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Climate and energy impact analysis of electric, hybrid-electric and hydrogen aircraft in prospective scenarios for air transport

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Abstract

To meet climate impact reduction objectives, the aviation sector must both accelerate the improvement of the fleet efficiency and the deployment of low-carbon energy carriers. This implies to develop new concepts of aircraft with a reduced climate impact than previous ones and possibly more energy efficient. One research direction is the investigation of electric, hybrid-electric and hydrogen aircraft concepts to possibly reduce emissions. Indeed, these concepts imply the direct usage of electricity or hydrogen from electrolysis which may be potential low-carbon energy carriers. Evaluating the climate impact benefits and energy implications of the deployment of such aircraft architecture is intricate. This paper presents an analysis of different deployment and technological assumptions for these concepts. The analysis which consists in assessing the climate impact benefits of these new aircraft architecture in terms of CO₂ effects will be performed. The assessment of absolute energy consumption will also be achieved. This will enable the performance comparison between architectures and to consider their contribution to the decarbonization of the whole air transport.

Introduction

To meet climate impact reduction objectives, the aviation sector must both accelerate the improvement of the fleet efficiency and the deployment of low-carbon energy carriers [1]. This implies to develop new concepts of aircraft with a reduced climate impact than previous ones. For instance, the investigation of new aerodynamic concepts [2] or lightweight structures are currently investigated [3]. Regarding propulsion systems, new engine concepts such as contra rotating fans seem to be a short-term interesting option to replace turbofan engines [4]. Concerning the use of alternative energy carriers, whereas some drop-in fuels, such as biofuels and e-fuels, could almost directly substitute for kerosene, others require dedicated aircraft architectures, such as electric, hybrid-electric and hydrogen ones. For instance, electric and hybrid-electric propulsion systems [5] are envisaged for general aviation and commuter type aircraft whilst the latter should cover applications from short to medium range aircraft. The main benefit of these architectures is a reduction in emissions when low-carbon electricity is used. Then, the second reason for this type of concept is to benefit from the high efficiencies of electric components already implemented in ground vehicles [6]. The third reason is that electric propulsion offers more exhaustive propulsion integration solutions that could yield better aero-propulsive efficiency [7]. The last reason is the possible synergies with other electric on-board systems that could result in improved overall aircraft

energy efficiency. Depending on the impacts of the integration at aircraft level, these improvements in efficiency could directly enable to reduce the energy consumption of aircraft.

Another critical topic is the in-flight non-CO₂ effects generated by aviation that contribute, in addition to CO₂ emissions, to global warming [8]. Electric aircraft based on hydrogen fuel cell technologies could reduce these effects, whereas battery-powered ones may eliminate them totally [1]. Nevertheless, including the contribution of non-CO₂ effects in technology assessment of aircraft architecture is necessary as they contribute at least as much as CO₂ to the global warming induced by aviation [8].

Finally, an important aspect to consider in technology assessment of future architectures is the energy resources consumption. The different energy pathways envisaged for aviation will use biomass or/and electricity as energy resources [1]. It is important to consider the different emission factors and conversion efficiencies of the different pathways. These latter can result in significant differences between the energy resources consumption. Depending on the energy consumption difference between the architectures, an electric aircraft powered by batteries may consume less electricity than an electric aircraft powered by hydrogen produced from electrolysis. The purpose of this paper is to compare electric and hydrogen aircraft architectures in terms of climate impact and energy resources consumption (kerosene and electricity). Here, a reduced set of

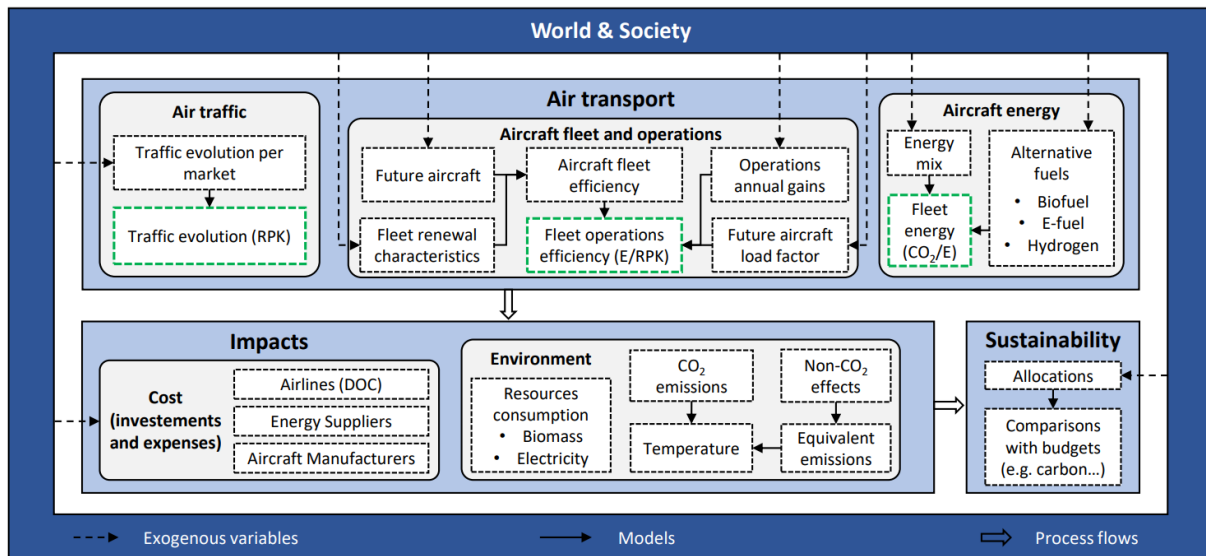


Fig. 1: Simplified architecture of AeroMAPS.

aircraft architectures and energy pathways will be considered. The energy consumption of aircraft architectures will be taken from the literature. The climate and energy impact analysis will be carried out using the AeroMAPS framework [9].

To this end, the paper is organized as follows. The AeroMAPS framework and the methodology to perform the analysis are presented in Section 1. Then, Section 2 defines the scope of the study in terms of market, aircraft architectures and energy pathways. Section 3 provides an outlook of the results obtained. Finally, Section 4 proposes some discussions on the assumptions and results of the study.

1. Methodology

1.1 AeroMAPS framework

This study relies on the use of AeroMAPS, an open-source framework for performing multidisciplinary assessment of prospective scenarios for air transport. The simplified architecture of the tool is given in Fig. 1. The framework relies on a set of exogenous inputs such as air traffic growth, improvements in aircraft technology and potential gains in operational efficiency. The input values defined by the user are fed into the main air transport module, which simulates the temporal evolution of the air transport system, including the air traffic, aircraft fleet and energy required to operate the aircraft fleet. The evolution of air traffic is modelled by simple exponential growths,

the value of which can be specified per period and per category (short/medium/long-haul passengers and freight). This demand is then satisfied by an aircraft fleet whose composition and performance can be defined by using fleet renewal models and introducing new aircraft into the fleet as discrete-time events. Finally, the energy implications associated with the defined aircraft fleet are assessed. The fleet uses a mix of energy carriers, including drop-in fuels (kerosene, e-fuel, biofuel) and non-drop-in fuel (hydrogen). The characteristics of these energy carriers (emission factor, efficiency...), such as the electricity mix (e.g., high/low-carbon grid or dedicated renewable), can also be specified.

In a second step, two other modules are used to estimate the economic and environmental impacts of the user-defined scenario and to assess its sustainability. The economic assessment involves the use of cost models to estimate, among other things, the Direct Operating Costs (DOC). The environmental assessment includes climate models to estimate both CO₂ and non-CO₂ effects on climate change. In particular, the estimation of the induced temperature evolution is based on the use of the climate metric GWP* which is relevant for Short-Lived Climate Pollutants (SLCP) such as aviation non-CO₂ effects [8]. The environmental module also estimates the consumption of biomass and electricity resources. Finally, a comparison of these impacts with sustainability targets (e.g. a carbon budget allocated to aviation) completes the scenario assessment.

1.2 Use in the context of this paper

For performing the study of this paper, the fleet renewal models, described in [10], have been particularly used. The main parameters required to define each aircraft architecture are the energy consumption evolution compared to a reference aircraft, and the energy carrier it uses. Additional ones, such as NO_x and particulate matter emission evolution, cruise altitude, and non-energy costs, are also available. In order to take into account architectures with limited range, subcategories can be added defining a dedicated submarket share. Once these assumptions are made, it is for instance possible to assess the evolution of the average energy consumption of a given market (e.g. short range) as shown in Fig. 2.

Moreover, the tool enables adjusting assumptions regarding biofuel, e-fuel, hydrogen characteristics. Moreover, the direct use of electricity has been added in the context of this paper, for taking into account electric and hybrid-electric architectures. This enables to plot the evolution of the emission factor of each pathway as shown in Fig. 3. These evolution include the share of the different pathways (e.g. steam reforming or electrolysis for hydrogen) as well as the corresponding characteristics (e.g. conversion efficiency, electricity emission factor).

2. Scenarios assumptions

In this study, AeroMAPS is used to generate different scenarios that explore the deployment of the different aircraft architectures (electric, hybrid-electric, hydrogen). These scenarios are compared with a reference scenario (0), and a dedicated one (4) includes a mix of all the architectures. The main hypotheses considered are presented in this section and summarized in Table 1.

2.1 Traffic and operations

In this study, the annual air traffic growth, expressed in Revenue Passenger Kilometer (RPK), is set to +3% on all markets. The load factor increases from 82% (2019) to 89% in 2060, leading to the estimates of Available Seat Kilometer (ASK). An 8% reduction of energy consumption is also assumed taking into account improvements in operations.

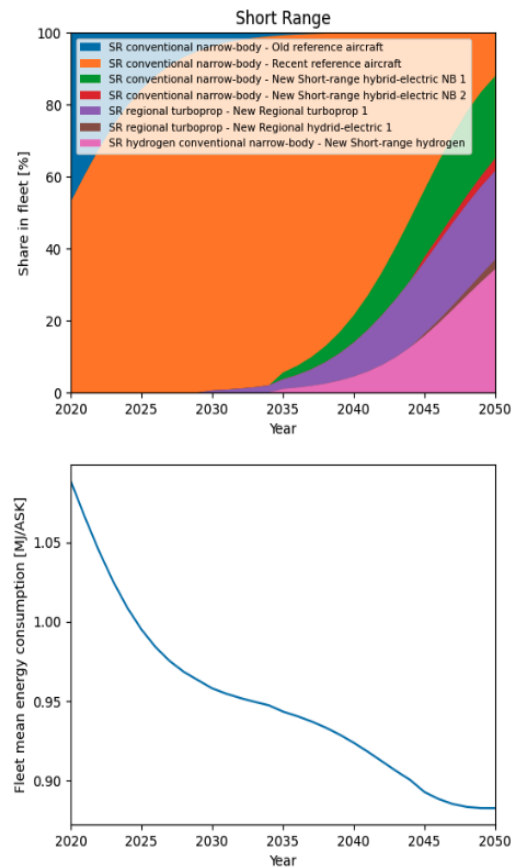


Fig. 2: Example of evolution of short-range energy consumption using the fleet renewal model.

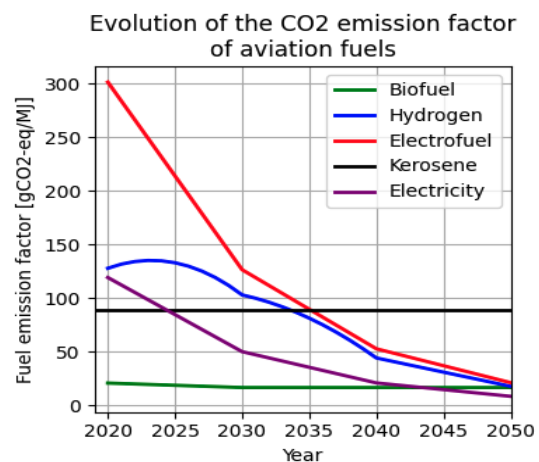


Fig. 3: Example of evolution of emission factors for each energy carrier.

Table 1: Assumptions regarding EIS, energy consumption and market share of each architecture.

Scenario	Type	Entry into service year [-]			Performance [%]			Share [%] (Range)		
		Min.	Reference	Max.	Min.	Reference	Max.	Min.	Reference	Max.
0	Advanced conventional		2035			-20			100 (-)	
1	Electric	2030	2040	2045	0 (for 400 NM)	50	100	1 (200 NM)	7 (400 NM)	16 (600 NM)
2	Hydrogen	2035	2035	2045	-5 (GI of 0.6)	5 (GI of 0.3 for 1000 NM)	20 (GI of 0.15 for 1000 NM)	11 (500 NM)	33 (1000 NM)	58 (2000 NM)
3	Hybrid-electric	2028	2030	2040	-20	-10	0	11 (500 NM)	33 (1000 NM)	47 (1500 NM)
4	Mix (3 reference scenarios)									

2.2 Fleet renewal and aircraft architectures

For all the scenarios, a duration of 20 years of renew 98% of the fleet is assumed. Moreover, the introduction of an advanced conventional aircraft is considered, available on all markets, assuming a 20% gain in energy consumption with an Entry-Into-Service (EIS) year of 2035. The performance is given with respect to a recent reference aircraft of each market (e.g. 0.95 MJ/ASK for the short range). A duration of 20 years of renew 98% of the fleet is assumed.

Then, depending on the scenario, electric, hybrid-electric or hydrogen aircraft are integrated. Depending on their performance, these architectures could operate on the short-range market (flights below 1500 km) or on the medium-range one (1500-4000 km). The potential market share of these aircraft is discussed in the next section.

For the different scenarios, EIS and performance are assumed for the disruptive aircraft. Their EIS year and energy consumption performance remain uncertain due to the performance and integration of new technologies. Hence, in addition to a reference scenario, extreme values are also considered. For instance, for hydrogen aircraft, an EIS year between 2035 and 2045 is considered. Similarly, the performance assumptions are estimated as a function of Gravimetric Index (GI) and range using a simple Breguet evaluation curve in [11]. In this case, three energy consumption evolution are considered with respect to the recent reference aircraft:

- +20% (less efficient) for GI=0.15 and a range of 1000 NM
- +5% (less efficient) for GI=0.3 and a range of 1000 NM
- -5% (more efficient) for GI=0.6 with little impact from the range

2.3 Market potential of the architectures

As mentioned previously, the different architectures have not the same potential in terms of range coverage. To estimate the potential market share of an architecture, world flight data of 2019 [12] is used to determine the fraction of total ASK covered with respect to the range of the aircraft (Fig. 4). For instance, although around 30% of the total seats offered are below 400 NM, these flights represent only 7% of the ASK, highlighting a limited potential for very short-range aircraft. Similarly, around 70% of the seats and 33% of the ASK are below 1000 NM. The different share assumptions for the scenarios considered in this paper are summarized in Table 1.

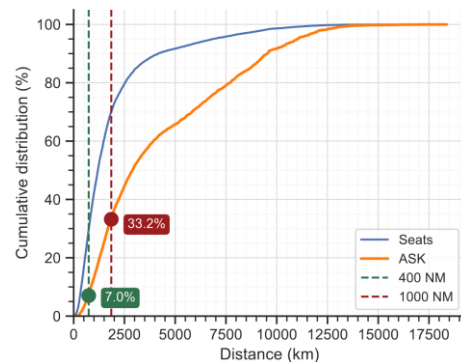


Fig. 4: Cumulative distribution of seats and ASK with respect to the flight distance in 2019.

To illustrate the results which can be obtained concerning the aircraft architectures and their market share, the mix scenario (4) is considered. The market shares have been modified so that electric aircraft are prioritized, then hydrogen aircraft and finally hybrid-electric aircraft. The illustration of this fleet renewal for this scenario is given in Fig. 5.

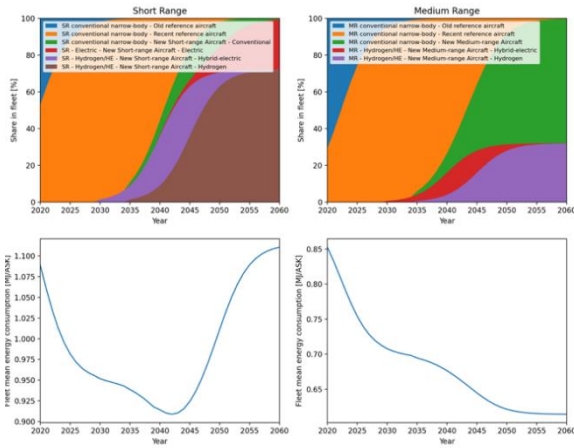


Fig. 5: Share in fleet and mean energy consumption of scenario (4).

2.4 Energy carriers and pathways

As mentioned previously, AeroMAPS offers over several energy pathways. For the study, the only drop-in fuel used is fossil kerosene. The hybrid-electric aircraft uses kerosene as well as electricity, considering a fixed energy hybridization factor (ratio between electric energy and total energy consumed) of 0.4 for this part. Nevertheless, this factor depends on the design and performance of the aircraft but also on how it is operated. A discussion will be provided in Section 4.

Concerning the production of electricity, it is assumed that the electricity is from dedicated renewables production (10 gCO₂/kWh here). For liquid hydrogen production, only the electrolysis pathway is considered, with electrolysis efficiency of 0.59 and liquefaction efficiency of 0.8. These assumptions lead to the fuel emission factors given in Fig. 6.

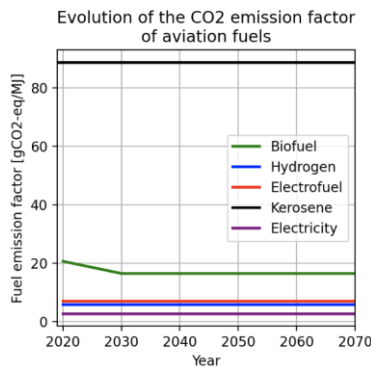


Fig. 6: Evolution of the fuel emission factors with electricity from dedicated renewables.

3. Results

3.1 Comparison of CO₂ emissions reduction

The different scenarios can be compared in terms of CO₂ emissions in 2050 and 2060 (Table 2).

We see that it is more interesting to introduce, at the fleet level, a hydrogen aircraft that is more efficient and covers a larger market share than the electric aircraft. Also, the hydrogen aircraft has more effect in reducing CO₂ emissions than the hybrid-electric aircraft. This shows that the emission factor, very low in this case, has a significant effect on the decarbonization capacity of hydrogen concepts. Nevertheless, Fig. 7 shows that the early introduction of hybrid-electric aircraft is a lever to start decarbonizing earlier.

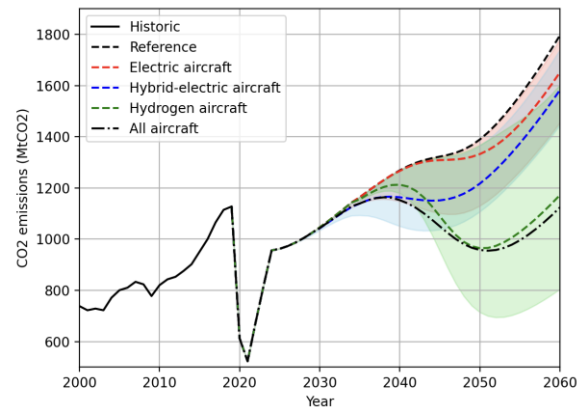


Fig. 7: CO₂ emissions evolution of the different scenarios with dashed line as reference.

3.2 Focus on cumulative CO₂ emissions and energy resources consumption

Cumulative CO₂ emissions are important metrics as they can enable estimating the corresponding temperature increase. Table 2 illustrates the interest in combining the different architectures in scenario (4). The scenario 4 is the most interesting scenario with reference values, but it can also be observed that it is also the one that consumes the most energy.

Table 2: CO₂ emissions, cumulative (2020-2050) CO₂ emissions and energy consumption of each scenario.

Scenario	CO ₂ 2050 [Mt]			CO ₂ cumulative [Gt]			Energy 2050 [EJ]			CO ₂ 2060 [Mt]		
	Min.	Reference	Max.	Min.	Reference	Max.	Min.	Reference	Max.	Min.	Reference	Max.
0		1389			34,6			15,7			1796	
1	1129	1332	1387	32	34,4	34,6	16,3	16,2	15,7	1453	1652	1778
2	714	965	1368	30,3	31,9	34,6	16,9	17,1	15,8	804	1172	1602
3	1107	1217	1365	30,8	32,6	34,5	15,4	16,2	15,9	1445	1583	1739
4		958			31,3			17,4			1124	

4. Discussions

4.1 Sensitivity to main parameters

As it has been highlighted in the previous sections, some assumptions and parameters have been fixed during the analysis.

First, the energy hybridization factor directly impacts the ratio of electricity consumed versus the kerosene consumed. The main reason why it would be interesting to perform a sensitivity analysis on this factor is that its value is highly uncertain due to the uncertainty on the performance of such aircraft and on how it will be operated in the market. This is emphasized by the fact that a very low carbon emission factor has been chosen for electricity. Therefore, the ratio between these two primary energy resources has a significant effect on the CO₂ emissions.

Secondly, the choice of the electricity emission factor is one of the main drivers for the CO₂ emissions. For example, some scenarios [1] show that the current electricity grid for hydrogen production would actually be disadvantageous compared to kerosene, and that for the next decade. Therefore, achieving a sensitivity study on this parameter would be particularly interesting. Furthermore, identifying the tipping points when the electric emission factor value enables the architecture to reduce emissions could be of great interest.

Finally, the share of the different drop-in fuel pathways has been fixed to use only fossil kerosene. Setting the shares to have something similar to ReFuelEU [9] could also change the conclusions and for example make the hybrid-elec architecture a more competitive solution.

4.2 Qualitative analyses

In addition to the previous discussion on the sensitivity to the main parameters, some qualitative analyses are provided in the following.

First, the carbon footprint of battery production was not

considered in this paper. However, this stage of the life cycle can have a significant impact, as shown for example in a study on electric drones [13]. More generally, a qualitative assessment of the literature shows significant differences across different types of cell chemistries. In addition, the carbon footprint of battery production is strongly influenced by the carbon intensity of the electricity used in the manufacturing process and, therefore, by the geographical location of the factories. It is also important to consider the future evolution of the electricity emission factor. For instance, the manufacturing of an NMC battery in China in 2020 emits about 85 kgCO₂e/kWh, while an LFP battery produced in Europe in 2040 would emit less than 10 kgCO₂e/kWh [14].

Then, from a climate point of view, this paper only quantifies the reduction in terms of CO₂ emissions. A more exhaustive analysis would include the effect of electric, hybrid-electric and hydrogen aircraft on non-CO₂ effects. Leaving aside battery production, electric aircraft would be particularly efficient due to the elimination of in-flight emissions. Hybrid-electric architectures would face the same consequences as conventional kerosene architectures, but with fewer emissions. [15] shows similar impacts for contrails with hybridization factors lower than 30%, but a reduction in contrail formation for higher values. Concerning hydrogen aircraft, many uncertainties remain due to the emission of more water vapour but the absence of combustion particles, which facilitate the formation of contrails. Nevertheless, it could result in a 20-25% reduction of climate impact overall depending on the propulsive strategy (combustion or fuel cell) [16]. Finally, these architectures could have lower flight altitudes (for example with the use of turboprop engines), which would lead to a reduction in contrails [17].

Last, but not least, a major element to consider in the development of these aircraft is their operating costs. Indeed, without regulations, subsidies or taxes, airlines are less likely to choose a more environmentally

friendly but more expensive aircraft. Among all airline costs, it is possible to distinguish the Direct Operating Costs (DOC), which are related to the operation of the aircraft itself. The total costs of airlines are accessible: an industry average of 0.076 \$/ASK can be calculated from industry publications [18,19]. Isolating DOC is more difficult, but average values between 0.035 and 0.097 \$/ASK can be found from US-based airline publications [20]. Note that the upper limit of the range corresponds to regional airliners, which could be linked to their weaker efficiency, lower capacity, and shorter operations. Although this paper does not provide a detailed cost analysis of electric, hybrid-electric or hydrogen-powered aircraft, it is possible to compare industrial or academic references to this DOC range. For example, [21] has announced that its aircraft will have DOC similar to those of a 50-passenger turboprop aircraft, while [22] specifies operating costs below 0.1 €/ASK. These values are close to the upper end of the DOC range mentioned above. Similar values can be found in academia, with a cost of 0.11 \$/ASK for [23]. Note that these references evaluate the DOC for smaller aircraft (19-35 seats) than those considered in [20] and in this paper. Finally, hydrogen-powered aircraft have a lower overall energy conversion efficiency, resulting in higher energy-related costs. Moreover, significant infrastructure changes and hydrogen-specific handling and overhaul procedures are also likely to increase the operating costs. Overall, [24] evaluates the potential cost increase between 10 and 70%.

Conclusions

This paper presents an application case of AeroMAPS to assess the environmental interest of several short-medium-range aircraft with associated deployment scenarios. Four main scenarios are considered. In addition to a reference scenario, the first considers the introduction of a battery electric aircraft in 2040 on routes below 400 NM. The second considers the introduction of a hydrogen-powered aircraft in 2035, on routes up to 1000 NM. The third option evaluated is the introduction of a hybrid-electric aircraft in 2030 on the same market segment. Finally, a mixed scenario considers all these options simultaneously.

The performance of these aircraft architectures is taken from the literature and introduced into the fleet using the AeroMAPS fleet renewal model. Four metrics are monitored to quantify the environmental impact of the scenarios: annual CO₂ emissions in 2050 and

2060, cumulative CO₂ emissions between 2020 and 2050, and energy consumption..

A sensitivity analysis provides upper and lower bounds for each case. The all-electric aircraft scenario is characterised by a small reduction in CO₂ emissions due to its short range and late introduction. The hybrid-electric aircraft scenario is interesting in the short term and its impact could be increased by considering low-carbon fuels instead of fossil kerosene. The hydrogen aircraft scenario is the most interesting in the long term, but is very sensitive to the decarbonisation of electricity.

These analyses could be complemented by a more detailed and comparable consideration of the performance of each aircraft, by designing them on a unique overall aircraft design software. The consideration of electric or hybrid-electric aircraft also makes a life cycle analysis approach more relevant due to the increased environmental impact of the production phase (e.g. battery). The realism of the analysis would be enhanced by a thorough integration of aircraft operating costs into the evaluation, ultimately linked to a market-based fleet model that replicates airline behaviour in terms of purchasing decisions. The scope of this enriched analysis would allow decision-makers to agree on the options that seem most relevant to them and to choose tools (taxes, standards, subsidies...) that would enable them to achieve the objective in question.

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