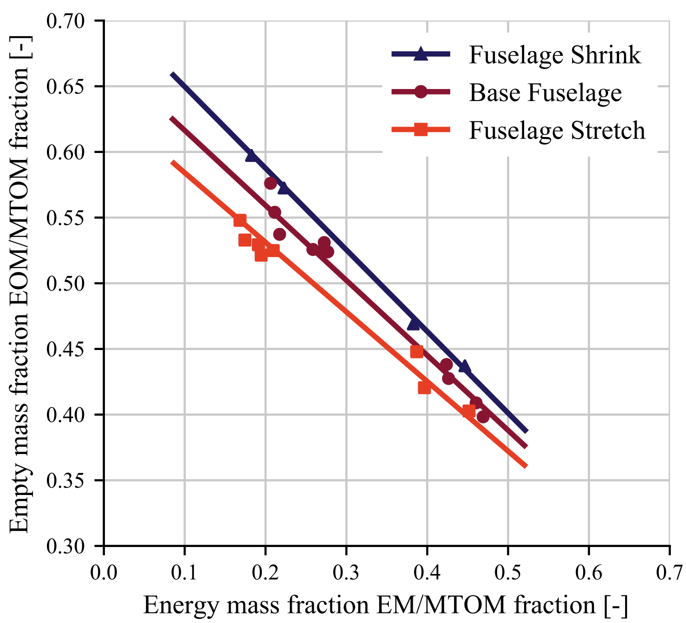


Fig. 2 Relationship between empty-mass fraction and fuel mass fraction, adapted from Ref. [22]. Data presented for baseline, shorter (shrink), and longer (stretch) fuselage variants of various aircraft families.

Here, the first term summarizes the body group (fuselage structure, fuselage systems, furnishings, etc.), which is directly related to the maximum payload mass (MPLM). The second term represents wing, tail, powerplants and landing gear, primarily related to MTOM. The last term represents flight deck crew and their accommodation and is relatively independent from payload or total mass. In addition, the unity equation [23] states the relationship between MTOM, OEM, MPLM and EM:

$$\text{MTOM} = \text{OEM} + \text{MPLM} + \text{EM} \tag{4}$$

Note that MPLM is *maximum* payload mass and EM is energy mass *at maximum payload*, i.e., this is the unity equation that applies for the *harmonic range*, with maximum payload carried in the fuselage and the wing tanks "filled up to MTOM". Combining Eqs. 3 and 4, we can derive equations for OEM and OEM/MTOM as a function of two variables, that are defined by the Top-Level Aircraft Requirements: MPLM (defined by payload requirements) and energy fraction EM/MTOM (defined by range requirements):

$$\mathrm{OEM} = \left(c_1 + \frac{c_2(1+c_1)}{1 - \frac{\mathrm{EM}}{\mathrm{MTOM}} - c_2}\right)\mathrm{MPLM} + \frac{c_2 c_3}{1 - \frac{\mathrm{EM}}{\mathrm{MTOM}} - c_2} + c_3 \tag{5}$$

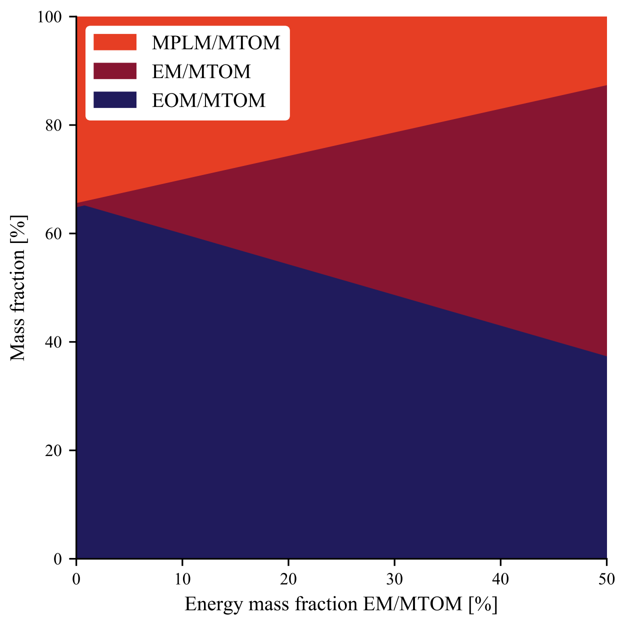
$$\frac{\mathrm{OEM}}{\mathrm{MTOM}} = \frac{(c1 + c2)\mathrm{MPLM} - c_1 \mathrm{MPLM}\frac{\mathrm{EM}}{\mathrm{MTOM}} + c_3\left(1 + \frac{\mathrm{EM}}{\mathrm{MTOM}}\right)}{(1+c_1)\mathrm{MPLM} + c_3} \tag{6}$$

where Torenbeek proposes coefficient values for narrowbody, fossil-fuel aircraft, shown in Table 1.

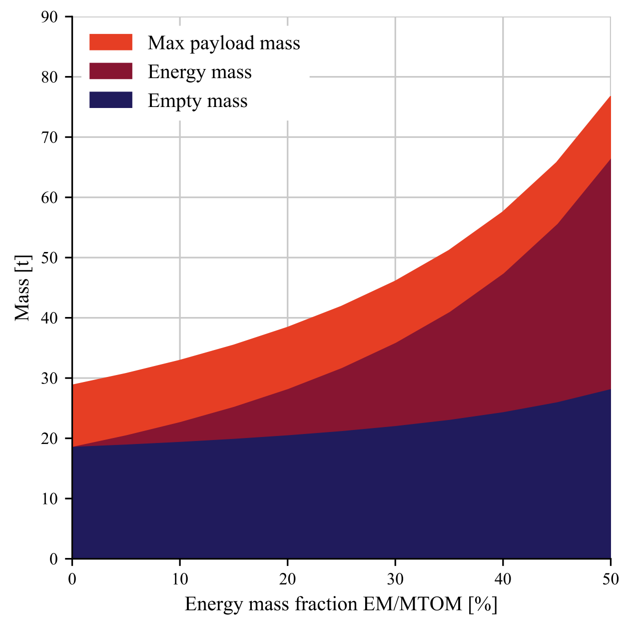
Table 1 Coefficients used in Eqs. 3–6 for single-aisle aircraft, based on Ref. [23].

Coefficient	Value
c_1 [-]	1.25
c_2 [-]	0.2
c_3 [kg]	500

With these coefficient values we can explore how mass and mass fractions vary with the energy fraction and with MPLM. For a single-aisle aircraft with a MPLM of 10,000 kg (representing a ±100 pax aircraft), we can express all mass fractions and masses (in kg) as a function of the EM/MTOM ratio, as shown in Fig. 3.



(a) Effect on mass *fractions*.



(b) Effect on masses.

Fig. 3 Effect of EM/MTOM fraction on the mass and mass breakdown of a 100-seater single-aisle aircraft.

Figures 3a and 3b show two correlations:

- A high energy fraction (EM/MTOM) correlates with a relatively *low* empty-mass fraction (OEM/MTOM).
- A high energy fraction (EM/MTOM) correlates with a relatively *high* empty mass (OEM).

This implies that fossil-fuel passenger aircraft, designed for long range, have a higher empty operating mass than aircraft designed for a similar maximum payload but a shorter range. Therefore, aircraft designed for long range, compared to aircraft designed for short range with similar maximum payload, have a higher fuel consumption per passenger kilometer, assuming all other factors equal. In other words, a low OEM/MTOM fraction correlates with a relatively high OEM and a less fuel-efficient aircraft.

The relationship between the different mass fractions and EM/MTOM, as expressed by Eq. 6 and shown in Fig. 3a, is almost independent of aircraft size, within the narrowbody class of transport aircraft. Reproducing this graph for a 70 seat (MPLM = 7000 kg) or 200 seat (MPLM = 20000 kg) narrowbody aircraft would yield nearly the same figure; with the exception of the slight difference caused by the constant c_3 (500 kg), representing items such as the flight deck crew and their accommodation. This size-independent result from this theoretical assessment is in line with the analysis of Obert, based on actual aircraft mass fractions [22]. The correlation between the empty-mass fraction and MTOM or number of seats, as shown in Fig. 1, does *not* imply a causal relationship between these parameters. Nearly all the lower-mass aircraft in these figures have a lower range, hence a lower EM/MTOM, which implies a relatively high OEM/MTOM.

This raises the question whether the observed relationship between masses and mass fractions, based on Eqs. 5, 6, and coefficients of Table 1 hold in the design space where OEM/MTOM is 45% or lower. The first-generation narrow-body jets, due to unfavorable specific fuel consumption, required high energy fractions to meet range requirements and realized empty mass fractions below 45% [19]. In Table 2 we compare the actual empty mass fractions with calculated mass fractions, using Eqs. 5 and 6 and the coefficients of Table 1. Though this is a rather small sample, the analysis suggests that these formulas and coefficients also can be used with an accuracy of ~3% in this design space.

Table 2 Comparison of actual OEM/MTOM data from Ref. [19] and Class-I estimates for first generation jets.

	OEM [kg]	MTOM [kg]	MPLM [kg]	OEM/MTOM (data)	OEM/MTOM (calculated)	Difference
B707-320	66224	151315	28000	43.8%	43.6%	−0.2%
DC8-63	69739	158760	30719	43.9%	44.2%	+0.3%
Il-62M/MK	71600	165000	23000	43.4%	40.9%	−2.5%

From the foregoing we can conclude that a 70−100 seat single-aisle, fossil-fuel aircraft with a low (<45%) OEM/MTOM ratio is feasible. Such aircraft would be the right reference aircraft for a short-range battery-electric aircraft. Current turboprops or regional jets have been designed for short ranges. Therefore, they require a relatively low EM/MTOM fraction, have a relatively high OEM/MTOM fraction, a relatively low OEM, and are very fuel efficient. In other words, short-range, fossil-fuel aircraft are well designed for their short-range missions, but do not offer the right reference for battery-electric aircraft. A battery-electric aircraft *inherently* has a high energy mass fraction—in this case, not because the aircraft is designed for "long" range, but because the energy carrier is very heavy compared to fuel. Hence, a battery-electric aircraft *inherently* has a lower empty mass fraction than a short-range fossil-fuel aircraft, and looks more like a first-generation jet in that sense. This effect is a result of how the various mass components of the aircraft scale, and does not require any assumptions regarding new technologies such as lightweight materials. Therefore, the first statement of Sec. III is a misconception.

B. Misconception 2: A Realistic Maximum Lift-to-Drag Ratio is Between 14 and 18

The maximum lift-to-drag ratio $(L/D)_{\max}$ of turboprop and jet aircraft is in the range of 14−18, as shown in Fig. 4*. However, if one assumes similar numbers for a battery-electric aircraft, one overlooks a significant scaling effect, which is directly linked to the energy mass fraction.

*The two regional-jet datapoints in Fig. 4 with $(L/D)_{\max}$ above 20 correspond to variants of the Fokker F28, as reported in Ref. [21]. We believe these data points are incorrect, given the $(L/D)_{\max}$ values of comparable aircraft.

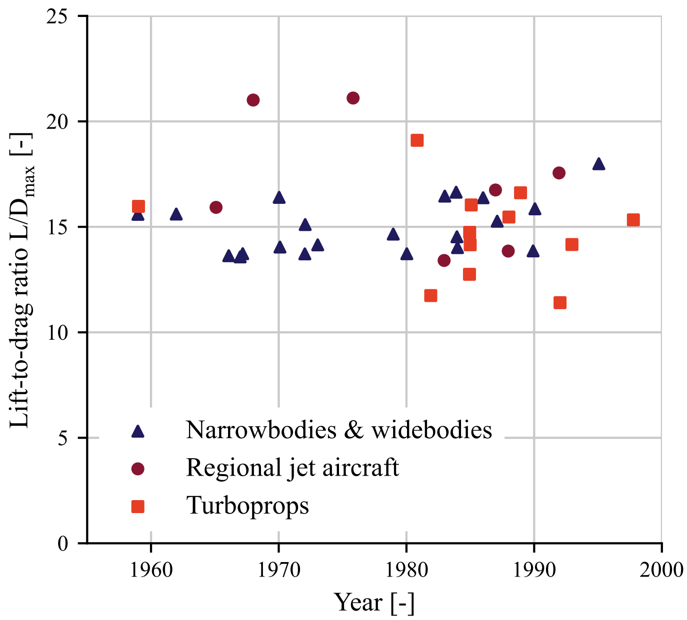


Fig. 4 $(\mathbf{L/D})_{\mathbf{max}}$ of various short-range turboprop and jet aircraft, adapted from Ref. [21].

A Class-I $(L/D)_{\max}$ estimate can be calculated using the following equation from Raymer [24]:

$$\left(\frac{L}{D}\right)_{\max} = k\sqrt{\frac{A}{S_{\text{wet}}/S_{\text{ref}}}} \tag{7}$$

The constant k, according to Raymer, depends on the type of aircraft, where 13 is a typical value for aircraft with a high aspect ratio wing and is used in this example.

For a given aspect ratio, $(L/D)_{\max}$ is determined predominantly by the ratio of wetted area and wing reference area ($S_{\text{wet}}/S_{\text{ref}}$). For "tube-and-wing aircraft", there is a strong correlation between the $S_{\text{wet}}/S_{\text{ref}}$ ratio and EM/MTOM ratio. Assuming a constant wing loading, constant aspect ratio and constant MPLM, an increase in EM/MTOM ratio driven by higher range requirements, causes an increase in MTOM. The fuselage size, driven by MPLM, remains unchanged, while the wing area grows linearly with MTOM. This assumes that the batteries will be located in the wing. This assumption can be justified, since the specific mass of battery packs is expected to be of the order of 2000 kg/m³, which is roughly 2.5 times more dense than Jet A1 fuel. Therefore, since in the past jet aircraft have been able to store fuel in the wing with a mass up to ~45% of their MTOM, we consider it a safe assumption that battery-electric aircraft, with a similar energy mass fraction and 2.5 times higher specific mass, can carry the batteries within the wing.

Note that the horizontal and vertical tail areas grow *more* than linearly with the wing area, assuming constant tail volume coefficients. The horizontal tail coefficient (c_{HT}) is defined as [24]:

$$c_{\text{HT}} = \frac{l_{\text{HT}} S_{\text{HT}}}{c_{\max} S_{\text{ref}}} \tag{8}$$

In this equation, l_{HT} is the tail arm, c_{mac} the mean aerodynamic cord, S_{HT} the planform area of the horizontal tail, and S_{ref} the wing planform area. From this equation, it can be concluded that for a given payload—and thus, fuselage length—a constant tail volume coefficient requires S_{HT} to grow more than proportionally with S_{ref}, since the mean aerodynamic chord grows with the square root of the wing area growth factor, while the tail arm l_{HT} remains constant. For the vertical tail area, the analysis is similar, with the exception that in the vertical tail coefficient denominator, span width must be used instead of mean aerodynamic chord.

As a result, both the total wetted area (of wing, tail and fuselage combined) and wing reference area grow. However, the ratio between wetted area and reference area reduces, since fuselage wetted area remains unchanged. This results in a higher $(L/D)_{\max}$. An example of the magnitude of this effect is shown in Table 3. This table compares two parametric designs of a 100-seat fossil fuel aircraft: the first with a 15% energy mass fraction. and the second with a 45% energy mass fraction, keeping all other design choices the same. The areas of the fuselage and tail are calculated using formulas and data from the parametric designs presented in Sec. IV.

Table 3 Comparison of Class-I $(L/D)_{max}$ estimates. MTOM estimated using Eqs. 5 and 6.

	Aircraft 1	**Aircraf 2**
EM/MTOM [-]	15%	45%
MPLM [t]	10	10
MTOM [t]	35.4	65.7
Aspect ratio, A [-]	12	12
Wing loading, MTOW/S_{ref} [N/m²]	5000	5000
Wing area, S_{ref} [m²]	71	131
Fuselage wetted area [m²]	285	285
Wing wetted area [m²]	145	270
Tail wetted area [m²]	28	79
Wetted-area ratio S_{wet}/S_{ref} [-]	6.5	4.8
Constant k [-]	13	13
Maximum lift-to-drag ratio, $(L/D)_{max}$ [-]	17.7	20.5

As shown in this example, $(L/D)_{max}$ grows by ~3 points, driven by an increase in energy fraction. In other words, the higher energy-mass fraction that is inherent to electric aircraft not only reduces the empty-mass fraction, but also increases the lift-to-drag ratio of the aircraft. Therefore, we suggest a new parameter in Eq. 2: the Electric Range Factor (ERF), which is the product of L/D and EM/MTOM, since these two parameters are strongly linked.

In conclusion, without using any low-TRL technology, battery-electric aircraft with a high energy mass fraction can achieve a significantly higher $(L/D)_{max}$ than today's turboprops or regional jets, due to a lower ratio of wetted area to wing-reference area. Therefore, the second statement of Sec. III is a misconception.

C. Misconception 3: Reserve Requirements Result in a Practical Range Close to Zero

EASA Rules for Air Operations (CAT.OP.MPA 180-182) specify the reserve fuel/energy for commercial IFR flights. For normal operations these required reserves consist of:

1) Contingency reserve fuel: 5% of trip fuel/energy.
2) Alternate reserve fuel: fuel for climb from Missed Approach Point at destination to landing at planned alternate.
3) Final reserve fuel: fuel for 30 minutes (turbine aircraft) or 45 minutes (piston-engine aircraft) loiter at 1500 ft above airfield

Given the variability of operational conditions encompassing factors such as payload, designated flight path, weather conditions, alternate selection, and other pertinent parameters, it follows that the required reserves necessary for each unique flight mission are inherently distinct. This inherent variability poses a design problem, as no universally applicable design requirement has been established for quantifying the required reserve fuel or energy. Consequently, in aircraft design, a proper determination of a minimal amount of required reserve fuel is imperative to validate whether the range requirements can be met, while accommodating for the required reserves across diverse scenarios. To illustrate, Mukhopadhaya and Graver [8] estimate a minimal alternate reserve equivalent to a 100-kilometer distance in cruise flight and a total amount of reserve energy equal to 263 km cruise flight for their proposed 90-seater aircraft. Here, we assume a reserve energy requirement equivalent to the energy required for a 300 km cruise flight.

In the course of routine airline operations, these reserves are hardly used. Diversions to alternate destinations are, fortunately for passengers, a rarity, and consumption of the final reserve fuel is treated as a serious incident by both operators and regulatory bodies. Consequently, it would make sense harbouring this reserve energy in a lightweight configuration, even if its usage would be relatively costly, considering the low usage frequency. A "turbine plus generator" reserve energy system, using SAF, can be an alternative to batteries for carrying the required energy reserve. Previous studies have investigated the use of a combustion engine for range extension [25]. However, in this discussion the key purpose of the combustion engine is to cover reserves, and not to extend the nominal mission range. While that remains an option, there are economic and environmental challenges associated to it.

Table 4 compares the mass of a reserve energy system based on batteries versus a turbogenerator-based system. For this comparison we assume the reserve gas-turbine mass based on a power-to-weight ratio (maximum continuous turbine power at sea level divided by MTOW) of 0.015 kW/N, equal to the electric motor power loading of the parametric designs presented in Section IV. A detailed assessment of required reserve power is outside the scope of this paper. The turbine mass estimation has been based on Roskam [26]. The generator mass has been determined, based on an assumed specific mass of the combined generator and rectifier of 10 kW/kg. This assessment shows that the mandated reserve energy can be transported with a markedly reduced mass vis-à-vis a rechargeable battery system.

Table 4 Mass comparison of turbine-generator based reserve energy system versus battery mass required for reserves.

	Battery mass for required reserves	**Reserve energy system mass for required reserves**
MTOM [t]	75	75
Cruise range as proxy for reserves [km]	300	300
Lift-to-drag ratio L/D [-]	20	20
Electric powertrain efficiency η_{elec} [-]	0.90	0.90
Propulsor efficiency η_{p} [-]	0.85	0.85
Energy required [MJ]	14400	14400
Energy required [kWh]	4000	4000
Battery mass 300 Wh/kg [kg]	13300	—
Efficiency turbogenerator [-]	—	0.33
Fuel energy required [MJ]	—	43700
Energy density Jet A-1 [MJ/kg]	—	43
Fuel mass required [kg]	—	1000
Range extender power/MTOW [kW/N]	—	0.015
Range extender power required [MW]	—	11.3
Specific power generator [kW/kg]	—	10
Specific power gas turbine (incl. accessories) [kW/kg]	—	3.5
Mass of range extender (gas turbine + generator) [kg]	—	4350
Total mass range extender & fuel [kg]	—	5350

A fuel based reserve energy system in combination with batteries as primary energy source, as proposed here, will spark many discussions with certification authorities and require new interpretations of airworthiness regulations. One could imagine that authorities would require redundancy in the reserve energy system design, with a certain minimum power to be provided by the system if one of the turbines or generators fails. Under the above presented specific mass assumptions for turbines and generators, this would lead to a mass increase; the exact magnitude depending on what would be the minimum required power in failed state. On the other hand, the assumed power-to-weight ratios of turbine and generator may prove to be conservative.

Therefore, an exact mass estimate depends on many assumptions regarding future technology and future regulations and is outside the scope of this paper. In the extreme case, even if two turbines and two generators would be required, both sized to the required maximum continuous power, the results shown in Table 4 indicate that the combined system mass with doubled turbine and generator mass would still be lower than the equivalent battery mass. In any situation, a turbine-generator reserve energy system proves lighter in comparison to reserve energy storage within rechargeable batteries. This reduces the impact of reserves on the feasible operational range. As a consequence, the third statement of Sec. III is a misconception.

D. Misconception 4: Negative Scale Effects Preclude Battery-Electric Propulsion for 50+ Seat Aircraft

Several authors state that for 9 to 19 pax CS-23 commuter aircraft battery-electric propulsion is feasible [8, 17, 18], but not for larger CS-25 (50+ pax) transport aircraft; for economic reasons and for technical reasons. The economic argument is that given the very low range of these aircraft, only niche routes can be flown with very little passenger demand, requiring only small aircraft. This economic argument can be rendered obsolete as soon as it has been proven that the range of electric aircraft is much higher than what has been assumed thus far, which is the intention of this paper. The technical argument is that larger transport aircraft will have a shorter range than commuter aircraft [8], suggesting that certain parameters that determine maximum range, scale negatively with aircraft size. We disagree with this technical argument for several reasons:

- As discussed in paragraph III.A, within the transport aircraft category (50 seats and more), the mass fractions are nearly independent of aircraft size, as is proven by the work of Torenbeek and Obert. However, when comparing CS 23 commuter aircraft and CS 25 transport aircraft, some positive scale effects can be observed, lowering the OEM/MTOM fraction for CS 25 aircraft compared to their CS23 counterparts. For example, one needs two pilots for both 19-seat and 50+ seat aircraft, thus the "pilot mass fraction" (which is incorporated in the OEM/MTOM fraction) is lower for larger aircraft. Similarly, avionics and instrumentation system requirements for IFR operations do not materially differ between commuter aircraft and transport aircraft, leading to a lower avionics mass fraction for transport aircraft.
- On subsystem level, some negative scale effects exist. For example, Moore et al. [27] point to a negative scale effect in electric propulsors. As electric motors scale with maximum torque, two motors with smaller propellers and higher RPM can offer a better power-to-mass ratio than one larger motor-propeller combination, providing the same power. However, this scale effect on subsystem level, can be utilized in both small and large aircraft through distributed propulsion.
- The reserve requirements for commercial IFR flights do not differentiate between CS-23 and CS-25 aircraft. If one opts for a fuel-based reserve energy system (combustion engine and generator), the power density (kW/N) of such machines is higher for high-power applications than for low-power applications. Therefore, for a given aircraft power-to-weight ratio, the mass fraction of the reserve energy system decreases with aircraft size. The mass fraction of required fuel for loiter (loiter fuel mass/MTOM) might be lower for CS-23 aircraft than for CS-25 aircraft, given that for most CS-23 aircraft the loiter speed is lower than for CS25 aircraft and required loiter reserve is determined by time (30 or 45 minutes). However, this effect is relatively small, as the fuel mass is only a small fraction of the total reserve energy system mass, as shown in the previous paragraph.
- Thanks to the square-cube law, the wing volume grows more than proportionally with aircraft size, which offers more opportunity to store batteries in the wing in CS-25 transport aircraft than in CS-23 commuter aircraft. Placing the batteries in the wing offers many benefits over battery placement in the fuselage: reduction of wing bending moment, utilization of the available wing space and reduction of the required fuselage space.
- There is also a significant aerodynamic scale effect [22]. The (flat plate) skin friction coefficient reduces with increased Reynolds number, hence with aircraft size. This effect causes a reduction in skin friction drag per m^2 wetted area, considering all other factors equal (smoothness, form factor, freestream airspeed, air density, viscosity). The overall effect is an increase in lift-to-drag ratio with aircraft size.

In conclusion, we do not observe any compelling reason why CS-23 battery-electric commuter aircraft would offer a larger maximum cruise range than CS-25 aircraft. The qualitative arguments mentioned here suggest otherwise, therefore the fourth statement of Sec. III is a misconception.

IV. A Revised Battery-Electric Maximum Range Equation

The previous section showed that range estimates for battery-electric aircraft often have been based on several misconceptions. This requires a new assessment of what the maximum cruise range could be under the right set of assumptions. In 2014, Moore and Fredericks [28] stated that "*The right question to ask is not 'What will it take for battery electric to match the same power and energy storage per weight of a conventional propulsion aircraft?' Instead the right questions to ask of electric aircraft are 'How can battery electric effectively compete with conventional propulsion aircraft even though they are energy constrained, what new aircraft types and architectures do the different characteristics enable, what evaluation metrics should be used in their comparisons, and how could electric aircraft evolve to eventually replace reciprocating and even turbine aircraft?'*" In that spirit, we developed twelve parametric aircraft designs and applied bottom-up 'Class II' mass and L/D estimates to assess which ERF values are realistic and, subsequently, what maximum cruise range is feasible.

A. Parametric Design Approach

We develop parametric designs for three aircraft seating classes (40, 80, and 120 seats) and, for each seating class, different ERF values (ERF = 6, 8, 10, 12), with top level aircraft requirements as stated in Table 5.

Table 5 Top-level aircraft requirements.

Requirement	Value
Payload mass	100 kg per pax
Cruise Mach number [-]	0.6
Take-off field length [m]	2000
Landing distance required [m]	1400
Max wingspan with folded wing tips [m]	36

The twelve parametric designs are based on following principles:

- *Think big*: starting point is a narrow-body (40−120 pax) passenger transport aircraft instead of commuter aircraft.
- *Think 1960ies*: first-generation narrow-body jets offer the right reference values for empty mass, payload and battery mass ratios.
- *Span Loading*: place the batteries in the wing to put the load where the lift is and use available wingbox volume.
- *Low power-to-weight ratio*: a maximum continuous power at sea level divided by maximum take-off weight value of 0.015 kW/N is feasible, thanks to distributed electric propulsion (DEP) (smaller impact of one-engine-inoperative scenarios) and a relatively long (2000m) TOFL requirement.
- *Optimum wing loading*: based on TOFL, landing distance, cruise speed and altitude requirements, the chosen optimum wing loading is 5000 N/m², above typical values for propeller aircraft (3000−4000 N/m²) and at the lower boundary of typical values for jet aircraft (5000−8000 N/m²).
- *Low-wing configuration*: thanks to DEP, the propeller diameter can be reduced, enabling a low-wing configuration with gear attached, which leads to a shorter, lighter landing gear and lighter fuselage, since the load path from gear to wing does not pass the fuselage.
- *Treat reserves differently*: a turbine-based reserve-energy system for required reserve energy.
- *High L/D is a free gift*: the chosen wing loading in combination with a chosen aspect ratio of 12, results in a wetted aspect ratio (span width squared divided by wetted area) of at least 2, well above most passenger aircraft [24].

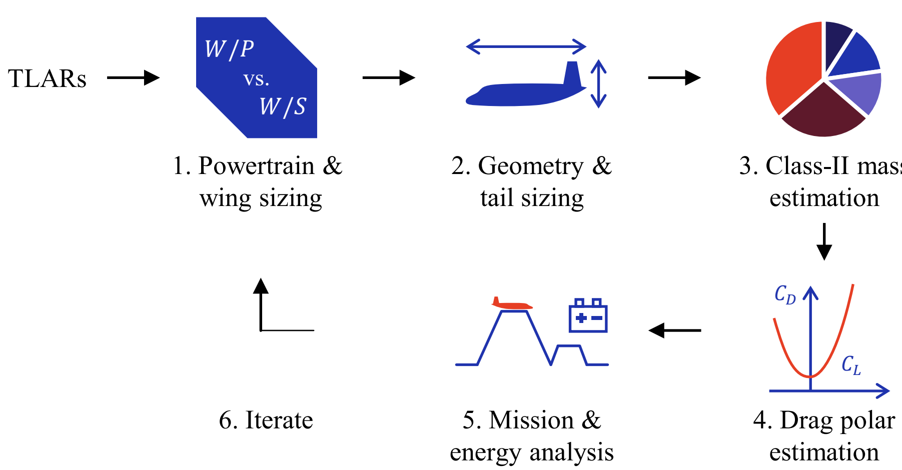


Fig. 5 Overview of sizing process used in this paper.

A tool was developed to perform the Class-II sizing of electric aircraft for the aircraft requirements specified above. The tool consists of five steps, as indicated in Fig. 5: calculation of the required wing and power loading, estimation main aircraft dimensions, calculation of component mass, calculation of aerodynamic polar, and an energy calculation performed by splitting the mission into four segments – climb, cruise, descent, and reserves. These five steps are performed iteratively to converge on the MTOM of the aircraft. We varied the cabin length for the 40, 80 and 120 seat variants and the maximum take-off mass and number of engines for the different ERF values. The number of engines has been chosen, ranging from 4 to 12 and with a maximum continuous power per engine below 1.5 MW. The wing geometry followed from the chosen wing loading (5000 N/m2) and aspect ratio (12) and tail sizes have been determined by keeping the tail coefficients constant across all parametric designs.

We used Class-II handbook methods to estimate the OEM and the aerodynamic performance (C_{D0} and L/D). Key assumptions regarding mass estimation and aerodynamic performance are identical to the assumption used in Paper II and given in Appendix A of that paper [11]. The results of the tool were compared to results from applying the method used in Paper II [11] and the tool was verified to produce comparable results for the complete range of aircraft configurations investigated here.

B. Results
Table 6 shows the key mass figures, mass fractions, $(L/D)_{\max}$ and maximum cruise range for each design. From this table it can be observed that $(L/D)_{\max}$ and EM/MTOM are practically independent of the aircraft size, in line with similar observations on fossil fuel aircraft as presented in Sec. II. Also, the $(L/D)_{\max}$ and EM/MTOM ratios increase simultaneously, as expected based on the analysis of Sec. III.B. Above all, the results presented here prove that conceptual designs according to the specifications of Table 5 and with an ERF of 12 are feasible. These designs offer a maximum cruise range above 1000 km, with the assumptions as stated in Sec. II.A.

To give a visual representation of the scaling effects, Fig. 6 shows the planform views of four designs in "corners" of the design space. The figure shows how fuselage size increases only with payload, while wing size increases with both

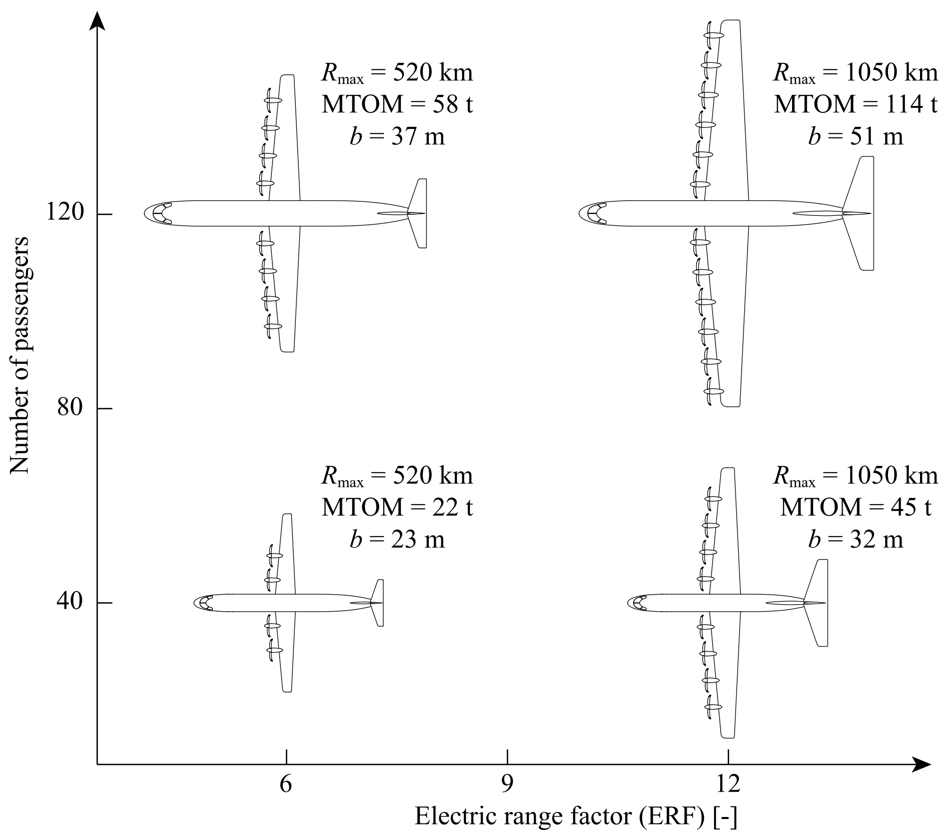


Fig. 6 Planform view of four parametric designs from Table 6, as function of number of passengers and ERF.

Table 6 Masses, $(\mathrm{L/D})_{\mathrm{max}}$ and max cruise range of 40-, 80-, and 120-seater designs with different ERF values.

Nº of pax	ERF	MTOM [t]	OEM [t]	EM [t]	$\frac{\mathrm{OEM}}{\mathrm{MTOM}}$	$\frac{\mathrm{EM}}{\mathrm{MTOM}}$	$(\mathrm{L/D})_{\mathrm{max}}$	$\mathrm{R}_{\mathrm{max}}$ [km]
40	6	22	11	6.7	51%	31%	19.5	520
40	8	27	13	11	47%	39%	20.7	700
40	10	33	14	15	43%	45%	22.2	870
40	12	45	18	24	39%	52%	23.0	1050
80	6	40	19	12	49%	31%	19.6	520
80	8	48	21	18	45%	38%	20.8	700
80	10	59	25	27	41%	45%	22.3	870
80	12	78	30	40	38%	52%	23.1	1050
120	6	58	28	17	49%	30%	20.0	520
120	8	69	31	26	45%	38%	21.2	700
120	10	85	36	37	42%	44%	22.7	870
120	12	114	44	58	38%	51%	23.6	1050

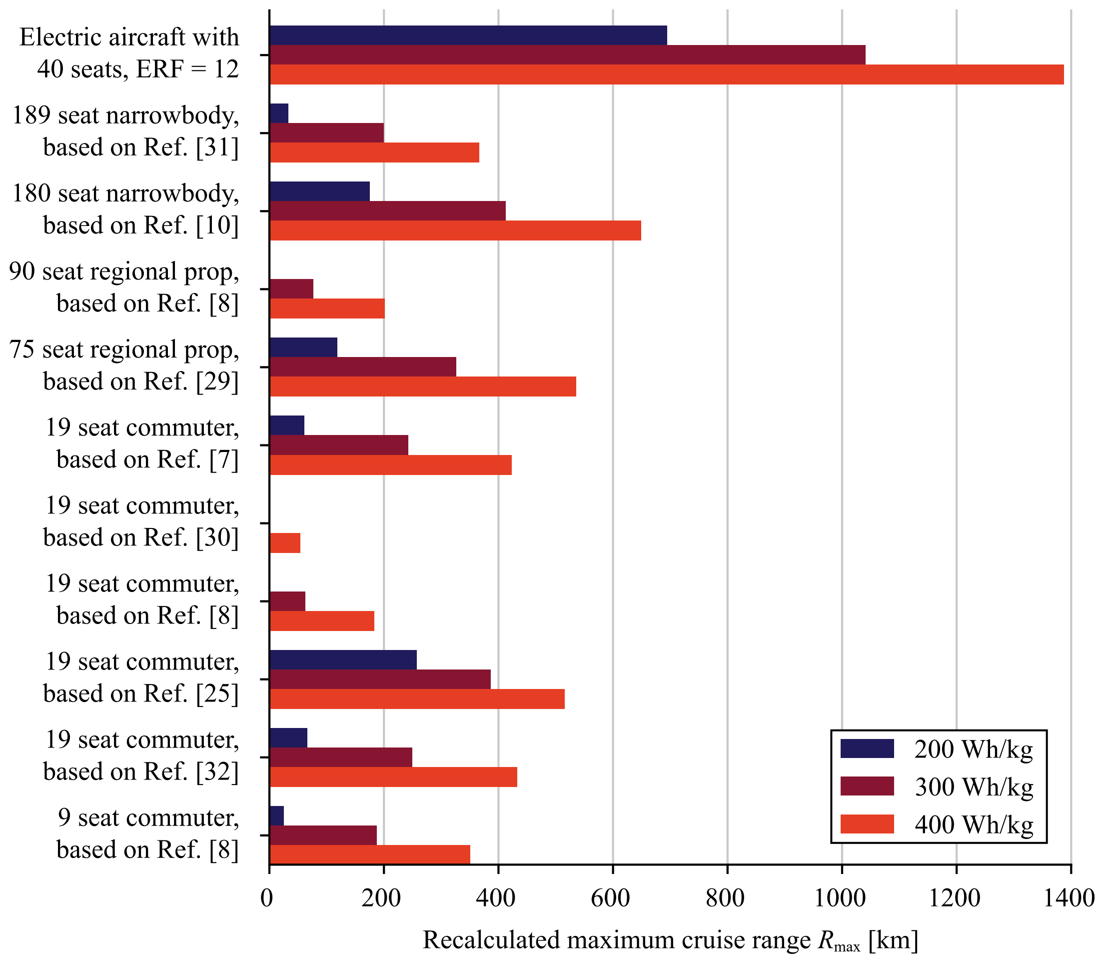


Fig. 7 Maximum cruise range of a parametric design with ERF = 12 from Table 6, compared with maximum cruise range computed for designs encountered in literature as function of usable battery energy density.

payload and ERF. The size of the wing relative to the size of the fuselage can be seen to increase with ERF, which translates into an increase in lift-to-drag ratio. The figure also shows how different electric aircraft within a certain mass range (e.g. MTOM = 45 t – 58 t) can cover different missions: many passengers for a short range (120 pax, ERF = 6), or a small number of passengers for a relatively long range (40 pax, ERF = 12).

Additionally, we assess the maximum cruise range of one of these parametric designs with highest ERF (40 seat with ERF = 12) with the maximum cruise range of configurations assessed by other authors [7, 8, 10, 25, 29–32]. In order to compare the different sources for a given battery-energy density, we re-calculate the range all the different configurations using Eq. 2. For this assessment, we estimate the ERF of other configurations based on the OEM/MTOM and $(L/D)_{\max}$ ratios reported in the respective papers. Where $(L/D)_{\max}$ is not mentioned, we used Eq. 7 to estimate this value. For aircraft designs where reserves are covered by the batteries, a distance of 300 km is subtracted from the maximum cruise range to account for reserves and make a like-for-like comparison. We apply the same electric powertrain efficiency and propulsor efficiency to both our parametric design and all aircraft presented in other studies. We perform this analysis for three hypothetical battery energy-density scenarios. Figure 7 indicates that for parametric designs based on the design principles as presented in Sec. IV.A, the maximum cruise range of battery-electric aircraft is substantially higher than previously envisioned.

V. Conclusions

We conclude that a battery-electric aircraft for up to 120 passengers with a battery-electric maximum cruise range beyond 1000 km, plus 300+ km reserve range, provided by a SAF-fueled gas turbine, is feasible, assuming a usable battery energy density of 300 Wh/kg. The discrepancy between the cruise range estimates presented in this paper and the range of electric aircraft as concluded in previous studies is caused by four misconceptions. Instead of these misconceptions, this paper proves the following:

1) An energy mass fraction (EM/MTOM) of ~50% is feasible for a battery-electric "tube & wing" aircraft. No advanced engineering or exotic materials are required.
2) A $(L/D)_{\max}$ above 20 can be achieved with battery-electric aircraft thanks to the inherently lower $S_{\text{wet}}/S_{\text{ref}}$ ratio, without using any low-TRL aerodynamic technology.
3) Energy to cover the required reserves can be carried in a hydrocarbon fuel-based reserve energy system to save mass and use more of the battery capacity for normal flight.
4) There are no observed negative scale effects that favor smaller commuter aircraft over larger transport aircraft for battery-electric aviation.

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References

[1] Advisory Council for Aviation Research and Innovation in Europe (ACARE), "Realising Europe's vision for aviation: Strategic research & innovation agenda, Vol. 1," Advisory Council for Aviation Research and Innovation in Europe, 2012.

[2] Friedrichs, J., Radespiel, R., Werij, H., and Vos, R., "Accelerating the path towards carbon-free aviation," report of the CoE "Sustainable and Energy Efficient Aviation" (SE2A) and Aeronautics Research Centre Niedersachsen (NFL), 2022.

[3] de Vries, R., Hoogreef, M. F. M., and Vos, R., "Range Equation for Hybrid-Electric Aircraft with Constant Power Split," *Journal of Aircraft*, Vol. 57(3), 2020. doi:10.2514/1.C035734.

[4] de Vries, R., and Vos, R., "Aerodynamic Performance Benefits of Over-the-Wing Distributed Propulsion for Hybrid-Electric Transport Aircraft," *Journal of Aircraft*, Vol. 60(4), 2023. doi:10.2514/1.C036909.

[5] Biser, S., Filipenko, M., Boll, M., Kastner, N., Atanasov, G., Hepperle, M., Keller, D., et al., "Design Space Exploration Study and Optimization of a Distributed Turbo-Electric Propulsion System for a Regional Passenger Aircraft," AIAA Propulsion and Energy Forum (virtual event), August 24-28 2020. doi:10.2514/6.2020-3592.

[6] Epstein, A. H., and O'Flarity, S. M., "Considerations for Reducing Aviation's CO_2 with Aircraft Electric Propulsion," *Journal of Propulsion and Power*, Vol. 35(3), 2019, pp. 572–582. doi:10.2514/1.B37015.

[7] Staack, I., Sobron, A., and Krus, P., "The potential of full electric aircraft for civil transportation: from the Breguet range equation to operational aspects," *CEAS Aeronautical Journal*, Vol. 12, 2021, pp. 803–819. doi:10.1007/s13272-021-00530-w.

[8] Mukhopadhaya, J., and Graver, B., "Performance Analysis of Regional Electric Aircraft," International Council of Clean Transportation white paper, 2022.

[9] Graver, B., Rutherford, D., and Zheng, S., "CO_2 emissions from commercial aviation: 2013, 2018, and 2019," International Council of Clean Transportation report, 2020.

[10] Gnadt, A. R., Speth, R. L., Sabnis, J. S., and Barrett, S. R. H., "Technical and environmental assessment of all-electric 180-passenger commercial aircraft," *Progress in Aerospace Sciences*, Vol. 105, 2019, pp. 1–30. doi:10.1016/j.paerosci.2018.11.002.

[11] de Vries, R., Wolleswinkel, R. E., Hoogreef, M. F. M., and Vos, R., "A New Perspective on Battery-Electric Aviation, Part II: Conceptual Design of a 90-seater," AIAA Scitech 2024 Forum, Orlando, FL, USA, January 8-12 2024.

[12] Hepperle, M., "Electric Flight – Potential and Limitations," *NATO Report STO-MP-AVT-209*, 2012.

[13] McDonald, R., "Batteries Are Not Fuel," , 2023. doi:10.31224/2803.

[14] Viswanathan, V., Epstein, A. H., Chiang, Y.-M., Takeuchi, E., Bradley, M., Langford, J., and Winter, M., "The challenges and opportunities of battery-powered flight," *Nature*, Vol. 601, 2022, pp. 519–525. doi:10.1038/s41586-021-04139-1.

[15] Hall, D. K., Greitzer, E. M., Dowdle, A. P., Gonzalez, J. J., Hoburg, W. W., Lang, J. H., Sabnis, J. S., et al., "Feasibility of Electrified Propulsion for Ultra-Efficient Commercial Aircraft Final Report," NASA Report CR–2019-220382, 2019.

[16] Schafer, A. W., Barrett, S. R. H., Doyme, K., Dray, L. M., Gnadt, A. R., Self, R., O'Sullivan, A., Synodinos, A. P., and Torija, A. J., "Technological, economic and environmental prospects of all-electric aircraft," *Nature Energy*, Vol. 4, 2019, pp. 160–166. doi:10.1038/s41560-018-0294-x.

[17] Webber, H., and Job, S., "Realising Zero-Carbon Emission Flight," Aerospace Technology Institute report FZ-0-6.1, September 2021.

[18] Air Transport Action Group (ATAG), "Waypoint 2050 – Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century," 2nd Edition, September 2021.

[19] Jenkinson, L. R., Simpkin, P., and Rhodes, D., *Civil Jet Aircraft Design*, Arnold, 1999.

[20] Durmus, S., "Deciphering the Relationship between the Mass, Size and Engine Properties of Boeing and Airbus Aircraft," Balikesir University Edremit School of Civil Aviation, Balikesir, Turkey, 2021.

[21] Babikian, R., Lukachko, S. P., and Waitz, I. A., "The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives," *Journal of Air Transport Management*, Vol. 8, 2002, pp. 389–400.

[22] Obert, E., *Aerodynamic Design of Transport Aircraft*, IOS Press, 2009.

[23] Torenbeek, E., *Advanced aircraft design: conceptual design, analysis and optimization of subsonic civil airplanes*, John Wiley & Sons, 2013.

[24] Raymer, D. P., *Aircraft design: A conceptual approach*, 6th Edition, AIAA Education Series, 2018.

[25] Atanasov, G., van Wensveen, J., PEter, F., and Zill, T., "Electric Commuter Transport Concept Enabled by Combustion Engine Range Extender," Deutscher Luft- und Raumfahrtkongress, Darmstadt, Germany, September 30 - October 2 2019.

[26] Roskam, J., *Airplane Design*, DARcorporation, 1985.

[27] Moore, M., Fei, X., JEdamski, D., Perry, A., Morejon Ramirez, L. A., Villa, I., and Lakshminarayan, V. K., "Unlocking Low-Cost Regional Air Mobility through Whisper Aero-Propulsive Coupling," AIAA Aviation 2023 Forum, San Diego, CA, USA, June 12-16 2023. doi:10.2514/6.2023-3456.

[28] Moore, M. D., and Fredericks, B., "Misconceptions of Electric Propulsion Aircraft and their Emergent Aviation Markets," 52nd AIAA Aerospace Sciences Meeting, National Harbor, MD, USA, January 13-17 2014. doi:10.2514/6.2014-0535.

[29] Karpuk, S., and Elham, A., "Influence of Novel Airframe Technologies on the Feasibility of Fully-Electric Regional Aviation," *Aerospace*, Vol. 8(6), 2021. doi:10.3390/aerospace8060163.

[30] Finger, D. F., de Vries, R., Vos, R., Braun, C., and Bil, C., "Cross-Validation of Hybrid-Electric Aircraft Sizing Methods," *Journal of Aircraft*, Vol. 59(3), 2022, pp. 742–760. doi:10.2514/1.C035907.

[31] Isikveren, A. T., Seitz, A., Vratny, P. C., Pornet, C., Plötner, K. O., and Hornung, M., "Conceptual studies of universally-electric systems architectures suitable for transport aircraft," Deutscher Luft-und Raumfahrt Kongress, Berlin, Germany, September 2012.

[32] Monjon, M. M. M., and Freire, C. M., "Conceptual Design and Operating Costs Evaluation of a 19-seat All-Electric Aircraft for Regional Aviation," AIAA Propulsion and Energy Forum (virtual event), August 24-28 2020. doi:10.2514/6.2020-3591.