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# Performance analysis and operating potential of a hybrid-electric regional aircraft with box-wing lifting architecture

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## Abstract

The payload-range diagram of a regional hybrid-electric box-wing aircraft is discussed in this paper. The operational characteristics of a hybrid-electric aircraft differ from those of an aircraft with traditional thermal propulsion. The shape of the payload-range diagram of the hybrid-electric aircraft is variable as far as multiple combinations in the amount of masses of batteries, fuel and payload to be transported on board are possible, and depending on the possibility of using different power split strategies during the mission. Different scenarios of hybrid-electric aircraft utilisation are outlined. In particular, the trade-off in the utilisation of the two energy sources to reduce fuel consumption or to extend the maximum flight distance is described in detail.

## 1 Introduction

Aeronautical research is increasingly driven towards developing solutions to reduce the environmental impact of aviation [1][2], in agreement with the requirements and constraints imposed by authorities. The European Commission aims to achieve climate neutrality for aviation in the EU by 2050; furthermore, an intermediate requirement is set for 2030, whereby a 55% reduction in greenhouse gas emissions must be reached [3]. Introducing hybrid-electric propulsion systems is currently considered a possible solution to reduce direct greenhouse gas emissions in commercial aviation; this propulsion system exploits the synergy of fuel and battery to reduce aircraft emissions [4].
Technological limitations related to electrical energy storage systems, which exhibit very low gravimetric energy densities compared to kerosene, make the development of medium and long-range hybrid-electric aircraft very unlikely, even considering the most optimistic future outlook for the improvement of batteries performance. The development of hybrid-electric aircraft in the short-range aircraft categories appears more feasible. For this reason, the present paper focuses on the regional aircraft category, which is the candidate for the earliest introduction of electrification of propulsion systems among commercial transport aircraft; an investigation of the synergies between new propulsive technologies and disruptive airframe architectures, which can increase the overall efficiency in comparison to conventional tube-and-wing configurations, is provided. In particular, this research describes the performance achieved from the integration of the hybrid-electric propulsion with the box-wing architecture, Figure 1.

Figure 1: Artistic representation of the hybrid-electric regional box-wing aircraft

In the paper, the possible advantages of the synergic implementation of these two technological advancements in the aircraft design are highlighted, combining the benefit of $CO_2$ reduction of hybrid-electric propulsion systems with the higher aerodynamic performance of the box-wing architecture [5][6]. This latter, introduced in 1924 by L. Prandtl as the "best wing system" for the minimization of the induced drag for a given lift and wingspan [7][8][9], allows to reduce the energy demand to accomplish a reference mission. Furthermore, as demonstrated in [10][11], this lifting

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system allows to transport larger weights compared to traditional aircraft, while maintaining the same wingspan and without penalties in terms of aerodynamic performance. For a conventional thermal propelled box-wing aircraft, these features allowed to cut the $CO_2$ emission per passenger-km up to 22%, as demonstrated in [12]. In the case of hybrid-electric aircraft, the increased lifting capability of the box-wing provides the possibility of transporting large quantities of batteries, hence fully exploiting the potential of hybrid-electric systems to minimize fuel burnt and $CO_2$ emissions. A detailed operating performance study of the regional box-wing hybrid-electric aircraft is presented in the following. In particular, possible different utilization strategies for the aircraft are analysed and discussed, starting from the definition of its payload-range envelope. The double energy source allows the optimisation of distinct figures of merit through different options of mass distribution between fuel and batteries. Each of these options is characterized by a specific power management strategy, i.e. to the split of power supply between the electric and thermal chains to meet the power request of each flight segment. For hybrid powertrains, there are several possibilities to define the electric and thermal power shares and each of these corresponds to different consumptions of fuel and electric energy.
For example, power management strategies can be identified to minimise fuel consumption in each point of the payload-range envelope; alternatively, power management profiles can be optimized to extend the nominal range of the aircraft, thus expanding the boundary of the payload-range diagram at the expense of higher fuel consumption.
The shape of the payload-range diagram may vary according to the different figures of merit selected, and therefore to the fuel-batteries mass distribution adopted. An extensive discussion of the performance potential of the hybrid-electric box-wing aircraft is presented, highlighting the possible advantages achievable from the introduction of this configuration in the regional transport segment. Specifically, through an in-depth analysis of the payload-range diagram, the potential of the hybrid-electric aircraft to minimise fuel consumption for typical missions in the regional category or, alternatively, to have much larger operational envelopes at the expense of higher fuel consumption, is described.

## 2 Design of the hybrid-electric box-wing aircraft

The present research falls in the path of the Italian project PROSIB (*PROpulsione e Sistemi IBridi per velivoli ad ala fissa e rotante*), carried out between 2018 and 2021; the project had several objectives, including the development of multidisciplinary conceptual design methodologies for hybrid-electric regional aircraft with tube-and-wing and box-wing architecture. Among the results, the project has identified the advantages (mainly in terms of block fuel reduction) and critical issues arising from the adoption of hybrid-electric propulsion to regional category aircraft (similar to the ATR42), through the development of an ad-hoc conceptual design methodology.
Hereafter, a brief overview of the design and performance analysis methodology is provided; for more details, the reader can refer to [13][14]. The main objective of the proposed methodology is to provide the conceptual design of hybrid-electric aircraft; specifically, it aims to estimate the main aircraft performance data by means of an ad-hoc developed design workflow that is depicted in Figure 2. The design workflow properly combines some typical aspects of the conceptual aircraft design (e.g. aerodynamic and structural evaluations) with new features related to the integration of a hybrid-electric propulsion system.

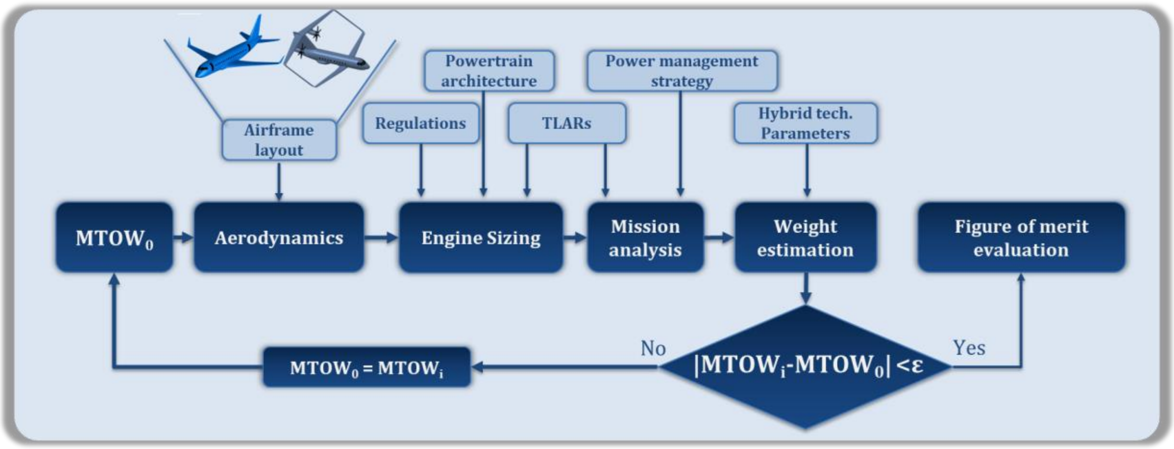


Figure 2: THEA-CODE workflow

The main modules of the design workflow are *Aerodynamics*, *Engine sizing*, *Mission analysis* and *Weight estimation*. The *Aerodynamics* module evaluates the aircraft polar drag; induced drag is estimated by means of AVL [15], a vortex lattice method solver, whereas the parasitic drag of the aircraft components is evaluated through the component build-up method [16]. The *Engine sizing* module estimates the required installed power of the hybrid-electric powertrain by means of the so-called matching chart [17][18]. Specifically, this diagram relates the aircraft specific power (P/W)

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with the wing loading (W/S), on the basis of the current regulations (FAR25 [19]). By properly handling this chart, it is possible to estimate the total power to be installed on board and how it is split between the electric motors ($P_{inst}^{emot}$) and the thermal engines ($P_{inst}^{ice}$). The degree of hybridization $H_P$, i.e. the ratio between the electric motors installed power and the total installed power, is the design parameter which defines this power distribution, and it is defined according to Eq. (1).

$$H_P = \frac{P_{inst}^{emot}}{P_{inst}^{emot} + P_{inst}^{ice}} \quad (1)$$

The *Mission analysis* block simulates the aircraft flight trajectory by means of a time-marching simulation, by integrating the aircraft point mass equations of motions with a forward Euler integration method. For the cases analysed in this work, a parallel hybrid-electric architecture has been selected for the powertrain; in this configuration, the thermal and electrical power sources can supply power to the propeller independently. The electric motor and the thermal engine are linked to the propeller by a gearbox, as schematically sketched in Figure 3.

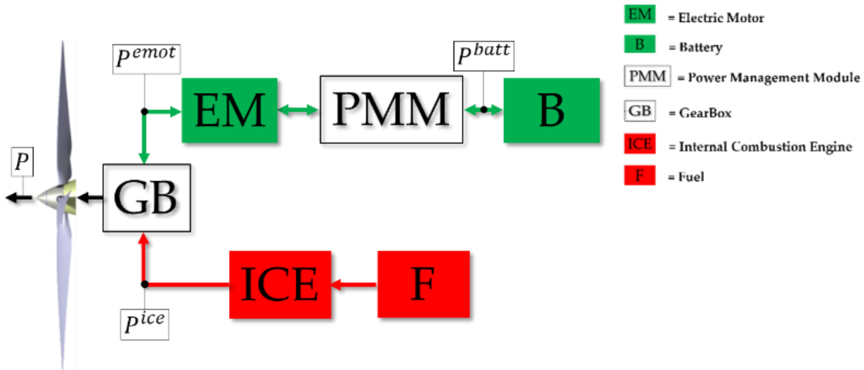


Figure 3. Scheme of the parallel hybrid-electric powertrain

Fuel and batteries weights are estimated by the *Mission analysis* block; propulsion system weight is evaluated by the *Engine sizing* block as the ratio between the engine installed power and its specific power. The weight of the other items is evaluated in the *Weight estimation* block; specifically, operatings and systems weight is computed by means of literature models [21]. Regarding to the structures, lifting system weight has been estimated by a FEM-based surrogate model [22], specifically developed for box-wing architectures, since no literature data are currently available. The weight of fuselage, landing gear and vertical tail, instead, is evaluated using the model provided in [21].
The design procedure ends if the convergence on MTOW is achieved. Once the aircraft is designed, fuel and batteries are arranged inside the aircraft; a qualitative scheme of volume allocation is depicted in Figure 4. Generally, the available volume for each energy source is larger than the quota requested at the design point: this allows to embark more batteries/fuel in case of off-design missions, as shown in section 4.1. The available volumes for fuel and battery are fixed for the designed configuration, which means that cannot be reallocations between batteries and fuel if their own maximum available volume is saturated.

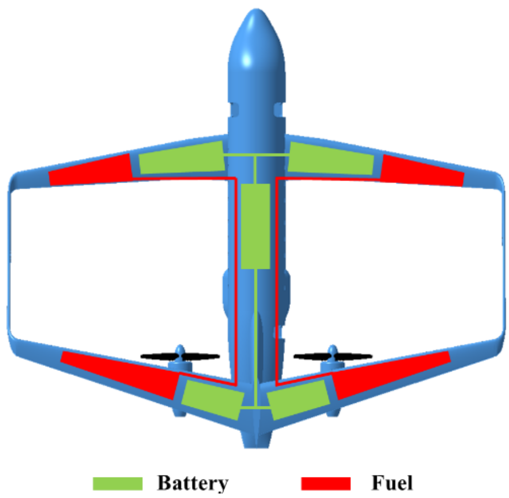


Figure 4: Qualitative scheme of fuel and battery available volume distribution.

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One of the most important aspects to estimate aircraft performance is the *Power management strategy*. In fact, the main difference between thermal propelled and hybrid-electric aircraft is that the latter can use two different onboard energy sources, namely fuel and battery. Specifically, this aspect introduces a new set of design variables, related to the supply strategy of the electric and thermal power throughout the flight. This involves some design challenges and opportunities for the development of hybrid-electric aircraft. On the one hand, the Battery Energy Density (BED) is much lower than Fuel Energy Density (FED): even considering the 2035 forecast according to which BED should achieve the goal of 500 Wh/kg (at pack level) [20], it would be a small fraction of today FED (12000 Wh/kg for kerosene). On the other hand, electric propulsion components exhibit higher efficiency; therefore, the proper selection of the design variables affecting the power supply management is fundamental to properly exploit the performance potential of the hybrid powertrain [14]. These variables are the thermal power fraction ($\Phi_i^{ice}$) and the electric power fraction ($\Phi_i^{el}$), defined for the *i-th* flight phase according to Eq. (2) and Eq. (3) respectively, where $P_i^{ice}$ is the power supplied by the thermal engine and $P_i^{emot}$ is the power supplied by the electric motor.

$$\Phi_i^{ice} = \frac{P_i^{ice}}{P_{inst}^{ice}} \tag{2}$$

$$\Phi_i^{el} = \frac{P_i^{emot}}{P_{inst}^{emot}} \tag{3}$$

Acting on these variables, different fuel-mass distributions can be obtained for the designed aircraft, hence allowing to minimize the fuel consumption or to target a different goal, if required. To design hybrid-electric aircraft, an initial assumption has been considered: batteries are used only in standard operating mission, while the diversion is accomplished by using thermal engines only. Since diversion rarely occurs, this assumption avoids to carry a larger mass of batteries onboard, which could have detrimental effects on the overall aircraft performance. The mission has been divided into macro phases, as depicted in Figure 5.

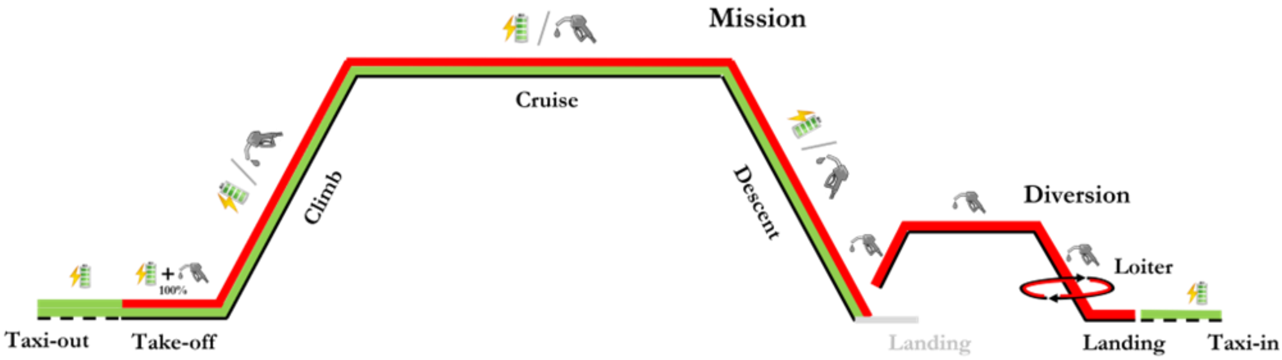


Figure 5: Mission profile with considered energy sources for each phase

If the $CO_2$ emission reduction is set as the main design driver, the design strategy need to determine the $\Phi_i^{ice}$ and $\Phi_i^{el}$ values that minimize the fuel consumption during the mission (block fuel). To do this, an optimization procedure has been set up [14] defining the block fuel as the objective function and $\Phi_i^{ice}$ as the main optimization variables, which together compose the vector $\boldsymbol{\Phi^{ice}}$. Assigned a set of values for this latter, the objective function is evaluated by summing up the fuel consumption of each flight phase, calculated integrating the term $\frac{dW}{dt}$ in Eq. (4).

$$\begin{cases} \dfrac{dW}{dt} = -PSFC\, P_i^{ice} \\ L = W \\ P = DV + \gamma V \\ P_i^{ice} + P_i^{emot} = P/(\eta_{gbox}\eta_{prop}) \\ P^{batt}\,\eta_{el} = P_i^{emot} \\ P_i^{ice} = \Phi_i^{ice} P_{inst}^{ice} \end{cases} \tag{4}$$

In Eq. (4), $W$ is the aircraft weight; $PSFC$ is the power specific fuel consumption of the engine, $L$ and $D$ are aircraft lift and drag, $\gamma$ and $V$ are aircraft trajectory slope and speed, $P$ and $P^{batt}$ are the power requested by the propeller and the power supplied by the battery pack (see Figure 3), $\eta_{el}$ is the efficiency of the electric chain, and $\eta_{gbox}$ and $\eta_{prop}$ are the efficiencies of the gearbox and the propeller. It is worth to underline that $\boldsymbol{\Phi^{ice}}$ relates only to climb, cruise and

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descent, whereas taxiing phase is performed by using electric power only and take-off is accomplished by supplying the whole available power from both thermal and electric sources.
The design methodology here described has been used to design hybrid-electric aircraft, with both tube-and-wing and box-wing architectures. A relevant example is given by the case investigated within the research project PROSIB, for which the top-level aircraft requirements (TLARs) are reported in Table 1.

Table 1: TLARs defined within the project PROSIB

| **TLARs** | |
|---|---|
| **Number of seats** | 40 |
| **Cruise Mach** | 0.4 |
| **Cruise altitude** | 200 FL |
| **Mission range** | 600 nm |
| **Balanced Field Length** | 1100 m |
| **Landing Distance Available** | 1100 m |

The obtained tube-and-wing and box-wing architectures, depicted in Figure 6, have a MTOW of about 23 tons and show a 21.5% and 39% reduction in fuel consumption compared to current thermal regional aircraft, respectively [14].

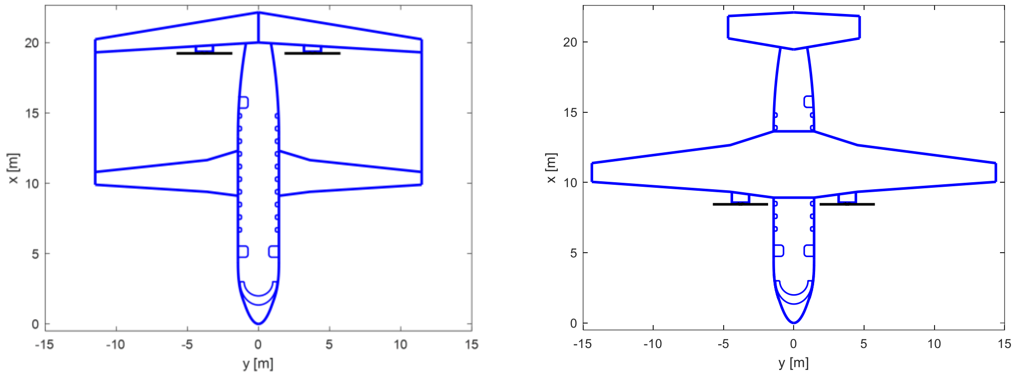


Figure 6: Top-view of tube-and-wing (left) and box-wing (right) hybrid-electric aircraft

The box-wing aircraft exhibits a larger reduction in fuel consumption, which is mainly related to: *i)* the larger aerodynamic efficiency, which reduces the energy request for the flight; *ii)* the lighter wing structures, due to the lower wingspan and to the lower load on each lifting surface of the box-wing, features that allow the structural components to have lower thickness, as demonstrated in [14]. The structural weight saving enables the possibility to embark a larger amount of batteries, hence the box-wing aircraft can store more electrical energy and can further reduce fuel consumption. By going deeper in the comparison between hybrid-electric box-wing and tube-and-wing aircraft, [14] has shown that at the design point the box-wing reduces the fuel consumption, and thus the direct $CO_2$ emissions, of about 22%, with respect to the hybrid-electric tube-and-wing. A wider comparison of the main performance is summarized in Figure 7. These promising outcomes have highlighted that the introduction of innovative airframes has the potential to improve the benefits of hybrid-electric propulsion. The results shown in the following of this paper are related to the regional box-wing aircraft shown in Figure 6-left.

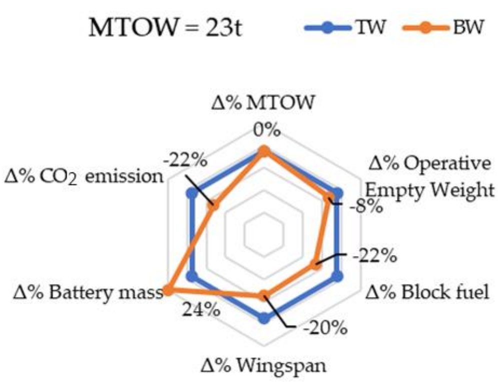


Figure 7: Radar chart of performance comparison between box-wing (BW) and tube-and-wing (TW) hybrid-electric regional aircraft [14]

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## 3 Approach for performance investigation: the payload-range diagram

Performance analysis is a crucial aspect in the design and development of an aircraft. As aeroplanes are complex machines, there are many different figures of merit that can characterise their performance [23]. In the case of commercial aircraft, figures of merit related to costs, pollutant emissions, fuel consumption, maximum take-off weight, have a fundamental importance in steering the design choices, from the early stages of the conceptual design. During the aircraft development, these figures of merit are evaluated at specific design points, typically specified in the top level design requirements. However, the typical operating conditions of the aircraft are different from those provided by the specification, as in practical use a variety of combinations of payload, mission range, fuel (and/or battery) weight, and hence take-off weight, may occur. A new aircraft, therefore, must prove to have a wide operational flexibility. In general, the term flexibility refers to the capability of a system to meet requirements that differ from the reference operating conditions [24]. For a transport aircraft, this implies the capability of the vehicle to fly efficiently the widest range of off-design missions, in terms of mission profile (e.g. speed, altitude), but mostly in terms of combinations of payload and flight distances [25]. The broader is the operating flexibility, the greater will be the relevance of the new aircraft in the commercial air transport market.
In this section, firstly the main differences between the operating flexibility of an aircraft with conventional thermal propulsion and one with hybrid-electric propulsion are described. Secondly, the operating potential of the hybrid-electric box-wing aircraft defined in Section 2 is explored. To support these investigations, the payload-range diagram is consistently used. Thus, in the following paragraphs the payload-range diagram of aircraft with thermal and hybrid-electric propulsion is described, with the purpose of identifying the main characteristics.

### 3.1 Aircraft with thermal propulsion

A qualitative step-by-step description of the payload-range diagram for aircraft with thermal propulsion is provided in this section in order to better explain the differences with hybrid-electric aircraft, in which the energy sources are two. Figure 8 shows the first part of the diagram, where the x-axis is the flight range, and y-axis is the difference between the aircraft weight and the empty operating weight ($W_{eo}$), which is constant and therefore subtracted from the total aircraft weight, for simplicity. The weight contributions represented in Figure 8 are: *i)* the payload weight $W_{pay}$, represented by the grey axis starting from the origin; *ii)* the fuel weight $W_{fuel}$, represented by the red axis with origin corresponding to the maximum value of the payload weight $W_{pay\ MAX}$; *iii)* the aircraft take-off weight $W_{TO}$, i.e. the sum of payload, fuel, and empty operating weight, limited at the top by the maximum take-off weight MTOW. Once the payload weight is set equal to its maximum, the fuel weight required to accomplish the mission is the key factor which determines the take-off weight of the aircraft; $W_{fuel}$ depends on the aerodynamic, ponderal and propulsive characteristics of the aircraft, and it assumes a distinct value for each range considered. Therefore, there is a monotonically increasing correlation between the $W_{TO}$ and the flight range, which is valid up to the so-called *harmonic point* [26], in which the take-off weight reaches the MTOW limit. This point of the payload-range diagram indicates the maximum range the aircraft can fly with the maximum payload, i.e. the harmonic range (HR).

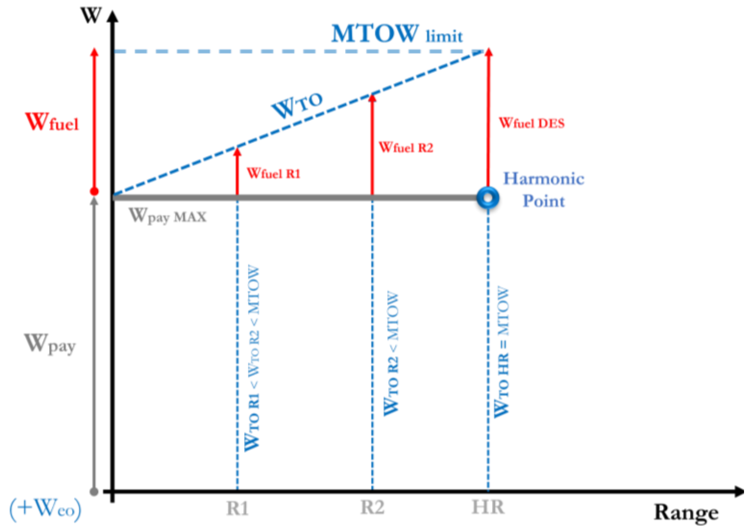

Figure 8: Payload-range diagram for aircraft with thermal propulsion - Part 1

To increase the flight distance beyond the harmonic range, it is necessary to reduce the payload mass, allowing an equivalent increase in fuel mass, as shown in Figure 9. Note that the origin of the y-axis related to the $W_{fuel}$ 'slides' on

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the $W_{pay\ MAX}$ line (e.g. $W_{fuel\ R3}$>$W_{fuel\ DES}$), thus giving a concise and general interpretation of this diagram. In this segment of the envelope, the take-off weight of the aircraft $W_{TO}$ is always equal to the maximum weight MTOW.

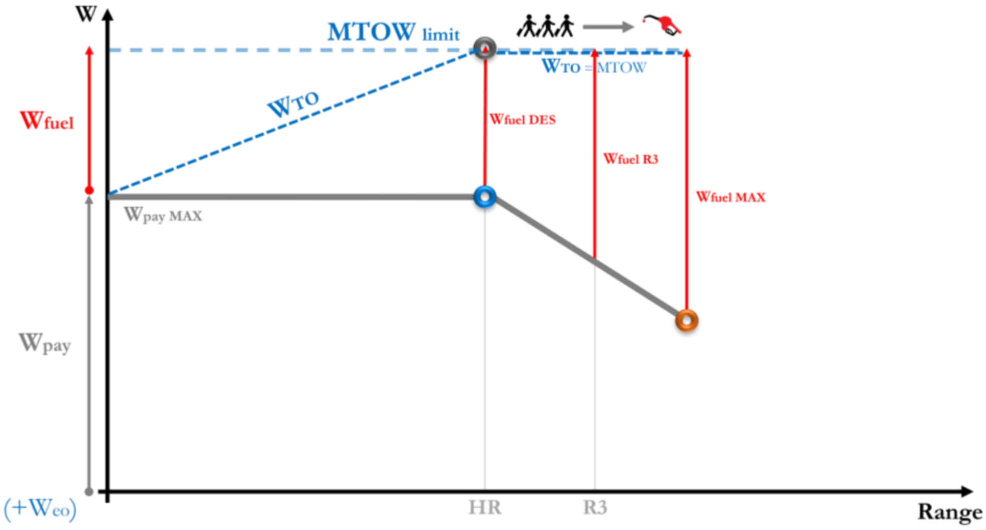

Figure 9: Payload-range diagram for a conventional thermal powered aircraft - Part 2

The trend depicted in Figure 9 stops once the maximum volume available in the tanks is saturated; from this point on, it is no longer possible to increase the fuel mass on board. Therefore, in order to achieve increases in flight range, it is necessary to reduce further the payload weight in order to obtain a lighter aircraft; the fuel weight is kept constant, equal to $W_{fuel\ MAX}$, as represented in Figure 10. When the payload weight decreases to zero, the aircraft reaches its maximum range, defined as *ferry range*. This condition is of minor commercial interest, unless for the conditions of aircraft delivery or empty aircraft transfer.

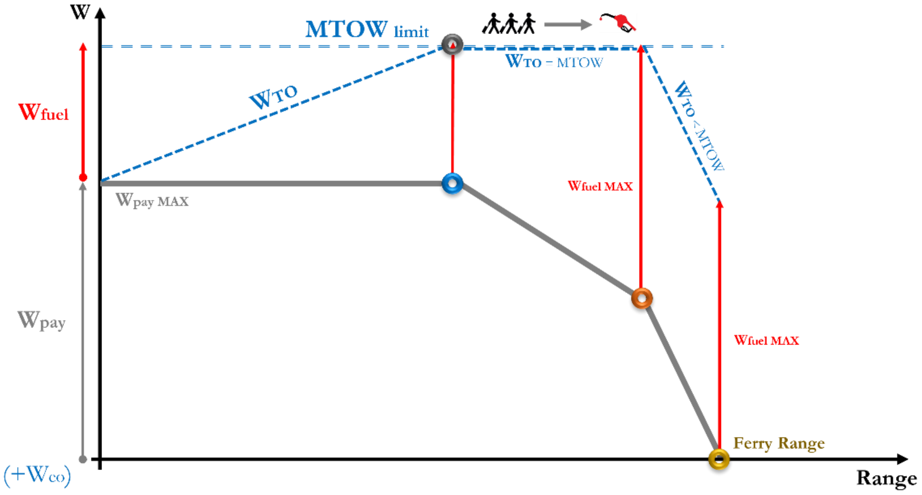

Figure 10: Payload-range diagram for a conventional thermal powered aircraft - Part 3

Figure 10 thus represents the complete generic payload-range diagram for an aircraft with conventional thermal propulsion. The edge of the envelope represents the limiting conditions in terms of payload maximisation; all the combinations within the envelope are feasible conditions for the considered aircraft.

### 3.2 Aircraft with hybrid-electric propulsion

Aircraft propelled by a dual source of power and energy show different operating performances which reflect into the payload-range diagram, described in the following as done for the previous case. The aircraft here considered is equipped with the parallel hybrid-electric powertrain, schematically reported in Figure 3.

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Compared to the thermal propulsion case, the first clear difference can be observed in the y-axis of the diagrams in Figure 11: the hybrid-electric aircraft has an additional item in its mass breakdown, namely the mass of the batteries. Therefore, the $W_{TO}$-Range trend is not univocally linked to the mass of a single energy source.
As shown in the following, the $W_{TO}$ depends on the onboard power and the fuel-batteries mass distribution, which than affect the split of the energy supply during the different stages of the mission. To better clarify this point, one may consider the qualitative examples shown in Figure 11, related to the same aircraft with different fuel-batteries mass distributions. In the case of Figure 11-left, the strategy adopted is targeted at minimising fuel consumption and consequently it maximises the mass of batteries on board. Due to the low energy density of the batteries, $W_{TO}$ reaches the MTOW limit well before the harmonic point. On the other hand, in the case of Figure 11-right, a different fuel-batteries mass distribution is adopted, in which a higher fuel consumption is allowed. In this instance, $W_{TO}$ reaches the MTOW for a longer range than in the previous case, although it could be shorter than the harmonic range.

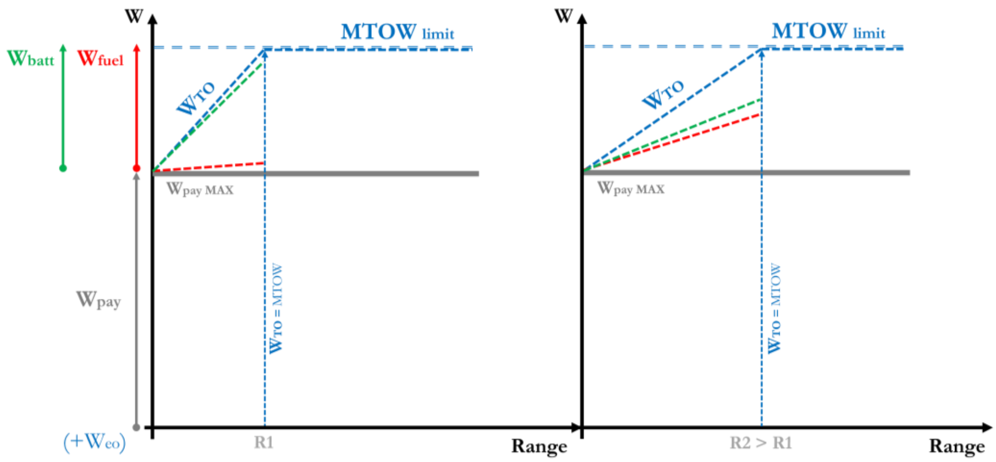


Figure 11: Effects of different fuel-batteries mass distributions on the first segment of the payload-range diagram for hybrid-electric aircraft

In order to build and discuss the next parts of the payload-range diagram, the case of Figure 11-left is considered. To increase the aircraft range while maintaining the maximum payload and fulfilling the MTOW constraint, it is necessary to reduce the battery mass and compensate the required energy demand by increasing the fuel mass, as shown qualitatively in Figure 12. The gravimetric densities of the two energy sources are very different from each other, so the mass variation of each of them with range has different absolute values, as the slopes of the dashed red and green lines in Figure 12 show. In this segment, differently from the thermal aircraft, the condition $W_{TO}$=MTOW always occurs. This segment should end at the harmonic point, which is defined as the point with the maximum range for the maximum payload, and where $W_{TO}$ equals MTOW for the first time. This definition of harmonic point is clearly no longer valid in the case of hybrid-electric aircraft; it is therefore more consistent to generically identify this point as the *design point*, i.e. the point that, according to the specifications, sets the requirements to size and/or optimise the aircraft.

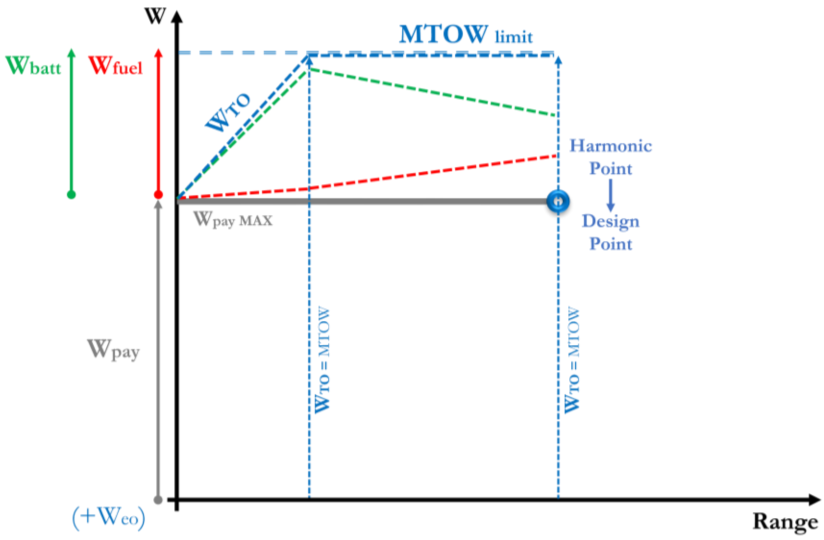


Figure 12: Payload-range diagram for hybrid-electric aircraft

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The most important difference between conventional thermal aircraft and hybrid-electric aircraft is how to manage the operations beyond the design point. In fact, in the case of aircraft with thermal propulsion, beyond the harmonic point it is only possible to exchange fuel and payload mass to increase the range and meet the MTOW constraint. In the case of dual energy aircraft there are at least three different strategies to increase the range beyond the design point, as described hereafter. It is worth highlighting, however, that the different strategies described in the following are qualitative; specific constraints, such as those on the maximum available power, both electrical and thermal, must always be fulfilled for the specific aircraft and the related missions considered.

1. The first strategy consists in exchanging payload mass for fuel mass, while keeping the battery mass constant. The payload decreases as fuel mass increases until the maximum available volume in the tanks is reached, as shown in Figure 13-left. In this segment, the $W_{TO}$=MTOW condition is maintained. As for the thermal aircraft payload-range diagram, the vertical axes indicating the mass of batteries and fuel slide along the $W_{pay\ MAX}$ line, allowing a concise interpretation of the diagram.

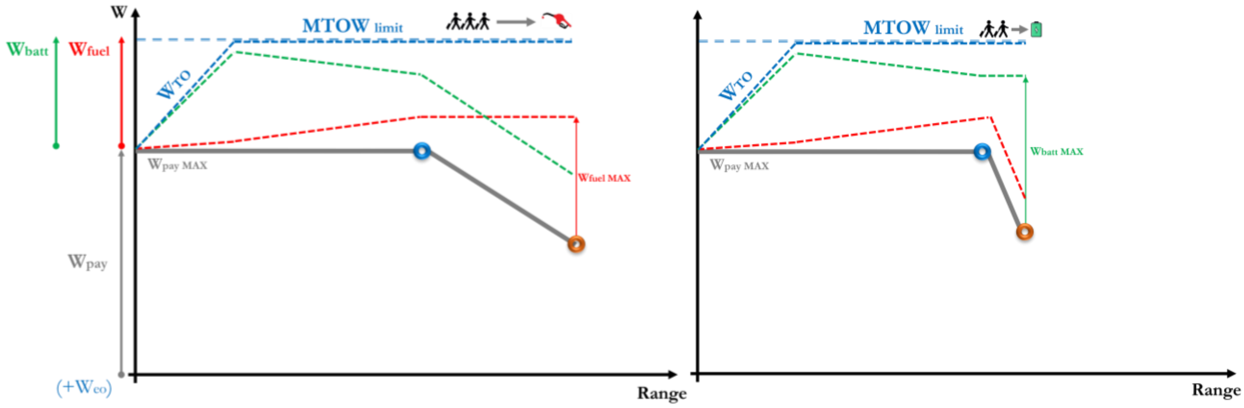


Figure 13: Strategies to extend the range beyond the design point: mass exchange between payload and fuel (left), mass exchange between payload and batteries (right)

2. In the second strategy the payload mass is exchanged for battery mass, while the fuel mass and MTOW are kept constant. In this case, the payload mass decreases, and the battery mass increases until the maximum volume available for the batteries is saturated (Figure 13-right). Since the specific energy density of batteries is about 24 times lower than fuel, the volume saturation point is anticipated significantly. Figure 14 shows a qualitative comparison between these two strategies: given the low gravimetric energy density of batteries compared to fuel, the second strategy does not appear to be effective in extending the range; however, it may be suitable if cutting the fuel consumption is the priority.

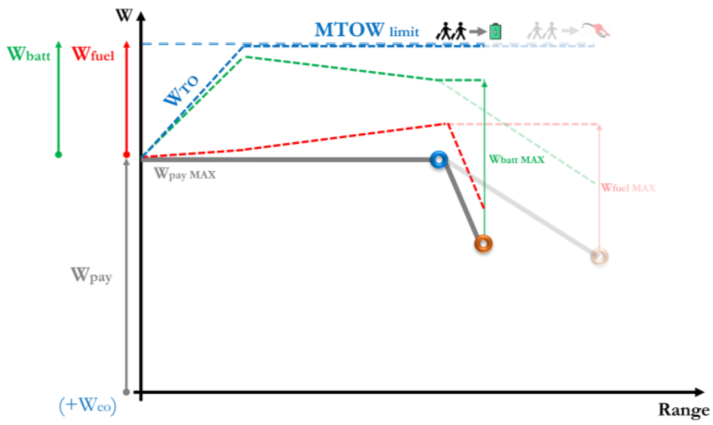


Figure 14: Comparison between swapping payload with fuel or batteries

3. In the third strategy, battery mass is exchanged for fuel mass as in Figure 15, while the payload mass is kept constant and always equal to $W_{pay\ MAX}$. As fuel has a much higher specific energy than batteries, very large design range extensions can be obtained.

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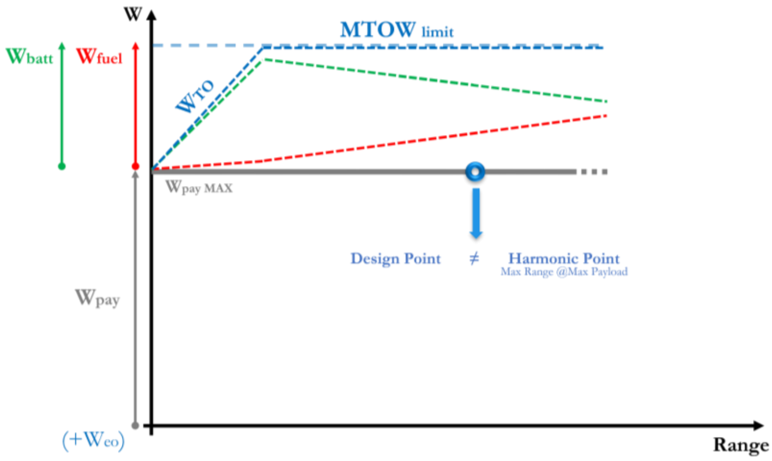

Figure 15: Strategy to extend the range beyond the design point: mass exchange between batteries and fuel

Using this strategy, it is necessary to define what is the maximum range extension achievable with the maximum payload, starting from the design point. The maximum range, defined in the following as *extended range ER*, depends on the specific characteristics of the aircraft and the propulsion system; in particular, following the diagrams in Figure 16, in which the details of the payload-range diagrams in the area beyond the design point are represented, the following cases occur:

- Case 1: the extended range is limited by the saturation of the maximum volume available for fuel; this depends on the design of the aircraft, in particular on the allocation of internal volumes for fuel and/or batteries.
- Case 2: the extended range is limited because the MTOW is reached, no more battery-fuel mass exchange is possible, hence it is necessary to start reducing the payload.
- Case 3: the extended range is limited by the lack of available energy or power, which depends on the sizing of the propulsion system and in particular on the hybridisation factor. Two subcases are possible:
  - 3a: electrical energy is not sufficient to accomplish one or more stages of the mission;
  - 3b: the power provided by the thermal engine is not sufficient to accomplish one or more mission stages.

The most restrictive constraint sets the limit on the maximum range achievable with the maximum payload.

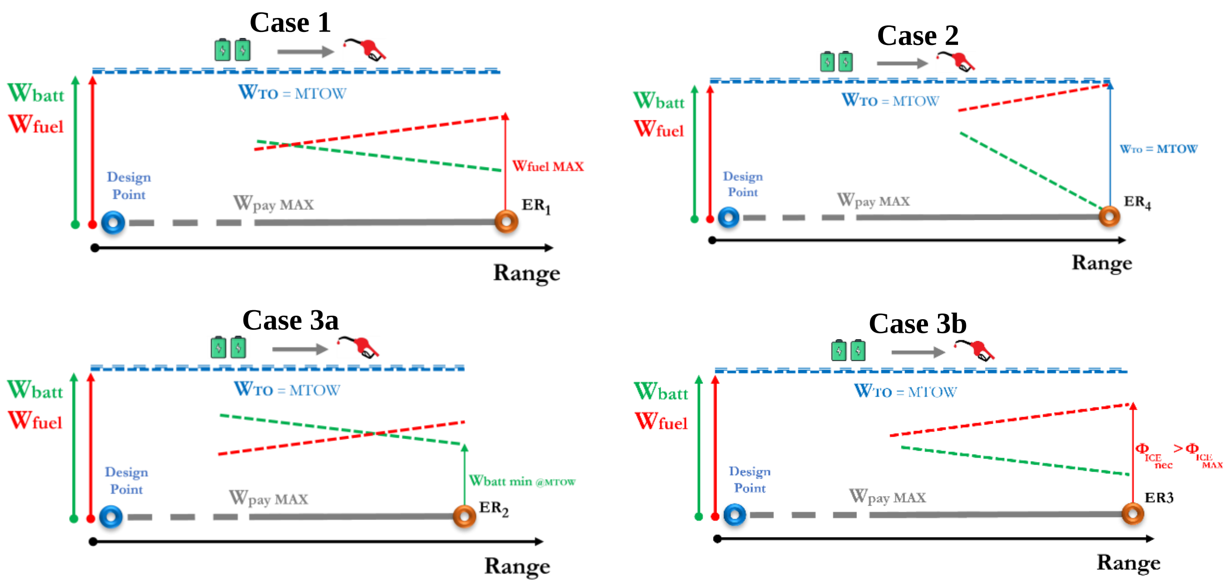

Figure 16: Four different scenarios to define the extended range

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# 4 Performance analysis and operating potential of hybrid-electric aircraft

## 4.1 Regional box-wing aircraft: results from a test-case

In this section, a quantitative example related to the operating performance of the box-wing aircraft described in section 3.2, is used as a reference. In the previous qualitative analysis, the operating performance of the dual energy powered aircraft have been described focusing on the payload-range diagram analysis and in particular on the definition of the ‘edge’ of the envelope. In this quantitative example, instead, also the performance trends inside the envelope are described in terms of fuel, battery, and take-off mass, highlighting any possible differences with respect to the thermal propulsion aircraft. Figure 17 shows the trends of block fuel and battery masses required for the missions inside the pax-range diagram of the reference aircraft. The pax-range diagram is constrained at the top by the design point mission, defined by the top level requirements reported in Table 1.

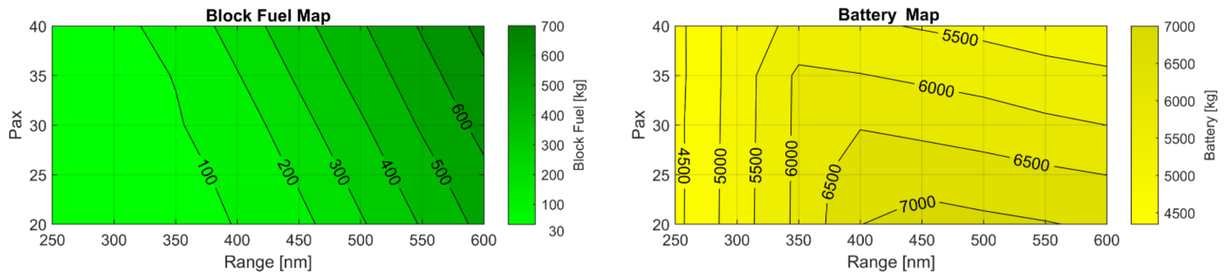


Figure 17: Block fuel (left) and battery mass (right) required for the missions inside the pax-range diagram

The power management strategy considered in this operating envelope is the one that aims to minimize the block fuel, by adopting the maximum available electric power during climb and cruise and compensating any excess of requested power with the thermal one. In other terms, the goal of this strategy is to maintain del values of and $\Phi^{el}_{climb}$ and $\Phi^{el}_{cruise}$ as close as possible to 1, which is not possible for all the passenger-range combinations since MTOW is limited to the design value (23 tons). In fact, any increase in the energy demand for flight, due for example to a larger payload or a longer range, implies an increment of the requested electric energy, leading to heavier battery packs; when this increment results in the condition WTO=MTOW, the $\Phi^{el}$ values have to be reduced and the power request has to be fulfilled increasing thermal power. This brings to a lighter battery pack and hence to the fulfilment of the MTOW constraint, also for the most demanding passenger-range combinations. The thermal and electric power fractions associated to the solution shown in Figure 17 are reported in Figure 18.

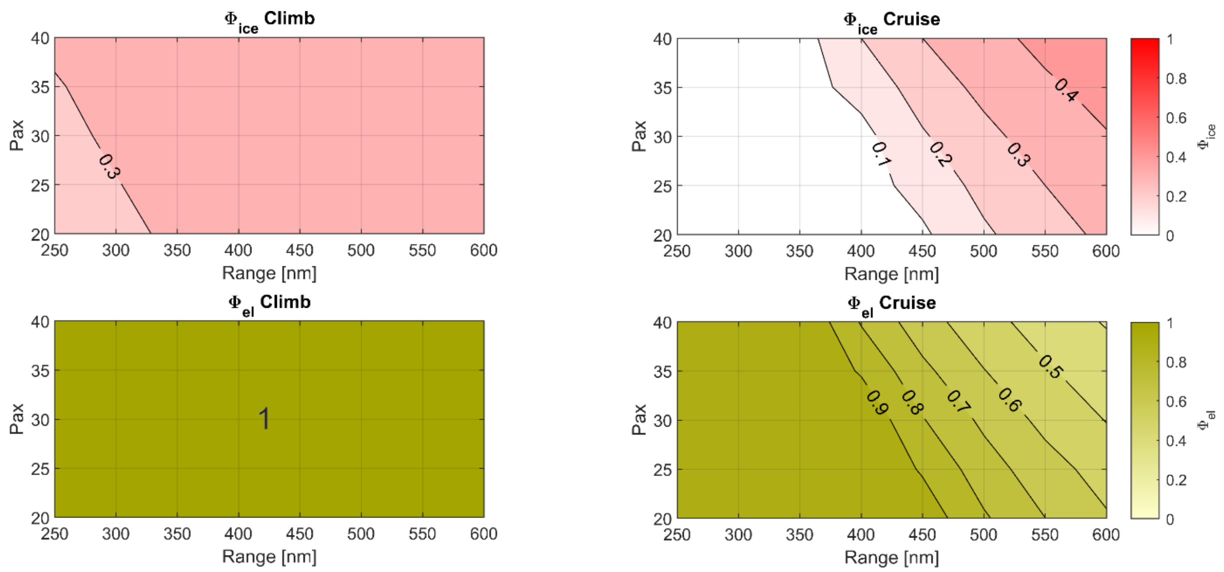


Figure 18: Thermal (top) and electrical (bottom) power fractions for climb and cruise for the missions inside the pax-range diagram

The battery mass shows some interesting trends (Figure 19-left); first, in the area of the pax-range envelope where fuel consumption is below 100 kg, the battery mass gradually increases as the range increases. The increasing trend stops when the take-off weight $W_{TO}$ reaches the MTOW value; beyond this line, the MTOW cannot be exceeded (Figure 19-right), and it is necessary to swap battery mass for fuel mass in order to accomplish the missions. This is due by

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increasing the thermal power fraction and reducing the electric power fraction in cruise, as Figure 18-right shows. In contrast to the conventional thermal aircraft, for which the $W_{TO}$ = MTOW condition only occurs on one segment of the diagram edge, in this case a large area within the envelope is subject to this condition (Figure 20-right). In this area of the envelope, once the payload is fixed, the gradual mass exchange between fuel and batteries occurs.

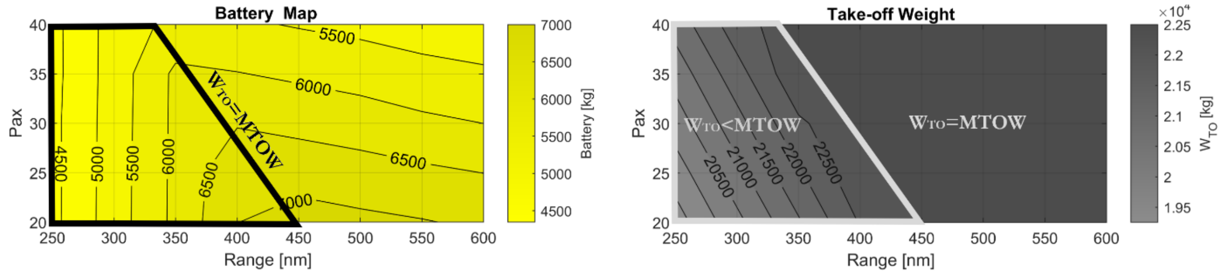

Figure 19: Battery mass (left) and take-off weight (right) trends inside the pax-range diagram

In Figure 20, the performance of the hybrid-electric aircraft are shown inside the complete payload-range envelope, thus also considering the range extension beyond the design point. As qualitatively described in the previous section, the mass swap between batteries and fuel allows to extend the maximum range of the aircraft beyond the design point. Essentially, this is caused by the large amount of battery mass that can be exchanged for fuel, whose specific energy is one order of magnitude higher than batteries one. Due to the large extension of the maximum possible range compared to the design range, a re-scaling of the diagrams of Figure 19 is necessary to make the performance representation in Figure 20 consistent.

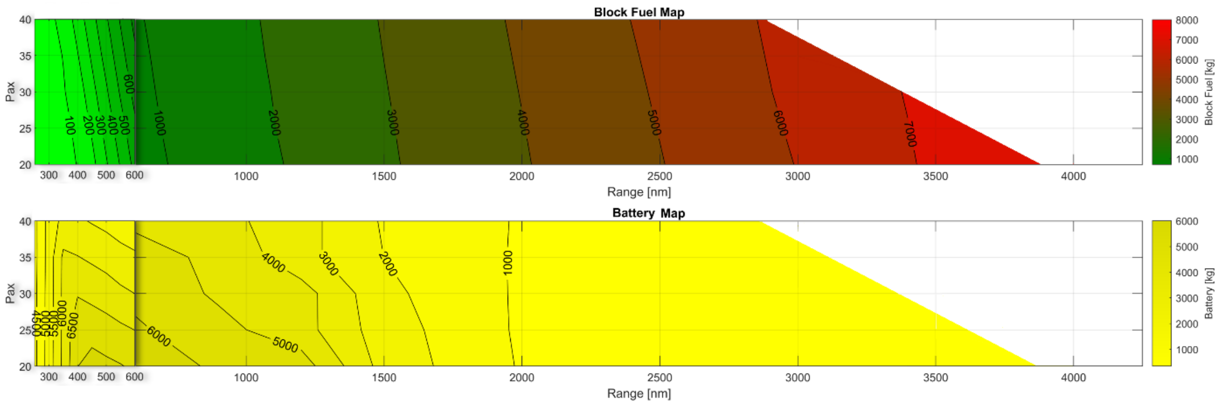

Figure 20: Fuel and battery trends inside the complete pax-range diagram

The hybrid-electric aircraft with parallel powertrain, therefore, may exhibit extensions to the nominal range that are significantly larger than those possible with an aircraft powered only thermally. This extension can be evaluated preliminarily during the design process and exploited to obtain the best operating characteristics for the type of aircraft to be developed, being aware that this flexibility comes at the cost of a higher fuel consumption.

## 4.2 General discussion of the results

As seen in the previous section, aircraft powered by dual-energy sources, whose energy densities differ significantly as it happens with fuel and batteries, have different operating capabilities than thermal propulsion aircraft. Assuming to keep the same payload mass, the possibility to exchange batteries with fuel leads to very different aircraft operating conditions. On the one hand, taking on board large quantities of batteries can favour the reduction of fuel consumption and direct emissions at the cost of a shorter range; on the other hand, since fuel has a much higher specific energy than batteries, exchanging battery masses with fuel allows for significant extensions of the operational envelope of the aircraft.

To better understand the trade-off between the “greenness” and the operational capacity of hybrid-electric aircraft, a qualitative example is provided in the following. Aiming to minimize the direct emissions, it is necessary to minimize fuel consumption for all the possible ranges up to the design point; as described in Section 4.1, this implies the need to take on board a large amount of batteries. The design of the regional aircraft, while considering the top level requirements, is hence steered towards the minimization of direct emissions. However, using this strategy beyond the

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design point limits the operational flexibility of the aircraft due to the low specific energy of the batteries. As a result, there will be little margins to go beyond the design point and cover longer ranges, determining a payload-range diagram shape as the one shown in Figure 21, which has been labelled as *'Green Operations'*.

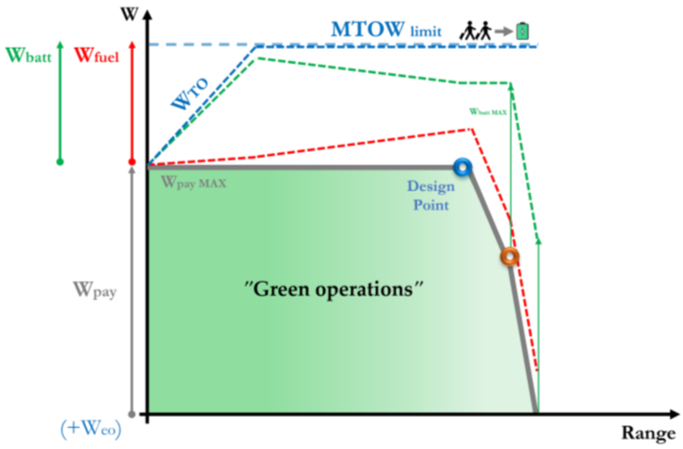


Figure 21: '*Green operations*' shape for the payload-range diagram of a hybrid-electric aircraft

Defining the *'Green Operations'* area is fundamental to set a baseline from which compromise solutions, if needed, can be determined and evaluated. A possible strategy for doing this is to gradually exchange battery mass for fuel mass and change the onboard power management accordingly. This way, it is possible to extend the operating envelope of the hybrid-electric aircraft beyond the design point, as Figure 22 shows. Therefore, by optimizing the power management strategy, the hybrid-electric propulsion may allow to achieve the minimum fuel consumption in the operating envelope of the typical missions for the *Regional* category [27], (*Green Operations* area). In addition, it may allow to design aircraft with much more extended operations than their conventional competitors, by operating in the space defined as *Extended operations* (Figure 22). The optimisation of power and fuel-batteries mass distribution within the mission allows to achieve different performance targets. With a single type of aircraft in fleet, it is possible to provide a 'green' utilisation of the aircraft operated as a *Regional*, and at the same time to diversify the offer by exploiting a much larger range compared to the typical utilisation.

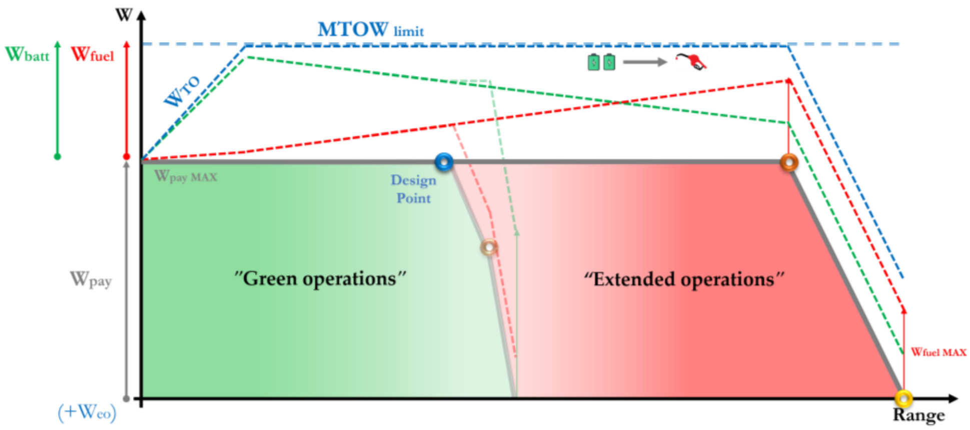


Figure 22: '*Extended operations*' shape for the payload-range diagram of a hybrid-electric aircraft

It is worth to remark that the results reported in this section can be generalized observing that the dual-energy source may introduce a new kind of operational flexibility, which increases as the difference between the energy density of the two sources is larger. This is not obvious, since this happens only if the aircraft is sized to use the energy source with the lower energy density mostly. In the case at hand, this is what happens if, aiming at reducing the fuel consumption for environmental reasons, the aircraft is designed to fly on batteries for a passenger-range region as wide as possible, within the design point; then, it is possible to achieve range extensions, hence providing much more flexibility, at the expense of larger fuel consumption.

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## 5 Conclusions

The potential advantages achievable through the use of hybrid-electric propulsion are not only related to the reduction in fuel consumption. In fact, this type of aircraft has significantly different operational characteristics from thermally propelled ones. In this paper, a study on the operational flexibility of hybrid-electric aircraft is presented, using the payload-range diagram analysis as a main tool for the discussion. Whereas conventional thermal aircraft, once MTOW is reached, can only exchange payload mass for fuel mass to extend their maximum flight distances, the situation is very different for hybrid-electric aircraft equipped with parallel powertrain. In fact, based on the breakdown of the onboard masses of fuel, batteries and payload, very different shapes of the pax-range diagrams can be attained. For example, in the case of operations aimed at reducing emissions, the need to take on board a large amount of battery mass will limit the maximum flight distances obtainable; conversely, by taking on board significant quantities of fuel instead of batteries, thus penalising performance in terms of emissions minimisation, it is possible to obtain very large extensions of the maximum flight distance. This is possible because the battery specific energy is lower, and so the large amount of battery swapped for fuel, whose specific energy is one order of magnitude higher, provides significant range lengthening. Therefore, the drawbacks associated to the battery utilization, that is needed to tackle the climate neutrality challenge, can be balanced from another perspective, i.e. the achievement of considerable operational flexibility, not possible with current regional thermal aircraft. This feature allows to differentiate the operations of the aircraft on the basis of the desired performance as well as of the targeted trade-off between "greenness" and transport capabilities.

The analyses here reported are not intended to lead to the conclusion that *Regional* hybrid-electric aircraft with 40 pax and 3000 nm may have applications of interest, at least currently; rather, it is intended to emphasise that there is a completely new operating potential for this type of non-conventional aircraft. Nonetheless, it is clear that the common classification of aircraft, based on passenger-range pairing, should be reconsidered when dealing with hybrid-electric aircraft. As seen, aircraft with typical *Regional* payloads can have very extended maximum ranges.

The disadvantage of dealing with batteries and their much lower energy density creates new opportunities in terms of operational capabilities and set the basis for future research and studies that can lead to a new perspective on aircraft performance. It is possible to consider, for example, that the features of dual-energy propulsion are favourable to develop hybrid aircraft with *Single-Aisle Class* payloads, that can minimise fuel consumption and emissions for *Regional* market segments but are also able to cover *Medium-Long Range* routes.

Possible further developments of this research concern the depth of the investigations about the power management strategies throughout the mission. In particular, handling the power fractions as time-varying continuous functions could allow to achieve lower fuel consumptions than those obtained with the discretisation used in this work.

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