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CONCEPTUAL STUDY OF HYBRID-ELECTRIC BOX-WING AIRCRAFT TOWARDS THE REDUCTION OF AVIATION EFFECTS ON LOCAL AIR QUALITY AND CLIMATE CHANGE

ABU SALEM Karim[1], CIPOLLA Vittorio[1], PALAIA Giuseppe [1], BINANTE Vincenzo[2], ZANETTI Davide[2]

[1]University of Pisa, Department of Civil and Industrial Engineering, Via G. Caruso 8, Pisa, Italy
[2] SkyBox Engineering, Via G. Caruso 8, Pisa, Italy

Abstract

This study presents an investigation on the integration of hybrid-electric propulsion on medium-haul aircraft with box-wing architecture. This investigation has been carried out to assess the potential of these two innovative technologies for reducing the environmental impact of transport aviation. Two different issues related to the emissions from aircraft operations have been analysed. The first issue, concerning the degradation of local air quality in airport areas, is related to aircraft operations near the ground, such as taxing, take-off, approach, and landing (Landing and Take-Off cycle, LTO). The second issue is related to the impact of aviation on climate change and involves the entire aircraft operating field. To face the two problems, two different and specific approaches of integrating hybrid-electric propulsion on the box-wing aircraft have been proposed. To address local air quality degradation, the hybrid propulsion system has been designed by considering the electric power completely dedicated to the LTO cycle, whereas the thermal power is used for non-LTO operations. Instead, a more general approach has been proposed to address the problem of climate-changing emissions, in which an optimisation procedure for power split management during flight has been used to search for cutting the overall fuel consumption. The results showed that using hybrid propulsion for a limited portion of the mission can provide favourable results when addressing the local air quality problem; theoretically, it is possible to perform LTO operations using only electric power, and thus without any direct pollutant emissions. The integration of hybrid-electric propulsion to minimise the overall fuel consumption, on the other hand, has shown unfavourable results. In particular, limited advantages in terms of block fuel are only obtained for very short distances of less than 1,000 kilometres, whereas fuel performance deteriorates for longer distances. This is mainly attributable to the performance of electric powertrain components, and especially to the low gravimetric energy density of batteries, which makes electric propulsion as an ineffective solution to the problem of reducing the total greenhouse emissions due to medium-haul aircraft.

Keywords: box-wing; hybrid-electric; local air quality; climate change; emissions.

1. Introduction

Transport aviation provides a relevant contribution to the problems of air pollution and climate change. Currently, one of the main objectives of aviation research is to reduce atmospheric emissions. This issue has gained more and more significance as the effects of both carbon dioxide (CO_2) and non-CO_2 emissions on society and environment are becoming increasingly disruptive. The impact of these emissions can be investigated at different levels, for example focusing on the alterations caused to local air quality or on the effects in terms of climate change.

The definition of local air quality mainly refers to the level of air pollution in the areas surrounding the airport zones, below the altitude of 915 metres (3000 ft) above ground level [1]; reducing local air pollution may have a significant impact on the quality of life and health of citizens, as polluting emissions due to aviation have a direct correlation with respiratory and cardiovascular diseases and associated premature deaths. The social impact is therefore multifaceted, since it ranges from the public acceptance of airports not far from neighbourhoods to the social cost of persons affected by the aforementioned diseases. In order to improve local air quality, it is necessary to focus on technological developments which reduce emissions of non-CO_2 pollutants, such as nitrogen oxides (NO_x), sulphur oxides (SO_x), volatile organic compounds (VOC) and particulate matter (PM), mainly during taxiing, take-off and initial climb, approach and landing.

The impact of aviation on global climate change, on the other hand, has different characteristics. First, CO_2 emissions have a predominant contribution in this respect, especially on long time scale effects; nevertheless, non-CO_2 emissions, such as NO_x, SO_x, carbon monoxide (CO), water vapour, also have a non-negligible impact, mainly on short term effects [2]. Pollutants from aircraft engines have a different impact on global warming whether emitted at high altitude or close to the ground. The social and environmental effects of climate change are also different from the alteration of local air quality; climate change involves in fact large-scale effects, such as severe localised meteorological events (sudden and extremely violent phenomena), increase in food and water shortages (especially in developing countries), disruption of ecosystems, worsening of the quality of life in wide areas of the globe, forced migration from currently inhabited areas, melting of polar ice, rising sea levels, large-scale damage to agriculture (e.g. soil acidification), desertification, etc.

From this overview, it is clear that the impact of aviation can be divided in two categories with different origins, causes and effects. On the one hand, to improve local air quality it is necessary to introduce technological and operational solutions capable to cut pollutant emissions in the so called LTO (Landing and Take-Off) cycle, where non-CO_2 emissions play a prevalent role. On the other hand, tackling climate-changing effects requires a general reduction of direct emissions, throughout the entire operational cycle and in particular in the cruise phase. In this case CO_2 emissions have a primary role, but it is necessary to cut all the emitted substances in order to minimize the detrimental effects on climate.

In this work, the challenges of reducing this twofold impact is addressed with the introduction of an innovative transport aircraft, integrating different levels of technological innovation. First, hybrid-electric propulsion [3] is introduced as an alternative to conventional thermal propulsion. Using electrical power for propulsion purposes could be a potential solution for the reduction of direct pollutant emissions. The integration of electric power systems into commercial transport aircraft is constrained by the technological maturity of the electric powertrain components. Among these, one of the most critical are batteries; the low gravimetric energy density of this component constitutes a strong limitation to the electrification of commercial transport aircraft. In this work, the energy density of batteries has been assigned to be in line with the predictions for the next decade [4]. Even in the future scenario, the specific energy of batteries is much lower than kerosene one, leading to a strong increase of empty weight. For this reason, the first strategy adopted in this paper to exploit power electrification is based on the partial integration of electric power, limiting its application to the LTO phase, hence aiming to cut emissions close to airport areas. Therefore, the electrification is here used as a mean to address aviation-related pollution issues related to local air quality. Starting from this scenario, the use of electric power is then gradually expanded, in order to evaluate its potential and limitations in terms of emissions reduction throughout the other flight phases.

The second innovation introduced concerns the airframe architecture; in particular, a box-wing lifting system is studied and adopted for this purpose. This unconventional architecture is able to provide a number of general benefits, also when combined with hybrid-electric propulsion. The main advantage is due to the fact that among all the lifting systems with the same span and lift, the box-wing is capable to minimize the induced drag [5][6], hence the energy required for the mission. This peculiar characteristic turns to be a significant advantage for the LTO flight phases, in which the lift coefficients are high and the induced drag is the main component of the total drag. The box-wing aerodynamic features can be exploited to increase the weight of the aircraft without increasing wingspan and without any penalty in aerodynamic efficiency. This enables the possibility to carry more batteries, finding a better compromise in terms of operational capabilities. The possibility to exploit the box-wing architecture to increase the aircraft weight for an assigned wingspan has been extensively investigated within the PARSIFAL project [7], funded by the European Commission in the framework of Horizon2020 programme. In this project, a medium-range box-wing aircraft has been developed considering the typical characteristics and size of aircraft such as Airbus A320 or Boeing 737, achieving a payload increase of about 66%, and a 22% reduction of fuel consumption per passenger-kilometre. A deeper description of the box-wing system features and the PARSIFAL results is provided in Section 3.1.

In this paper, different hybrid-electric box-wing aircraft solutions are introduced to face the problems of optimizing local air quality and minimizing the impact of aviation on climate change. The design and performance analyses are performed by means of in-house developed conceptual design methodologies conceived to address the design of hybrid-electric aircraft [8], and previously used for research on hybrid-electric 42 passengers regional aircraft with both box-wing and tube-and-wing architectures [9]. In this work, similar design approaches are adapted to study larger aircraft with a number of passengers larger than 150, whereas the range is used as a design variable for each configuration evaluated. A more comprehensive description of the design procedure is provided in Section 3.2.

As a first step, a reference box-wing aircraft available in literature [10], depicted in Figure 1, is considered for a hybrid-electric retrofit of the propulsion system. The retrofit procedure of the powertrain allows modifications to the propulsion system only, whereas the external shape of the aircraft and its general design cannot be changed. This also means that the Maximum Take-Off Weight (MTOW) of the aircraft cannot be exceeded; this aspect is restrictive on the maximum battery mass that can be embarked and may limit the use of electric power only to some of the mission phases. This limitation is here exploited to optimize the aircraft operations from a local air quality perspective.

As a second step, an entirely new hybrid-electric box-wing solution is developed, without the constraints imposed by the retrofit procedure, especially in terms of maximum take-off weight and overall dimensions. The hybrid-electric powertrain is designed and optimized for a wider use throughout the operational mission, with the aim of decreasing the aircraft's overall fuel consumption, its direct CO_2 and non-CO_2 emissions, and thus reducing its climate impact.

The results obtained show that the synergy between the box-wing architecture and the hybrid-electric propulsion, with a proper power management strategy, allows to eliminate direct emissions in airport areas, providing a viable solution for the local air quality improvement. Conversely, the approach aiming at minimizing the fuel consumption throughout the entire operational mission, leads to poor solutions in terms of actual potential of drastically reduce the climate-changing footprint of this class of aircraft. The introduction of propulsion hybridization by means of electrical power seems to be a non-effective solution to reduce the fuel consumption for medium range transport aircraft.

2. Environmental impact of the transport aviation

2.1 Local air quality

As it is well established, commercial aircraft operations have increased with high growth rates over the past decades [11], and the trend is also expected to continue for the next decades [12]. This has led to an increase in traffic at airports, which have often been overloaded or even saturated [13]. The analysis by [14] points out that in the US, more than half of the 35 busiest airports have already been subject to aerodrome expansions in the past two decades to meet the increased demand. Aircraft engines produce a variety of pollutants, such as NOx, CO, hydrocarbons (HC), sulphur dioxide (SO_2), PM. Several studies have shown that air pollutants produced by ground air traffic at large airports can affect the air quality in the airport surroundings and possibly in its whole region [14][15][16][17] with a very negative impact on human health. Millions of people live in the vicinity of airports and are therefore regularly exposed to air pollution from aviation activity; these people are negatively affected by the adverse health consequences of degrading air quality [14][18]. Increases in cardiovascular, respiratory and hypertension diseases have been observed near airport areas [14][16][19]. As a result of these increments, there have been reported incremental trends in premature deaths [20]. Studies on these pathologies have led to the fact that the most dangerous pollutants associated with premature mortality rates include PM [15][21]. The impact of aviation on the concentration of these pollutants in areas around airports has been shown to be predominant [15]. The typical operative mission of an aircraft can be divided into near-ground operations and airborne operations. Aircraft pollutant emissions occurring at ground level have a greater impact on air quality in regions where there is an airport [20][22]. To distinguish the two phases, a standard has been identified that separates LTO (Landing and Take-Off cycle) operations from non-LTO operations, as defined by ICAO [23]. The LTO cycle includes all activities in the proximity of the airport that take place below an altitude of 3000 ft (915 m), i.e. taxi-out, take-off with climb-out to 915 m, approach to the runway from an altitude of 915 m, landing and taxi-in. Several studies have tried to estimate the influence of each stage of the LTO cycle on the type and magnitude of noxious emissions. In [15][20], it is shown that the highest PM and NO_X emissions derive from the high-thrust operating modes of the engine, such as take-off and climb-out, whereas HC and CO emissions are mainly attributable to the low-thrust phases, such as taxiing. These results are important to establish strategies to tackle the problem of air quality degradation, by introducing adequate technical solutions. For example, [21] suggests that the use of a single engine for the taxiing phases does not reduce PM and NO_X emissions, but may be useful for lowering CO and HC emissions. The same conclusions would be reached with the implementation of electrical systems for the ground handling of the aircraft during the taxiing phase, as suggested by [24]. However, these solutions are partial and probably of minor overall impact [21], whereas a breakthrough change is necessary to achieve a thorough reduction of pollutant emissions in the vicinity of airport areas.

For this reason, this study focuses on the integration of hybrid-electric propulsion for medium-range transport aircraft, which are able to perform all the stages of the LTO cycle with electric power exclusively. In this way, all direct pollutant emissions from aircraft operations would be eliminated.

2.2 Climate change

The climate change that is affecting the present era is manifesting itself as a progressive global warming. Research studying this phenomenon agrees that this climate change is mainly influenced by the increasing emissions of greenhouse gases, and that these emissions are mainly of anthropogenic origin, i.e. derived from human activities. To assess the contribution to climate change of an emitted substance, such as CO_2, a metric called radiative forcing (RF) has been introduced [25]. Positive RF values indicate that the considered pollutant has a heating effect on the atmosphere.

Emissions coming from aviation have a contribution to the radiative forcing, which is positive and therefore heating [26]. The main factors from fuel combustion that have a relevant impact on RF are CO_2, NO_x, water vapour (H_2O), soot particles [27][28]. When released at the typical cruise altitudes of transport aircraft, these pollutants interact according to complex processes with the atmosphere, resulting in radiative effects [29].For example, NO_x emissions provide a positive value to RF as the result of several reactions acting on different timescales: on the short term (weeks to months), NO_x cause the formation of ozone via smog reactions, providing a warming effect (positive RF); on a long timescale (about 10 years), they induce methane degradation and secondary effects that reduce the ozone concentration, with a cooling effect (negative RF) [30].

The transport aviation currently contributes an estimated 3.5% to 4.9% of the total anthropogenic contribution to the radiative forcing of climate change, according to [26]. Furthermore, according to [26], the contribution of aviation to the RF may increase about 3-4 times by 2050, thus becoming increasingly influential on the global warming process.

The phenomenon of global warming, therefore, has different implications than those described for the problem of local air quality, and also different impacts on humans. Several studies have focused on the effects of climate change on the planet, humans and society. In [31] it is stated that, although the forecasts are uncertain, even the most optimistic ones foresee dire scenarios for the planet; climate change will lead to the collapse of entire ecosystems, to a drastic reduction in crop productivity, with direct effects on human life. Specifically, [32] predicts that the effects on agricultural production will have significant detrimental effects on growth, productivity, and welfare for the human population for the 2050 scenario. According to [33], climate change could undermine efforts to attempt to end world hunger; the current stability of the food production system would be at risk and would make the already currently difficult situations even more critical. The most food vulnerable countries, along with areas most susceptible to flooding, drought, and rising temperatures will also be subject to dramatic migration flows, as described by [34]. In addition to large-scale effects, climate change will also have direct effects on human health, as described in [35]; in addition to increasing vulnerability to high temperatures of some categories of people, climate change could influence the spread of new infectious diseases. Climate change, therefore, poses a challenge on a global scale that involves all of humanity. Decisive and high-impact actions must be taken today to pursue a path against climate change, in order to mitigate its catastrophic effects. Transport aviation, therefore, must also play its part.

The solutions proposed to date mainly concern technological improvements related to aerodynamic refinement, development of more efficient engines, and optimisation of structures and materials to achieve weight reductions [26]. However, as the problem of aviation's impact is related to its growth, and air traffic growth forecasts seem to be much more predominant than evolutionary technological development, making improvements in little steps seems to be no longer sufficient. To clearly address the problem of greenhouse emissions related to transport aviation, it is necessary to think, develop, and introduce completely disruptive and radical innovations [28]. Thus, radically innovative airframe and propulsion designs are to be investigated. In this study, the integration of hybrid-electric propulsion, which has the potential to reduce fuel consumption, with box-wing aircraft architecture is proposed. Such a lifting architecture has already shown intrinsic potential in reducing the climate impact of transport aviation, as described in [36].

3. Materials and methods

3.1 The baseline box-wing aircraft

The starting point for this study is a box-wing aircraft taken as reference, whose design is the main outcome of the PARSIFAL project. Concluded in 2020, PARSIFAL (*'Prandtlplane ARchitecture for the Sustainable Improvement of Future AirpLanes'*) [7] has been funded within the framework of the Horizon2020 programme, with the primary purpose of assessing the environmental and operational potential of an innovative box-wing aircraft, known as PrandtlPlane (PrP) [37]. The interest in the PrandtlPlane configuration derives from its theoretical capability to have superior aerodynamic performance, and hence to provide opportunities for significant reductions in fuel consumption and pollutant emissions. The PrandtlPlane configuration is based on a box-wing lifting architecture, a wing configuration that, if properly designed, minimises induced drag among all the aircraft with the same wingspan and lift. This idea, theorised by Prandtl [5] and demonstrated by Frediani [6], was then used to conceive and develop an aircraft with the potential for more efficient aerodynamic performance than conventional architecture. The PARSIFAL project has demonstrated this theoretical framework, developing a medium-range transport aircraft with a PrandtlPlane configuration showing the following improvements with respect to a conventional competitor of the Short-Medium Range class [38][39]:

- An increase in passenger number of 66%, from 186 to 308;
- A maximum reduction in fuel consumption per passenger-kilometre of 22%;
- The wingspan is ≤ 36 metres, and the aircraft is therefore compatible with the same airport aprons (identified by the ICAO 'C' standard [40]) as the conventional competitor aircraft, despite having a significant increase in payload.

The superior aerodynamic efficiency and the lifting characteristics of the box-wing system have therefore been exploited to decrease fuel consumption per passenger, to maintain the same wingspan as the conventional competitor and therefore operate from the same aprons, and to increase the payload. To allocate more passengers, a new fuselage design has been developed, as depicted in Figure 1-right in comparison with the conventional aircraft.

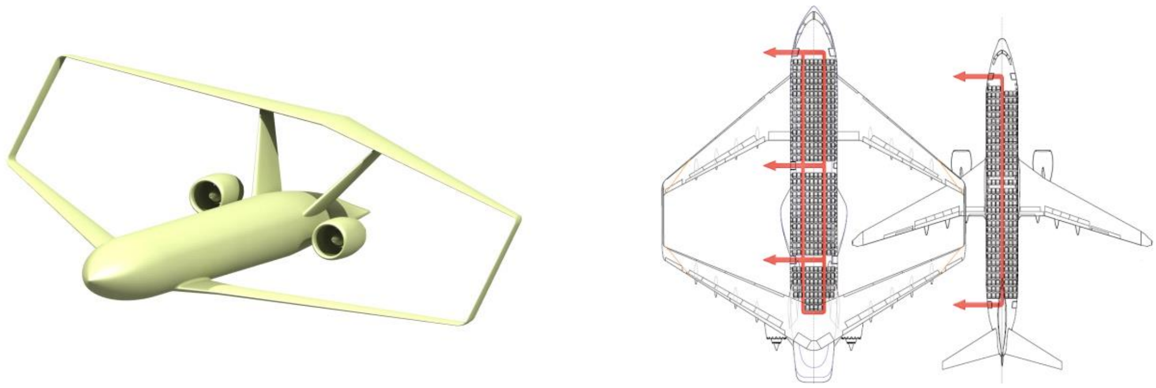

Figure 1 – Baseline PrP: artistic view (left), comparison with a typical single-aisle aircraft (right)

The characteristics of this aircraft are therefore definitely favourable for a subsequent development step aimed at a further reduction in fuel consumption, for example through the integration of hybrid-electric propulsion. The possibility of exploiting the box-wing configuration to increase aerodynamic efficiency, and at the same time also to significantly increase the weight of the aircraft without performance penalties, is a key success factor in the electrification process. It is well known, in fact, that the main drawback of electric propulsion lies in the significant weight increase due to the presence of very heavy components such as batteries. In addition, the new fuselage design proposed in

PARSIFAL also allows for large volumes for on-board battery allocation. The characteristics of the PrandtlPlane developed in PARSIFAL therefore represent an opportunity to obtain the best possible benefits from the integration of hybrid-electric propulsion. This work aims to explore this potential at a conceptual level.

3.2 Hybrid-electric aircraft design methodology

An in-house developed environment for the conceptual design and performance analysis of hybrid-electric transport aircraft has been used in this study. This tool, firstly conceived to study regional hybrid aircraft [8], has been applied in this research to design short-medium range hybrid aircraft with more than 150 passengers. The conceptual design platform for hybrid-electric aircraft is called THEA-CODE (*'Tool for Hybrid Electric Aircraft COnceptual Design'*) and its workflow is schematically shown in Figure 3. The tool performs aircraft sizing going through the following main steps:

- Aerodynamic evaluations: the aerodynamic performance of each configuration are estimated through the Vortex Lattice Method code AVL [41] to evaluate trim, stability and induced drag, whereas consolidated literature methods are used to evaluate parasitic drag [42] and wave drag [43]. In addition, when higher fidelity datasets are available, it is possible to use these data to perform aerodynamic evaluations (see the retrofit case described in Section 3.3.2).
- Propulsion system: the sizing of thermal engines and electric motors is carried out by using information from the so-called matching chart (Figure 2), which is a diagram that correlates the required specific power (P/W) with the aircraft's wing loading (W/S) [44][45]. The requirements on specific power to be installed on board are provided by regulations, as proposed in [46]. In case of hybrid-electric propulsion design, from this graph is also possible visualizing the power split between thermal and electric installed power.

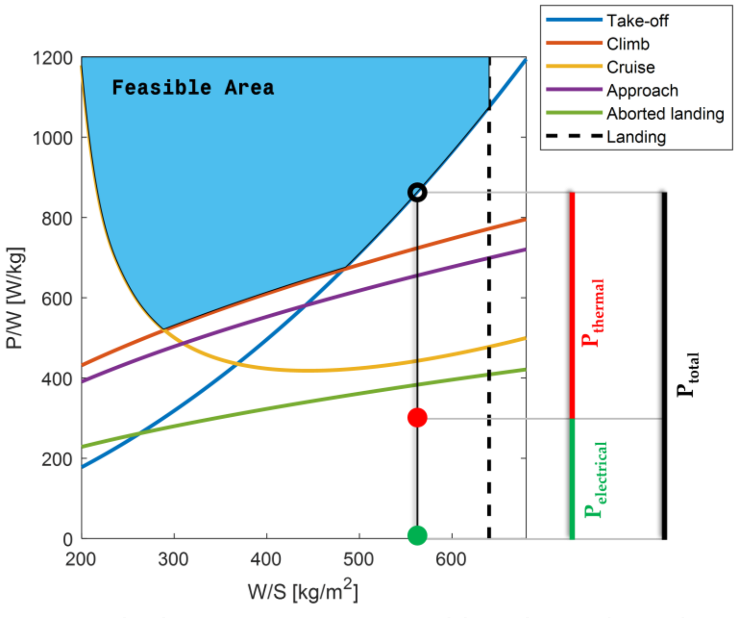

Figure 2 - Qualitative example of a matching chart P/W-W/S

- Mission analysis: in this block, a time-marching simulation of the design mission is carried out according to the indications given in [47][48]; specifically, the mission is split in taxi-out, take-off, climb, cruise, descent, climb to alternate, cruise to alternate, descent, loiter, approach, and taxi-in phases. For each mission stage, the aircraft point-mass equations of motion are time-integrated to evaluate the cinematic and the performance. The simulation in each time step takes the aerodynamic and weight characteristics of the aircraft evaluated in the other blocks of the workflow into account. The main outcome of the simulation is represented by the fuel consumption and/or required battery mass.
- Aircraft weight estimation: the total weight of the aircraft is computed considering the payload weight, provided as input, the fuel and battery weight, provided by the mission analysis module, and the operative empty weight, evaluated according to the methodologies proposed in [49].

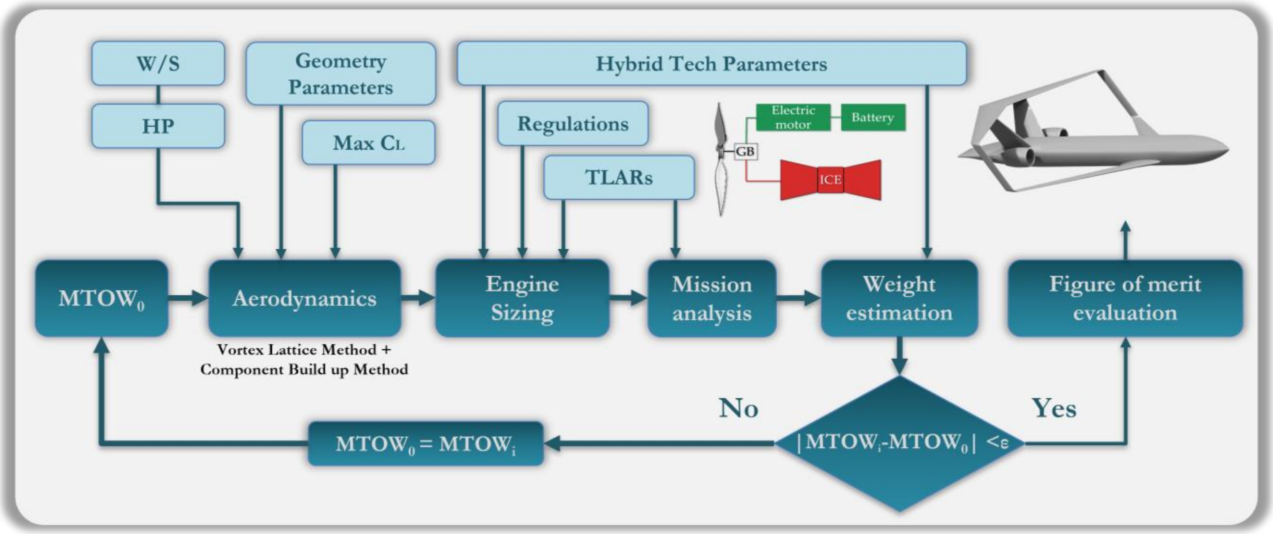

Figure 3 – Simplified scheme of the THEA-CODE design workflow

The design procedure is initialised by providing as input a set of Top Level Aircraft Requirements (TLARs), the information on the technological level of the electrical machines and batteries, and a starting geometry. The THEA-CODE sizing procedure ends once convergence on the maximum take-off weight is reached. Since the detailed description of the code is beyond the scope of this paper, for more details please refer to [8][9], where there is an in-depth and detailed description of the design methodology. For the sake of clarity, it is worth to underline that THEA-CODE is not conceived to modify and/or optimise the geometry of the aircraft during the sizing phase, but it can only homothetically scale a geometry provided as input as the weight and wing loading vary. THEA-CODE has in fact been developed to work synergically with the aerodynamic optimisation program AEROSTATE, described in detail in [50][51][52], which has been specifically developed to act on the geometrical parameters describing the box-wing lifting systems. The combined use of the two codes is described in [9].

3.3 Retrofit and design strategies

3.3.1 Common assumptions

The parameters related to the technology level of the electrical machines and batteries used in this conceptual study are the following:

- Hybrid-electric powertrain architecture = parallel. The integration of the two power units, at this conceptual stage, is assumed according to the scheme proposed in [53]. Specifically, the electric motor is directly connected to the low pressure shaft of the engine inside the fan hub. This solution avoids the necessity of a gearbox since the electric motor is connected to the high speed shaft; moreover, the electric motor is located in the cold section of the engine, reducing the possibility of overheating [53]. This architecture allows to simultaneously supply power to the fan from both the thermal and electrical sources; the two power source can supply the power in different shares during the mission stages.
- Battery energy density (BED) = 500 Wh/kg [54];
- Electric motor power density = 15 kW/kg [54];
- Cables density per linear meter = 6.5 kg/m [53].

3.3.2 Retrofit strategy

The first strategy to integrate electric propulsion into the box-wing aircraft is based on the retrofit of the baseline aircraft. With this procedure, only the propulsion system of the aircraft is designed, whereas the external shape and primary structure are kept unvaried from the baseline aircraft. This procedure has the advantage of allowing for an agile and flexible reconfiguration of a given aircraft, but it has the disadvantage of leaving no room for modifications of most of the aircraft features. Since the shape of the aircraft is the same, also aerodynamic performance are not different; for this study, therefore, the aerodynamic database produced in [48] has been used to carry out the aerodynamic evaluations. In a retrofitting procedure, it is necessary to respect most of the constraints considered for the design of the reference aircraft, the main of which is the compliance with the MTOW of the baseline aircraft. In fact, the main structure of the aircraft is sized according to this MTOW value and therefore the retrofit procedure must be constrained not to exceed it. In addition, there is also a number of components whose weight do not change during the hybrid propulsion retrofit. Given the conceptual level of the present approach, the structural weight can be included among these fixed weights , including wing and fuselage, the landing gear, and the on-board systems. Instead, the weight of other items can differ from the baseline aircraft; among these, there is obviously the weight of the propulsion system, which is totally re-designed, but also the weights of the operational items directly related to the number of passengers. In fact, the retrofit procedure includes the possibility of varying the requirement on the maximum number of passengers, hence the weights of the items directly related to it, such as cabin furnishing and hold arrangement, are therefore re-evaluated for each configuration considered. The possibility of varying the maximum number of passengers has been implemented for two main reasons. Firstly, reducing the payload offers the opportunity of increasing the mass of batteries and electrical power systems, which are heavy components, and at the same time respecting the constraint on the MTOW of the baseline aircraft. Secondly, as the wings are used to accommodate fuel, reconfiguring the cabin and/or the hold for a different payload provides additional solutions for accommodating the batteries inside the fuselage.

There are already other case studies in the literature concerning hybrid-electric retrofit of transport aircraft; some of the most relevant can be found in [55][56][57]. However, in previous studies, the integration of hybrid propulsion for transport aircraft was primarily aimed at reducing the overall environmental impact of the aircraft, through the attempt to reduce overall fuel consumption. In this study, instead, the objective of the hybrid retrofitting is to fully suppress polluting emissions in the proximity of airport areas, and thus limiting the impact on local air quality degradation, as described in Section 2.1. This objective has a direct impact on the aircraft retrofit procedure, mainly on the sizing constraints of the propulsion system and on the split of installed power between the thermal and electrical systems. In particular, in this conceptual study, the phases defined as the LTO cycle have been carried out with the exclusive use of electric power; this strategy totally avoids the use of thermal engines for standard operations purposes in these phases and therefore eliminates noxious emissions in airport areas. All the other flight phases, i.e. climb, cruise, descent, diversion and loiter, are instead accomplished with the sole use of thermal power. The choices for the use of the two power sources for the retrofitted box-wing configurations are schematically shown in Figure 4.

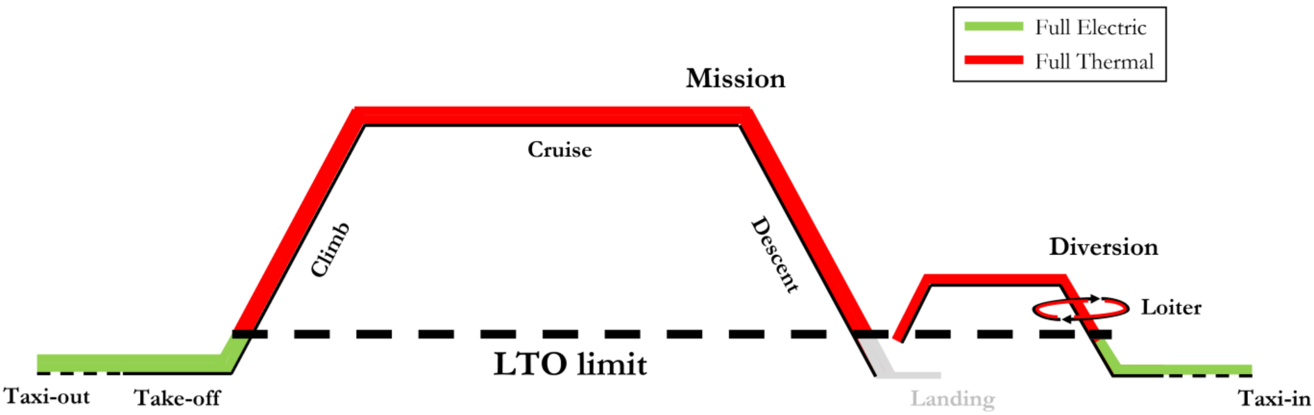

Figure 4 – Power split and supply strategy for the retrofit procedure

Given the power utilisation strategy employed in the retrofitting strategy, the propulsion system is sized by following this simplified procedure: the electric motor is sized to meet the take-off requirement; the thermal engine is subjected to the most restrictive constraint of the whole matching chart, as usual. Consequently, in this case, the matching chart reported in Figure 2 is split in two parts: one, relevant to the electric propulsion sizing (Figure 5-left), and one related to the requirement on thermal specific power (Figure 5-right).

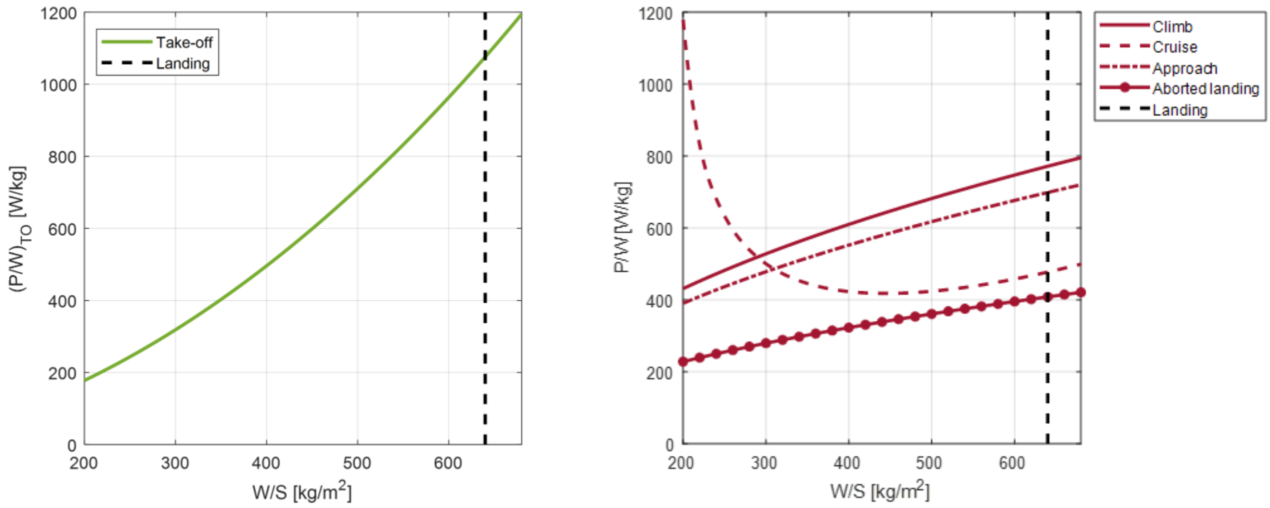

Figure 5 – Qualitative matching charts for the retrofit strategy: electric (left) and thermal (right) propulsion systems

3.3.3 Design strategy

The design procedure completely differs from the retrofit procedure, both in methods and objectives. In the case of design, design THEA-CODE has been used as the objective function evaluator inside an optimization procedure, specifically set up to identify the most promising hybrid-electric configurations. The purpose of the short-medium range box-wing aircraft design strategy is to identify possible solutions that can significantly reduce fuel consumption and therefore greenhouse emissions during the whole mission. For this reason, the objective function to be minimized within the optimization procedure is the block fuel, and thus representing a substantial difference from the retrofit strategy.

The optimizer can act on five different design variables, which are:

- W/S: the aircraft wing loading, where W is the design weight and S is the lifting system reference surface;
- H_P: the hybridization factor of the installed power, defined as in Equation (1), where P_{el} is the electrical installed power, and P_{ice} is the thermal installed power;

$$H_P = \frac{P_{el}}{P_{el} + P_{ice}} \tag{1}$$

- $\Phi_{ice\ CL}$: the thermal share of the supplied power in climb;
- $\Phi_{ice\ CR}$: the thermal share of the supplied power in cruise;
- $\Phi_{ice\ DE}$: the thermal share of the supplied power in descent.

As stated in Section 3.3.1, the power management strategy with the adopted powertrain architecture allows the possibility of simultaneous supply, and in different proportions, of thermal and electrical power in climb, cruise, and descent phases of the standard mission. The taxing and take-off phases, instead, are fixed and are not handled by the optimizer. Specifically, it is preliminarily decided that the taxiing phase is accomplished using electric power only, whereas the take-off is performed using both thermal and electric power. The diversion needs to be taken into account for sizing, but since it is not performed in standard operations, its emissions does not have a significant impact in terms of climate change. For this reason, it is decided to accomplish the whole diversion with thermal power only. This avoids the need to carry a larger amount of batteries, which would increase the empty weight of the aircraft, reducing the achievable performance without any practical advantages. Figure 6 schematically summarizes the power management strategy along the full mission considered in the design procedure.

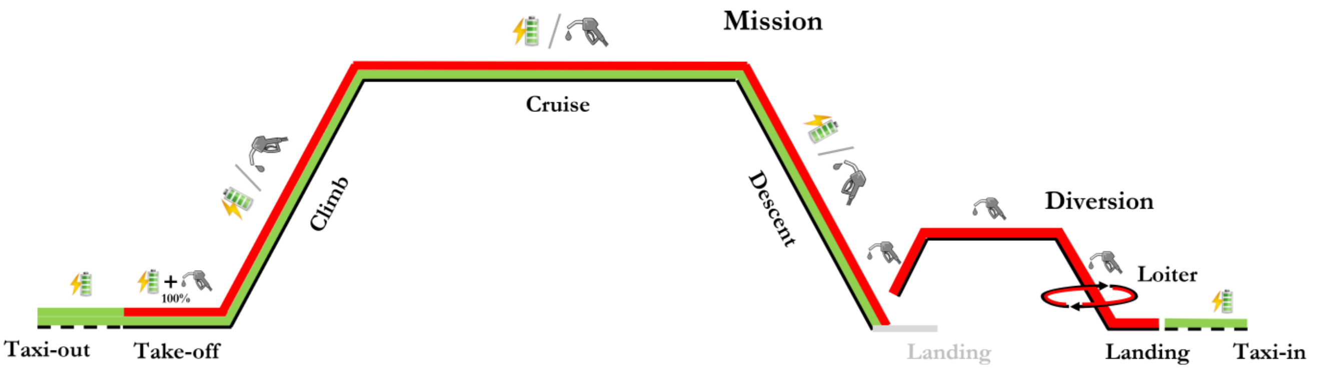

Figure 6 – Qualitative power split and supply strategy considered in the design procedure

4. Results

In this section, the results related to the development of the hybrid-electric box-wing aircraft are proposed and discussed. In particular, results related to the retrofit of the baseline aircraft, and the possibility of using such a power hybridization strategy to suppress noxious emissions in the LTO phase, are proposed in Section 4.1. Section 4.2, on the other hand, reports results related to the design of the box-wing hybrid-electric aircraft, carried out to explore the possibility of significantly reducing greenhouse gas emissions through the integration of electric propulsion.

4.1 Retrofit strategy towards the improvement of local air quality

The retrofitting procedure, discussed in Section 3.3.2, has been extensively applied to the hybrid-electric aircraft study, with the aim of obtaining an exhaustive amount of information to identify useful trends. To this end, therefore, sensitivity studies have been conducted involving two of the main design requirements for a commercial transport aircraft: the number of passengers and flight distance. The other requirements, such as required runway length, cruising speed and altitude, are left fixed and equal to those of the baseline aircraft [48]. The results of the performance sensitivity analyses are critically discussed and compared with those of the box-wing baseline aircraft.

4.1.1 Sensitivity to payload and range

Payload and range sensitivity analyses have been carried out by varying the maximum number of passengers between 150 and 300, and the flight distance between 750 and 5700 km; the latter value represents the harmonic range, i.e. the maximum range with the maximum number of passengers, of the baseline aircraft [48]. Payload and range sensitivity studies have been done in two different steps, as described below:

- in the first step, called *design phase*, the aircraft is retrofitted for each pair of values of the number of passengers and flight distance. For example, an aircraft with a number of passengers equal to 180 and a flight distance equal to 2000 km will have a cabin reconfigured to have a number of seats equal to 180 and will have its harmonic range set to 2000 km. The hybrid propulsion system is sized to meet the power requirements for this specific design point. For this design point, the W_{TO} value calculated by the retrofitting procedure corresponds to the MTOW of the analysed configuration and is always lower than the MTOW of the baseline aircraft.
- in a second step, called *analysis phase*, a number of configurations are selected from those evaluated in the design phase, and the performance within their allowable payload-range envelope are evaluated.

The results of the first step, the *design phase*, are shown below. Figure 7 shows the values of battery mass (left) and block fuel mass (right) needed to perform the missions corresponding to the values of range and number of passengers indicated on the axes of the diagrams. As might be expected, both the mass of batteries and the fuel needed for the mission increase as the number of passengers and range increase. The mass of batteries, which are used only in LTO phases, is mainly needed for the take-off phase, which requires the supply of maximum electrical power. The trend of the contour lines of the battery mass is in agreement with the trend of the maximum take-off weight of the retrofitted aircraft, whose map is shown in Figure 8-left. In fact, the installed electrical power (Figure 9-right) is constrained by the power requirement on take-off, which depends mainly on the take-off mass of the aircraft. Therefore, the battery mass follows the same trend as the number of passengers and the range change. The trend appears to be different for the mass of block fuel (Figure 7-right); the effect of range variation is much more pronounced than that of the number of passengers. This is mainly due to the fact that fuel consumption is predominant in the cruise phase, and, in this phase, it is the distance travelled that has a major impact on fuel consumption.

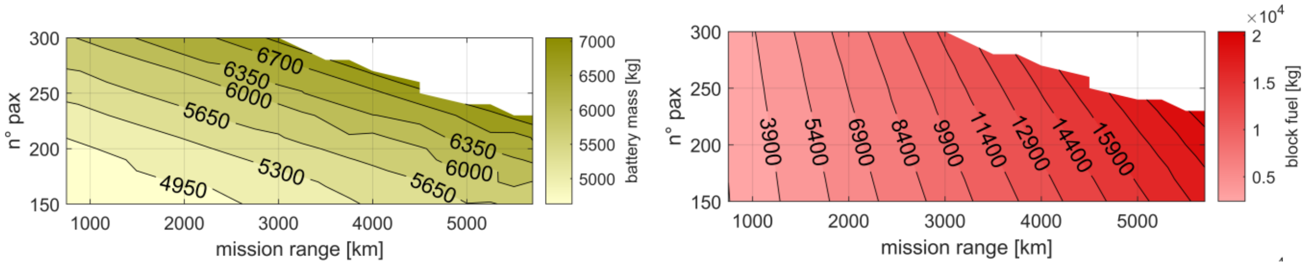

Figure 7 – Battery mass (left) and block fuel mass (right) maps varying pax number and range

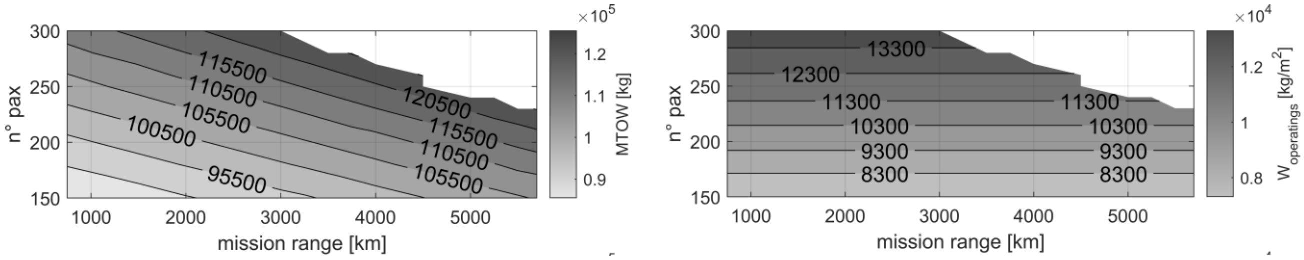

Figure 8 – Take-off (left) and operatings items (right) weights maps varying pax number and range

Figure 8-left shows the maximum take-off weight trend for each retrofitted configuration as payload and range change. It is interesting to note that there is an unfeasible area of the payload-range envelope, which, on the other hand, is admissible for the baseline aircraft [10]. This is due to the increase in operating empty weight with respect to the baseline thermal aircraft, caused by the on-board installation of electric machines and batteries; the constraint on $MTOW_{MAX}$, which must be respected in retrofit designs as described in Section 3.3.2, hence results in a contraction of the maximum operability of the hybrid-electric aircraft, in terms of maximum range and payload. However, since the retrofit design also includes a reduction in the number of passengers, part of the weight increase due to the integration of electric propulsion is compensated by a reduction in the weights of operating items directly related to the number of passengers, as shown in Figure 8-right. These items include, the masses of seats, interior furnishings, galleys, on-board crew, emergency equipment, oil, documents, and toilet fluids.

Figure 9 and Figure 10 show the results related to the hybrid retrofitting of the propulsion system, in terms of specific power P/MTOW and installed power P, respectively. The results are given in terms of requested power for the whole hybrid powertrain (left), for the thermal part (centre), and for the electrical part (right).

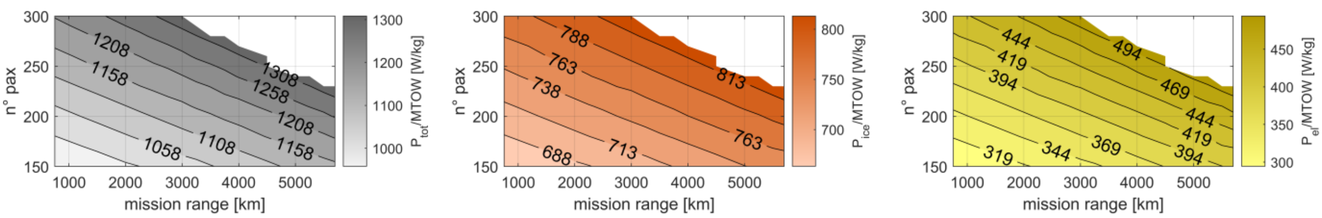

Figure 9 – Specific power maps varying pax and range: total (left), thermal (centre), electric (right)

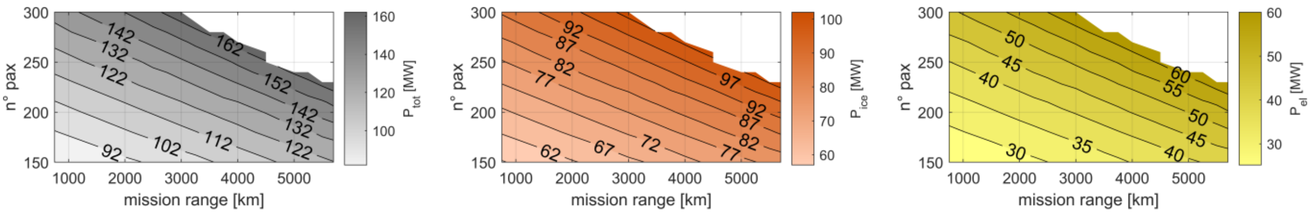

Figure 10 – Installed power maps varying pax and range: total (left), thermal (centre), electric (right)

As already mentioned in Section 3.3.2, the sizing requirement for electric propulsion is that relating to take-off; this follows from the preliminary choice given by the designer. With regard to thermal propulsion, on the other hand, the sizing requirement for the case study carried out in this work is that relating to the climb phase. The specific power demand, for both the thermal and electrical parts, decreases as the payload and/or range decreases, and therefore as the take-off weight decreases. Indeed, the decrease in take-off weight implies the same trend on the wing loading: it should be recalled that in the retrofit procedure, the structure of the aircraft remains unchanged from the reference aircraft. Since also the shape of the lifting system is the same, as the take-off weight decreases, there is a corresponding reduction in wing loading, as shown in Figure 11-left. Wing loading is a fundamental variable in the evaluation of the specific power required during take-off and climb. Therefore, as the W/S decreases, there is a beneficial reduction in the specific power required, and consequently in the total power to be installed on board (Figure 9 and Figure 10).

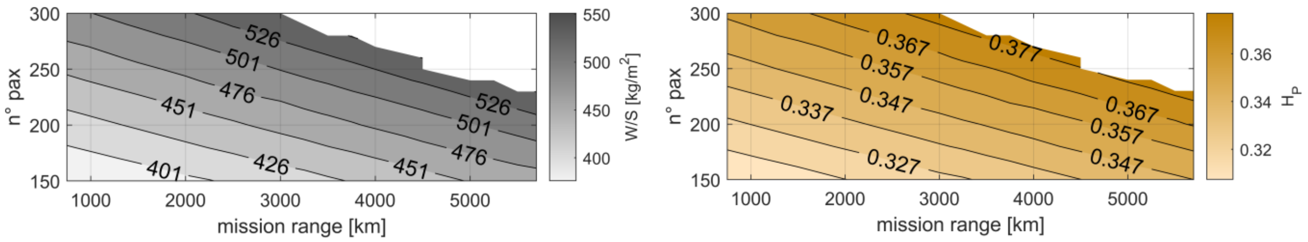

Figure 11 – Wing loading (left) and hybridization factor (right) maps varying pax number and range

In the subsequent *analysis phase*, two configurations have been selected from those assessed in the *design phase*, and their potential and performance have been evaluated. In this particular example, two configurations with different characteristics have been selected: one sized to have a maximum number of passengers equal to 250 and a design range equal to 2000 km, and named *Configuration 1*, and another one sized to have a maximum number of passengers equal to 300 and a design range equal to 3000 km and named *Configuration 2*. A comparison in terms of weights between the two retrofitted configurations is proposed in Figure 12. Figure 12-left shows the trend of the take-off weight (W_{TO}) for the two configurations, whose MTOW is shown in the diagrams in Figure 12-right. It should be recalled that the maps of Figure 12 (and also Figure 14, Figure 16) correspond to the performance of the two selected configurations (*analysis maps*), whereas in the maps presented from Figure 7 to Figure 9, each pax-range pair corresponded to a different aircraft retrofit (*design maps*). Therefore, the variable represented in Figure 12-left represents the W_{TO}, whereas the MTOW corresponds to the value related to the design point, as shown in the diagrams in Figure 12-right. The MTOW of *Configuration 1* is 109420 kg, whereas that of *Configuration 2* is 125200 kg, which is equal to the upper possible limit for the MTOW.

The differences between the two configurations lie mainly in:

i) propulsion system masses, both thermal and electrical, due to the differences in power requirements between the two aircraft. In particular, *Configuration 1* has a lower specific power requirement (Figure 13-right), due to the lower wing loading of the configuration; furthermore, the lower MTOW implies a further reduction in the total power to be installed (Figure 13-left);

ii) masses of the operating items, which mainly depend on the maximum number of passengers;

iii) mass of fuel and batteries required for the design point.

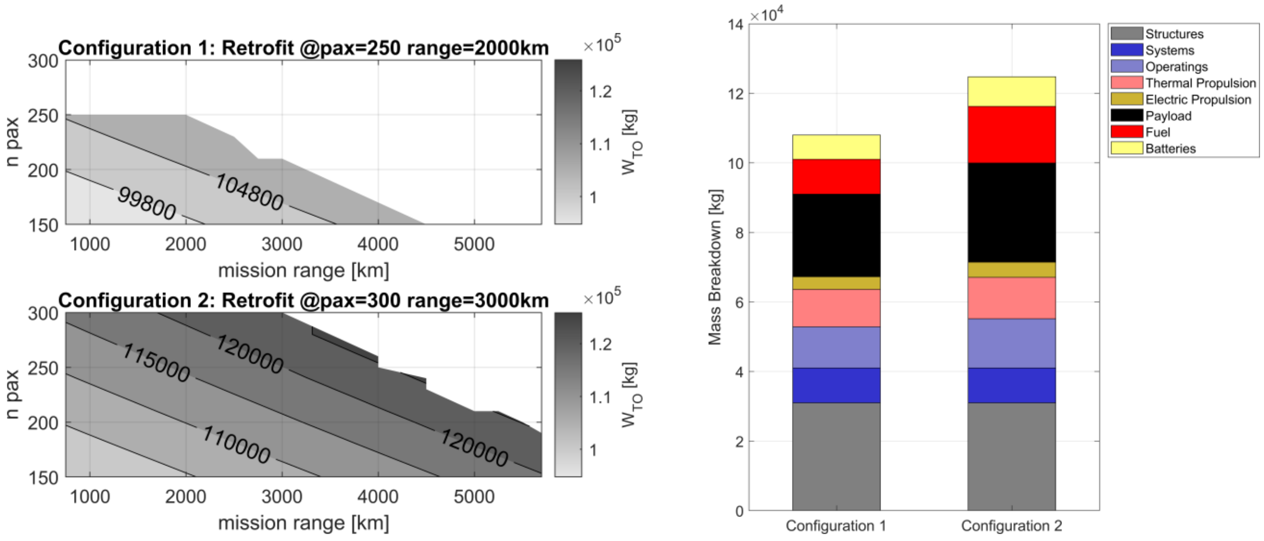

Figure 12 – Take-off mass trend varying pax number and range (left), MTOW breakdown (right)

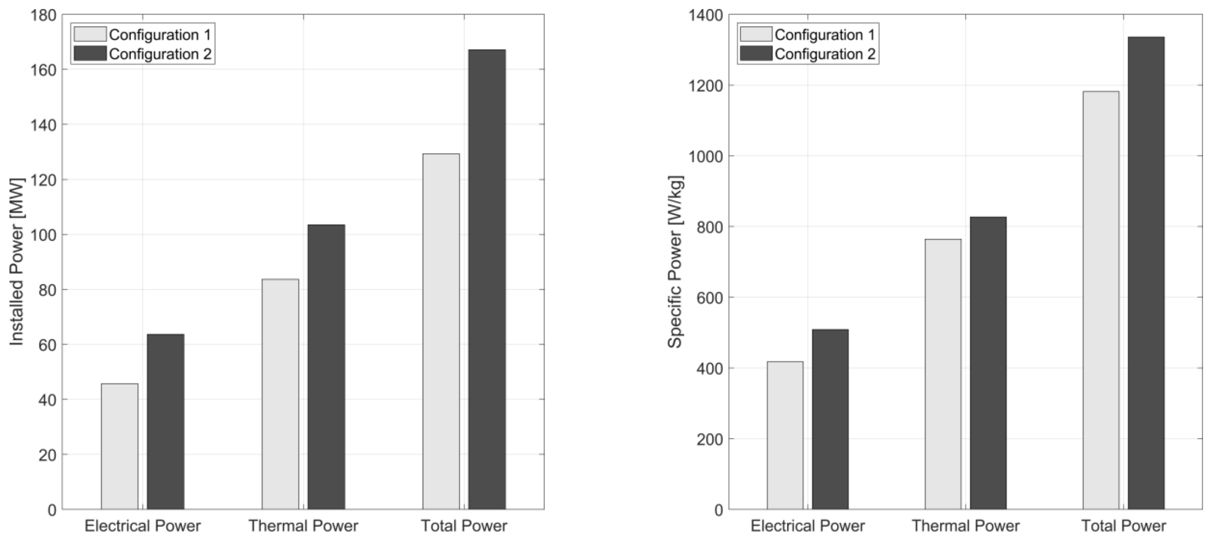

Figure 13 – Installed power (left) and specific power (right) breakdown

The lower amount of fixed masses, i.e. that related to the propulsion system and the payload-related operating items, for *Configuration 1* compared to *Configuration 2* results in a lower energy demand to perform the flight, and therefore in a general benefit on both battery mass and block fuel, as depicted in Figure 14. On the other hand, *Configuration 1* has a much more limited operational envelope than *Configuration 2,* which is mainly due to the different choice of the design point. Being designed for a smaller payload and range, in fact, *Configuration 1* has a lower installed power, which constraints the operational envelope in areas where the power demand is within this limit. *Configuration 2*, on the other hand, is only limited by the MTOW of the baseline aircraft and therefore has a wider operational envelope, but – for the same payload-range combination – has a higher block fuel.

Therefore, the choice of which configuration should be further developed, and in general how to drive the selection of the design point, relies on an in-depth assessment of the pros and cons between improving the environmental footprint of the aircraft while reducing its operational capabilities.

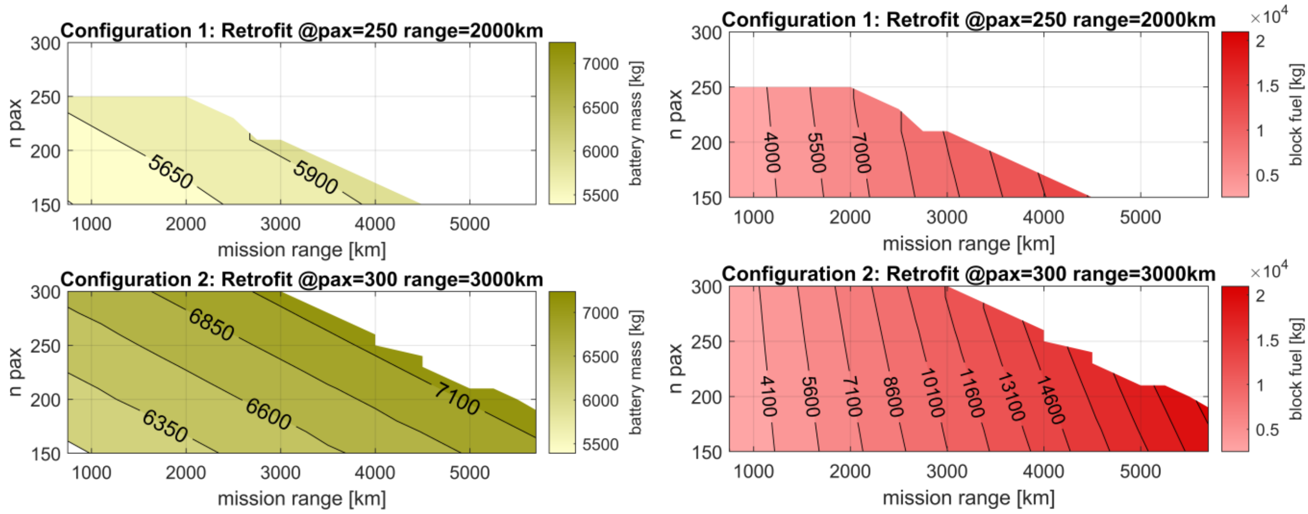

Figure 14 – Battery mass (left) and block fuel mass (right) maps varying pax number and range

4.1.2 Performance comparison with the baseline box-wing aircraft

In this section, performance comparisons between the retrofitted hybrid-electric configurations and the baseline box-wing aircraft are presented. The analysis is mainly focused on the capabilities of the hybrid-electric configuration to eliminate the use of the thermal engine in the LTO phase, and to suppress noxious emissions in the airport areas, and the impacts of this strategy on the overall fuel consumption performance.

First, the fuel consumption of the baseline thermal powered box-wing aircraft is presented. Figure 9 shows the consumption maps when varying the number of passengers and range of the baseline box-wing aircraft [48]. In order to make the comparison more effective, given the purposes for which the hybrid-electric retrofit of the baseline aircraft is proposed, the fuel consumption of the baseline has been divided into LTO block fuel (Figure 15-left), non-LTO block fuel (Figure 15-centre), and the percentage of LTO block fuel of the total mission consumption (Figure 15-right). The fuel for diversion and reserves is not included in these graphs.

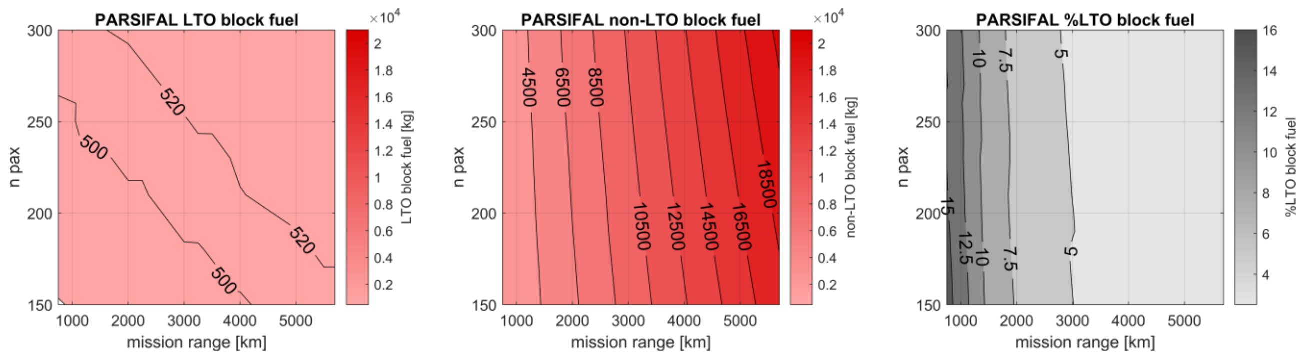

Figure 15 – LTO (left), non-LTO (centre), and LTO percentage (left) fuel for the baseline aircraft

With the retrofit strategy implemented in this study, the introduction of the hybrid-electric propulsion eliminates the fuel consumption in the LTO phase, since this phase is entirely carried out using electric power. The graphs in Figure 16 show the comparison between the block fuel of the two hybrid-electric configurations described in Section 4.1.1 and the baseline box-wing aircraft; in particular, Figure 16-left shows the comparison in terms of block fuel difference, whereas Figure 16-right shows the percentage variations. The first row of Figure 16 refers to *Configuration 1*, which has a significantly smaller operational envelope than the baseline aircraft but shows a block fuel reduction for the majority of the passenger-range combinations. The reduction is more significant for low range missions, as they are more sensitive to LTO phase performance. The second row in Figure 16 refers to *Configuration 2*, for which the operational envelope is larger than *Configuration 1*; however, since its higher empty weight, the comparison with the baseline in terms of percentage variation of block fuel shows negative values only for a fraction of passenger-range envelope. Although for

Configuration 1 the amount of fuel saved is small in absolute terms, the purpose of the retrofit procedure is fully achieved, since the cut of pollutant emissions in the proximity of airport areas comes without penalties in block fuel in the whole operational envelope. For *Configuration 2*, instead, the block fuel differences becomes positive as the range increases.

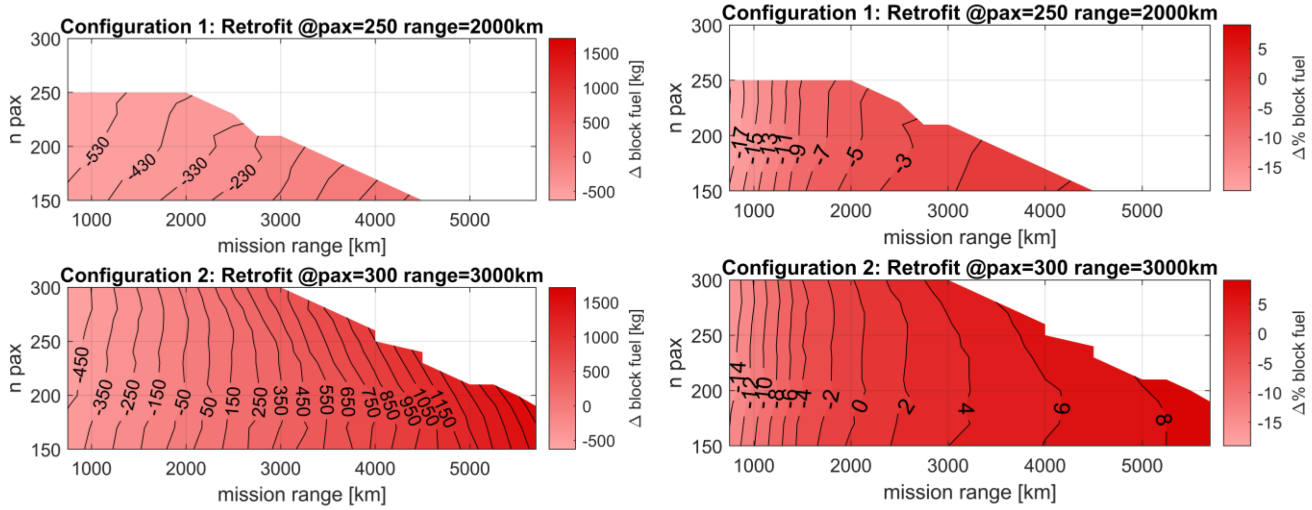

Figure 16 – Block fuel absolute difference (left) and percentage difference (right) between the hybrid configuration and the baseline aircraft

A trade-off scenario is again in place; in fact, both the retrofitted configurations present the complete elimination of LTO emissions, and thus of direct pollution in the surroundings of the airport areas. To achieve this, on the other hand, the two configurations must pay a price in terms of overall performance compared to the baseline aircraft. In particular, *Configuration 1* presents a significant reduction in the operational envelope, whereas not exhibiting significant degradations in fuel consumption throughout its operational field. *Configuration 2*, on the other hand, presents a fairly wide operational envelope and weakly penalised compared to that of the baseline aircraft, however it presents performance degradations in terms of block fuel, especially for high values of mission range. The purpose of choosing and analysing two sufficiently different retrofitted configurations is to illustrate this conclusion.

At this conceptual stage, the designer can explore different retrofitting strategies to try to achieve the main objective, i.e. the elimination of LTO phase emissions. However, given the problems associated with integrating electric power systems, above all the high weight of motors and batteries, it is also necessary to analyse all the general trade-offs to minimise penalties in terms of the overall performance of the hybrid-electric aircraft.

4.1.3 Sensitivity to battery energy density

The current state of battery technology is still far from allowing BED values close to 500 Wh/kg; this value is reasonably valid for aircraft with entry into service beyond 2035. In order to assess the current potential of hybrid propulsion towards local air quality, a sensitivity analysis has been therefore carried out by varying the BED. In particular, starting from the reference value used in this work (500 Wh/kg), the BED has been gradually reduced. The BED values used for the hybrid retrofit of the reference aircraft are 400, 300, 200 Wh/kg. The results obtained are shown in Figure 17 and Figure 18. In particular, Figure 17 reports the required battery mass values, and Figure 18 reports the take-off weight values, inside the pax-range diagrams. What can be observed is that, as the BED decreases, the amount of batteries required to satisfy the mission phases assigned to electrical power increases. This increase in mass leads to the saturation of the MTOW for missions with smaller pax-ranges couples than the reference with BED equal to 500 Wh/kg. In other words, the gradual reduction of BED implies a gradual contraction of the aircraft's feasible mission envelope, and therefore penalisations on its operating performance. These penalisations still seem to be acceptable for BED values of 400 Wh/kg, whereas they may be inhibiting for the effective introduction of such a hybrid aircraft for values of 200 Wh/kg. However, it is interesting to note that, although limited to local air quality issues, there are feasible solutions even with BED values corresponding to those currently achievable.

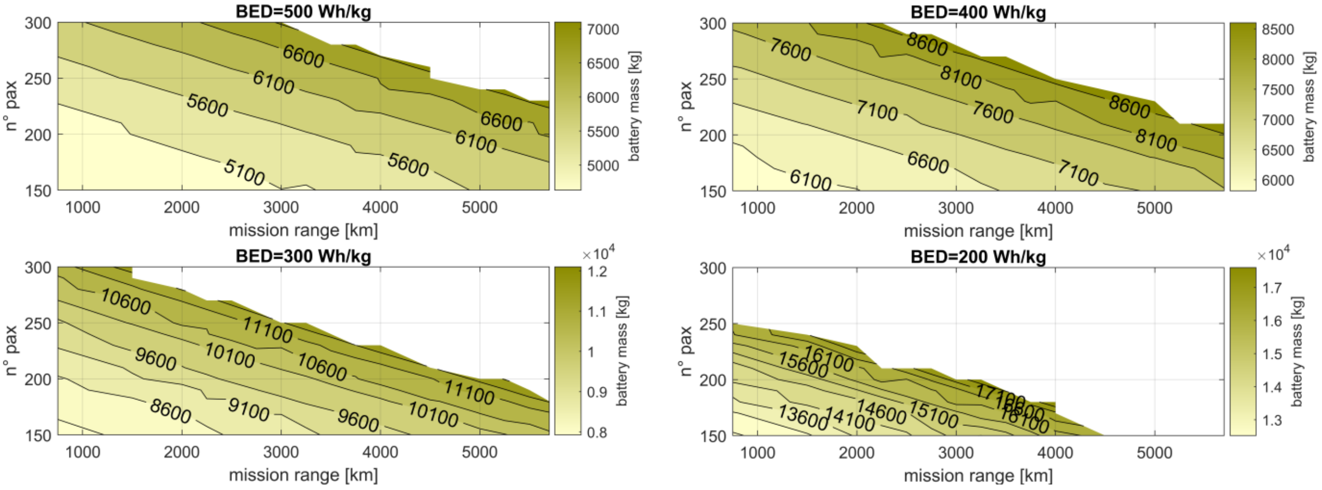

Figure 17 - Battery mass maps inside the pax-range envelope varying BED

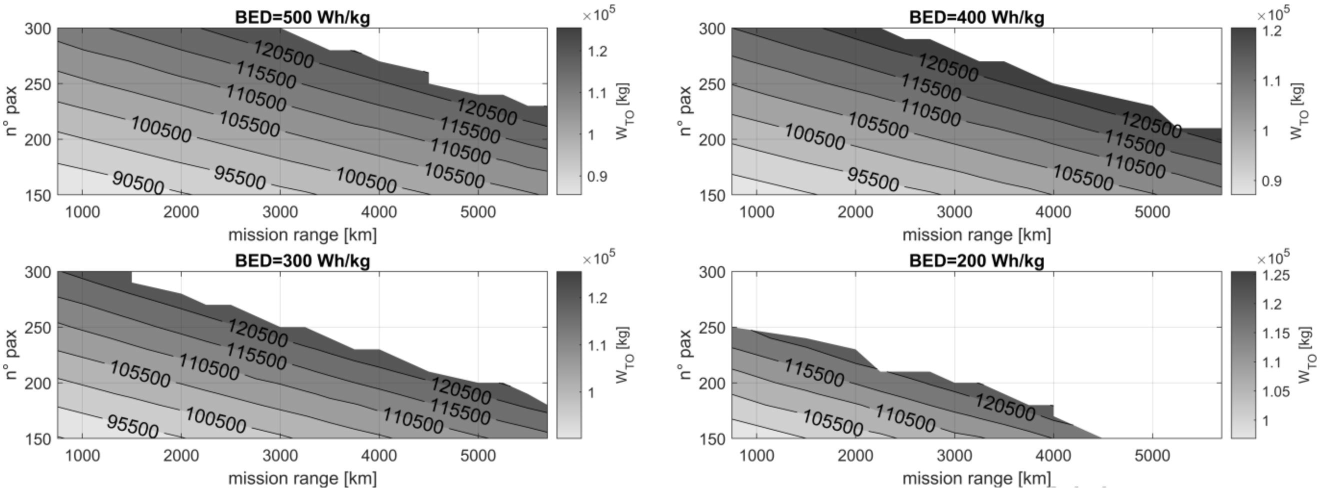

Figure 18 – Take-off weight maps inside the pax-range envelope varying BED

4.2 Design strategy towards the reduction of greenhouse emissions

In this section, the results of the design of box-wing aircraft with hybrid-electric propulsion are reported and discussed. The design procedure differs substantially from the retrofitting procedure, since in this latter the aircraft shape is kept frozen, and therefore the lifting system is the same of the baseline aircraft; in the design procedure, instead, the lifting system is designed for each configuration evaluated. Furthermore, in the case of retrofit, the empty operating weight breakdown is unvaried, with the only exception of the propulsion system and internal furnishings, whereas in the design procedure the weight of each component is computed for each aircraft configuration.

As described in Section 3.3.3, the design and integration of the hybrid-electric propulsion of the box-wing aircraft has been carried out using an optimisation procedure; the design variables chosen are: the wing loading (W/S), the hybridisation factor of the installed power (H_P), the thermal share of the supplied power in climb ($\Phi_{ice\ CL}$), cruise ($\Phi_{ice\ CR}$), and descent ($\Phi_{ice\ DE}$). The wing loading design variable, in addition of being of primary relevance to define the matching chart, and thus to size the propulsion system, has been also used to re-scale the geometry of each configuration evaluated during the optimisation procedure. Indeed, to avoid increasing the complexity of the optimisation procedure by introducing also the geometrical parameters of the box-wing as design variables, the geometry of the baseline aircraft has been homothetically scaled (see Figure 19), by using the wing loading as a scaling factor to re-size the wing area starting from the take-off weight estimation provided by THEA-CODE. This approximation is useful in this conceptual exploration phase to reduce computation time, while maintaining a lifting system derived from the baseline configuration, and therefore with good aerodynamic characteristics. For future development, it is however necessary to design each configuration by means of dedicated aerodynamic analyses with different levels of fidelity, such as those performed for the box-wing aircraft developed in the PARSIFAL project [58][59][60]. This is particularly required to obtain configurations that meet aeromechanical requirements on stability and trim in the longitudinal plane, as discussed in detail in [48][51].

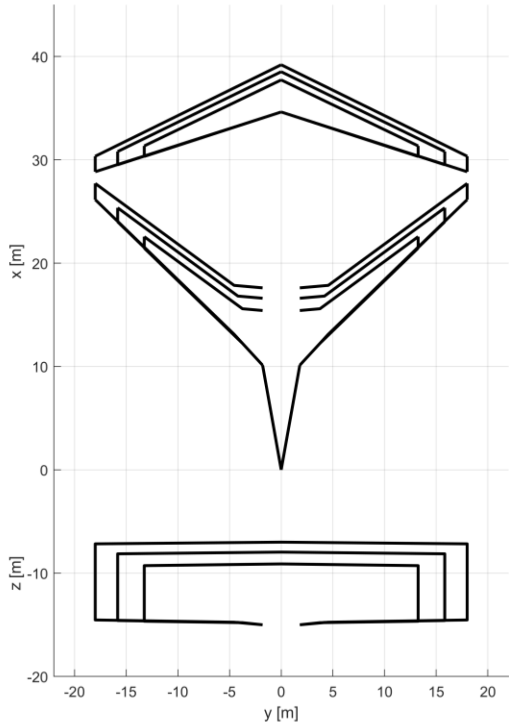

Figure 19 – Examples of scaled box-wing geometries

To obtain a sufficiently detailed overview at this conceptual exploration stage, different optimisations have been performed as the specification inputs varied. In particular, configurations with a number of passengers of 150, 200, 250, 300 have been evaluated and design routes of 1000, 2000, 3000, and 4000 km have been considered. The objective function to be minimized is the block fuel. In addition, in order to evaluate only configurations with effective integration of a quota of electric propulsion, the design variable relative to H_P has been set strictly larger than zero ($H_P > 0$). The power management strategy adopted in this case is described in Section 3.3.3. An additional case with $H_P=0$, i.e. the assessment of the box-wing aircraft with only thermal power at different payload and range, has been done with the same design methodology, and the results have been used to make performance comparisons with the corresponding hybrid-electric configurations.

To better understand the results of the optimization, first a comparison between the outcomes of the optimal hybrid-electric configurations and the thermal ones is proposed. Figure 20-left shows the percentage variations of MTOW and block fuel between the hybrid-electric and the full-thermal configurations, whereas Figure 20-right shows the comparison in terms of absolute values. From Figure 20-left, it emerges that the integration of hybrid propulsion leads to block fuel reduction only for short ranges, around the value of 1000 km. In such case, a larger percentage increase of the MTOW is associated, suggesting that to achieve the goal of reducing block fuel it is necessary to embark a large quantity of batteries. The advantage of block fuel reduction rapidly disappears with the increase of range, for all the values of payload considered. The hybridization of the propulsion leads to an increase in block fuel up to the 15% when the design range reaches the value of 4000 km. These results highlights that, with the current forecast on the battery technology level, introducing the hybrid-electric propulsion in medium range aircraft does not provide the expected advantages; on the contrary, it provides increases in fuel consumption with respect to a conventional thermal competitor if typical medium-haul routes are considered. Moreover, although fuel reduction is achieved for ranges as short as 1000 km, the quantitative improvements are too small (<200 kg, see Figure 20-right) to have an impact on the reduction of aviation greenhouse gas emissions.

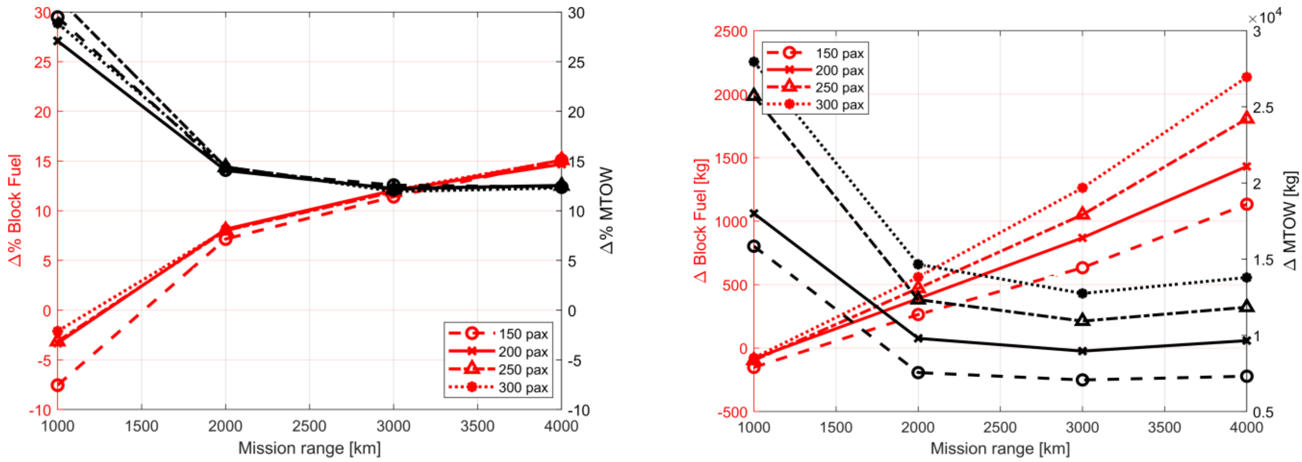

Figure 20 – MTOW and block fuel comparison between the hybrid-electric and the full-thermal configurations: percentage variation (left), absolute difference (right)

The comparison between the optimal hybrid-electric configurations and the thermal ones in terms of absolute values of MTOW and block fuel is depicted in Figure 21.

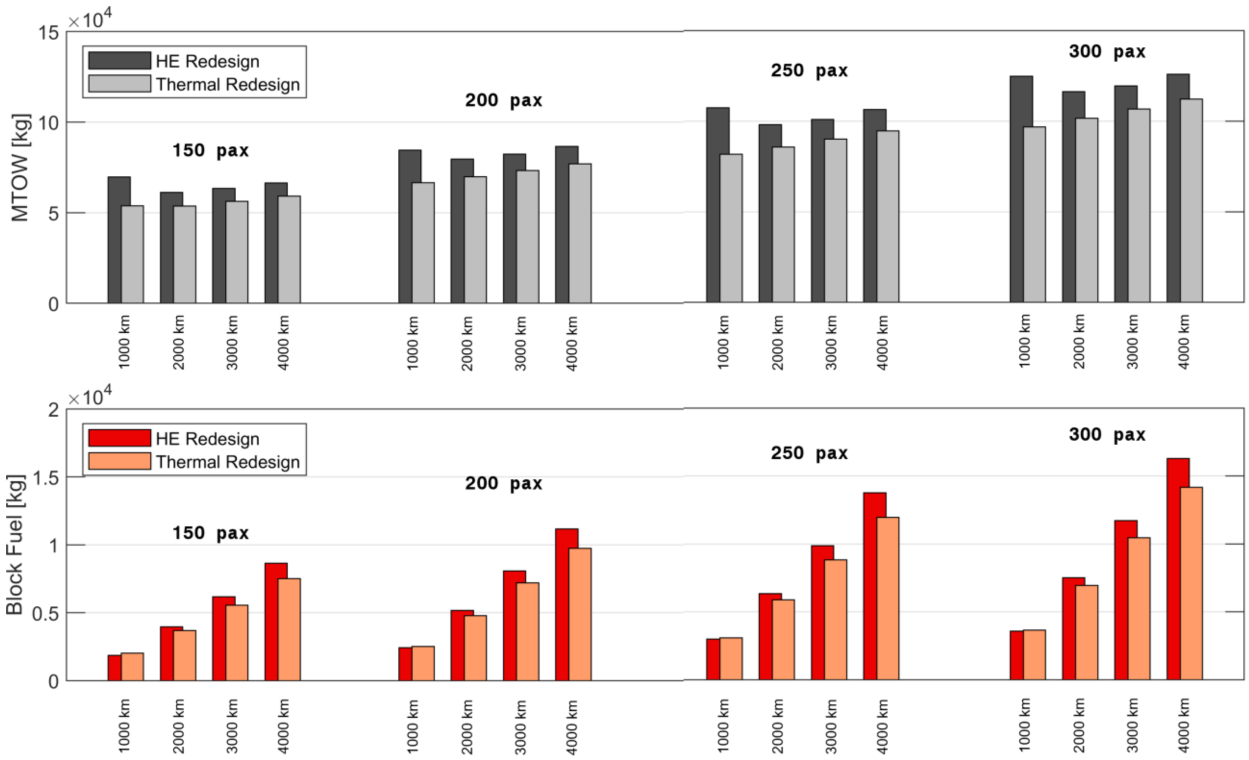

Figure 21 – MTOW and block fuel comparison between hybrid-electric and full-thermal configurations with different payload and range requirements: MTOW (top), block fuel (bottom)

Figure 22 and Figure 23 show the main outcomes from the optimization of hybrid-electric configurations. The following aspects are worth to be underlined:

- looking at battery mass values in Figure 22, it can be seen that the larger battery amount is present for the cases with range equal to 1000 km; this indicates that only for missions at lowest ranges, and therefore with lower energy demand, the increase in mass due to the batteries and electric power systems is still worthy of a reduction in block fuel;
- as Figure 23 shows, apart from the share of electrical energy required for ground operations (that are not design variables), the optimizer looks for solutions in which electric power is used primarily in climb.
- from Figure 23, it is observed that the optimal solutions exhibit almost zero electric power

supply in the cruise phase. Since this phase is the most energy demanding, and considering the technological level adopted for the batteries, using electric power in cruise would result in such detrimental weight increases that there would be no benefit in terms of block fuel minimization;

- Descent is practically irrelevant in the overall energy breakdown (Figure 23).

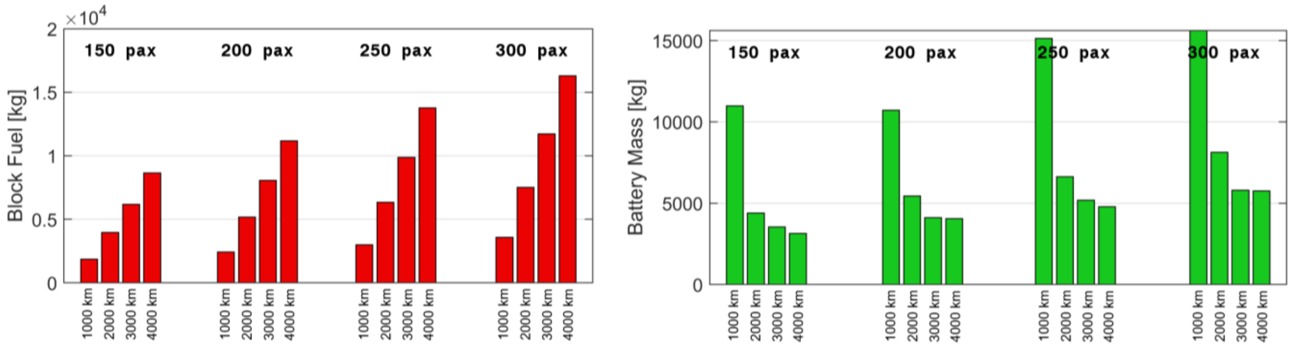

Figure 22 – Main outcomes from the optimization procedure with different payload and range requirements: block fuel (left), battery mass (right)

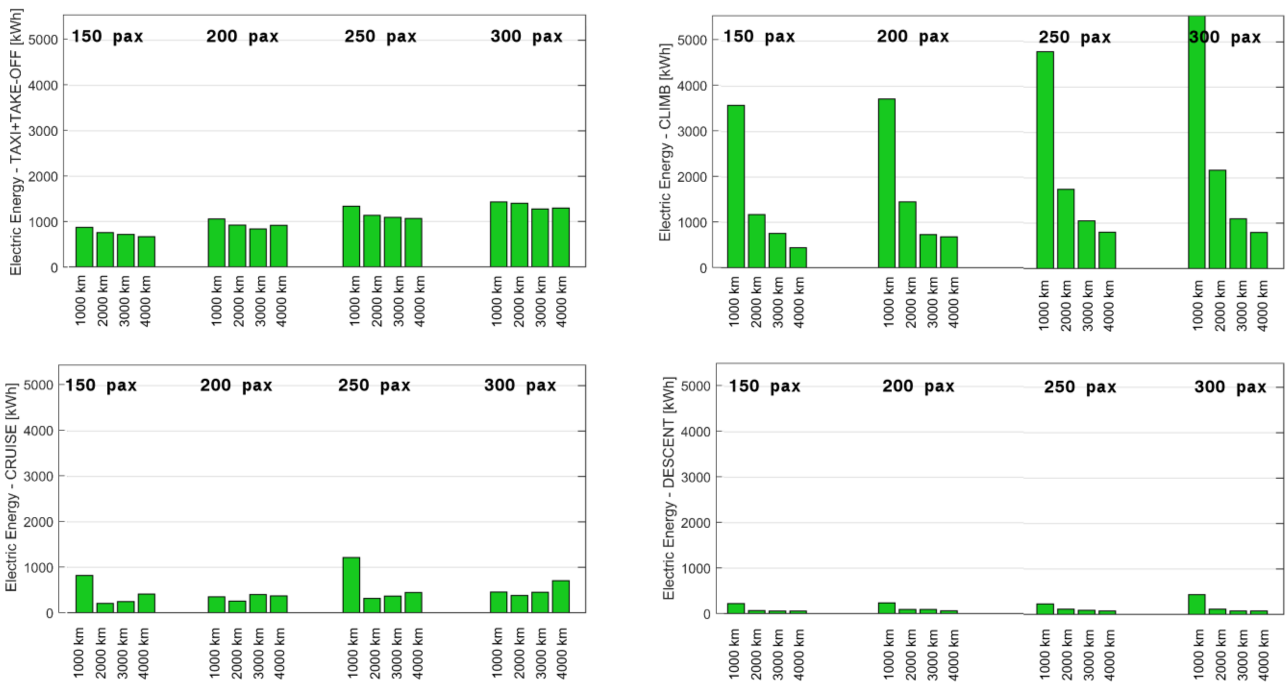

Figure 23 – Energy from batteries necessary for each phase of the mission for the optima configurations with different payload and range requirements: taxing and take-off (top-left), climb (top-right), cruise (bottom-left), descent (bottom-right)

As summary, the only case where a block fuel advantage is obtained for hybridized aircraft lies in the case with range equal to 1000 km, for all the four payload evaluated. However, the gain with respect the thermal configurations turns out to be significantly limited to reasonably have no practical significance in reducing aviation's impact on climate change, and thus power hybridization is not valid of actual application in these conditions.

4.2.1 Sensitivity to battery energy density

With the only purpose of investigating trends and sensitivities, the same previous study has been carried out with a higher value of battery energy density, moving from 500 Wh/kg to 1000 Wh/kg. Although many conceptual studies on hybrid-electric propulsion integration on transport aircraft use this latter value -or higher- as a possible reference ([61][62][63][64]), specialized technical research in the field is more cautious and definitely less optimistic. Indeed, predictions made by [4], tend to set the actual maximum energy densities achievable in the coming decades at values not exceeding 500 Wh/kg. Therefore, the use at this stage of higher BED values, is done purely for theoretical purposes, to assess whether there are actually benefits for medium-range aircraft, at all for very optimistic values of the battery technology used.

The graphs in Figure 24 show the comparison of the optimal configurations found with BED of 500 and 1000 Wh/kg, respectively. As might be expected, the configurations with BED=1000 Wh/kg show better performance in terms of block fuel. In percentage terms, the improvement is substantial for configurations with 1000 km range, for each passenger class considered. In these cases, configurations with BED=1000 Wh/kg manage to lower mission fuel consumption, at the expense of higher battery load and thus higher MTOW. Improvements are significantly more limited for higher range cases. In particular, for the 3000 km and 4000 km cases, the optimizer finds the same split and power supply strategies for the two BED levels considered. In particular, no solutions are found with relevant electric power utilization in the cruise phase, whereas a part of the electric power is supplied in the climb phase. A totally different scenario there is for the 2000 km case. In this case, with the 1000 Wh/kg batteries, the optimizer manages to find solutions that do not diverge in weights, whereas using a share of the electric power in cruise. However, such solutions introduce a huge increase in the mass of batteries on board, and thus of the MTOW, and consequently need massive installed power on board (Figure 24).

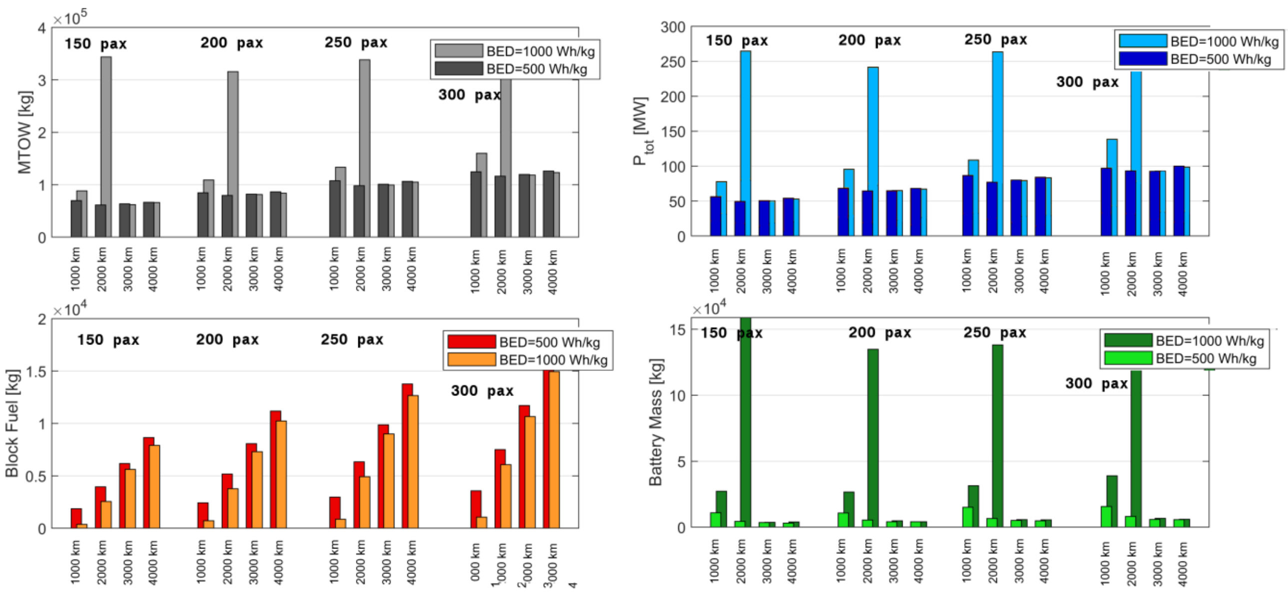

Figure 24 – Main outcomes from the optimization procedure for different payload and range requirements and different battery energy densities BED: MTOW (top-left), installed power (top-right), block fuel (bottom-left), battery mass (bottom-right)

Figure 25 shows the comparison between the optimal configurations with BED=1000 Wh/kg and the corresponding full-thermal configurations. A favourable percentage of block-fuel reduction is evident only for short routes (1000 km), whereas for routes above 3000 km there is no improvement. A slight improvement is detectable for cases at 2000 km, however, the huge increase in take-off weight and installed power makes it practically self-defeating the electric power integration.

In the end, even assuming a highly optimistic development of the level of battery technology, the integration of electric propulsion for aircraft with characteristics compatible with the medium-range market seems not to be a technically significant way to drastically reduce the greenhouse emissions of transport aviation.

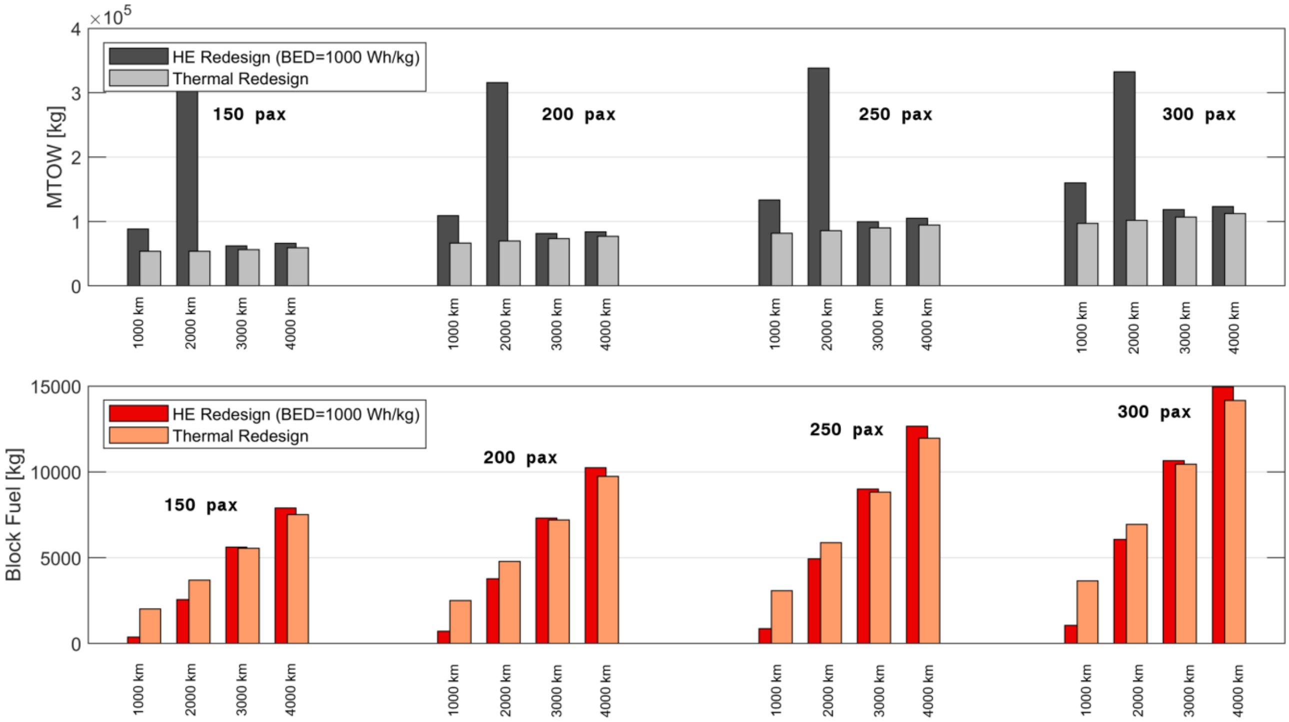

Figure 25 – MTOW and block fuel comparison between hybrid-electric for BED = 1000 Wh/kg and full-thermal configurations: MTOW (top), block fuel (bottom)

5. Conclusions

In this paper, the conceptual study of the integration of hybrid-electric propulsion on a box-wing medium-range transport aircraft has been addressed. The box-wing architecture has been selected on the basis of the promising results available in literature on the performance potential of this design; in particular, such a lifting configuration can carry higher weights than a conventional aircraft, without penalties in terms of size, and with advantages in aerodynamic performance and fuel consumption. The main purpose of this study is to evaluate the impact of hybrid-electric propulsion on the mitigation of pollution produced by transport aviation. The main results obtained are:

- Hybrid-electric propulsion appears as an effective solution to tackle the problem of the degradation of air quality in airport areas. This problem is related to the pollutant emissions produced by aircraft during taxiing, take-off, climb-out and approach (LTO cycle), and can be eliminated through the appropriate integration of a share of electrical power on board. Specifically, electrical powertrain must be sized to meet the power required for the LTO cycle, whereas thermal power is used in the other phases. In this way, the use of thermal engines in areas close to the ground is avoided, and pollutant emissions that deteriorate local air quality are suppressed.
- Hybrid-electric propulsion does not emerge as an effective solution for reducing greenhouse emissions coming from medium-range aircraft, and thus seems to have no potential for mitigating the climate-changing impact of transport aviation. This is mainly attributed to the low energy density of batteries, which does not allow the design of hybrid-electric aircraft with significant fuel savings in typical short-medium haul routes. Even considering the most optimistic forecasts for future battery technology development, it is evidenced that the use of hybrid-electric propulsion can only have a marginal impact on reducing greenhouse emissions.

This study, hence, indicates that alternative solutions to hybrid-electric propulsion must be explored to address the impact of transport aviation on climate change. New energy sources or new propulsion technologies capable of drastically reduce greenhouse emissions must be developed for medium-haul transport aircraft class. On the other hand, the problem of local air quality in airport areas can be addressed with the use of electric power.

The results of this research, therefore, open up the field for the development of a new type of hybrid propulsion; the benefits of electric propulsion can be utilised for LTO operations, whereas for the reduction of greenhouse emissions, the thermal part must exploit fuels that are climate-friendly compared to conventional kerosene. Among these, there is hydrogen, which has the potential to totally eliminate CO_2 emissions. The PrandtlPlane configuration used as a reference in this study, due to its large internal volume availability, can be suitable for the development of a new hybrid, electric-hydrogen, propulsion system, in which the electric power is used to eliminate pollutants in airport areas, whereas the hydrogen-based propulsion has the potential to be a real solution to tackle the climate-changing impact of aviation.

In addition, further investigation into the influence of airframe architecture can be central in the study of breakthrough solutions to reduce the pollutant impact of aviation. Starting from conceptual studies such as the one presented in this paper, it is possible to develop design and performance analysis frameworks that can evaluate and compare the effects of integrating different types of propulsion with different types of airframes.

Copyright Statement

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