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REGULAR PAPER

Environmental and techno-economic evaluation for hybrid-electric propulsion architectures

C.P. Nasoulis*, G. Protopapadakis, E.G. Ntouvelos, V.G. Gkoutzamanis and A.I. Kalfas

Laboratory of Fluid Mechanics and Turbomachinery, Department of Mechanical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
*Corresponding author. Email: nasoulic@meng.auth.gr

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Abstract
Hybrid-electric propulsion is a promising alternative to sustainable aviation and is mainly considered for the commuter and regional aircraft class. However, the development of hybrid-electric propulsion variants is affected by the technology readiness level of electric components. The components' technology will determine the electrification benefit, compared to a conventional aircraft, and will suggest which is the most beneficial variant and which has a closer entry into service date. Within this work, three different dates are explored, namely 2027, 2030 and 2040, to size three Parallel and three Series hybrid-electric architecture variants using an in-house aircraft sizing tool. All variants are compared to a conventional configuration sized using technological assumptions of 2014, with the main comparison metrics being the aircraft block fuel, energy consumption, direct operating cost and holistic environmental impact. On one hand, the Parallel configurations have reduced maximum take-off mass and mission energy consumption compared to the Series, however, the latter show a greater potential for block fuel reduction and require less onboard energy for the same mission. The annual operating cost evaluation indicates that the Parallel hybrid variant of 2030 has greater operational costs than the respective Series variant; however, it has reduced capital costs compared to the latter, making it more economical to operate considering both costs. Additionally, in the case of an energy recession, both hybrid variants of 2030 show a further cost reduction, with the Series having a total reduction of 10.4% excluding capital costs, compared to the reference aircraft. Moreover, the life cycle assessment shows that the Series variants have a lower environmental impact, both compared to the reference aircraft and the Parallel variants. The former could be up to 59.7% less detrimental to the environment than the reference aircraft, whereas the latter up to 23.9%, with the integration of renewable sources for electricity production. Finally, by the year 2040, the Series variant shows outstanding performance in all comparison metrics, compared to the Parallel and the reference aircraft.

Nomenclature

AECEF	aircraft energy conversion efficiency factor
AEO	all engines operating
DOC	direct operating cost
DoH	degree of hybridisation
EIS	entry into service
LCA	life cycle assessment
LTO	landing and take-off
MTOE	million tonnes of oil equivalent
MTOM	maximum take-off mass
OEI	one engine inoperative
OEM	operating empty mass
SFC	specific fuel consumption
SoC	state of charge

TLAR	top-level aircraft requirements
TRL	technology readiness level

1.0 Introduction

In 2019, 8.6% of the global oil consumption was caused by the aviation sector, translating to approximately 347 million tonnes of oil equivalent (MTOE), according to "Key World Energy Statistics 2021" [1], a value 3.3% greate compared to 2018, and 7.5% greater compared to 2017 [2, 3]. In addition, when compared to 1973, the aviation sector oil consumption has increased over 180% [1]. All things considered, a sustained increase in the need for air transportation is evident, with a simultaneous environmental challenge, taking into account the oil demand increase. This increase has a substantial environmental impact, therefore strict emissions-oriented regulations began to emerge in the past years, dictating up to 50% and 80% reduction in carbon dioxide and nitrous oxides emissions respectively, by the year 2020, compared to 2000 [4]. In addition, these goals are becoming stricter when it comes to "Flightpath 2050" [5], underlining the need for novel propulsion systems development. Said that, aircraft electrification is an ongoing endeavor with promising environmental benefits, compared to conventional aircraft configurations.

Considering the technological advancements of batteries [6], the benefits of aircraft electrification are currently limited to small aircraft classes, like unmanned aerial vehicles (UAVs) and general aviation (GA) aircraft, due to their reduced power demand, with electric concepts already in service [7]. Considering that the previous aircraft classes have already shown significant benefits in terms of block fuel reduction [8], the next class that should be hybridised is the commuter class [9–12], whereas effort has been put in the direction of regional aircraft as well [7]. Apart from block fuel and energy consumption evaluation, there are several aspects that should be included in the hybrid-electric propulsion assessment, to determine the potential benefit of aircraft electrification compared to conventional configurations, like direct operating cost (DOC) and life cycle assessment (LCA). Considering DOC, there are several methodologies to assess the economic feasibility of propulsive units [13–15], but there is a lack of assessment for smaller aircraft categories, such as the commuter aircraft (19-seater), especially if novel propulsive architectures are considered. Moreover, for the aircraft environmental impact evaluation, previous works indicated that the main contributor to the LCA is aircraft operation [10, 15]. However, aircraft electrification brings new challenges and raises new research questions about the subject [16]. The impact of batteries and electric powertrain integration on the overall aircraft environmental score must be explored. Additionally, various hybrid-electric configurations must be considered to determine the most environmentally friendly variant and finally, a comparison must be made to determine if hybrid-electric aircraft is a better candidate than conventional aircraft in terms of environmental impact.

Towards this direction, this work aims to investigate the impact of technology readiness level (TRL) of critical powertrain components on the design of hybrid-electric architecture variants. Two hybrid-propulsion systems are examined, namely the Parallel and the Series configurations, and three aircraft are sized for each configuration, considering different entry into service (EIS) dates, one for each date. Then their key performance metrics, namely fuel and energy consumption, are compared to a conventional configuration with an EIS date of 2014. In addition, the DOC evaluation and the LCA for each aircraft are performed and compared to the reference aircraft to determine if an optimum configuration exists or to explore possible trade-offs between designs.

2.0 Methodology

2.1 Top-level aircraft requirements

The top-level aircraft requirements (TLAR) are selected according to the authors' previous work described in [11] and the mission profile used for the design evaluation is a simple mission profile

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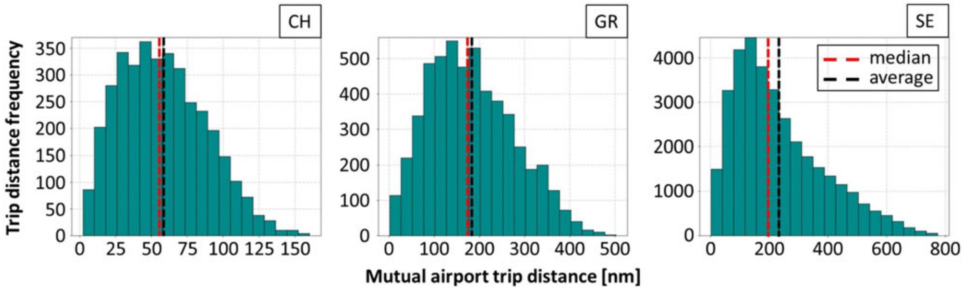

Figure 1. *Mutual airport distance distribution in Switzerland, Greece, and Sweden for a point-to-point network.*

including a diversion mission. The design range is 400nm with an additional 100nm of reserves, cruising altitude is at 10,000ft for both all engines operating (AEO) and one engine inoperative (OEI) cases, cruise speed is 235 KTAS (0.35 M), and 30 min of loiter time are considered. Both conventional and hybrid aircraft follow the same TLAR, are sized for the same mission profile, and the powertrain units are sized for the OEI case. The maximum passenger number for a Level 4, CS-23 certified, normal-category aircraft is 19, [17] while the maximum payload capacity is selected to be $1,900kg$, considering 100kg per passenger (87kg per person, and 13kg carry-on luggage) [11].

The maximum range selection is a result of an airport network study, considering possible operating markets in European countries. Three countries were selected to consider several country shapes, i.e. Greece, Sweden and Switzerland. Greece has large island complexes with small airports and the mainland is at the tip of the Balkan peninsula. Sweden has a longitudinal axis almost three times the latitudinal, and Switzerland is small, almost square, but with the Alps posing flight altitude restrictions. With the global coordinates of the aerodromes placed on the map for all three countries, their mutual distance is calculated, following a point-to-point mission strategy, using the haversine formula. The mutual airport distance distribution for all three countries is shown in Fig. 1, with the average and median distance marked. By observing Table 1, the maximum average airport distance appears in Sweden, as it's the largest country of the three. However, when compared to the average airport mutual distance in Greece, it is only 20% greater, considering that Greece has less than one-third of Sweden's area, but many airports are scattered in island complexes. Furthermore, the coverage rate for various mission ranges is calculated and shown in Table 1, namely for the 300, 400 and 600 nm cases. It appears that for a mission range of 600 nm, the coverage rate reaches 100% for Greece and Switzerland and 97.6% for Sweden, whereas when a range of 400 nm is selected, the coverage rate remains almost unaffected for Greece and Switzerland but is reduced to 85.3% for the case of Sweden. However, since the majority of Sweden's airports are located in the southern half of the country, the 85% coverage rate is considered acceptable, and the mission range of 400 nm is selected. Additionally, an extra 100 nm of reserves range is considered for redundancy purposes in the design, which can be utilised in the case of Sweden to increase the coverage rate.

2.2 Aircraft powertrain requirements

The Parallel hybrid configuration consists of two electrically boosted turboprop engines, whereas the Series hybrid consists of four propellers connected to four electric motors, as shown in Fig. 2. A turboshaft engine is located aft of the Series aircraft configuration, which is coupled to an electric generator able to either charge the batteries or provide power directly to the electric motors. The power output of the gas generator is selected according to the aircraft operating modes, which will be described in the following paragraph.

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Table 1. *Coverage rates for different mission ranges in Greece, Sweden, and Switzerland*

Country	≤300nm	≤400nm	≤600nm	Average distance nm
GR	87.55%	99.16%	100%	183
SE	72.15%	85.35%	97.59%	232
CH	100%	100%	100%	58

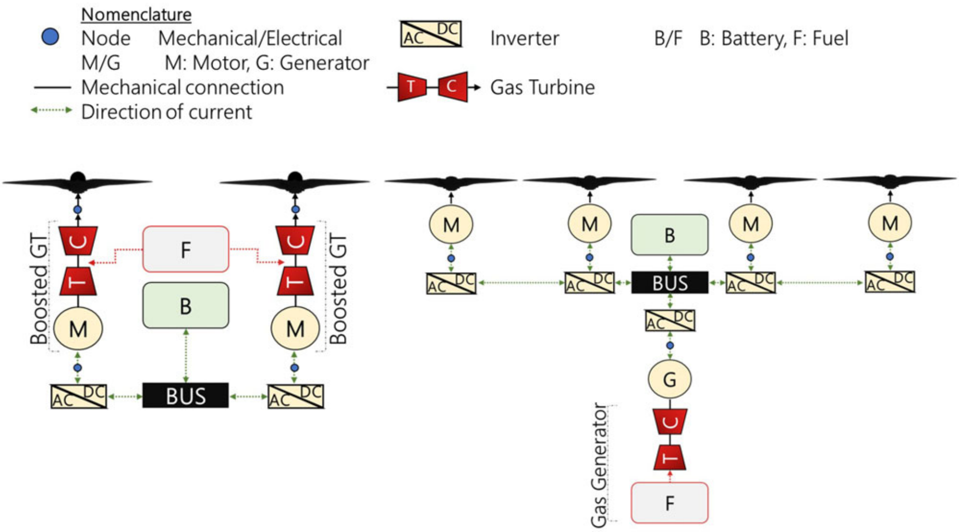

Figure 2. *Parallel (left) and Series (right) hybrid-electric propulsion configurations.*

The Parallel configuration operates as conventional during ground operations, descend and approach phases, whereas it operates in hybrid mode in all other phases, as observed in Fig. 3. Additionally, onboard charging is not possible, due to the powertrain architecture (Fig. 2). Furthermore, the Series hybrid configuration operates in electric mode during ground operations, in conventional mode during descend, approach and loiter phases, and in hybrid mode during the rest. The Series architecture enables onboard charging during all conventional operating modes in which the gas generator's available power exceeds the mission segment power requirement. The power output of the gas generator is defined by the loiter mission segment, as it is the most demanding phase of which the aircraft operates in conventional mode. Moreover, to prolong the battery life, the charging current is limited to $C/3$ of the selected batteries' C-rating, and the maximum charging power is calculated using that current limit. The power management strategy selected for each propulsion architecture aims to maximise the contribution of the electric motors and batteries to the overall thrust production while maintaining a battery state of charge of at least 20% at the end of the mission, for battery preservation and safety reasons.

Considering the state of the art of electrical components, three different EIS dates are explored and presented in Table 2. A different battery type is considered for each EIS date, based on their current TRL [9], namely Solid State LI-ion batteries, Li-Sulfur and Li-Air, for 2027, 2030 and 2040, respectively. Each battery technology promises a different gravimetric specific energy at cell level that ranges from $350 - 1,050$Wh/kg. However, the cell-level specific energy must be translated into pack-level specific energy, prior to estimating the total amount of batteries required in a hybrid-electric aircraft. In that direction, the mass of the accumulator container, cooling system and electronics must be accounted for, in the overall battery system mass calculation. The electronics and the electronic auxiliaries masses

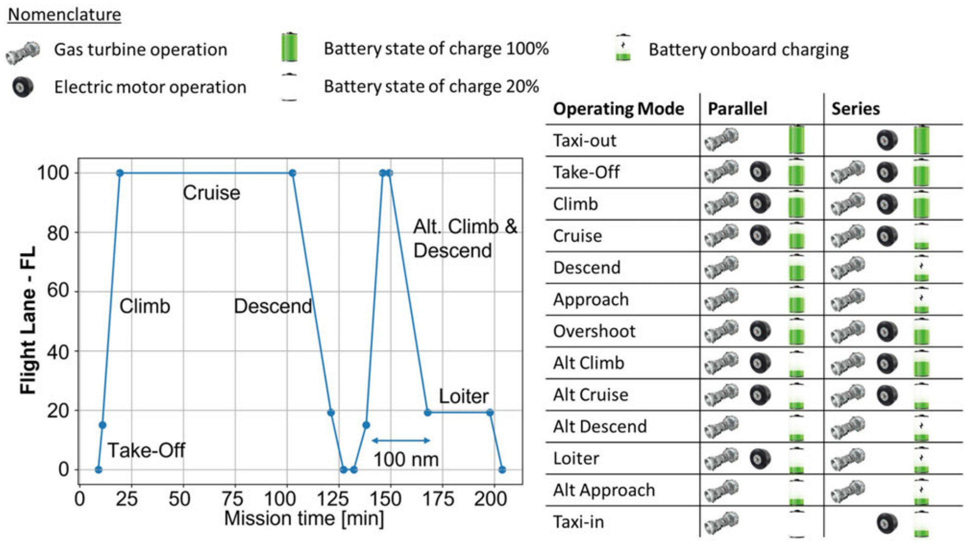

Figure 3. *Design mission profile definition (left) and hybrid-electric operational modes (right).*

are estimated empirically, whereas the container mass is calculated as a function of battery cells dimensions, and finally, the cooling system dimensions and mass are calculated analytically [18]. Moreover, a remaining state of charge (SoC) of 20% at the end of each mission is considered for safety reasons and to prolong battery life. Finally, the battery end-of-life threshold is set at 80% of its initial capacity.

The specific power of electric motors and power electronics is selected in relevance to the work of Nasoulis et al. [11] and Jansen et al. [19], respectively, and is adjusted for the different EIS dates. The motors specific power examined in the timescale of 2027–2040 ranges from 6 to 16 kW/kg, considering that today's electric motors have a specific power of 5 kW/kg[1] (calculated for the maximum continuous power), whereas research suggests that this metric can reach up to 16 kW/kg for a partially superconducting wound field synchronous motor [19, 20]. In order to achieve motors with high specific power, research indicates that a higher number of pole counts, moderate shear stress and higher rotational speed are some of the advancements required, as specific power has a declining trend with power increase [21–23]. A more detailed analysis and review of the state-of-the-art, TRL and scalability challenges on electric propulsion components can be found in [9, 11, 24]. Finally, the gas turbine used in the reference aircraft shows similar efficiency and fuel consumption to PT6A-67D turboprop engine [25], whereas the gas turbines used in the hybrid-electric configurations are based on the reference, assuming a specific fuel consumption (SFC) reduction ranging from 8% to 27% for the various EIS dates. The power management strategy and the hybrid-electric operational modes presented in Fig. 3 are maintained for the examined EIS dates, to focus on the impact of technological improvements on hybrid aircraft design.

2.3 Aircraft sizing

For aircraft sizing, an in-house tool is used, developed to size novel aircraft designs, using unconventional propulsion units, such as hybrid-electric propulsion [11]. This model follows a component build-up method to apply a weight-based aircraft sizing approach, that captures the impact of aircraft dimensions on the maximum take-off mass, and vice-versa. This implicit connection allows capturing the impact of the additional propulsive components mass, i.e. electric motors, batteries, etc., on aircraft mass and dimensions, allowing for a clean sheet design, rather than a retrofit approach. Then, the actual

[1] https://emrax.com/e-motors/emrax-348/

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Table 2. Electric powertrain system characteristics for the different entry into service dates

Entry into service date	2027	2030	2040
Battery type	Solid State Li	Li-Sulfur	Li-Air
Cell level specific energy [Wh/kg]	350–450	650–750	950–1050
Pack level specific energy [Wh/kg]	195–255	365–420	535–590
Specific power [W/kg]	550–650	650–750	850–950
Nominal voltage [V]	705	1,050	1,320
Maximum voltage [V]	800	1,200	1,500
Specific power (electronics) [kW/kg]	9–11	17–19	24–26
Specific power (motors) [kW/kg]	6–8	9–11	14–16
Gas turbine SFC reduction [%]	(−8, −12)	(−18, −22)	(−23, −27)

block fuel requirement for the mission is calculated, using a modified Breguet equation that integrates the electric propulsion system through the definition of the power-level degree of hybridisation (DoH) for each mission phase. The power-level DoH is defined as the ratio of the electric power (EL) to the summation of the thermal power (TH) and electric power (EL), at any given mission phase, as shown in Equation (1). The aircraft's energy-level DoH is calculated as the ratio of battery energy (Bat) to the total onboard energy (fuel and batteries). Finally, the aircraft sizing tool is linked to the DOC and LCAevaluation tools.

$$H_P = \frac{P_{EL,i}}{P_{EL,i} + P_{TH,i}}, H_E = \frac{E_{Bat}}{E_{Fuel} + E_{Bat}} \tag{1}$$

2.4 Direct operating cost

The present method for the calculation of aircraft DOC follows the guidelines set by the work of Hoelzen et al. [26] where the DOC and capital costs for a 70-passenger hybrid-electric regional aircraft are calculated, and it is modified accordingly to fit smaller aircraft class like the commuter. The modifications mainly focus on the tuning of the equations' constants, to scale the formulae for smaller aircraft. The present model calculates the DOC requiring data, such as aircraft sizing parameters, and energy and aircraft manufacturing pricing, as shown in Fig. 4. The aircraft sizing parameters are classified into airframe parameters, namely maximum take-off, operating empty mass, wing span, etc., propulsion parameters, like maximum power output and propulsion system mass, etc., and mission parameters, such as block fuel, batteries energy, mission range, etc. The DOC calculation includes key cost indicators, such as energy cost per flight (both fuel and batteries), maintenance expenses, operational fees (crew, airport, and traffic control), as well as capital costs.

The total DOC is a function of energy, maintenance, crew and fees costs, whereas the annual capital cost is calculated separately. That is because the annual capital cost is higher during the first years of the depreciation period, whereas all other costs remain constant through that period. The capital costs include the aircraft and onboard batteries costs, and for the aircraft capital costs, the gas turbine, electric motors, motor controllers and airframe costs are considered. The gas turbine cost is calculated to be 543 €/kW for a turboprop engine similar to PT6A-67D[2,3], therefore a range of 500-600 €/kW is selected for the analysis. For the airframe cost, the Beechcraft 1900D is used as a reference, considering its price when sold new in 1991 [27], which is then realised to include USD to euro exchange rates, inflation and increased material costs, due to the integration of composite materials in the structure, especially for the years 2030 and 2040. As a result, a range between 1,400 and 1,600 €/kg is selected in the present analysis. The electric motor and motor controller costs are derived from Hoelzen [26],

[2] https://www.easa.europa.eu/en/downloads/7787/en
[3] https://www.pwc.ca/en/landing-pages-folder/pt6a-smart-solutions

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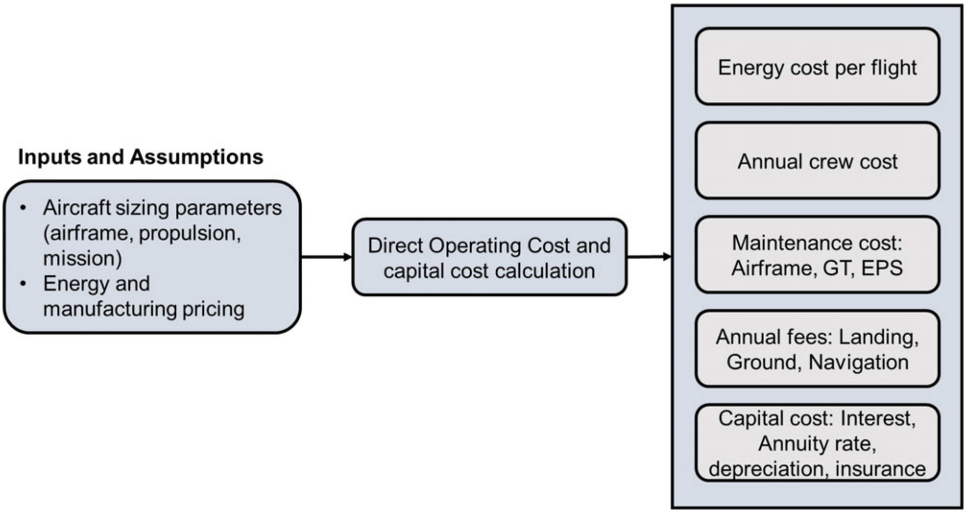

Figure 4. *Direct operating costs and capital costs computational pipeline overview.*

and a range of 120–180 €/kW for the motors and 50–100 €/kW for the inverters is selected herein respectively. On the other hand, for the batteries' capital costs, three battery packs are considered per aircraft, with a lifetime of 1,500 cycles per pack. The battery cost per kWh is selected to be in the range of 130–170 €/kWh[4], taking into account that the batteries price may rise in the future, in case of increased demand. The depreciation cost of the initial investment is calculated using the annuity rate, which requires depreciation rate, interest rate and residual value factors as inputs. These values were also selected to be in harmony with the work of Hoelzen et al. [26] A different depreciation period is selected for batteries; therefore, a second annuity rate is calculated, and the batteries' depreciation rate is considered a function of their lifetime.

Energy costs can fluctuate during the depreciation period, according to the energy market price, both for fuel and electricity production; therefore, a sensitivity analysis for fuel and electricity prices fluctuation will be presented in the results section. Maintenance costs include airframe materials, propulsive system, technology and labor costs. Airframe materials are related to the aircraft's block time and a fixed repair cost per flight [28]. The labor cost is assumed constant for all examined configurations and engine maintenance costs are expressed using the maximum power requirement and V_1 velocity at take-off condition, as it is the most critical engine loading condition. Finally, the technology cost is considered a function of the aircraft's basic dimensions, i.e. wingspan and fuselage length, and it is compensated by the airlines for fleet maintenance. The annual fees costs include air traffic management and airport costs and can be categorised into ground operation, navigation and landing fees.

2.5 Environmental impact assessment

In this section, the methodology for adapting the classical LCA to account for novel propulsion systems, such as hybrid-electric propulsion, is discussed as means to answer the research questions posed in the Introduction section. The model is based on the work of Johanning et al. [30] and is adapted accordingly to evaluate the environmental impact of hybrid-electric aircraft that is still in the conceptual design phase.

The approach is based on ISO 14040:2006, where the inventory must be described and then its impact can be calculated [31]. The inventory analysis assessment is the first step and includes all aircraft

[4]https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/

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life phases, namely the aircraft design and development, production, operation of aircraft, and finally the end-of-life. However, material information, engine emissions, information about different process types, etc., are difficult to be known a priori. Commercial and non-open access databases exist, such as Ecoinvent 3 [32], that can be used to assess the impact of the above; however, for the scope of this study, a more conservative approach is followed. The level of detail for each life phase is limited to the extent of databases found in the open literature, for aircraft production and operation [30].

$$x_{PKM,CO_{2,cruise}} = m_{fuel} \cdot IOF_{CO_2} \cdot PKM_f \cdot Palo_{pax} \tag{2}$$

An example of the inventory analysis can be found in Equation (2), concerning the evaluation of the CO_2 emission caused by the fuel consumption during the cruise phase. In Equation (2) the $x_{PKM,CO_{2,cruise}}$ $[kg_{CO_2}/PKM]$ is the emissions of CO_2 per passenger per kilometer (PKM), m_{fuel} $[kg_{fuel}]$ is the consumed fuel during the cruise flight phase, PKM_f $[PKM/flight]$ is the number of kilometer-passenger per flight, $Palo_{pax}$ $[kg_{passenger}/kg_{payload}]$ is the percentage of passenger mass on total payload mass and IOF_{CO_2} $[kg_{CO_2}/kg_{fuel}]$ is the emission conversion factor. The latter can be calculated with a higher fidelity model or taken from literature through lower fidelity studies, considering however parameters such as the type of aircraft, type of engine, type of fuel, etc. Similarly, all other phases and emissions can be calculated [30]. As it can be understood, the inventory analysis is mainly based on statistics that define the emission conversion factor. For that reason, its assessment can be greatly improved if information coming directly from manufacturers and operators can be included in the computational pipeline.

The next step is to translate the total gaseous emissions and material consumption into more comprenhensive indicators; therefore, the ReCiPe method is employed [33]. This method exploits characterisation factors that are able to indicate the environmental impact per unit of the stressor (e.g. per released emission or kg of extracted resource). There are two different categories of impact–the midpoint and the endpoint. The former refers to climate change, ozone depletion, toxicity and more. For example, it calculates the impact of 1kg of emitted CO_2 on climate change. The latter has three categories, namely human health, ecosystem quality and resource scarcity, that can be combined to form a single final score with respect to the input. The selected non-dimensional parameter selected to define the final score is the unit of impact per passenger per kilometer.

The typical equation for the assessment of the value of the impact of a certain emission to the midpoint category, Md_Y, is presented in Equation (3), where X indicates an emission, x_{PKM_X} $[g_X/PKM]$ the quantity of emission X in grams per passenger per kilometer, and $CFmidpoint_{Y,X}$ the coefficient that indicates the impact of emission X on the midepoind category Y.

$$Md_Y = \sum_X (x_{PKM_X} \cdot CFmid\,point_{Y,X}) \tag{3}$$

In the ReCiPe method, depending on the importance that is given to each of the midpoint categories, there are three different ranks that can be utilised: (i) the Individualist, which is short-term and assumes that technology can avoid many future problems; (ii) the Hierarchist, that is considered a consensus model; and (iii) the Egalitarian, which is a long-term model based on preventive principle thinking. For this work, the Hierarchist version is used, a balance between the Individualist and Egalitarian methods, including global normalisation and average weighting set. Depending on the rank, the $CFmidpoint_X$ of each midpoint category is changed accordingly[5]. Specifically for climate change, as Johanning is proposing, the Schwartz, E. and Kroo approach is used for assessing the impact of the cruise emissions depending also on the altitude [34]. Note that in the work of Johanning (2016) the coefficients used in order to perform the assessment were based on a ReCiPe version of 2008 [35]. In this work, the coefficients were updated with the newer available version of 2016 [33].

Once all midpoint categories are evaluated, the three endpoints can be calculated. The equation to advance from midpoint to endpoint categories is very similar as can be seen in Equation (4), where $CFendpoint_{E,Y}$ is the coefficient to transform the value of the midpoint category Y, into an endpoint division E, that can be human health, ecosystem quality and resource scarcity. In addition, $Norm_Y$ represents

[5]https://www.rivm.nl/documenten/recipe2016cfsv1120180117

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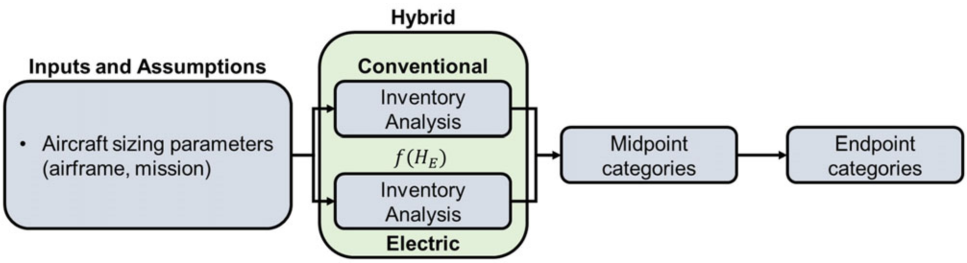

Figure 5. *Flowchart of life cycle assessment evaluation.*

$$X_{PKM,natural_{gas}} = El_{design} + Fl_{test} + \cdots + \overbrace{\underbrace{Bat_{prod} + El_{flight}}_{\text{Electric component}} + \underbrace{Ker_{prod} + Ker_{flight}}_{\text{Conventional component}}}^{\text{Hybrid configuration}}$$

Figure 6. *Example of life cycle assessment updated equations.*

a normalisation factor that is used to normalise the results of each midpoint category, Y, with respect to an endpoint category, E. This is used since a midpoint class can affect more than one endpoint tier.

$$Ed_E = \sum_Y \left(Md_Y \cdot \frac{CFendpoint_{E,Y}}{Norm_Y} \right) \tag{4}$$

In order to compute the final single score, that can give the overall environmental impact of the aircraft, Equation (5) is used. A weighting factor can be used, W_E, in order to define the importance of each of the three endpoint categories to the study. This parameter also depends on the rank introduced earlier.

$$SS = \sum_E (Ed_E \cdot W_E) \tag{5}$$

The work of Johanning et al. considers conventional or fully electric engines only. Thus, modifications have been made to explore hybrid-electric aircraft architectures. Towards this direction, the model is expanded to include the possibility to have both electricity and kerosene consumption during a flight phase, using the energy-level DoH as described in the Aircraft Sizing section. The modification is presented in Fig. 5, where the original streamlines are presented, i.e. for the conventional and fully electric configurations. In addition, the hybrid configuration is presented that combines data from both streamlines and merges the two, upstream of the midpoint categories block. Finally, for the hybrid configuration, both electric and conventional propulsion systems must be considered, including the batteries.

For that reason, some of the equations computing the overall inventory emissions have been modified to include hybrid configurations. For instance, the equation computing the natural gas consumption has been modified as shown in Fig. 6, where $X_{PKM,naturalgas}$ is the natural gas consumed, Bat_{prod}, El_{flight}, Ker_{prod} and Ker_{flight} are the battery production, electricity consumption, kerosene production and kerosene consumption, respectively. Prior to these modifications, the tool allowed the selection of one component at a time, making it impossible to study hybrid configurations.

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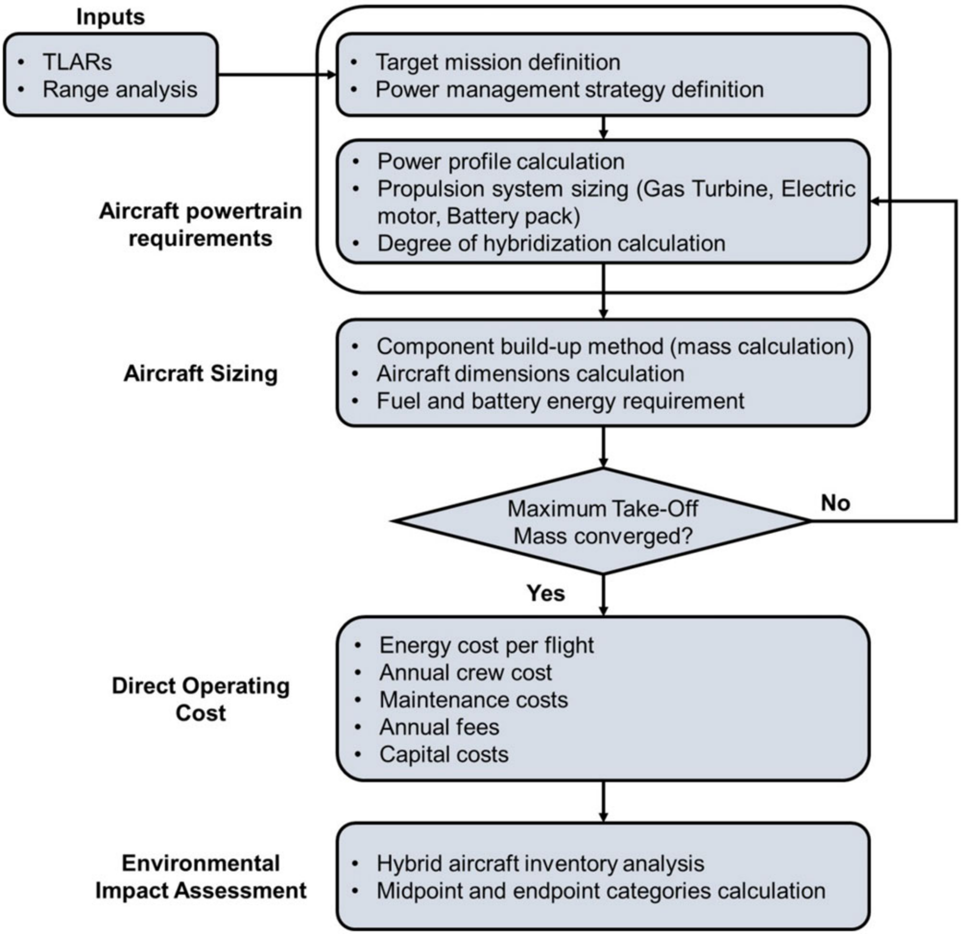

Figure 7. *Environmental and techno-economic evaluation overall flowchart.*

Having explained the modules of the proposed approach in the previous sections, the overall computational pipeline is presented in Fig. 7.

3.0 Results and discussion

3.1 Aircraft variants sizing evaluation

In this section, the results from the aircraft sizing evaluation for all hybrid-electric aircraft variants will be discussed and compared to the reference aircraft with EIS 2014. A Monte Carlo simulation is set to run the proposed framework, assuming a uniform distribution for the variables presented in range in the Methodology section, for a sample size of 1,000 evaluations. The mean values of the evaluation metrics are presented in Table 3, whereas the results with their standard deviation are included in Appendix, in Table A1, bounded within a 95% confidence interval. The aircraft power requirements have been calculated for the OEI case, which justifies the high power requirements for all aircraft. The OEI case for both reference aircraft and parallel configurations is the same, meaning that one of the two wing-mounted engines is not functioning. In a similar manner, the OEI case for the Series hybrid also refers to the malfunctioning of a wing-mounted electric motor, whereas the case in which the gas generator is not operating is not considered, due to the increase of batteries' mass to compensate for the generator

Table 3. Conceptual design summary for the reference and hybrid-electric aircraft variants

Configuration	Reference aircraft	Parallel 2027	Parallel 2030	Parallel 2040	Series 2027	Series 2030	Series 2040
EIS	2014	2027	2030	2040	2027	2030	2040
P_{GT} [kW]	2 × 1,350	2 × 1,780	2 × 1,300	2 × 1,200	1 × 1,660	1 × 950	1 × 770
P_{EM} [kW]	0	2 × 500	2 × 370	2 × 350	4 × 1,430	4 × 750	4 × 600
m_{fuel} [kg]	1,203	1,344	920	799	855	492	402
$E_{batteries}$ [kWh]	0	847	678	658	2,377	1,417	1,216
$E_{consumed}$ [kWh]	2,679	4,165	3,210	2,968	6,752	3,946	3,294
$E_{onboard}$ [kWh]	14,364	16,900	11,673	10,195	12,591	7,296	6,017
$m_{batteries}$ [kg]	0	3,800	1,671	1,077	10,873	3,592	2,096
$m_{propulsion}$ [kg]	739	1,050	906	871	2,904	1,424	1,016
$MTOM$ [kg]	7,555	13,006	9,473	8,603	23,116	11,912	9,569
OEM [kg]	4,451	5,963	4,981	4,827	9,488	5,927	5,170
S_{ref} [m^2]	37.95	65.35	47.59	43.22	116	59.84	48.07
b [m]	20.43	26.81	22.88	21.8	35.7	25.65	22.99
H_P [%]	0	21.9%	22%	22%	77.5%	76.1%	76.21%
H_E [%]	0	5.01%	5.81%	6.45%	18.9%	19.4%	20.2%
$AECEF$ [−]	0.186	0.246	0.275	0.291	0.54	0.541	0.547

power loss. When comparing the power requirements, it is evident that the power demand for the same mission increases, with the increase of the maximum take-off mass, which has an impact on the energy consumption as well, that is discussed next.

The maximum take-off mass of all hybrid-electric variants is increased, compared to the reference aircraft, as expected, due to the additional mass of the electric power system and batteries, as seen in Fig. 8. Additionally, the CS-23/FAR-23 maximum take-off mass certification limitation of 8,618kg is violated, [17, 36] except for the Parallel 2040 hybrid-electric variant. This indicates that the cell-level battery gravimetric specific energy density should be greater than 1,000Wh/kg for the Parallel configuration to comply with the commuter class airworthiness certification standards. On the other hand, the Series hybrid remains outside the certification limits, even for the EIS date of 2040, but it shows a greater sensitivity to technological improvements than the Parallel. In order to have a compliant Series design, the batteries' cell-level gravimetric energy has been determined to be greater than 1,400Wh/kg, using the aircraft sizing tool. However, despite the maximum take-off mass increase, the block fuel reduces for most of the hybrid-electric configurations, as shown in Fig. 8. The Parallel configuration of 2027 has a block fuel penalty of 12%, due to the batteries and electric components' mass increase; however, for an EIS date of 2030 or greater this configuration promises a block fuel reduction of up to 34%, compared to the 2014 reference aircraft. Meanwhile, all Series configurations show a block fuel reduction compared to the reference, even the Series 2027, with almost three times the maximum take-off mass than the 2014 conventional aircraft. The block fuel reduction for the three EIS dates is 29%, 59%, and 67%, respectively. Although the block fuel evaluation is in favor of the Series configuration, the total energy consumption should be assessed, too, before reaching any conclusions.

Considering mission energy, it is categorised into onboard stored energy and mission energy consumption. The onboard stored energy is the total amount of energy that is stored in the aircraft to complete the mission including both energies from fuel and batteries, as shown in Equation (6), where LHV is the jet-A average lower heating value, which is considered 43MJ/kg (11.95kWh/kg) [37]. On the contrary, mission energy consumption refers to the total amount of energy consumed at each mission phase, which is calculated using the power requirement and duration of each mission phase, provided by the aircraft sizing tool, as shown in Equation (7). As previously mentioned, the increase of the maximum take-off mass increases the power requirement for each mission segment, and since the mission for all

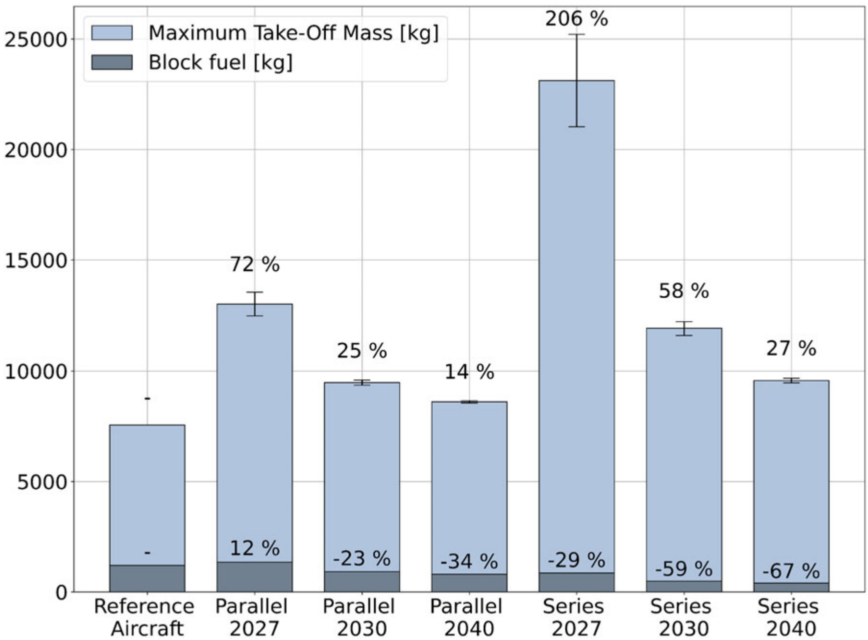

Figure 8. *Mean maximum take-off mass and block fuel (with standard deviation) comparison between the reference aircraft and the hybrid-electric variants.*

configuration variants remains the same, the overall mission energy consumption increases for all hybrid variants, as shown in Fig. 9. This indicates that it is of utmost importance to change the infrastructure of electricity production along with the transition to electrified propulsive systems and increase the percentage of renewable sources – or rely solely on renewables – in the electricity mix, in order to have a meaningful impact on energy reduction and emissions, instead of shifting them to a different sector.

$$E_{onboard} = E_{batteries} + m_{fuel} \cdot LHV \tag{6}$$

$$E_{consumed} = \sum_{i}^{n} (P_i \cdot dt_i) \tag{7}$$

In spite of mission consumption being greater for the hybrid variants, the onboard stored energy requirement is lower than the reference aircraft for all hybrid aircraft except the Parallel variant with the 2027 EIS date, as presented in Fig. 9. That is because the 2027 EIS date electric powertrain characteristics shown in Table 2 are not sufficient to provide an electrification benefit for the Parallel configuration and because the Parallel 2027 showed a block fuel penalty of 12% compared to the reference case. For the 2030 and 2040 EIS date Parallel variants, the onboard energy requirement is reduced by 19% and 29% respectively, compared to the reference aircraft, whereas for the Series variants the onboard energy reduction ranges from 12% to 58% for the EIS between 2027 and 2040, respectively. That is because, for the hybrid variants, a portion of the onboard stored energy passes through the electric power system, which has a higher efficiency compared to the thermal engine. As a result, the more energy that passes through the electric powertrain, the more efficient the thrust conversion becomes. That said, the aircraft energy conversion efficiency factor (AECEF) is defined in Equation (8). For the reference aircraft, this factor is 0.186, meaning that only 18.6% of the total energy stored in fuel form is required for the mission, and the rest are conversion losses in the propulsion system and gas turbines. Accordingly, this

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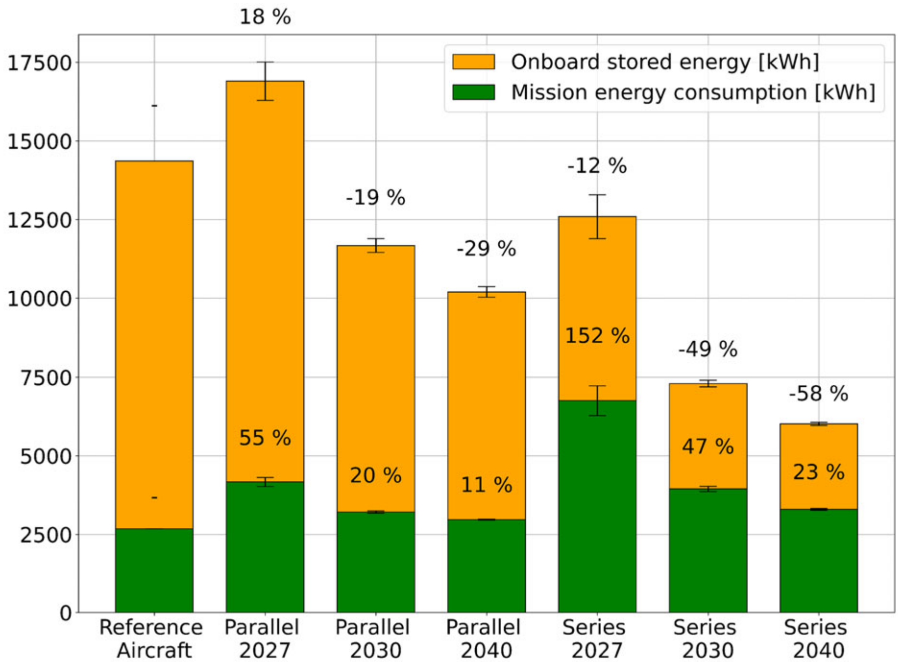

Figure 9. *Mean onboard stored energy and mission energy consumption (with standard deviation) between the reference aircraft and the hybrid-electric variants.*

factor ranges from 0.246 to 0.291 for the Parallel hybrids with EIS 2027–2040, respectively, whereas the factors for the Series variants range from 0.54 to 0.547 respectively for the aforementioned EIS dates.

$$AECEF = \frac{E_{consumed}}{E_{onboard}} \tag{8}$$

3.2 Environmental impact assessment evaluation

In this section, the environmental effect of the life cycle of the hybrid-electric aircraft variants with the 2030 EIS date is presented. The selection of 2030 can be justified from the analysis of the previous section, as these hybrids start to show substantial benefits compared to the reference aircraft, in terms of block fuel and onboard energy. The life cycle impact single score per passenger per kilometer for each aircraft is shown in Fig. 10, including the share of each LCA phase to that score. The hybrid-electric 2030 EIS variants are compared to the 2014 reference aircraft, considering two scenarios: the first scenario considers electricity production from the EU electricity mix (EU-mix), whereas the second – and more optimistic – scenario considers electricity production from renewable sources. As shown in Fig. 10, the reference aircraft has the highest environmental impact (0.092), as expected. Then, the Parallel hybrid follows, with $0.074 \pm 0.12\%$ (-19.5%) and $0.07 \pm 0.12\%$ (-22.8%) for the EU-mix and renewables electricity production, respectively. Finally, the Series variant has the lowest environmental impact with $0.044 \pm 0.08\%$ (-52.1%) and $0.037 \pm 0.07\%$ (-59.7%) accordingly for the electricity production phases, with the latter being almost half of the respective Parallel's score. Considering using renewable sources for electricity production, it is observed that the Series variant is even more preferable, as the environmental impact score is reduced by 15.9% compared to the case in which electricity is produced using the EU-mix, whereas the respective reduction for the Parallel variant is 5.4%. Furthermore, it is observed that the cruise and the landing and take-off (LTO), i.e. the operation phase of the LCA, are

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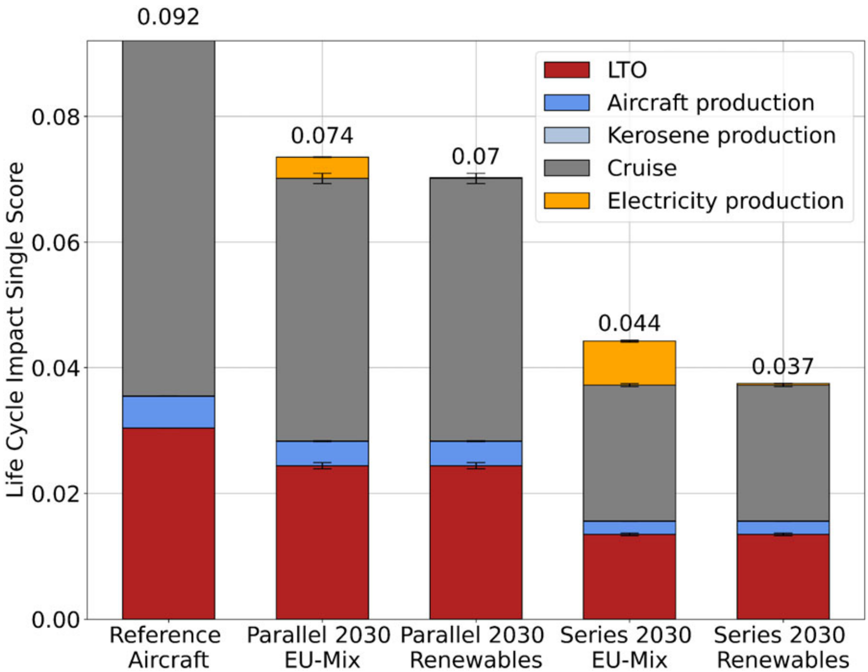

Figure 10. *Life cycle impact mean single score (with standard deviation) per passenger per km per LCA phase.*

the dominant contributors to the total impact. This observation is aligned with the literature mentioned in the introduction section.

As the operation LCA phase seems to be the one with the greatest impact, it is, as expected, related to the onboard stored energy and mission energy consumption presented in Fig. 9. Additionally, the kerosene production impact is reduced significantly, compared to the findings in a previous work [10]; however, this reduction is explained by the variation of certain coefficients in the ReCiPe update from 2008 to 2016, where the importance of kerosene production is reduced, compared to 2008.

Finally, Fig. 11 presents the life cycle impact single score per passenger per kilometer of the examined variants, but with the shares of emissions, aiming to quantify the impact of the major emissions on the final score. It is observed that the NO_X emissions, along with the CO_2 emissions are the leading contributors. The former pollutant is responsible for the photochemical oxidant formation phenomenon, while the latter affects climate change. Considering ReCiPe 2016, it boosts mainly the NO_X emissions, which are present mainly during the operation LCA phase and are not produced during the kerosene production phase, justifying the updated behaviour. In Fig. 11, both NO_X and CO_2 absolute values of hybrid variants are less than the reference aircraft. For the Series configuration especially, the NO_X emissions are reduced significantly, compared to the Parallel, due to the additional block fuel reduction presented in Fig. 8.

3.3 Direct operating cost evaluation

In this section, the direct operating cost assessment results are presented for all hybrid-electric aircraft variants and compared to the reference aircraft case. As mentioned in the methodology section, the DOC evaluation separates the constant annual costs, namely energy, maintenance, crew and fees costs, from the capital cost, which is higher during the first years of the depreciation period. Therefore, the cost assessment of the hybrid variants presented in Table 4 summarises the total annual cost both with and

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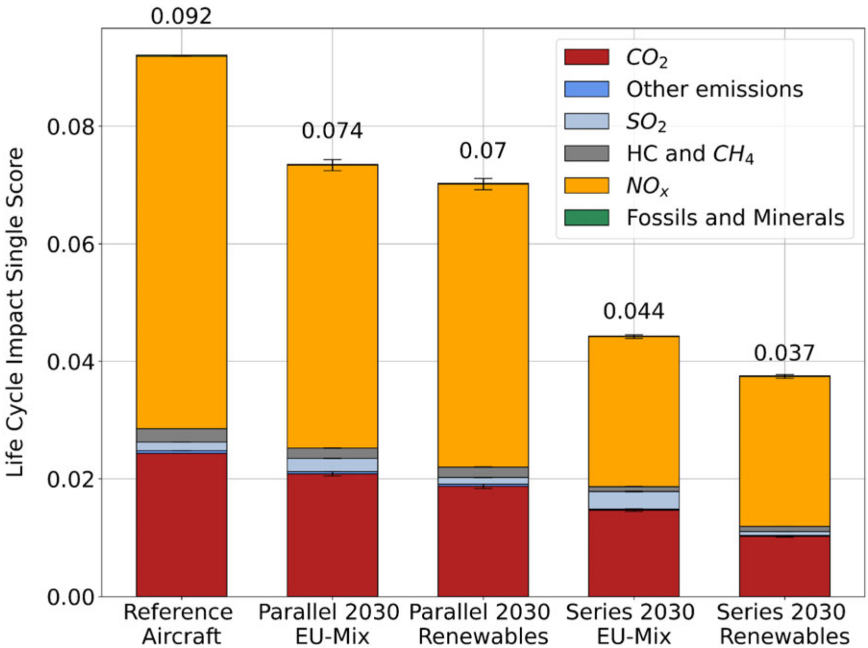

Figure 11. *Life cycle impact mean single score (with standard deviation) per passenger per km per emission.*

without capital costs, with the latter presented in parenthesis. The second and third columns of the table include the mean annual costs and cost differences (Equation (9)) compared to the reference aircraft for estimated fuel and energy prices range of 0.75–0.85 €/kg[6] and 65–165 €/MWh [38], respectively, whereas the results with their standard deviation, bounded within a 95% confidence interval, are included in Table A2 in Appendix. Moreover, the last two table columns include the operating cost assessment in case of an energy recession scenario, with a 150% and 340% increase on the average fuel and electricity price of the previous range accordingly.

$$\Delta Cost = \frac{Cost_{reference} - Cost_{hybrid,i}}{Cost_{reference}} \tag{9}$$

It is observed that both Parallel and Series variants with the EIS of 2027 show increased annual operating costs with and without the capital costs included, for both energy pricing scenarios. Considering also that the 2027 Parallel shows a block fuel penalty instead of a reduction, it can't be considered a potential candidate for aircraft electrification. In addition, for the first pricing scenario assessment, both hybrid variants with EIS 2030 show increased operating costs compared to the conventional reference aircraft when the capital costs are included in the calculation. However, if the capital costs are excluded, the Parallel hybrid shows a marginal improvement in terms of operating costs (0.4% reduction in the annual costs), whereas the Series hybrid shows reduced costs by 4.4%. Finally, for the EIS date of 2040, both hybrid variants have reduced annual operating costs when the capital costs are included, with the Parallel and Series hybrids showing cost reduction by 0.5% and 3.9% respectively compared to the reference aircraft. Moreover, the annual costs further reduce when the capital costs are excluded from the evaluation, indicating a 6.8% and 13.9% cost reduction for the Parallel and Series hybrids respectively.

On the other hand, for the evaluation considering the case of an energy recession, the need for a transition towards electrified propulsion becomes more evident. The direct operating cost evaluation indicates

[6] https://www.iata.org/en/publications/economics/fuel-monitor/

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Table 4. *Annual direct operating cost evaluation summary, with and without capital costs, for the nominal and energy recession scenarios*

Configuration	Annual operating costs[1]	Difference[1]	Annual operating costs[2]	Difference[2]
Reference aircraft	6.22 M (4.53 M)	–	8.85 M (7.08 M)	–
Parallel 2027	8.09 M (5.55 M)	30.1% (22.5%)	11.66 M (9.01 M)	31.7% (27.2%)
Parallel 2030	6.56 M (4.51 M)	5.5% (−0.4%)	9.11 M (6.97 M)	2.9% (−1.7%)
Parallel 2040	6.19 M (4.22 M)	−0.5% (−6.8%)	8.40 M (6.36 M)	−5% (−10.2%)
Series 2027	9.81 M (6.19 M)	57.7% (36.6%)	13.17 M (9.46 M)	48.8% (33.5%)
Series 2030	6.65 M (4.33 M)	6.9% (−4.4%)	8.77 M (6.35 M)	−0.9% (−10.4%)
Series 2040	5.98 M (3.9 M)	−3.9% (−13.9%)	7.74 M (5.58 M)	−12.5% (−21.3%)

[1]Fuel price: 0.75–0.85 €/kg, electricity price: 65–165 €/MWh
[2]Fuel price: 2 €/kg, electricity price: 500 €/MWh.

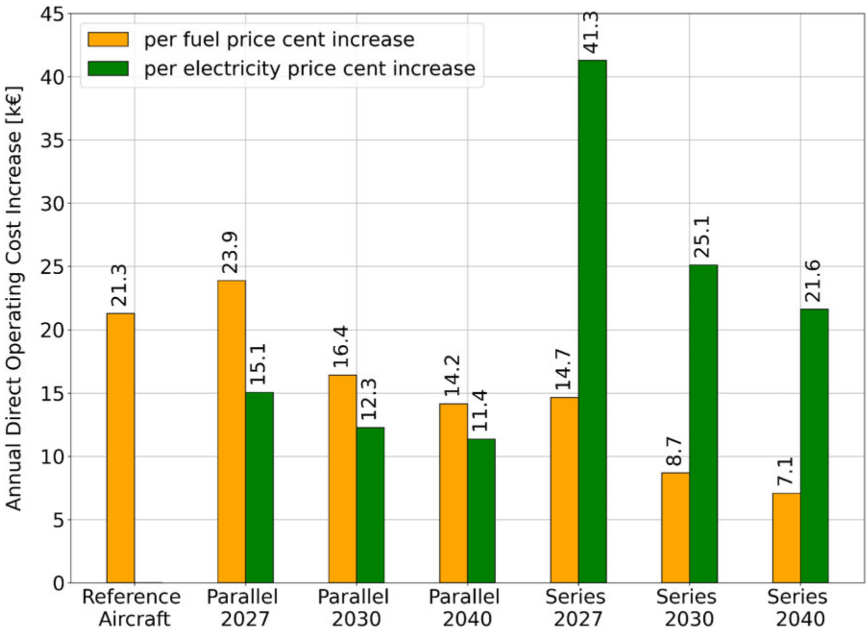

Figure 12. *Annual direct operating cost increase per euro cent increase in fuel and electricity prices for the reference and hybrid aircraft.*

that for the year 2030, both Parallel and Series variants show reduced operating costs compared to the reference aircraft by 1.7% and 10.4%, respectively, if the capital costs are excluded. Finally, the 2040 Series variant has the potential to reduce annual operating costs by 21.3% compared to the reference case, whereas the 2040 Parallel hybrid can achieve only half of that cost reduction.

Having evaluated an energy recession scenario, it is necessary to quantify the sensitivity of all examined aircraft to fuel and electricity price fluctuation. A sensitivity analysis has been conducted for the purposes of this work and presented in Fig. 12, quantifying the impact of the increase of fuel and energy prices per euro cent on the total annual cost. For the reference aircraft, the annual direct operating energy costs increase by 21.3 k€, for each euro cent of fuel increase, whereas for the Parallel and Series variants range from 14.2–23.9 k€ and 7.1–14.7 k€, respectively, per euro cent increase. Furthermore, considering the electricity price the annual energy cost increase ranges from 11.4–15.1 k€ and 21.6–41.6 k€ per euro cent increase for the Parallel and Series aircraft accordingly. The Parallel variants are more

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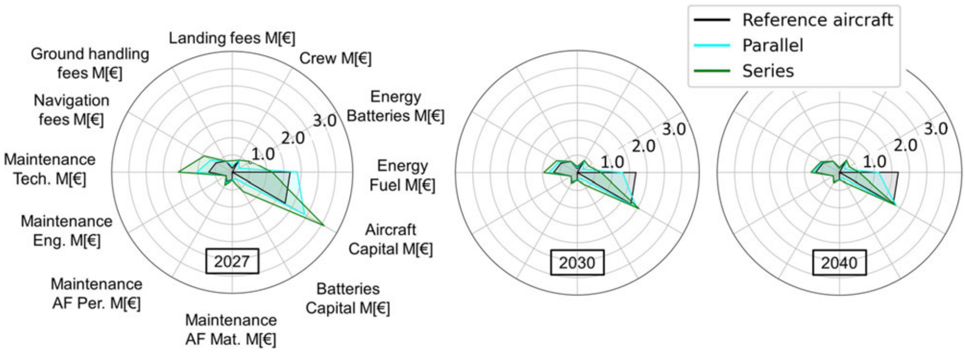

Figure 13. *Summary of mean annual operating costs per category in M€ for the reference and hybrid aircraft, for entry into service dates 2027 (left), 2030 (middle), and 2040 (right).*

sensitive to a fuel price increase than to an electricity price increase, as expected, due to the propulsion configuration architecture. On the other hand, the Series variants are more sensitive to electricity price fluctuation, with the 2027 Series being almost three times more sensitive than the Parallel 2027, whereas the Series 2030 and 2040 are almost twice more sensitive that the respective Parallel ones. This sensitivity of the Series configurations on the electricity price fluctuation further supports the need to transition to clean, renewable energy sources for electricity production.

Finally, an overview of the mean annual direct operating cost is presented in Fig. 13. The breakdown of each cost per category is summarised in the radar plots of Fig. 13, comparing all hybrid electric variants to the reference aircraft for all three different EIS dates. One of the most important parameters driving the direct operating cost evaluation is the aircraft capital cost, which for the reference aircraft has the same share of the total annual cost as the fuel energy cost. However, the aircraft capital cost reduces significantly with the increase of the EIS date, starting from 3 M€ to 2.5 M€ for the Series and Parallel 2027 variants, respectively, and tends to converge to the respective value of the reference aircraft (1.77 M€) for the 2040 variants. Another very important variable that highly affects the total annual operating costs is the fuel energy cost, following the same trend as the block fuel reduction, as expected, that has been thoroughly discussed in the previous sections. Finally, another parameter having a significant impact on annual operating costs is the technology maintenance cost of airliners to maintain their fleet, which is a function of the aircraft's basic dimensions, like wing span and fuselage length. Overall, Fig. 13 indicates that all costs, except the fuel and batteries energy costs and batteries capital cost, tend to converge to the reference aircraft's respective costs until the year 2040.

4.0 Conclusions

The conceptual design of six hybrid-electric aircraft variants was performed, considering three different EIS dates, namely 2027, 2030 and 2040, assuming different component technology readiness levels for each date. The aircraft powertrain requirements for each variant were determined and imported to an in-house aircraft sizing tool, to assess all hybrid-electric designs in terms of mission performance, direct operating costs and environmental impact. The selected main mission range of 400 nm, was derived from a dedicated airport network study in European countries, offering a point-to-point coverage rate greater than 86% for all examined countries. The Series and Parallel hybrid-electric variants were compared to a conventional reference aircraft with 2014 technology, in order to quantify the electrification benefit, considering several metrics.

The maximum take-off mass of the Series hybrid variants was more sensitive to the selected service dates than that of the Parallel, whereas the latter had a greater potential to comply with the CS-23/FAR-23 airworthiness certification mass limitation. The Parallel variants with a service date of 2030 and beyond, showed a block fuel and onboard energy reduction of up to 34% and 29%, respectively, whereas the Series of 2027 and beyond promised a reduction of up to 67% and 58% to the aforementioned metrics. However, the Parallel variants showed lower total mission energy consumption –being the lightest of the hybrid variants – suggesting the importance of clean electricity production for substantial emission and energy reduction.

The LCA suggested that the operation phase was the dominant contributor to the environmental impact and that the Series hybrid had the lowest impact single score. The 2030 Series hybrid had an environmental impact score reduction of 59.7%, compared to the reference aircraft, for the case of electricity production by renewable sources, whereas the 2030 Parallel configuration had a respective reduction of 23.9%. Moreover, it was observed that the Series variant was more sensitive to the means of electricity production than the Parallel, as the environmental impact score was reduced by 15.9% for the green energy production case, compared to the respective EU-mix case. On the other hand, the environmental impact score for the 2030 Parallel variant was reduced by 5.4% in the case renewables were used, instead of the EU-mix. Additionally, the NO_X and CO_2 emissions were quantified to have the greatest impact on the assessment, especially the former, due to the photochemical oxidant formation phenomenon.

The direct operating cost evaluation indicated that the most critical parameters affecting the total annual cost were the aircraft capital, the fuel energy and the maintenance technology costs and that the hybrid variants became preferable to operate compared to the conventional, with the technological progress in batteries. In the scenario that the energy cost would be reduced in the future, the direct operating cost evaluation proposed that the hybrid-electric variants would be economically preferable to operate on an annual basis by 2040, should the capital costs be considered in the annual operating cost, whereas they would be preferable than the reference aircraft by 2030 if the capital costs were not included. However, in an energy recession scenario, the urge toward the transition to electrified propulsion was even more evident, as the Series variant of 2030 had lower annual operating costs than the conventional of 2014, regardless of the capital cost consideration.

In conclusion, for the 2027 date, neither the Parallel nor the Series configurations were outstanding electrification candidates for different reasons. The former because of the increased fuel and energy consumption due to the overall mass penalty, and the latter due to the immense maximum take-off mass and operational cost. For the 2030 date– the assumptions of which were the most realistic about the future – the Series showed greater block fuel and onboard mission reduction but had a maximum take-off mass of 12 tonnes, 2.5 tonnes heavier than the Parallel. Moreover, the environmental impact score and operating costs of the Series were reduced compared to the Parallel, but the latter had almost 300 k€ reduced capital costs. Therefore, for 2030, the Series variant would be the best option, when first aiming at environmental aspects, whereas the Parallel would be preferable if a cost-effective, but still eco-friendly solution was in target. Finally, for the year 2040, the Series was by far the most suitable solution comparing all metrics.

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APPENDIX

Table A1. *Conceptual design summary for the reference and hybrid-electric aircraft variants within 95% confidence interval*

Configuration	Reference Aircraft	Parallel 2027 $\mu \pm \sigma$ 95% CI	Parallel 2030 $\mu \pm \sigma$ 95% CI	Parallel 2040 $\mu \pm \sigma$ 95% CI	Series 2027 $\mu \pm \sigma$ 95% CI	Series 2030 $\mu \pm \sigma$ 95% CI	Series 2040 $\mu \pm \sigma$ 95% CI
P_{GT} [kW]	2 x 1,350	2 x 1,780 ± 70 (1,774, 1,783)	2 x 1,300 ± 15 (1,299, 1,301)	2 x 1,200 ± 7 (1,199.7, 1,200.4)	1 x 1,660 ± 77 (1,655, 1,665)	1 x 950 ± 10 (949.5, 950.5)	1 x 770 ± 8 (769.5, 770.5)
P_{EM} [kW]	0	2 x 500 ± 20 (500, 503)	2 x 370 ± 4 (369.8, 370.3)	2 x 350 ± 2 (349.9, 350.1)	4 x 1,430 ± 120 (1,423, 1,436)	4 x 750 ± 18 (749, 751)	4 x 600 ± 6 (599.5, 600.3)
m_{fuel} [kg]	1,203	1,344 ± 49 (1,341, 1,347)	920 ± 18 (920, 922)	799 ± 14 (798, 799.7)	855 ± 45 (852, 858)	492 ± 6.4 (491.9, 492.7)	402 ± 3.5 (401.8, 402.3)
$E_{batteries}$ [kWh]	0	847 ± 28 (845, 849)	678 ± 11.5 (677, 679)	658 ± 17 (657, 659)	2,377 ± 164 (2,366, 2,387)	1,417 ± 30 (1,415, 1,419)	1,216 ± 20 (1,215, 1,217)
$E_{consumed}$ [kWh]	2,679	4,165 ± 141 (4,156, 4,174)	3,210 ± 32.5 (3,208, 3,212)	2.968 ± 16 (2,967, 2,969)	6,752 ± 473 (6,722, 6,781)	3,946 ± 83 (3,940, 3,951)	3,294 ± 30 (3,292, 3,296)
$E_{onboard}$ [kWh]	14,364	16,900 ± 610 (16,862, 16,937)	11,673 ± 220 (11,659, 11,687)	10,195 ± 168 (10,184, 10,204)	12,591 ± 696 (12,548, 12,634)	7,296 ± 103 (7,289, 7,302)	6,017 ± 50 (6,14, 6,20)
m_{bat} [kg]	0	3,800 ± 402 (3,774, 3,824)	1,671 ± 85 (1,655, 1,676)	1,077 ± 35.5 (1,75, 1,79)	10,873 ± 1552 (10,777, 10,969)	3,592 ± 226 (3,578, 3,606)	2,096 ± 79 (2,91, 2,101)
$m_{propulsion}$ [kg]	739	1,050 ± 17 (1,49, 1,51)	905 ± 3 (904.7, 905.1)	871 ± 1.2 (870.7, 870.85)	2,904 ± 229 (2,889, 2,918)	1,424 ± 32 (1,422, 1,426)	1,016 ± 10 (1,15, 1,17)
MTOM [kg]	7,555	13,006 ± 532 (12,973, 13,039)	9,473 ± 113 (9,465, 9,480)	8603 ± 49 (8,599, 8,605)	23,116 ± 2,093 (22,987, 23,246)	11,912 ± 300 (11,893, 11,930)	9,569 ± 103 (9,562, 9,575)

Table A1. *Continued*

Configuration	Reference Aircraft	Parallel 2027 $\mu \pm \sigma$ 95% CI	Parallel 2030 $\mu \pm \sigma$ 95% CI	Parallel 2040 $\mu \pm \sigma$ 95% CI	Series 2027 $\mu \pm \sigma$ 95% CI	Series 2030 $\mu \pm \sigma$ 95% CI	Series 2040 $\mu \pm \sigma$ 95% CI
OEM [kg]	4,451	5,963 ± 532 (5,958, 5,968)	4,981 ± 17 (4,980, 4,982)	4,827 ± 7.5 (4,826.4, 4,827,4)	9,488 ± 507.5 (9,456, 9,519)	5927 ± 70 (5,922, 5,931)	5,170 ± 22 (5,169, 5,172)
S_{ref} [m^2]	37.95	65.35 ± 2.67 (65.17, 65.5)	47.59 ± 0.57 (47.55, 47.62)	43.22 ± 0.24 (43.2, 43.23)	116 ± 10.5 (115.5, 116.8)	59.84 ± 1.5 (59.75, 59.93)	48.07 ± 0.51 (48.04, 48.1)
b [m]	20.43	26.81 ± 0.55 (26.77, 26.83)	22.88 ± 0.13 (22.87, 22.89)	21.8 ± 0.06 (21.8, 21.8)	35.7 ± 1.61 (35.6, 35.8)	25.65 ± 0.32 (25.63, 25.67)	22.99 ± 0.12 (22.98, 23.0)
H_P [%]	0	21.9% ± 1% (21.83%, 21.96%)	22% ± 0.28% (21.98%, 22.01%)	22% ± 0.19% (21.99%, 22.01%)	77.5% ± 1.7% (77.4%, 77.6%)	76.1% ± 0.5% (76.07%, 76.13%)	76.21% ± 0.26% (76.19%, 76.22%)
H_E [%]	0	5.01% ± 0.23% (4.99%, 5.02%)	5.81% ± 0.14% (5.8%, 5.82%)	6.45% ± 0.19% (6.43%, 6.46%)	18.9% ± 1.3% (18.82%, 18.98%)	19.4% ± 0.4% (19.37%, 19.42%)	20.2% ± 0.3% (20.18%, 20.21%)
AECEF [%]	0.186	24.6% ± 1.2% (24.52%, 24.67%)	27.5% ± 0.6% (27.46%, 27.53%)	29.1% ± 0.5% (29.06%, 29.13%)	54% ± 5% (53.7%, 54.3%)	54.1% ± 1.4% (54%, 54.2%)	54.7% ± 0.7% (54.65%, 54.74%)

Table A2. *Annual direct operating cost evaluation summary, with and without capital costs, within 95% confidence interval*

	Reference aircraft	Parallel 2027	Parallel 2030	Parallel 2040	Series 2027	Series 2030	Series 2040
With capital	6.22 ± 0.08	8.09 ± 0.21	6.56 ± 0.1	6.19 ± 0.08	9.81 ± 0.5	6.65 ± 0.13	5.98 ± 0.10
95% CI	(6.22, 6.23)	(8.08, 8.10)	(6.55, 6.56)	(6.19, 6.2)	(9.78, 9.84)	(6.64, 6.66)	(5.97, 5.99)
Without capital	4.53 ± 0.06	5.55 ± 0.16	4.51 ± 0.07	4.22 ± 0.06	6.19 ± 0.31	4.33 ± 0.09	3.9 ± 0.07
95% CI	(4.53, 4.54)	(5.54, 5.56)	(4.51, 4.52)	(4.22, 4.23)	(6.17, 6.21)	(4.32, 4.34)	(3.89, 3.90)

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