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Research paper

# Evaluating the economic landscape of hybrid-electric regional aircraft: A cost analysis across three time horizons

Valerio Marciello [a], Vincenzo Cusati [a,b,*], Fabrizio Nicolosi [a], Karen Saavedra-Rubio [c,d], Eleonore Pierrat [c,d], Nils Thonemann [c,d,e], Alexis Laurent [c,d]

[a] *Department of Industrial Engineering, University of Naples "Federico II", Via Claudio 21, Naples, 80125, Italy*
[b] *Smartup Engineering s.r.l., Piazza Salvatore Di Giacomo, 123, Naples, 80123, Italy*
[c] *Section for Quantitative Sustainability Assessment, Department of Environmental and Resource Engineering, Technical University of, Denmark, Kgs. Lyngby, 2800, Denmark*
[d] *Centre for Absolute Sustainability, Technical University of, Denmark, Kgs. Lyngby, 2800, Denmark*
[e] *Institute of Environmental Sciences (CML), Leiden University, Einsteinweg 2, Leiden, 2333 CC, The Netherlands*

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ABSTRACT

This article presents the results of a prospective cost analysis of future regional aviation solutions, specifically focusing on hybrid-electric regional aircraft for 50 passengers. The study spans three time horizons (short term, medium term, long term) and employs a validated workflow to estimate costs for various solutions, including conventional, hybrid-electric, and hydrogen-based architectures. A specialized cost model is introduced to assess the electric components of the powertrain, emphasizing maintenance expenses and energy costs. Despite the environmental promise of hybrid and electric solutions, the results reveal significantly higher direct operating costs (up to 69.8%) compared to conventional options. The study highlights the importance of targeted policies to incentivize sustainable alternatives, suggesting potential solutions such as discouraging kerosene-based aircraft and promoting sustainable aviation fuel. These insights provide valuable guidance for industry stakeholders navigating the path toward a more sustainable and economically viable aviation future.

## 1. Introduction

As the aviation industry moves towards a greener future, it is crucial to understand the economic implications of adopting new technologies, such as electric propulsion systems and sustainable aviation fuels (SAFs). Through a detailed examination of potential costs and benefits, this study aims to shed light on the economic viability of these emerging technologies, providing a predictive analysis of direct operating costs (DOCs) of several future aircraft scenarios. The focus is on a regional platform accommodating 50 passengers. The presented analysis is part of a broader scope that investigates the trade-offs between technical, economic, and environmental implications of new propulsion solutions, aiming to identify recommendations for stakeholders navigating the complex landscape of sustainable aviation. The study, framed in the context of the Clean Sky 2 GENESIS[1] project, has been supported by the collaboration of academic and industrial partners, which has made it possible to evaluate the impact of the most promising technologies at the aircraft level. In particular, the scenarios have already been characterized by Marciello et al. in a previous study [1], showcasing the evolution of the technologies over three future time horizons (short term, ca. 2030; medium term, ca. 2040; long term, ca. 2050). In the appendix section, the interested reader can find more insights on the technologies considered and the evolution of their maturity in the coming decades. Marciello et al. have performed the conceptual design of all configurations, also quantifying the potential reduction of direct pollutant emissions [1]. Later, Thonemann et al. have conducted a life cycle analysis on the configurations for the holistic evaluation of their environmental impact [2,3]. These previous studies have highlighted a modest advantage of hybrid-electric architectures, the reduction of life-cycle CO2 associated with the use of SAFs, and the significant environmental benefits promised by hydrogen. However, the expected advantages still remain to be considered together with the consequent increases in DOC, potentially leading to an economic unfeasibility of the solutions. To fill this gap, the present article delves into a comprehensive exploration of the DOCs associated with hybrid-electric regional aircraft.

In a context of fierce economic competition, it is difficult to find room for innovative propulsion solutions whose primary function is

* Corresponding author at: Department of Industrial Engineering, University of Naples "Federico II", Via Claudio 21, Naples, 80125, Italy.
*E-mail address:* vincenzo.cusati@unina.it (V. Cusati).

1 The GENESIS project: https://www.genesis-cleansky.eu/.

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**Nomenclature**

**Abbreviations**

| | |
|---|---|
| ACARE | Advisory Council for Aviation Research and Innovation |
| AEA | Association of European Airliners |
| ATA | Air Transport Association of America |
| CAPEX | Capital Expenditure |
| CO2 | Carbon Dioxide |
| DEP | Distributed Electric Propulsion |
| DOC | Direct Operating Cost (USD/flight) |
| EIS | Entry Into Service (year) |
| ETS | Emissions Trading Scheme |
| GHG | Greenhouse Gas |
| H2 | Hydrogen |
| HEFA | Hydroprocessed Esters and Fatty Acids |
| IATA | International Air Transport Association |
| ICE | Internal Combustion Engine |
| IOC | Indirect Operating Cost (USD/flight) |
| LCC | Life Cycle Cost |
| LCI | Life Cycle Inventory |
| LF | Load factor |
| Li–Ion | Lithium-Ion |
| $Li–O_2$ | Lithium-Air |
| Li–S | Lithium-Sulfur |
| MTOM | Maximum Take-Off Mass |
| OPEX | Operational Expenditure |
| PEMFC | Proton-Exchange Membrane Fuel Cell |
| RDTE | Research, Development, Test, Evaluation |
| SAF | Sustainable Aviation Fuel |
| SOFC | Solid Oxide Fuel Cell |
| SPK | Synthetic Paraffinic Kerosene |
| TLAR | Top-Level Aircraft Requirement |
| TOC | Total Operating Cost (USD/flight) |
| TRL | Technology Readiness Level |
| USD | United States Dollar |

**Roman Symbols**

| | |
|---|---|
| $C$ | Cost (USD) |
| $f$ | Frequency of occurrence (–) |
| $N$ | Number (–) |
| $Price$ | Price (USD) |
| $Profit$ | Profit on aircraft sale (USD) |
| $Rate$ | Interest rate (–) |
| $RV$ | Residual value fraction (–) |
| $Salary$ | Annual salary (USD/year) |
| $t$ | Time duration (h) |
| CPI | Consumer Price Index (–) |
| LR | Labor Rate (USD/h) |

**Subscripts**

| | |
|---|---|
| Energy | Referred to energy sources |
| FT,Prod. | Due to flight test operations |
| Labor | Linked to maintenance operations |
| Unit | Referred to the unit size |
| Year | Per year |

not to reduce operating costs. At the same time, the imperative to address environmental concerns, if not accompanied by market competitiveness, could even lead to the collapse of the sector. As a matter of fact, to reduce greenhouse gas (GHG) emissions, some countries, such as France, have already banned regional flights, for which relevant train alternatives exist [4]. Generally speaking, the interest of aircraft operators is that aircraft generate sufficient revenue to exceed its operational cost. Completely neglecting the important cost penalties linked to electrification may prevent its establishment on the market, making the economic transition impracticable.

In the first place, macroeconomic scenarios may have a big impact on the success of hybrid or electric concepts over kerosene-based solutions, directly affecting the uncertainty about the prices of different energy sources [5]. Gonzalez-Gara et al. [6] note that SAFs produced via renewable energy can reduce the carbon footprint of the aviation sector, but require high carbon taxes and technological improvements to become competitive with fossil-based jet fuel. Jain et al. [7] highlight that low SAF prices may lead to higher fleet-level emissions, due to a reduction in ticket price and consequent higher demand. Studies such as the one of Zhou et al. [8], focused on the analysis of carbon neutrality pathways in China, underline that the supply of green electricity is of primary importance for achieving concrete sustainability goals. On the other hand, according to the model-based analysis of Capros et al. [9], the use of electricity will play a critical role in achieving EU's climate neutrality by 2050, but it will require a considerable increase in the global volume of power generation [9]. In parallel to solutions based on direct electrification, there are also a few literature examples available for Urban Air Mobility and general aviation related to the use of hydrogen as the primary energy source. Among these, Mukhopadhaya [10] explore the feasibility of retrofitting general aviation aircraft with hydrogen fuel cell systems and offer a detailed analysis of the costs associated with this technology. However, the cost items considered by the authors are related only to hydrogen, without assuming any model for aircraft operating costs. Still regarding hydrogen, Hoelzen et al. [11] argue that the availability of a low-cost, green liquid hydrogen supply infrastructure is crucial for the economic viability of hydrogen aviation. The paper of Brandle et al. [12] concludes that low-carbon hydrogen from renewable energy sources has the potential to become cost-competitive with low-carbon hydrogen from natural gas by 2030. Other studies, such as those by Degirmenci et al. [13], focus on the critical impact of hydrogen use on airport infrastructures and the cost of hydrogen storage, noting that the optimal supply chain will depend on airport location and feedstock accessibility.

In light of these uncertainties, policymakers should strive to provide adequate incentives to support the ecological transition, in line with the objectives of the Advisory Council for Aviation Research and Innovation in Europe (ACARE) [14]. A first step in this direction has been taken by the European Emissions Trading Scheme (ETS). Employing a market-driven strategy, the ETS encourages a reduction in GHG emissions through the trade of emission allowances, which translates into a surcharge on carbon emissions [15]. On 1st May 2023, the carbon price was 90 USD per metric ton of equivalent CO2 emitted [15], but it is expected to increase steadily in order to pursue the target of reducing GHG emissions by 55% for 2030 [14]

A similar argument applies to the need for targeted policies aimed at discouraging the use of conventional aircraft in favor of hybrid-electric ones. Some European airports have individually adopted charging systems that weigh on polluting emissions, but at the moment they do not yet represent a standard: at the end of October 2022, out of the 3174 global airports in AirportCharges, only 43 had adopted emissions-based charges [16]. To take into account possible incentives from authorities and airports, Scholtz et al. model a climate toll charging system based on the mitigation of standard air navigation charges, as a linear function of the aircraft's degree of hybridization [17]. In general, the evolution of navigation and airport charges for hybrid-electric aircraft constitutes a further source of uncertainty that cannot be overlooked.

Beyond the role of policymakers in influencing the ecological transition, a crucial role is also played by aircraft designers. As articulated by Kundu [18], the commitment to cost-consciousness starts in the conceptual design phase, where an accurate preliminary cost estimate enables thoughtful consideration of design choices. In this sense, designers have the responsibility to evaluate the economic implications of their decisions since the preliminary design stages, underlining the need for simple but effective and general methods and approaches.

Fortunately, numerous standardized methods for estimating operating costs exist in the literature, such as the *Air Transport Association* (ATA) method [19] or the *Association of European Airliners* (AEA) method [20]. However, for alternatively powered aircraft, many of the available standard methods fail due to the lack of statistics based on real data, thus requiring a careful selection and generalization. For instance, the impact of powertrain hybridization on cost could be evaluated by considering only its effect on the structural and maximum take-off weights. However, additional acquisition and maintenance costs associated with the use of innovative aircraft components should also be taken into account but this is often not done exhaustively.

Various authors have proposed different approaches to account for such cost contributions. Zhang et al. model the acquisition and maintenance costs of electrical components as additive to the costs of conventional components and included battery replacement costs among maintenance expenses [21]. However, the study does not consider any additional maintenance costs, e.g. linked to electric machines and power electronics, nor the influence of the reduced thermal power requirements due to hybridization on the maintenance cost of combustion engines [19]. The work of Monjon et al. [22] evaluates the costs for a 19-seat all-electric aircraft based on the *DOC+I* method proposed by NASA from McDonnell Douglas. However, the authors only consider the battery costs for the electric configuration, neglecting the effect of hybridization on maintenance operating costs. The work proposed by Fioriti et al. follows a task-based approach for the estimation of maintenance costs, concluding that electrification can lead to significant reductions in operational expenditures (OPEX) of regional transport aircraft [23]. In the case of hybrid-electric powerplants, the authors assume a fixed percentage reduction in maintenance costs compared to a similar conventional aircraft, rather than tying the estimate to the specific architecture. Other authors roughly approximate the maintenance cost of hybrid-electric aircraft as a fraction of the maintenance cost of conventional aircraft [24]. Schuh et al. [25] investigate the economic viability of a 19-seat electric commuter aircraft from an operator's perspective. Their approach relies on various cost assumptions for operating expenses instead of using estimation relationships that could be applicable to a business model, not providing any useful feedback for the aircraft design process.

In summary, the review of the state of the art highlights a lack of consolidated methods for estimating the costs of innovative aircraft. This clashes with the importance of carefully considering economic feasibility, in order to avoid erroneous conclusions about achievable levels of environmental sustainability. In this sense, the present article first proposes in Section 2 a novel approach for the estimation of the aircraft's DOCs. Particular attention is paid to the estimation of capital expenditures (CAPEX) and maintenance costs, generalizing their definitions while remaining consistent with the case of conventional architectures. In addition to being useful for the purposes of the prospective study of interest, the proposed workflow is also reusable by aircraft designers within multidisciplinary design and analysis chains. Following, the application on a 50-passenger turboprop platform presented in Section 3 provides insights into the economic impact of hybridization for small regional aircraft. Here, future scenarios are presented along with economic assumptions consistent with current trends and forecasts, which serve as input for the cost analysis. The results of the cost analysis are presented in Section 4. Contrary to what is generally done in the literature, the investigated hybrid-electric airplanes are not the product of retrofitting but have been rather designed from scratch, representing an optimized use of innovative technological solutions at the aircraft level [1] in compliance with minimum market-driven top-level aicraft requirements (TLARs) [26]. In this way, this study aims to provide an extensive comparative and prospective analysis of different scenarios towards which regional aviation could transition, identifying the most competitive solutions from an economic point of view. This aircraft-level analysis intends to provide an overview of the future prospects for the regional class, in the absence of equally detailed studies in the literature. In this sense, for each scenario, the different cost items are dissected and analyzed, delving into the aspects of acquisition, maintenance, energy consumption, and overall operational efficiency for hybrid-electric aircraft. Although the presented analyses have a predictive nature and are based on current trends and expert estimates, considerations of uncertainty are included as well. The results of the study will ultimately be useful to inform strategic decision-making, foster innovation, and pave the way for a sustainable and economically viable future for aviation.

## 2. Materials and methods

In the vast body of literature, numerous methods for estimating operating costs exist. Most of these classify the different cost items according to their level of influence on the operating cost of the aircraft. Several cost elements, such as fuel expenses, maintenance costs, depreciation, and noise-related charges, are directly influenced by aircraft-related factors, including its size and total mass. These expenses fluctuate based on the specific aircraft's performance and usage. On the other hand, certain cost items, including ticketing, sales, promotional activities, passenger services, and others, are not directly associated with the aircraft itself and are unrelated to its unique characteristics. In this sense, aircraft's Total Operating Cost (TOC) can be broken down into two key categories as mathematically expressed by Eq. (1).

$$TOC = DOC + IOC \tag{1}$$

where $TOC$ represents the Total Operating Cost, which encompasses all costs associated with operating the aircraft; $DOC$ stands for Direct Operating Cost, representing the immediate expenses directly linked to the aircraft's operation; and $IOC$ stands for Indirect Operating Cost, encompassing costs that are indirectly associated with the aircraft's operation. These cost components are crucial for the financial success and sustainability of airline operations. Using the classical nomenclature proposed by Jenkinson [27], the DOC primarily encompasses expenses related to flight operations. These include fuel costs, expenditures for flight crew and cabin crew salaries, maintenance expenses, depreciation of aircraft, interest on loans, and insurance premiums. Additionally, modern-day airline operations must factor in additional costs, such as landing fees, carbon and noise taxes, and various government charges (e.g., navigation fees). These charges are essential components of the overall operational expenses faced by airlines. In contrast, the IOC encompasses all remaining operating expenses that are not directly tied to the aircraft itself or its specific characteristics. This cost item includes expenses related to the depreciation of ground facilities and equipment, expenditures for sales and customer service activities, as well as administrative and overhead costs.

In the next sections several methods are described for the calculation of both DOC and IOC. The methods have been adapted and compiled by the authors into a single analysis workflow, with the capability to estimate the operating costs of a generic aircraft configuration at the early stages of its design workflow. Fig. 1 summarizes the cost items considered in this study. However, most of the focus is on estimating DOCs, since they provide a more targeted and immediate insight

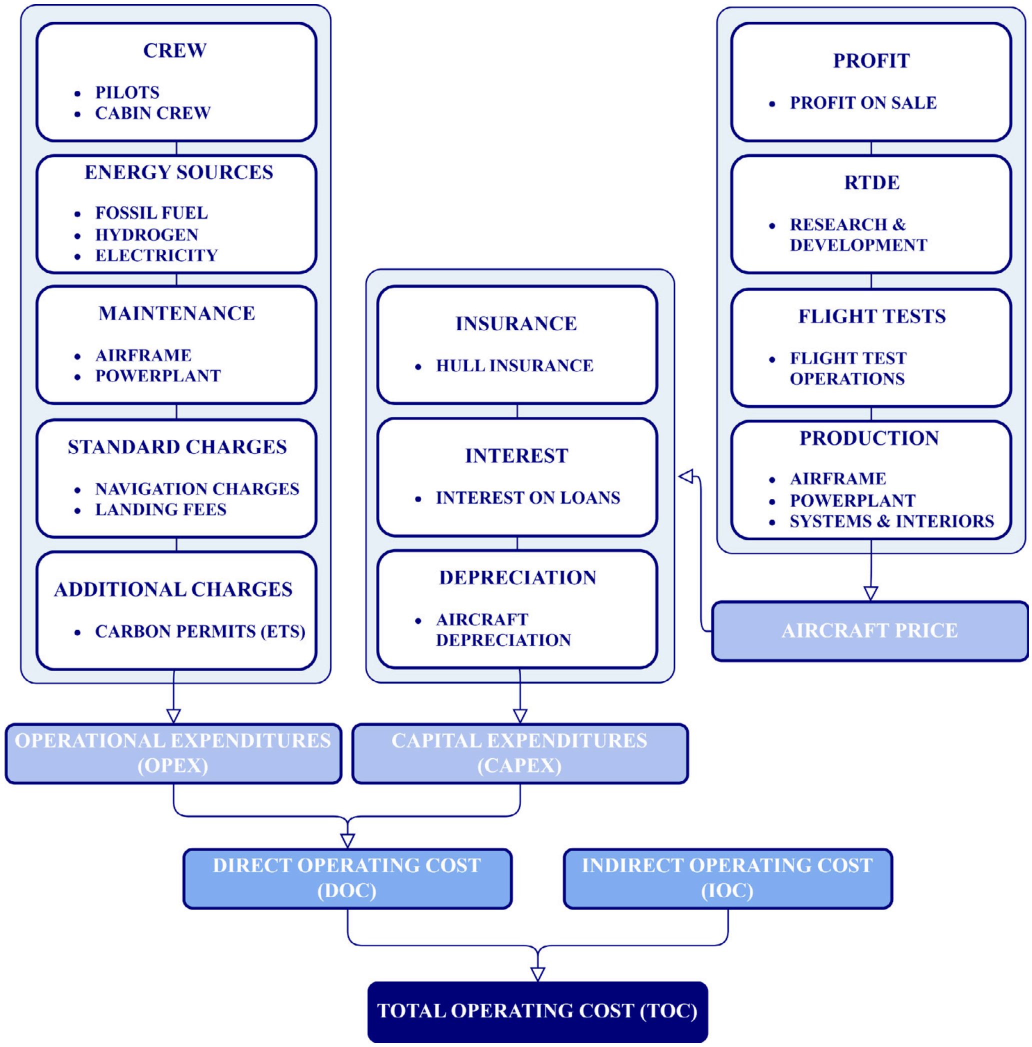


**Fig. 1.** Components of the total operating cost of an aircraft considered in the present work.

into the ongoing operational expenses associated with the aircraft's regular flights. The proposed approach has the advantage of being general and valid for any propulsion architecture, detailing cost items usually overlooked while remaining faithful to the most widespread standard methods. Before applying the analysis workflow to the purposes of the prospective studies of the next chapter, the workflow has been validated on the basis of data available for a conventional airplane in the same category as the case study. The outcome of the validation is reported in Section 2.3.

### 2.1. Indirect operating costs

Precisely estimating IOC can be challenging, as these costs are closely linked to how an airline chooses to manage its operations. In contemporary methods, IOC is often modeled as a percentage of the overall operating costs. Consequently, the TOC of an aircraft is influenced by various factors, including fuel consumption, maintainability, reliability, noise emissions, and the total time the aircraft spends in service. For the purposes of this work, the method proposed by Sforza is considered [28], having the advantage of relating the IOC to a few overall mission and aircraft parameters, likely available from the early stages of the aircraft design. These include the design mission range, the maximum take-off mass (MTOM) of the aircraft, and the number of passengers, also taking into account the expected load factor (LF).

### 2.2. Direct operating costs

While the DOC represents only one facet of the economic profitability of an airliner or private aircraft, it warrants significant attention. This emphasis is justified due to several factors contributing to DOC being directly linked to the technical and operational characteristics of the aircraft. Importantly, these factors are within the direct control and influence of the design team [29]. Therefore, meticulous consideration and optimization of DOC-related components during the aircraft's design phase can significantly impact the overall economic viability of the aircraft. In this context, the DOC will be further broken down into two main cost items, representing CAPEX and OPEX, as shown in Eq. (2).

$$DOC = DOC_{CAPEX} + DOC_{OPEX} \tag{2}$$

While CAPEX is directly connected to aircraft ownership, OPEX is directly related to the operation of the aircraft during its operational life. Eqs. (3) and (4) further detail the compositions of CAPEX and OPEX.

$$DOC_{CAPEX} = DOC_{Depreciation} + DOC_{Insurance} + DOC_{Interest} \tag{3}$$

$$DOC_{OPEX} = DOC_{Energy} + DOC_{Crew} + DOC_{Maintenance} + DOC_{Charges} \tag{4}$$

The next subsections explain in more detail the individual cost components featuring in Eqs. (3)–(4).

#### 2.2.1. Capital expenditures

The process of estimating the capital costs for acquiring a new aircraft is a multifaceted effort, and it often begins with determining an estimate of the aircraft's market price. In the aviation literature, various methods have been devised for statistically estimating the price of aircraft. One such method, presented by Jenkinson et al. [27], offers a straightforward approach. Jenkinson's method establishes a linear relationship between the aircraft's market price and its operational empty mass. However, it is essential to note that this relationship primarily helps determine the market price of the aircraft and does not provide insights into the actual manufacturing costs. Jenkinson's approach also establishes a correlation between engine price and key engine parameters such as cruise thrust and specific fuel consumption. This correlation is applicable primarily to jet engines and allows for a rough estimation of the airframe's cost by subtracting the engine price from the total aircraft cost. Similarly, Sforza has developed an approach akin to Jenkinson's but incorporates more contemporary data to establish a correlation between aircraft price and operational empty mass [28]. Unfortunately, like Jenkinson's method, Sforza's approach focuses on estimating costs at the aircraft level and does not offer specifics on the isolated propulsion system costs. Recognizing the need for approaches that enable the estimation of development and production costs of the airframe independently of the market value of the complete aircraft, the authors have sought alternatives. One such noteworthy cost model is presented by Roskam [30]. Roskam's method is versatile and can be applied to estimate costs for both military and civil aircraft programs. Roskam's cost equations are characterized by their exponential nature, with primary variables including the aircraft's mass, maximum speed, and production rates. Additionally, Roskam provides relationships for estimating the costs of different engine types, encompassing turbofan, turboprop, and piston engines, as well as a distinct estimate for propellers. For the purposes of the present application, Roskam's method has been deemed the most suitable choice for estimating the cost of the airframe and the conventional portion of the propulsion system. Roskam's definition of the aircraft price can be summarized as in Eq. (5).

$$Price_{Aircraft} = C_{Production} + C_{FT,Prod.} + C_{RDTE} + Profit \tag{5}$$

where $Price_{Aircraft}$ represents the estimated market price of the aircraft, $C_{Production}$ is the production cost, $C_{FT,Prod.}$ encompasses the cost of flight test operations, and $C_{RDTE}$ covers Research, Development, Test, and Evaluation (RTDE) expenses. The program development cost, represented by $C_{RDTE}$, is influenced by the complexity of the aircraft under analysis. This initial investment is recovered by the manufacturing company through the sale of a break-even production quantity of aircraft [30]. Breaking down the cost of aircraft production further:

$$C_{Production} = C_{Airframe} + C_{Powerplant} + C_{Systems} + C_{Interiors} \tag{6}$$

Roskam's method elaborates on estimating the various cost components mentioned in Eqs. (5)–(6), which, for the sake of brevity, are not detailed in this document [30]. The primary data required for aircraft price estimation encompass manufacturing and engineering hourly labor rates, aircraft mass, maximum cruise speed, and a few other high-level descriptive parameters of the aircraft. In particular, as for estimating the cost of the powerplant, Roskam provides empirical formulas mainly applicable to conventional (turboprop) engines and propellers. Having a breakdown of the powerplant costs for conventional components available, this approach can be easily generalized for hybrid-electric architectures by simply summing the estimated cost of all-electric components. For the purposes of the present work, a generic approach is adopted based on unit pricing. In this context, unit prices could pertain to unit power or unit capacity, depending on whether the component represents a power exchanger or a storage system. Thus, the acquisition cost of a generic electric component is represented by Eq. (7):

$$C_{Electric\ Component} = N_{Components} \cdot Price_{Unit} \cdot Size \tag{7}$$

where $N_{Components}$ represents the number of units of the same type, and the $Size$ parameter can be expressed in different measurement units depending on the definition of the unit price $Price_{Unit}$ (e.g., USD/kW for power exchangers or USD/kWh for energy storage systems). This definition is applicable to various powertrain components, including electric storage devices, power electronics, electric motors, electric generators, and fuel cell systems.

Once the price of the aircraft has been estimated, it is possible to estimate the CAPEX associated with the single flight performed, as expressed by Eq. (3). Depreciation reflects the fact that the aircraft is losing its initial value through time and it can be sold at any moment to its residual value. In Eq. (8), $Lifespan_{Aircraft}$ is the expected lifespan of the aircraft expressed in years, $RV_{Aircraft}$, is the residual value of the aircraft at the end of life, and $N_{Flights,Year}$ is the number of flights per year. The aircraft residual value can be assessed by considering the expected lifetimes of its components and the evolution of their value over time. When the lifetime of any component is longer than the aircraft lifespan, it contributes to the aircraft residual value provided that it has not completely depreciated over time.

$$DOC_{Depreciation} = \frac{Price_{Aircraft} \cdot (1 - RV_{Aircraft})}{Lifespan_{Aircraft} \cdot N_{Flights,Year}} \tag{8}$$

The cost of insurance (Eq. (9)) is calculated starting from the value of the total initial investment and the insurance premium rate, $Premium$.

$$DOC_{Insurance} = \frac{Investment \cdot Premium}{N_{Flights,Year}} \tag{9}$$

Finally, the interest cost (Eq. (10)) refers to the payments or fees claimed as interests on loans. It can be calculated by applying an interest rate $Rate_{Investment}$ to the value of the total initial investment, over a specific interest period expressed in years ($Period_{Interest}$).

$$DOC_{Interest} = \frac{Investment \cdot Rate_{Interest} \cdot Period_{Interest}}{Lifespan_{Aircraft} \cdot N_{Flights,Year}} \tag{10}$$

where the total investment may represent the price of the aircraft including additional spares.

#### 2.2.2. Energy sources

For a precise and accurate cost estimation, it is imperative to begin by acquiring knowledge of the current fuel and electricity prices. Typically, fuel prices are expressed in USD per gallon in the United States, or Euros per liter in Europe, and this data must be obtained for the specific year in which the cost estimation is needed. The International Air Transport Association (IATA) website provides reliable and up-to-date fuel price information [31]. However, the source does not provide forecast prices, so further research is necessary to conduct predictive analyses for future scenarios. In addition, the introduction of alternative energy sources for propulsion requires a generalization of this cost item, making it necessary to give the broader definition of *energy costs*. The cost of each energy source, whether conventional kerosene, SAF, hydrogen or electricity, may be conveniently expressed in cost per unit of available energy.

$$DOC_{Energy} = Price_{Energy,Unit} \cdot Requirement_{Energy} \tag{11}$$

For instance, in Eq. (11) $Price_{Energy,Unit}$ is expressed in USD/kWh provided that the mission energy requirement $Requirement_{Energy}$ is expressed in kWh. When multiple energy sources are used to complete the same mission, for example the hybrid-electric aircraft, the total energy cost is given by the sum of the individual contributions of each energy source used.

### 2.2.3. Crew

The *crew cost* includes the salaries of the cockpit and cabin staff. As a first approximation, the crew cost can be obtained simply by multiplying their salary by the number of crew members.

$$DOC_{Crew} = \frac{Salary_{Pilots} \cdot N_{Pilots} + Salary_{Attendants} \cdot N_{Attendants}}{N_{Flights,Year}} \tag{12}$$

where $N_{Pilots}$ and $N_{Attendants}$ represent the numbers of pilots and flight attendants, respectively. However, it is worth noting that the number of wages to be paid is not simply equal to the number of staff members needed on board for a flight. In fact, according to European regulations, the number of flight hours for each member cannot exceed 900 h in the same calendar year [32]. This aspect has been taken into consideration in calculating the crew cost, through an increase in the number of staff members based on the number of expected flight missions.

### 2.2.4. Maintenance

Prediction of maintenance costs poses challenges due to the absence of a standardized definition for items falling under this category. Indeed, estimating the overall costs involved has always been a complex endeavor, primarily owing to the diverse nature of maintenance tasks across different aircraft and the inherent variations in operational contexts. In practice, maintenance tasks are often further subdivided into airframe and engine components. A well-known approach is the one put forth by ATA [19]. The method consists of an integrated approach capable of estimating labor and materials for both (conventional) engines and airframe maintenance as a whole, encompassing costs associated with routine inspection, servicing, and overhaul activities related to airframes, engines, avionics, systems, and more. Given its simplicity of implementation, the reduced number of parameters required, and above all the high level of standardization, the ATA method has been preferred for the present application. The interested reader may refer directly to the source for estimating relationships.

When estimating the DOC for hybrid and electric architectures, the ATA estimation approach requires complements to its methodology to account for electric systems, including components such as batteries, fuel cell systems, electric machines, and power electronics [17,21]. In the present work, the maintenance costs of the electrical components are considered additive to the conventional cost items. Notably, while internal combustion engines often have lifespans equal to or longer than the aircraft they power, this is not the case for specific electrical components like batteries. In such cases, the cost of replacements is considered within maintenance expenses rather than as additional acquisition costs [21]. To summarize all these aspects, a general formula for the estimation of the DOC per unit flight has been implemented in Eq. (13). In the equation, $N_{Replacements}$ represents the number of replacements expected during the service life of the aircraft and depends on the expected service life of the component itself. The cost of each replacement is modeled as the cost of acquiring a new unit, less any recovery obtainable from the residual value of the discarded component, $RV_{Component}$. Furthermore, additional base maintenance costs can be taken into account by considering a maintenance labor rate, $LR_{Maintenance}$, the maintenance hours required, $t_{Labor}$, and the maintenance frequency, $f_{Maintenance}$, expressed as reciprocal of the number of flights before the next check. The formula is valid for a generic hybrid-electric component of the propulsion system.

$$DOC_{Maint,Component} = \frac{N_{Replacements}\left(Price_{Component} - RV_{Component}\right)}{Lifespan_{Aircraft} \cdot N_{Flights,Year}} + LR_{Maintenance} \cdot t_{Labor} \cdot f_{Maintenance} \tag{13}$$

### 2.2.5. Charges

In this context, *standard charges* include navigation charges and landing fees. Ground handling charges have not been considered in this analysis. However, they are generally proportional to the number of passengers, so their value would be the same for all the configurations analyzed below, which therefore remain perfectly comparable. Navigation charges are prescribed by EUROCONTROL and are an increasing function of the maximum take-off weight and the distance flown [33]. The value of the charge depends in part on the departure airport and the specific route, making it difficult to have a general way to evaluate it in advance. The same applies to landing fees, which are levied differently by each airport. Generally, they are also a function of the mass of the aircraft and the number of passengers. To eliminate the dependency of both navigation charges and landing fees on specific airports, the AEA method is adopted [20].

Finally, additional charges cover the equivalent CO2 emissions charges according to the ETS [15]. In Eq. (14), $Price_{Carbon,\ Unit}$ is the CO2 allowance price, while $Mass_{CO2,\ Flight}$ is the produced mass of CO2 emissions during each flight. The additional factor $k_{ETS}$ takes into account the fraction of free-assigned emission certificates. For the purposes of the study conducted in the next chapter, a unit factor will be assumed for conventional aircraft, and a factor equal to zero in the case of exclusive use of alternative fuels (SAF or hydrogen).

$$DOC_{ETS} = Price_{Carbon,\ Unit} \cdot Mass_{CO2,Flight} \cdot k_{ETS} \tag{14}$$

### 2.2.6. Inflation

When collecting data and economic assumptions for economic assessments, they are often drawn from heterogeneous sources that refer to different geographical contexts and reference years. For this reason, the presence of the *inflation* effect poses a significant risk to the accuracy of economic calculations, introducing a dynamic element that can distort the real value of monetary metrics over time if the economic assumptions do not refer uniformly to the same level of inflation. Therefore, it is important to preliminarily correct all assumptions for inflation. In this work, an inflation correction factor has been systematically applied to each collected value, reporting all costs in equivalent USD for the year 2020 (2020USD). The correction is proposed in Eq. (15).

$$C_{2020} = C_{Reference\ Year}\,\frac{CPI_{2020}}{CPI_{Reference\ Year}} \tag{15}$$

The same relationship is also used to correct all DOCs and estimates produced by the adopted estimating relationships, already presented in this section. For example, methods for estimating aircraft price [30] and standard charges [20] refer to the economic year 1989. The ratio between the Consumer Price Index (CPI) in 2020 and the one in 1989 is 2.09, meaning that 1 USD in 1989 is worth 2.09 USD in 2020 [34].

## 2.3. Workflow calibration

In order to validate the analysis workflow, a case study has been selected and analyzed. The reference aircraft is the ATR42-500, similar to today's reference baseline used for the application provided in this work. ATR reports the results of an internal evaluation of the DOC associated with the aircraft for a 300 nmi mission [35]. In order to reproduce the study, the same main technical and economic assumptions reported by the source have been used and are reported in Table 1. The missing assumptions, however, have been made in harmony with those that are presented later in Section 3.1. In addition to this, no additional charge coming from carbon permits has been considered. The costs of crew, maintenance, navigation charges, and landing fees are estimated rather than assumed as by ATR [35]. In the ATR analysis, ground handling charges have been neglected, and the same has been done in the present study.

Fig. 2 shows a good match between the calculated cost and the expected results. The good agreement on the CAPEX can be traced back to a reasonable estimate of the price of the aircraft. As a matter of fact, the estimated price for the aircraft is 12.3 million USD. To have feedback on the quality of this result, it can be considered that the catalog price of the ATR42-500 reported by Jane's All World Aircraft 2007–2008 [36] was 14.0 million USD in 2004 [37]. However, it is typical

**Table 1**
Main economic assumptions for the cost workflow validation [35].

| | Value | Units |
|---|---|---|
| Range | 300 | nmi |
| Fuel price | 2.06 | USD/gal |
| Spares | 10% aircraft price | – |
| Depreciation | 12 years with 20% residual value | – |
| Financing | 85% of investment over 10 years | – |
| Insurance | 1% of aircraft price per year | – |
| Block fuel (incl. taxi) | 797.0 | kg |
| Block time (incl. taxi) | 1.28 | h |
| Turnaround time | 0.42 | h |
| Annual utilization | 1800 flights per year | – |

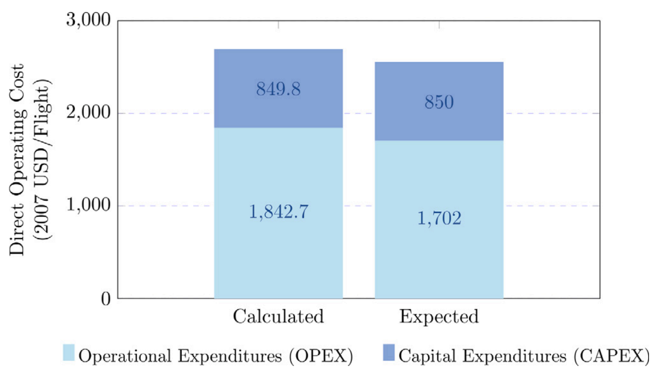


**Fig. 2.** Comparison between calculated direct operating cost (DOC) and expected values. The case study is an aircraft similar to the ATR42-500 [35].

for an aircraft manufacturer to apply discounts to the value reported in the catalog. ATR reports a discount of 10% of the catalog price [35]. Taking these data into account, the value estimated by the developed workflow is only 3.3% higher than the real price. This error can be further reduced when one considers that the applied methodologies appears to underestimate the cost of program development, with an estimate of 24 million USD versus 50 million USD reported by Jackson et al. [36]. In fact, when considering the real development cost instead of the calculated one, the 3.3% difference reduces to 0.6%. Fig. 3 shows a more detail breakdown of the operating expenditures. The 4.0% error on crew cost is explained by the assumption of a different annual salary, not explicitly reported by ATR. The error on the charges, also small (5.2%), can be easily explained by considering the statistical nature of the relationships used by the adopted methodologies. The same argument applies to the error committed on airframe and powerplant maintenance, equal to 69.3% and 45.2%, respectively. Although the maintenance cost error is high, this cost item accounts for just 18.7% of the total OPEX, which translates into an error of only 10.6% on the OPEX and about 7.0% on the total cost. In conclusion, the predictions seem to be in satisfying agreement with the expected values, which is even more relevant, being the case study relative to an aircraft in the same class as the present application. This would be sufficient for the comparative analysis, which is the object of the next chapter. However, the statistical models for development cost, charges and maintenance costs have been calibrated through corrective scale factors in order to cancel the percentage errors relating to the case study. The same calibration factors have been used to obtain all the results, which are presented in the next chapter.

## 3. Economic study of future scenarios

The environmental impact of aviation has gained public attention in the last few years. In addition, the foreseen financial benefits of increased energy efficiency have motivated the transport industry to

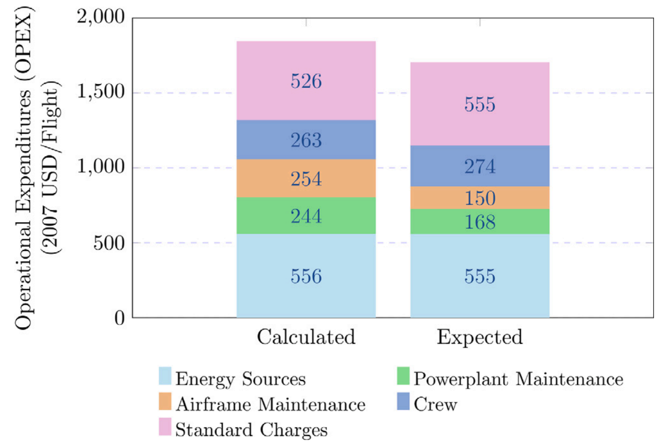


**Fig. 3.** Comparison between calculated operational expenditures (OPEX) and expected values. The case study is an aircraft similar to the ATR42-500 [35].

invest in propulsion alternatives. In the context of the GENESIS project, different scenarios have been defined on the basis of foresight technology analyses aimed at identifying the most promising available technologies for three different time horizons [1], i.e., the ones with the highest expected Technology Readiness Level (TRL). The forecasting has been based on current trends, historical data, and expert opinions, as well as the theoretical limit of existing technologies, to extrapolate their performance for three different Entry Into Service (EIS) years. More details about the estimated TRLs and the consequent technology assumptions for each scenario are reported in the appendix section. In parallel, a predictive market analysis has been performed, aimed at identifying possible future operational scenarios and the parameters that could make the final product economically attractive. The focus is on a 50-passenger regional aircraft, so the ATR42-600 has been identified as a reference aircraft for major design decisions [26]. Moreover, the market analysis has made it possible to define technical benchmarks helpful in identifying a complete set of TLARs, which have served as boundary conditions for the following multidisciplinary design and analysis activities [26]. Then, the most promising technologies with a sufficient technology readiness level have been considered, and several innovative configurations have been designed and analyzed for each of the three different time horizons:

- Short-term (EIS 2030):
  - Conventional aircraft with Internal Combustion Engines (ICE).
  - Hybrid-electric configuration with ICE, lithium-ion (Li – Ion) batteries and Distributed Electric Propulsion (DEP).
- Medium-term (EIS 2040):
  - Conventional aircraft with ICE.
  - Hybrid-electric aircraft with ICE, lithium-sulfur (Li – S) battery and DEP.
  - Hybrid-electric aircraft with Proton-Exchange Membrane Fuel Cells (PEMFC), Li – S battery, pressurized hydrogen (H2) tanks and DEP.
- Long-term (EIS 2050):
  - Conventional aircraft with ICE.
  - Hybrid-electric aircraft with PEMFC, lithium-air ($Li – O_2$) battery, cryogenic H2 tanks and DEP.
  - Hybrid-electric aircraft with Solid-Oxide Fuel Cells (SOFC), $Li – O_2$ battery, cryogenic hydrogen tanks and DEP.

Each of the listed configurations has been designed in compliance with the same set of TLARs, using an approach based on the analysis of the design mission. In particular, each of the configurations is capable of covering a range of up to 600 nmi with 50 passengers, although the typical mission for this category of aircraft is around 200 nmi [26]. The degree of hybridization and the geometry of each concept have been determined through extensive design explorations aimed at minimizing fossil fuel consumption and direct pollutant emissions [1]. An innovative design workflow developed by the University of Naples "Federico II" has been used for this purpose. The interested reader may refer to the work of Marciello et al. [1] for further insights into the design process and mass and propulsion characteristics of each configuration.

The design and analysis activities have revealed very promising potential advantages of hybrid-electric solutions in terms of climate change impact mitigation, which could meet the short and long-term objectives envisaged by ACARE's agenda [14]. However, as highlighted in Section 1, DOCs play a leading role in determining the commercial success of an aircraft. Therefore, the present work aims to apply the methodologies discussed in Section 2 in order to evaluate the economic feasibility of the analyzed scenarios. It allows for determining the feasibility of a transition to more environmentally sustainable solutions or a set of recommendations and actions needed to remedy the difference between the economic convenience of conventional and innovative solutions.

Starting from the configurations listed above for the three different time horizons, several economic scenarios have been defined. In particular, for conventional or hybrid-electric configurations using internal combustion engines, distinct scenarios have been considered depending on whether pure kerosene or 100% blend of SAF is used. The SAF mixture composition and its expected cost are hypothesized as a function of the time horizon. This, along with other economic assumptions, are discussed in more detail in the next section. To consistently manage the different time horizons, the unit of measurement adopted is the US dollars, with a fixed reference level for inflation relating to the year 2020. The DOC per flight unit has been selected as the reference metric.

### 3.1. Economic assumption

For the purposes of cost estimation, several economic assumptions are necessary. The focus of this study is on the calculation of DOC rather than TOC, which means that only cost items directly related to the aircraft operation have been considered. In addition to that, ground handling charges have not been considered. The number of flights per year has been estimated starting from a statistical relationship between the range and the number of hours of annual utilization, provided by the AEA for short-medium range aircraft [20]. In this case, the method leads to an average of 6 flights per day for a 200 nmi typical mission. The 200 nmi mission is taken as a reference for the analyses conducted in Section 4. The above numbers of flights have been kept the same for all configurations in order to ensure homogeneity.

The need to estimate capital costs has led to the need to define some economic assumptions, which are reported in Table 2. Many of these assumptions have been taken from the same case study used for the validation since it refers to an aircraft similar to the reference baseline [35]. These include the cost of financing, the interest rate, and the insurance premium. Further economic assumptions have been made on the basis of values suggested by Roskam for the purpose of preliminary evaluations for different aircraft categories [30]. Among these, a profit margin of 10% has been considered for the sale of a new aircraft. Secondary information such as the aircraft production rate, which have an impact on the price of the aircraft when using Roskam's equations, have been used as calibration parameters to align the results of the cost tool result with the case study presented in Section 2.3. Then, the same values have been adopted for all the configurations analyzed in the study. Finally, a lifetime of 20 years has been assumed for all the aircraft analyzed, with no residual value for the airframe and the systems.

**Table 2**
Main economic assumptions for the analysis of future aircraft scenarios.

| | Value | Units |
|---|---|---|
| Airframe spares | 10% airframe price | – |
| Systems spares | 10% systems price | – |
| Depreciation | 20 years | – |
| Financing | 85% of investment over 10 years | – |
| Insurance | 1% of aircraft price per year | – |
| Interests on loans | 5% of initial investment per year | – |
| Profit on sale | 10% of aircraft price | – |
| Pilot annual salary | 74 730 | 2020USD/year |
| Crew annual salary | 47 730 | 2020USD/year |
| Engineering labor rate | 43.56 | 2020USD/h |
| Manufacture labor rate | 24.80 | 2020USD/h |
| Maintenance labor rate | 31.30 | 2020USD/h |
| Maintenance frequency | Every 500 flights | – |

**Table 3**
Main economic assumptions for electric storage systems.

| Technology | Units | Short-term (EIS 2030) Li–Ion | Medium-term (EIS 2040) Li–S | Long-term (EIS 2050) Li–$O_2$ |
|---|---|---|---|---|
| Unit price | 2020USD/kWh | 100.0 | 79.0 | 61.0 |
| Lifespan | years | 3.0 | 2.0 | 2.0 |
| Residual value | % | 21.6 | 28.4 | 22.0 |

Estimates of the salaries of pilots and cabin crew members have been derived from publicly available statistics. The average salary of captain and first officer is obtained by averaging the salaries of 12-year experienced pilots from several regional airlines, updated to 2022 [38]. For the configurations analyzed, the presence of a flight attendant is foreseen, whose salary has been assumed based on the information reported by the U.S. Bureau of Labor Statistics [39]. Other relevant labor rates have been derived from Ref. [40], where the US Bureau of Labor Statistics reports wage estimates for several occupations in the aerospace sector. In particular, the engineering, manufacturing and maintenance labor rates have been assumed as the median hourly wages for "industrial engineers", "production occupations" and "Installation, maintenance and repair occupations" respectively [40]. These values, net of inflation, have been considered constant for all time horizons. For this application, it has been assumed that one maintenance check in the hangar takes place every 500 flight hours [41].

The capital cost associated with thermal engines is evaluated by applying the estimating relationships discussed in Section 2. A residual value of 20% and a cost of spares equal to 30% of the nominal price have been assumed [27].

Data on the price of innovative technology components for future time horizons come from the Life Cycle Inventory (LCI) databases built within the GENESIS project [2]. Main assumptions related to electric storage systems are reported in Table 3. An expected lifespan of the batteries between 2 and 3 years has been considered [42]. The unit price of batteries has been derived from current values and trends based on expert assumptions [43,44]. The cost of replacements, intended as maintenance cost, has been evaluated considering the forecast market price at that point in time, including inflation and the residual value of the component replaced. The residual value at the end of life has been assessed considering a yearly depreciation rate of 40% [42]. Last but not least, installation costs have been assumed to be equal to 10% of the battery price based on expert assumptions [45].

The unit cost of the PEMFC system has been derived from expert estimations [2,46] and is reported in Table 4. Data reported by the U.S. Department of Energy [47] for a 100 kW system, and by NOW GmbH relating to the fuel cell value chain [48], served as a guidance to derive these assumptions. The sources refer to stationary fuel cells for

 

**Table 4**
Unit prices assumed for fuel cell systems.

| Technology | Unit | Medium-term (EIS 2040) | Long-term (EIS 2050) | |
|---|---|---|---|---|
| | | *PEMFC* | *PEMFC* | *SOFC* |
| Unit price | 2020USD/kW | 356.4 | 151.2 | 830.0 |

**Table 5**
Sustainable aviation fuel market mix used for each time horizon [37,54].

| | Short-term (EIS 2030) | Medium-term (EIS 2040) | Long-term (EIS 2050) |
|---|---|---|---|
| Biofuel | 100.0% | 92.0% | 72.0% |
| E-fuel | 0.0% | 8.0% | 28.0% |

heat and power generation but it has been assumed that similar stacks and systems can also be used for aircraft applications. The maintenance costs have been estimated for a complete stack replacement once in a lifetime and a contribution for each regular maintenance interval for the replacement of minor components (e.g., filters, cooling liquid, sensors, hoses, etc.) [46]. The unit cost for SOFC is based on data reported by the U.S. Department of Energy [47] for a 250 kW SOFC system and on the indication provided by Whiston et al. [49], whose review has also been exploited to get indications on maintenance cost. The price of fuel cells has been complemented with that of hydrogen storage, estimated starting from the cost breakdowns reported by Alves et al. [50]. Finally, a unit price of approximately 60.0 USD/kW has been assumed for electric machines and a unit price of about 250–280 USD/kW has been taken for power electronics for all time horizons, with slight variations depending on the specific component [51].

Data on the price of energy sources has been collected from several predictive studies. The price of kerosene, electricity, SAF, and hydrogen have been estimated based on the literature. Average, low, and high estimates have been extracted for each fuel and time horizon. The price of kerosene has been derived from the global oil price forecast from the International Energy Outlook 2021 and corrected by the estimated difference between the global oil price and the jet-A price between 2016 and 2019 [31,52]. The period of 2019–2023 has been excluded due to the large influence of the COVID-19 pandemic and the war in Ukraine, which have been assumed to have only residual effects on the prices between 2030 and 2050. The electricity price range has been taken from simulations reported by Capros et al. [9], which assumed that 80% to 100% of EU's GHG emissions are decreased in 2050 and which used the PRIMES energy-economics model. The low electricity price scenario corresponds to a mix of technologies (electrification, hydrogen, carbon neutral e-fuels, and energy efficiency measures) combined with circular economy and biofuels incentives in 2040 and the emergence of carbon neutral e-fuels in 2050. The high electricity price scenario corresponds to the strategy focused on energy efficiency in 2040 and the mix of technologies in 2050. The SAF price has been assumed to be equal to the cost of production, transmission and distribution in the absence of robust market price forecasts. First, the cost of hydroprocessed esters and fatty acids — synthetic paraffinic kerosene (HEFA-SPK) and Fischer–Tropsch e-fuels have been retrieved. The lack of price forecast can be attributed to the lower TRL of e-fuel conversion technology (Fischer–Tropsch with carbon capture) and the uncertainty on feedstock availability and price (palm oil and carbon capture and storage) [53].

The average cost of HEFA-SPK across feedstock for 2030 has been retrieved from Bullerdiek et al. and does not include any carbon price [5]. The low and high values correspond to different feedstock options. The values for 2040 and 2050 have been extrapolated, assuming a reduction of production costs of 15% per decade [7] because TRL and public policies are expected to foster biofuel market penetration. The average e-fuel price for 2030 and 2050 has been derived from Gonzalez-Garay et al. assuming that the production cost of Fischer–Tropsch e-fuel in Spain, using both direct air capture and point source capture as carbon source, are representative of European costs [6]. Moreover, the cost in 2040 has been interpolated linearly between 2030 and 2050 costs, hence assuming a linear decrease in costs. The price of SAF used in the cost analysis accounts for the blend of HEFA-SPK and e-fuels, assumed on the basis of the expected market mix for each time horizon and reported in Table 5 [37,54].

The production and distribution costs of hydrogen have been assumed to be good proxies for market prices in the absence of price forecasts. The average, low and high hydrogen prices in 2050 have been derived from JRC-EU-TIMES model simulations published by Blanco et al. [55]. The lower value corresponds to a scenario of −80% of GHG emissions, and the higher value to a scenario of −95% of GHG emissions with carbon capture and storage in the EU. Prices for 2030 and 2040 have been estimated, assuming a reduction of approx. 10% per decade [12]. The prices have been converted to 2020USD using an average inflation rate of 2% (except kerosene) as no specific inflation rate is provided in the references. The average exchange rate euro to USD in 2020 used in calculations is 1.142 [56]. Fig. 4 summarizes the assumptions on all the unit prices of energy sources for the three time horizons considered.

Finally, an increase in the cost of carbon allowances has been forecast compared to today's prices set by the EU's ETS. Based on the most recent regulatory actions decided by the European Commission, it is assumed that free allowances for the aviation sector will be phased out by 2030 and that the use of sustainable aviation fuel will be sped up, financed with twenty million free allowances [57]. Reference values for future time horizons have been assumed on the basis of forecasts made by BloombergNEF, with respect to the hybrid market scenario considered by the source [58]. This has led to a price of 200 USD/ton CO2-eq for 2030, 150 USD/ton CO2-eq for 2040 and 100 USD/ton CO2-eq for 2050. The uncertainty is defined on the basis of the range proposed by Ref. [58] considering different market scenarios. According to the source, offset prices will range between 11 USD and 215 USD per ton CO2-eq. in 2030, before narrowing to 47–120 USD/ton in 2050. This results in uncertainty ranging from −95%/+8% up to −53%/+20% for the long term, and which depends on the possible market behaviors. Added to this uncertainty is the possibility that the European Commission may actively intervene in order to further increase the carbon price. In July 2021, the Commission announced that the emission allowances will shrink by 2.2% per year from 2021 onwards, in order to increase the pace of emissions cuts [15]. However, in the current study, the carbon price is only taken into account for kerosene-powered aircraft, since SAF and hydrogen have been considered exempt from surrendering allowances [59].

## 4. Results and discussion

In this section, the results of the analysis conducted are reported in terms of DOC breakdown, for the different scenarios and time horizons considered.

### 4.1. Short-term horizon

Fig. 5 shows the breakdown of the DOC for the different scenarios considered in the short-term horizon with respect to a 200 nmi mission. The four scenarios are obtained considering two different alternatives for fossil fuel (kerosene or SAF) for both the conventional and the hybrid-electric configurations. As explained in Section 3.1, an increase in the cost of carbon allowances has been forecast for future time horizons. Except for this, no incentive has been applied to standard charges by virtue of the use of environmentally sustainable

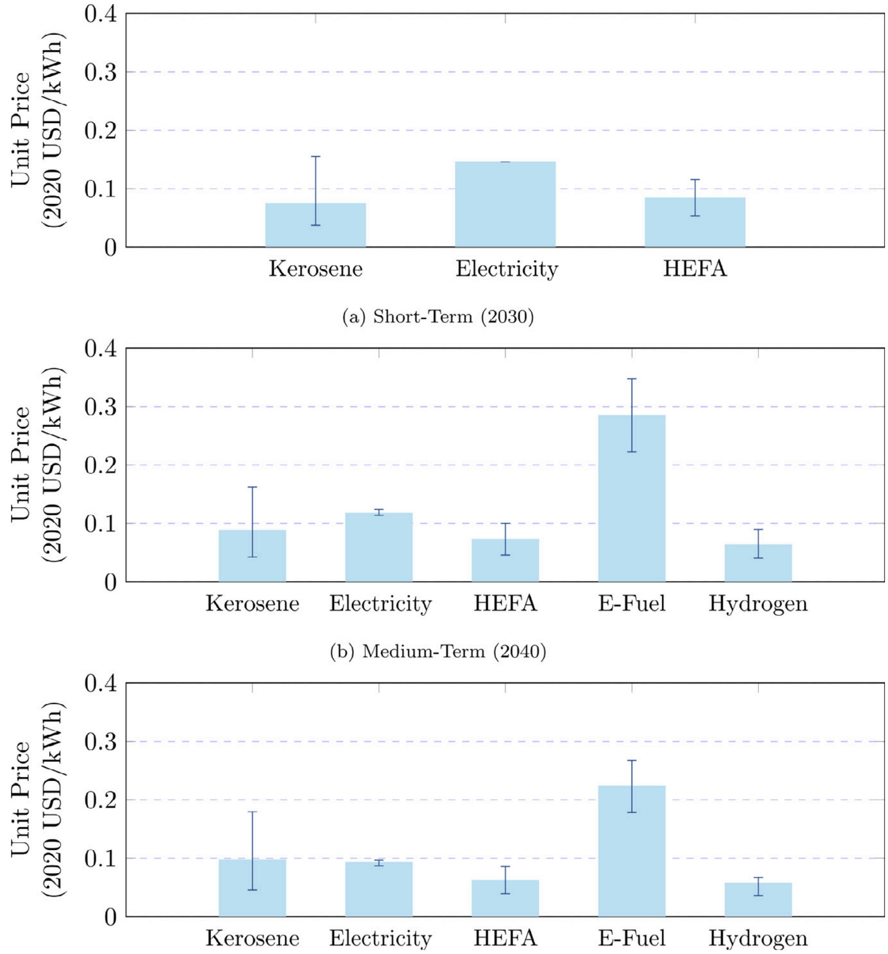


**Fig. 4.** Range of unit prices for each energy source and time horizon: kerosene [31,52], SAF HEFA-SPK [5,7], SAF E-fuel [6], hydrogen [55], electricity [9]. A reference specific energy of 33.3 kWh/kg is considered for hydrogen, while 12 kWh/kg is considered for kerosene and SAF.

technologies. It immediately emerges that the cost of hybrid-electric aircraft is much higher than that of conventional aircraft. The reason, rather than residing on a more complex and expensive powertrain, lies in the high development costs of an unconventional configuration and, above all, in the much greater mass of the aircraft. This drastic increase in the aircraft price is reflected in the capital cost per unit flight, which is 57.1% higher than in the conventional case. For the same reason, the costs of standard charges and airframe maintenance also show a significant increase, as they are related to the size of the aircraft. Considering the estimated fuel and electricity prices for the year 2030, it is worth noticing that the price of energy sources is higher for the hybrid-electric configurations than the conventional one using kerosene. Despite electricity is cheaper than fuel, the energy required for the mission is much higher for hybrid-electric configurations by virtue of their higher weight. For the scenarios where SAF is used instead of kerosene, the price of energy sources is higher in the former due to the higher price of SAF compared to kerosene. Nevertheless, the configurations with SAF show a lower total DOC, thanks to the exemption from the additional charges foreseen by the ETS. For example, the DOC of the conventional configuration with SAF is 7.5% lower than the same configuration using kerosene. Overall, the hybrid-electric configuration could only be advantageous if specific taxation policies were applied to discourage the use of conventional configurations. Under the hypothesis that navigation taxes and landing fees are not applied differently for innovative aircraft, the ICE-bat configuration with SAF could only be advantageous if the price of carbon permits rises to 580 USD/ton CO2-eq., compared to the 200 USD/ton CO2-eq. forecast for 2030. Unless this happens, it may be concluded that the best solution in the short term is, from an economic point of view, a conventional configuration with intensive use of SAF. However it is important to note that the presented results do not include considerations about the uncertainty on the main economic assumptions, especially in relation to the price of energy sources already discussed in Section 3.1. It is here anticipated from Section 4.4 that, even taking uncertainties into account, conventional aircraft using SAF are the best candidates to compete with kerosene-based alternatives in the short-term, but the latter could still be more economically convenient in the most pessimistic scenario.

### *4.2. Medium-term horizon*

Fig. 6 shows the estimated DOC breakdown for the five scenarios analyzed for the medium-term. Four of them correspond to the same scenarios already considered for the short-term, and the last one refers to the hydrogen-based configuration with PEMFC. As in the short-term horizon, the ICE-bat configuration is anticipated to be more expensive than the conventional one, with a price above 35 million USD. Even more expensive is the PEMFC-bat configuration (41.5 million USD) due

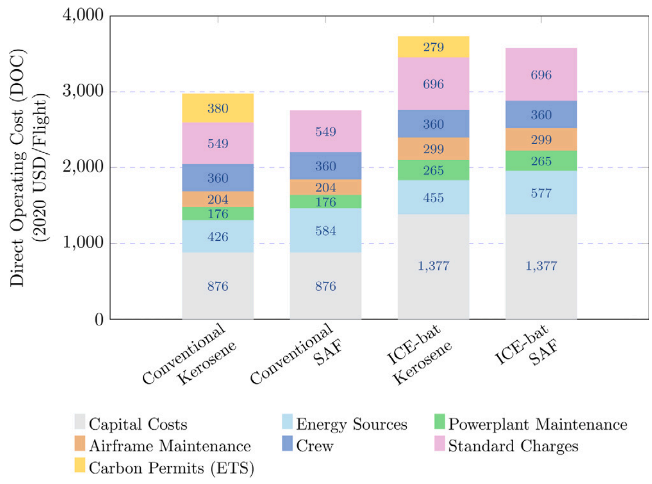


**Fig. 5.** Comparison between direct operating costs (DOC) of the short-term scenarios considered (200 nmi mission).

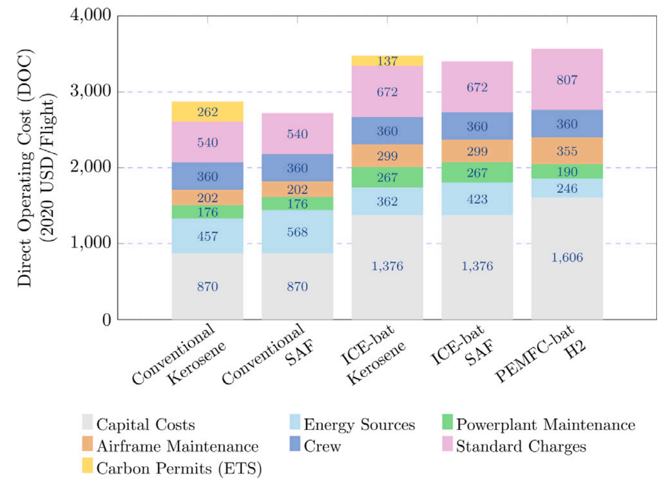


**Fig. 6.** Comparison between direct operating costs (DOC) of the medium-term scenarios considered (200 nmi mission).

to its technological complexity and greater mass. Similar considerations about charges and maintenance also apply in this case. Stressing the differences between ICE-bat and PEMFC-bat configurations, the cost of thermal engines (1.6 million USD) is balanced by the cost of fuel cells and hydrogen tanks together. Therefore, the increase in capital cost associated with the powertrain is mainly linked to electric machines and power electronics, as the shaft power required for the heavier PEMFC-bat configuration is higher. Similarly the cost of the airframe is higher due to the bigger size of the aircraft [1]. However, the improved energy efficiency due to technology advancements makes it possible to slightly reduce the cost associated with the energy sources, making it fall below the energy cost of the conventional aircraft. For the medium-term ICE-bat configuration, fuel consumption is 34.4% lower than the equivalent short-term configuration [1], while having similar electricity consumption. The price of electricity is 19.4% lower than in the short-term but it only accounts for about one-third of total energy costs. These aspects reflect in a difference in energy costs of 26.6% between the two ICE-bat configurations using SAF, or 20.4% when considering the use of kerosene. Similarly to the short-term scenarios, the price of energy sources is higher when SAF is used instead of kerosene, due to the higher price of SAF. Nevertheless, for the configurations using SAF the total DOC is less than the kerosene-based. Once again, this is due to the exemption from the additional charges foreseen by the ETS. In this time horizon, the DOC of the conventional configuration using SAF is 5.3% lower than that of the corresponding kerosene scenario. The total DOC for the PEMFC-bat configuration is comparable to that of the ICE-bat using SAF. Both configurations cost more than the conventional scenario with the same entry into service year and could only be advantageous if the price of carbon permits rises to about 500 USD/ton CO2-eq., compared to the 150 USD/ton CO2-eq. forecast for 2040. Therefore, it may be concluded that for the medium term, the configuration with the lowest DOC is a conventional configuration using SAF. This conclusion is based only on a best estimate without taking into account uncertainties, and the same considerations already made for the short-term apply here.

### 4.3. Long-term horizon

The results for the long-term horizon are presented in Fig. 7. In this case, in addition to the two conventional scenarios already analyzed for the previous time horizons, two different hydrogen-based configurations have been considered, differing only in the fuel cell technology used. The hydrogen-based configurations are confirmed to be the most expensive also in the long-term, with prices of around 45 million USD. Their DOC is higher than the reference value of around 25%–27% compared to conventional aircraft of the same time horizon. Both hydrogen-based configurations could only be advantageous over conventional ones if the price of carbon permits rises to about 240 USD/ton CO2-eq. otherwise and once again, the conventional configuration using SAF would be the one with lower DOC. Even taking into account the uncertainties, better explored in the next section, the economic inconvenience of hydrogen seems to be quite probable. Nevertheless, it should be considered that the use of hydrogen implies a considerable reduction in the operational expenditure, which reaches 8.62% for the SOFC-bat scenario. Therefore, if hydrogen large-scale production brings down capital expenditures, hydrogen configurations remain promising and could even become cheaper than a suitably penalized kerosene-based alternative.

### 4.4. Uncertainties and limitations

The breakdowns in Figs. 5 and 7 refer to the authors' best estimate, which is based on some primary assumptions. First of all, the expected unit costs of the energy sources have been assumed considering the most reliable forecasts for each time horizon (see Section 3.1). In particular, SAF and hydrogen costs have been used as proxies for price, and given their expected increasing demand, there is an underlying risk that these assumptions have been underestimated. Therefore, the uncertainty of these assumptions has not been considered so far, but needs to be taken into account before drawing conclusions on the results. A similar uncertainty also applies to the evolution of the price of carbon in the coming decades. Except for the carbon pricing, no incentive has been applied so far to standard charges by virtue of the use of eco-sustainable technologies. As suggested by Scholz et al. [17], this could be a viable option to incentivize the operation of hybrid aircraft through a reduction in navigation charges that is proportional to the degree of hybridization.

In order to include uncertainties in the study, additional optimistic and pessimistic scenarios have been considered for each of the cases analyzed above. Pessimistic scenarios are such in the sense of making hybrid-electric solutions less economically sustainable, while optimistic

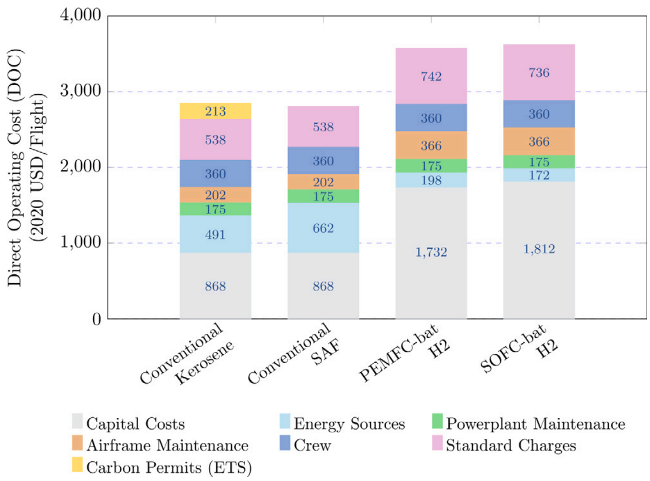


**Fig. 7.** Comparison between direct operating costs (DOC) of the long-term scenarios considered (200 nmi mission).

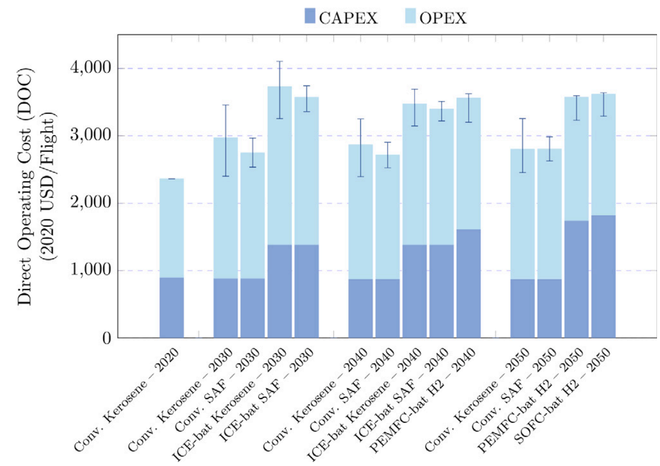


**Fig. 8.** Comparison between the direct operating cost (DOC) of all scenarios considered in three different time horizons, plus an additional today's reference. The error bars represent the uncertainty associated with the price of energy sources, the carbon price and the air navigation charges (200 nmi typical mission).

scenarios are those where hybrid-electric solutions compete better with polluting conventional alternatives. All scenarios are summarized in Fig. 8. In addition to the configurations already seen previously, the additional case of today's conventional aircraft has also been considered for comparison purposes, referring to a 2020 technology level. The error bars in the figure represent the range of uncertainty between the most optimistic and the most pessimistic cases. The width of the bars results from the uncertainty on the price of fuels, electricity, and carbon price, and on possible reductions on airport charges included here using the approach of Scholz et al. [17]. These reductions, proportional to the degree of hybridization, are motivated as an incentive to employ more environmentally friendly technologies. As a main finding, independent of the existing uncertainties, the aircraft's direct operating costs are expected to increase over time, regardless of the propulsion system. As a matter of fact, hybrid-electric scenarios result in being less economically attractive than the conventional cases in any of the three future time horizons. The maximum difference occurs for a hybrid-electric configuration in the short-term horizon: the DOC comes to be greater than the latter by up to 68.9% when the most optimistic scenario is considered for the short-term conventional aircraft. However, on average, the difference with respect to conventional aircraft is mitigated by the increase in the price of kerosene and carbon. In addition, when the most pessimistic scenario is considered for the conventional aircraft (i.e., highest carbon price and fuel cost) and the best scenario is considered for the hybrid aircraft (reduction of navigation charges, low price of alternative energy sources), the latter would present DOCs perfectly comparable with those of conventional configurations using kerosene, for each time horizon. In this sense, the currently planned evolution of the carbon price seems to respond to the need for the technological transition, but only in the most optimistic scenario and if it is accompanied by adequate tax relief policies. A more realistic alternative is represented by the use of sustainable aviation fuels on conventional architectures. On average, scenarios where SAF is used are successful against those with kerosene (up to −7.5%), despite the higher price of SAF, thanks to the exemption from carbon permits. Preferring SAF to electrification seems to be a way to stabilize the economic viability of future regional aviation, but of course, the savings in environmental impact would be smaller [60]. The existing uncertainties do not allow to draw universal conclusions, thus further research is needed to mitigate uncertainties, particularly in relation to energy and carbon prices, as these factors have the most profound impact on determining the cost hierarchy among the various scenarios under consideration.

### 4.5. *Estimation of ticket prices*

A final application concerns the estimation of the ticket price for a 200 nmi flight. To obtain a complete estimate of the ticket price, in addition to considering the IOC, one should also include the ground handling charges, as well as a profit margin on the sale. In 2022, Rotterdam The Hague [61] the charge per passenger was 17.37€, plus an 11.06€ security surcharge. This value, converted into 2020USD dollars, was taken as a reference for the purpose. A profit margin of 10% has been assumed on the ticket price, corresponding to a passenger load factor of 80%. The final result is summarized in Fig. 9. For hybrid-electric configurations in the short-term, the increase compared to today's reference aircraft is between 22 and 36%, which progressively decreases over time until it settles between 19 and 27% for long-term hydrogen-based configurations. Although evaluating the social impact of this increase in the cost of flying goes beyond the scope of this work, the results suggest that the impact of hybridization on the final consumer is quite limited. Therefore, the consequences on the entire regional aviation market does not seem much extensive.

## 5. Conclusions

This paper has presented a comprehensive cost analysis of future regional aviation solutions, focusing on hybrid-electric aircraft for 50 passengers.

A novel analysis workflow has been presented, representing a useful reference for analysts looking for a comprehensive approach to estimating the DOC of hybrid and electric aircraft. Requiring a relatively small number of data and assumptions, the analysis workflow is suitable for preliminary multidisciplinary analyses or design applications. Since statistical data is not available for innovative aircraft featuring the new technologies considered, the validation of the workflow has been carried out using a conventional aircraft as a benchmark. Future developments include overcoming this limitation by testing the effectiveness

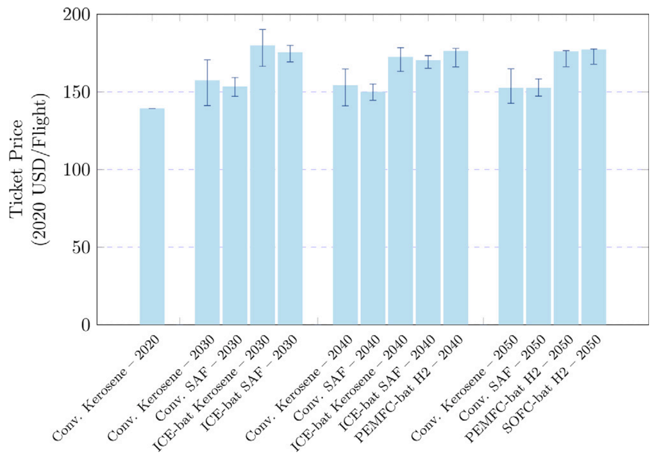


**Fig. 9.** Comparison between predicted ticket prices for all scenarios considered in three different time horizons, plus an additional today's reference. The error bars represent the uncertainty associated with the price of energy sources, the carbon price and the air navigation charges (200 nmi typical mission).

of the workflow in scenarios similar to those analyzed here, as soon as sufficient public data becomes available.

The workflow has been applied to an extensive comparative analysis of several aircraft scenarios, spanning three different time horizons (short-term, medium-term, long-term). Operating costs have been estimated for various propulsive solutions, including conventional, hybrid-electric, and hydrogen-based architectures. The findings underscore a significant disparity, revealing that hybrid-electric solutions entail notably higher direct operating costs—potentially up to 69.8% more compared to their conventional counterparts. The high costs are attributed to the complexity and mass penalties associated with the use of hybrid-electric architectures, which negatively impact acquisition costs, maintenance costs, and charges. This emphasizes the urgent necessity for targeted policies and incentives aimed at encouraging the adoption of sustainable alternatives within the aviation sector. While discouraging kerosene-based aircraft usage could be a potential solution, it hinges on public acceptance of a ticket price increase of up to 36% over the coming decades. In this context, the utilization of sustainable aviation fuel alongside conventional propulsion emerges as a promising interim solution, potentially offering cost advantages provided that a secure large-scale supply of sustainable fuel is guaranteed. These findings provide valuable guidance for industry stakeholders, policymakers, and researchers to inform strategic decision-making, foster innovation, and pave the way for a more sustainable and economically viable future for regional aviation.

Future developments may involve refining economic assumptions based on updated technological and macroeconomic trends, and integrating the analysis workflow for cost analysis into a holistic aircraft design workflow for improved compromises between environmental and economic considerations compared to optimizing based solely on environmental or economic performance.

## CRediT authorship contribution statement

**Valerio Marciello:** Formal analysis, Data curation, Conceptualization, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Vincenzo Cusati:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fabrizio Nicolosi:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Karen Saavedra-Rubio:** Conceptualization, Investigation, Writing – review & editing. **Eleonore Pierrat:** Writing – review & editing, Investigation, Conceptualization, Data curation, Formal analysis. **Nils Thonemann:** Writing – review & editing, Investigation, Conceptualization. **Alexis Laurent:** Writing – review & editing, Supervision, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix. Aircraft scenarios

The present appendix contains a brief description of the scenarios covered by this study. All configurations have been designed using a preliminary design tool based on flight mission analysis, suitable for both conventional and hybrid-electric configurations [1]. For each time horizon considered, the most mature technologies have been identified based on expert opinions. Fig. A.1 reports the evolution trends for the TRL of different propulsion technologies, estimated in the context of the Clean Sky 2 GENESIS project. Based on these trends, several representative aircraft have been defined, as reported in Tables A.1–A.3. In addition, all hybrid-electric or hydrogen-based configurations feature 10 distributed propellers to benefit from improved lifting capabilities thanks to aero-propulsive effects. The work of Marciello et al. reports further details on the configurations, their performance and properties [1].

**Table A.1**
Summary table of the major technologies implemented for all of the concepts analyzed for the short-term horizon.
*Source:* Adapted from Ref. [1].

| Scenario | ICE | ICE - bat |
|---|---|---|
| Fuel | Kerosene (Jet A-1) | SAF (HEFA-SPK) |
| Thermal engines | 3-spool TP | 3-spool TP |
| Batteries | – | Li–Ion |
| Fuel cells | – | – |
| Hydrogen tanks | – | – |
| Primary electric machines | – | Liquid cooled PMSM |
| Secondary electric machines | – | Liquid cooled PMSM |
| Power electronics | – | SiC converters |
| Wing material | Al alloy | Carbon/Epoxy |

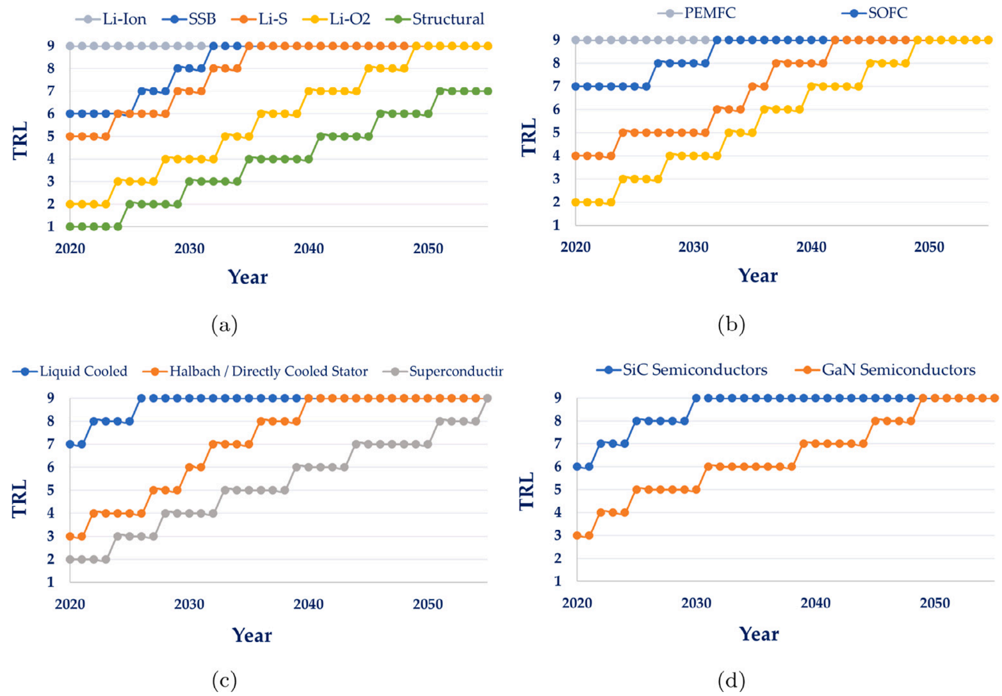


**Fig. A.1.** Current TRL and future forecasts for innovative propulsion technologies. **(a)** Batteries [62]. **(b)** Fuel cells [63]. **(c)** Electric machines [64]. **(c)** Power electronics [65].

**Table A.2**
Summary table of the major technologies implemented for all of the concepts analyzed for the medium-term horizon.
*Source:* Adapted from Ref. [1].

| Scenario | ICE | ICE-bat | PEMFC-bat |
|---|---|---|---|
| Fuel | Kerosene (Jet A-1) | SAF (SPK Blend) | Hydrogen |
| Thermal engines | 3-spool TP | 3-spool TP | – |
| Batteries | – | Li–S | Li–S |
| Fuel cells | – | – | PEMFC |
| Hydrogen tanks | – | – | Pressurized tanks |
| Primary electric machines | – | Halbach array PMSM | Halbach array PMSM |
| Secondary electric machines | – | Liquid cooled PMSM | Halbach array PMSM |
| Power electronics | – | SiC converters | SiC converters |
| Wing material | Al alloy | Carbon/Epoxy | Carbon/Epoxy |

**Table A.3**
Summary table of the major technologies implemented for all of the concepts analyzed for the long-term horizon.
*Source:* Adapted from Ref. [1].

| Scenario | ICE | SOFC-bat | PEMFC-bat |
|---|---|---|---|
| Fuel | Kerosene (Jet A-1) | Hydrogen | Hydrogen |
| Thermal engines | 3-spool TP | – | – |
| Batteries | – | Li–$O_2$ | Li–$O_2$ |
| Fuel cells | – | SOFC | PEMFC |
| Hydrogen tanks | – | Cryogenic tanks | Cryogenic tanks |
| Primary electric machines | – | Halbach array PMSM | Halbach array PMSM |
| Secondary electric machines | – | Halbach array PMSM | Halbach array PMSM |
| Power electronics | – | GaN converters | GaN converters |
| Wing material | Al alloy | Biodegradable Bio fibers | Biodegradable Bio fibers |

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