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Modelling and simulation of new regulatory measures in prospective scenarios for air transport

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Abstract

Air transport contribution to annual anthropogenic CO_2 emissions is evaluated at 2.6%, as well as additional climate impacts. In order to assess the future environmental impacts of air transport, the AeroMAPS open-source framework was previously developed for simulating prospective scenarios, including a specific module to evaluate the costs of alternative fuels.

This paper presents additional cost models to evaluate the direct operating cost at the fleet level, as well as the manufacturing non-recurring and recurring costs. The potential role played by regulatory measures for aviation decarbonization is assessed, considering two examples. First, the consequences of setting low-carbon fuels blending mandates are investigated, and options available to design them are reviewed, highlighting the need to find a compromise between deep decarbonization over time and economic efficiency. Secondly, setting stringent aircraft energy intensity rules can be used to ensure the fleet is renewed at the right moment to respect a given cumulative CO_2 emissions target, or other objectives. An illustrative example shows the interest of an early introduction of a given new aircraft type.

Abbreviations

ATAG	Air Transport Action Group
AtJ	Alcohol-to-Jet
CapEx	Capital Expenditures
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DOC	Direct Operating Costs
EU ETS	European Union Emissions Trading Scheme
FT	Fischer-Tropsch
HEFA	Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
MACC	Marginal Abatement Cost Curve
MFSP	Minimal Fuel Selling Price
NPV	Net Present Value
NRC	Non-Recurring Costs
OpEx	Operational Expenditures
RC	Recurring Costs
RPK	Revenue Passenger Kilometers
SAF	Sustainable Aviation Fuels
TLARs	Top Level Aircraft Requirements

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1. Introduction

Even though climate change and its human origin are now consensual topics, greenhouse gases emissions are still growing, failing to follow the trajectories required to meet the Paris Agreement [1]. Indeed, for the ambitious 1.5°C target, the annual emissions should be reduced by 84% by 2050, and by around 6% annually [2]. The aviation sector is a relatively modest greenhouse gases emitter and represents around 2.6% of total CO_2 emission [3]. Nevertheless, it is on a step increasing slope, with a 34.7% increase between 2013 and 2019 [4, 5], while the total human-related greenhouse gases emissions rose by only 4.5% [6]. Moreover, airliners can create contrails and cirrus-induced clouds when they fly at their cruise altitude, which could double the impact of aviation on the temperature [7].

With this context as a background, several actors started to work on action plans to decarbonize the air transport industry. For instance, industrial groups such as the Air Transport Action Group (ATAG) [8] and the International Air Transport Association (IATA) [9] or a European industrial consortium [10] each published roadmaps to reach CO_2 neutrality in 2050. However, none of these plans are legally binding. The International Civil Aviation Organisation (ICAO), United Nation's dedicated aviation body, also agreed on CORSIA, a plan to cap international aviation emissions at 2019 levels [11]. However, the use of carbon offsets is permitted within this program, meaning gross emissions are not capped by this mechanism. In parallel, domestic aviation emissions as well as other exceptions such as those from flights to/from least developed countries and/or small islands are excluded of CORSIA.

Besides, academia also stepped into the subject by reviewing the implication of those plans as well as providing their own transition pathways [12–15]. Scenarios in the previous references requires radical changes compared to the business-as-usual carbon emissions trajectory. Meeting the industry targets requires, in addition to the continuation of the aircraft efficiency improvement trend, to improve operations and to use alternative sources of energy, such as drop-in Sustainable Aviation Fuels (SAFs) or low-carbon hydrogen [8]. Unlike the fuel efficiency improvement, which tends to reduce operating costs by cutting fuel consumption, the use of alternative fuels will have a significant impact on aviation costs. Indeed, unlike fossil kerosene whose price is driven by exclusivity and scarcity rents, using low-carbon energy sources involves several energy conversions steps, with incumbent energy losses and costs. For instance, the minimal price at which any mature SAF should be sold to be economically viable ranges from 2 to 8 times the median selling price of kerosene over the past 20 years [16, 17]. A scenario in which a great share of those fuels is used would significantly increase airlines operating costs [17]. Operating hydrogen aircraft might also affect operation through longer refuelling times for instance [18].

A relevant point highlighted by the scientific literature [19] and more recently by the ICAO [20] is that one should rather evaluate a given transition scenario by looking at the cumulative emission rather than at a mid-term target, such as the net CO_2 neutrality in 2050. Those cumulative emissions can be compared to the estimated carbon budgets to stay below given levels of temperature increase [2]. However, the Intergovernmental Panel on Climate Change (IPCC) determines carbon budgets on a global scale and allocating this budget to each sector is a political matter. In the case of the air transport sector, [3] show that, in most scenarios, the aviation sector will have to moderate its growth or consume a larger share of the carbon budget than its current contribution to the annual greenhouse gases emissions. Ultimately, this could result either from decisions taken by the legislative authorities or from the free evolution of the market, which will be subject to varying degrees of carbon pricing. These include, for example, the inclusion of European air transport in the EU Emissions Trading Scheme (EU ETS) [21], or the future introduction of mandates for the incorporation of SAFs [22]. On a global scale, the ICAO has also introduced regulatory measures on the carbon intensity of new aircraft [23], although these are insufficient to have tangible effects on fleet composition.

In any case, new regulatory measures could be implemented in the coming decades, which requires modelling and evaluation work. As a consequence, it is essential to have tools that enable rapid assessment of the climatic, social, and economic consequences of every decision taken to guide the future of the air transport sector. This ambition can be partially achieved with Integrated Assessment Models (IAM), macro-models that bring together several technical disciplines to simulate the response of the air transport system to external disturbances, such as new regulations. A balance between demand and supply, affected by disturbances, is the basis on which these models operate. However, they usually require a relatively long run time, and only a few open-source models are available in the scientific literature [24]. Moreover, the analyses rarely include an assessment of the effects of regulatory measures on the scenarios, in terms of cost or environmental impacts.

The objective of this paper is to perform the modelling and simulation of new regulatory measures in prospective scenarios. This work follows on from the development of the dedicated tool named AeroMAPS[1] (previously named CAST) [19]. This open-source software uses a simplified approach that enables a near-instantaneous assessment of the sustainability and economic impact of given scenarios for the future evolution of air transport. More details on the tool are given in Section 2. Several new cost models, covering SAFs, direct operating costs and manufacturing costs are integrated in this paper, to enhance the scenario analysis capabilities of AeroMAPS

[1] Code: https://github.com/AeroMAPS/AeroMAPS & User interface: https://aeromaps.isae-supaero.fr/

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while maintaining its rapid computation capacity. Thus, it can help law and policymakers to evaluate and compare various policies to decarbonize aviation without requiring an extensive expert knowledge.

This paper is structured as follows. Section 2 provides background information on the AeroMAPS tool and the methodology it adopts to simulate decarbonisation pathways for aviation. The various cost models used are described in Section 3. Finally, two exploratory cases for new regulatory measures are presented in Section 4. The final section presents concluding remarks and suggestions for further work.

2. Methods and tools

As mentioned in the introduction, the work presented in this paper is a direct continuation of what led to the development of AeroMAPS [19, 25, 17, 26]. Thus, in this section the existing framework is briefly described and some missing models to perform a detailed policy evaluation will be identified.

AeroMAPS core principle is to simulate user-defined prospective scenarios for air transport evolution in the medium and long-term (until 2050). It requires the user to define with an adequate accuracy exogenous input such as traffic growth, technology improvements or operational efficiency potential gains. These values are used as inputs for a main module simulating the air transport, as illustrated on Fig. 1. This module is composed of three submodules, each one representing a term of the Kaya equation for air transport provided in Eq. (1). Air traffic level *RPK* is modelled by simple exponential growths, whose value can be chosen per decade and per flight category (Short/Medium/Long-Range and Freight). This demand is then satisfied by a fleet of aircraft whose composition and performance are defined by two possible models. The simplest could be defined as a top-down model and represent the aircraft efficiency improvement through an annual efficiency gain, defined by the user with its own knowledge. Since this value could be hard to define with accuracy, the other approach consists in using fleet renewal models, introducing new aircraft in the fleet as discrete time events. In this case, the user should provide each aircraft performances (for instance by using preliminary aircraft design tools), entry-into-service year, final market share and its penetration speed into the fleet as parameters of logistic functions. Operational gains can be modelled with a similar approach, using a final potential gain in 2050 and an implementation speed. Combining aircraft and operation efficiency models allow to evaluate the second term of the Eq. (1), *E/RPK*. The energy carbon content CO_2/E is evaluated by the last submodule. The fleet uses a given energy mix, composed of user-defined share of drop-in fuels (kerosene, e-fuel, biofuel) and non-drop-in fuel (hydrogen) in relation with the fleet submodule. The impact of the power grid carbon content on electricity-base fuels is also modelled.

$$CO_2 = RPK \times \frac{E}{RPK} \times \frac{CO_2}{E} \tag{1}$$

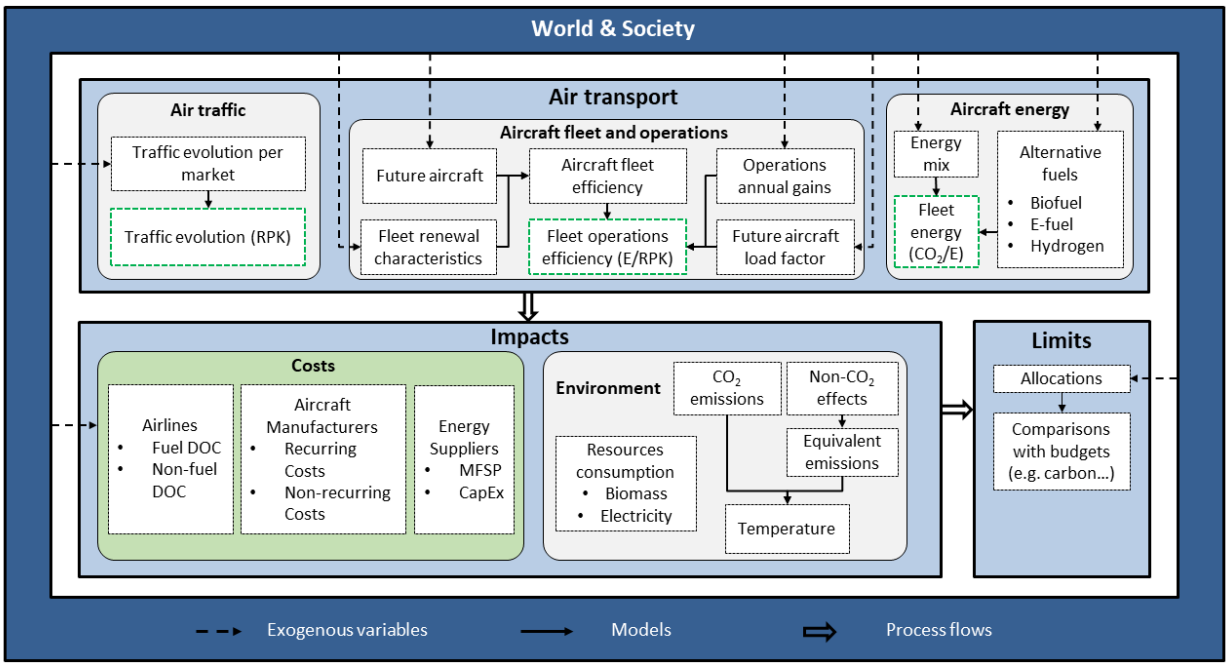

Figure 1: AeroMAPS architecture and its main models.

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The second module uses the outputs of the simulated air transport to compute impact metrics. There are two main impact categories. On the one hand, environmental metrics are computed. CO_2 emissions are computed using each fuel consumption and its emission factor. The temperature induced by non-CO_2 impact of aviation is also estimated by using a simplified metric, the GWP^* that allows a relatively accurate estimation of the impacts on temperature due to short-lived climate pollutants [27]. Since the use of alternative energy carriers involves dealing with their limited availability, the resource consumption of the scenario is also computed. On the other hand, cost metrics (in green on Fig. 1) are evaluated and will be described in detail in the next section. The analysis is limited to first order actors (airlines, manufacturers, energy suppliers): the impact on second-tier actors and stakeholders is not observed as of the current version of the software. Moreover, the economic analyses are limited to costs so far: how each actor will transfer its costs onto its customers is not within the scope of this evaluation.

Finally, the environmental metrics can be compared with external limits or indicators, to evaluate the sustainability of a given scenario. This can be done, for example, by comparing the CO_2 emissions of a scenario with an allocated share of a carbon budget, or similarly for available resources. At a later stage, this could be the case with economic investment capacities or expenses budgets defined by the user.

3. Cost models

A more thorough description of the various cost models is given in the following. A recap of the energy cost models is first provided. Alternative energy cost models were presented in detail in [17], with a model taking as an input each fuel pathway annual energy consumption to derive annual energy expenses and the required investments chronology for the energy sector. This paper also introduces two other cost models, the first one evaluating the impact of the energy transition on airlines, while the second evaluates the cost induced for the aircraft manufacturers. Lastly, a methodology for comparing costs is provided.

3.1 Recap of the energy cost models

Alternative energy carriers modelled in the framework are split in two categories. First, the drop-in fuels, which can be directly used into conventional aircraft (or at least blended with fossil kerosene), with little or no modification on the aircraft. Such drop-in fuels include biofuels and electrofuels. The second category is the non-drop-in fuels such as hydrogen or ammonia, whose use requires major modification on the aircraft.

Three biofuel production pathways are modelled within AeroMAPS: Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), and Alcohol-To-Jet (AtJ). Regarding their production costs, three main drivers are identified by the literature [28, 29]: the capital required to build a conversion plant (Capital Expenditures – CapEx), and the operational expenditures, in which we can distinguish between the supply of energy to be converted, referred to as feedstock in the following, and other expenses (personnel, various inputs, maintenance, etc.), referred to as OpEx. Despite large new scale-up plans for theses fuels like ReFuelEU (mentioned in the introduction), these are still niche markets, meaning that no mature price exists for the trade of these biofuels. A proxy metric used is the Minimal Fuel Selling Price (MFSP). It is the fuel selling price at which the fuel production project has a null Net Present Value (NPV). This value is the difference between the expenses and the revenues from a project during all its lifespan and considering the time value of money: a large investment immobilized in a project whose revenues occurs much latter represents an opportunity cost. It is considered by the discount rate *r*, which discounts future cash flows. Overall, the MFSP can be determined using Eq. (2), where $CAPEX_t$ are the capital expenditures at year *t*, $OPEX_t$ the operational expenditure on the same year, feedstock expenditures $FEED_t$ excluded. P_t is the quantity of fuel produced. One can see that *MFSP* is indeed the minimal constant price at which the fuel should be sold to ensure the project profitability.

$$MFSP = \frac{\sum_{t=0}^{N-1} \frac{CAPEX_t}{(1+r)^t} + \frac{OPEX_t}{(1+r)^t} + \frac{FEED_t}{(1+r)^t}}{\sum_{t=0}^{N-1} \frac{P_t}{(1+r)^t}} \quad (2)$$

In AeroMAPS, the biofuel MFSP were directly taken from a literature review [16, 28, 29], and the CapEx values were also taken or estimated by reversing Eq. (2) under standard financial assumptions. It allows to estimate the annual investment required in each production pathway besides computing the MFSP of the fuel used. Once this MFSP is known, computing the extra cost for the airlines is straightforward by subtracting the cost incurred by purchasing a similar amount of fossil kerosene, assuming both fuels are perfect substitutes.

A last metric is used: the carbon abatement cost *CAC*. It combines the MFSP of a fuel with its environmental benefit, which is modeled in the environmental impact module of the tool, described in detail in [30]. For the biofuel *i*, it is the ratio between the cost difference ΔC to the fossil reference and the emission factor difference ΔEF with the

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same fossil reference, as shown in Eq. (3). It is used with €/tCO$_2$ as a unit and allows to evaluate the economic efficiency of various alternative fuels. The concept can be generalized to any decarbonization measures.

$$CAC_i = \frac{\Delta C}{\Delta EF} = \frac{C_i - C_{fossil}}{EF_{fossil} - EF_i} \tag{3}$$

Both electrofuels and hydrogen are modelled in an equivalent way as biofuels. Schematically, hydrogen can be either used directly, burned in a gas turbine or as a fuel of a redox reaction in a fuel cell, or indirectly through the production of a synthetic kerosene. In the latter case, it is combined with CO$_2$ in a Fischer-Tropsch (amongst others) pathway to produce a drop-in fuel. The cost modelling follows a similar process as before, but the Eq. (2) is this time directly used as an explicit hydrogen MFSP model. Besides, it is adapted to index the hydrogen price on the yearly electricity price (equivalent of feedstock for biofuels). Only electrolysis hydrogen production is modelled so far. Reference technological values on CapEx, OpEx and efficiencies are taken from [31, 32]. When hydrogen is directly used, the cost of other production steps has to be added to its total cost. For instance, for volume reasons, its use in aircraft could require its liquefaction, and the supply chain (transport, storage and refueling) would be modified as well. Those costs are also modelled in the module [17]. Finally, computing an additional cost for the airlines should take into account that the aircraft efficiency could be modified when using hydrogen. Therefore, the total cost is given by Eq. (4), where *FC* is the fuel consumption of hydrogen or the reference fuel for the same operations and *C* their respective unitary costs. The carbon abatement cost is thus computed using Eq. (3) as well. The economic modelling of electrofuels is similar, though a last cost component should be accounted for: the CO$_2$, whose direct air capture is a major cost driver.

$$\Delta C = FC_{H_2}.C_{H_2} - FC_{fuel}.C_{fuel} \tag{4}$$

An overview of the energy cost model outputs is given on Fig. 2, with a decomposition of the different cost drivers of each production pathways mentioned in the previous section. For both hydrogen and electrofuels, the impact on price of the energy grid load factor sensitivity (30% and 95%) is also given.

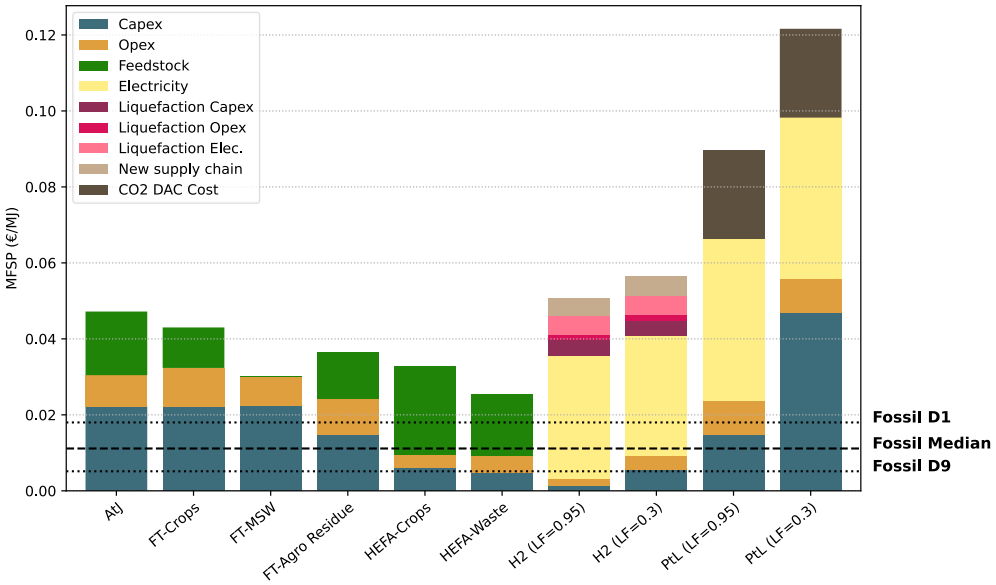

Figure 2: Minimal Fuel Selling Price decomposition of alternative energy pathways modelled in AeroMAPS.

3.2 Direct operation cost model

Airlines cost can be split into two informal categories: the costs directly related to operating an aircraft and those related to general business operations named non-operating costs (administration, sales, ...). For the former category, they can be further split between Direct Operating Cost (DOC) and indirect operating costs. Like non-operating costs, indirect operating costs are not directly linked to the aircraft operation but rather to passenger service. With a simplified approach, there are five main categories in the DOC: capital (owning an aircraft), crew, fuel, maintenance, and fees/taxes.

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Explicit direct operating cost models are presented in [33], on a per flight hour basis. These models depend directly on the aircraft characteristics. They were recalibrated using United States Bureau of Transportation Statistics traffic [34] and financial data [35, 36], and adapted to a per flight basis in [26]. Since AeroMAPS uses a global top-down approach to model flights by simulating the evolution of the Revenue Passengers Kilometres (RPK) for different markets rather than aggregating many flights, the direct use of these cost models would be of little interest. Therefore, average values for selected aircraft and distance categories were extracted from the results of [26] based on the full simulation of a year (2019) of US airlines flight. Note that it introduces an obvious geographical bias, some costs being widely dependent on the country or the airline (crew, capital structure, age of the fleet, …). However, the lack of reliable detailed financial data to recalibrate the cost model made this limitation necessary.

The average costs per DOC categories and aircraft type (regional jet, single aisle aircraft on short and medium range routes and long-range) are shown on Fig. 3. Values per Available Seat Kilometre (ASK) are used. Particular attention should be paid on navigation and landing fees, whose value is highly dependent on the country or even the airport involved. Handling costs have not been considered here, as they depend on the payload rather than the aircraft. Capital costs are particularly low in [35, 36] compared to [33], probably because of the amortized nature of the US fleet in 2019.

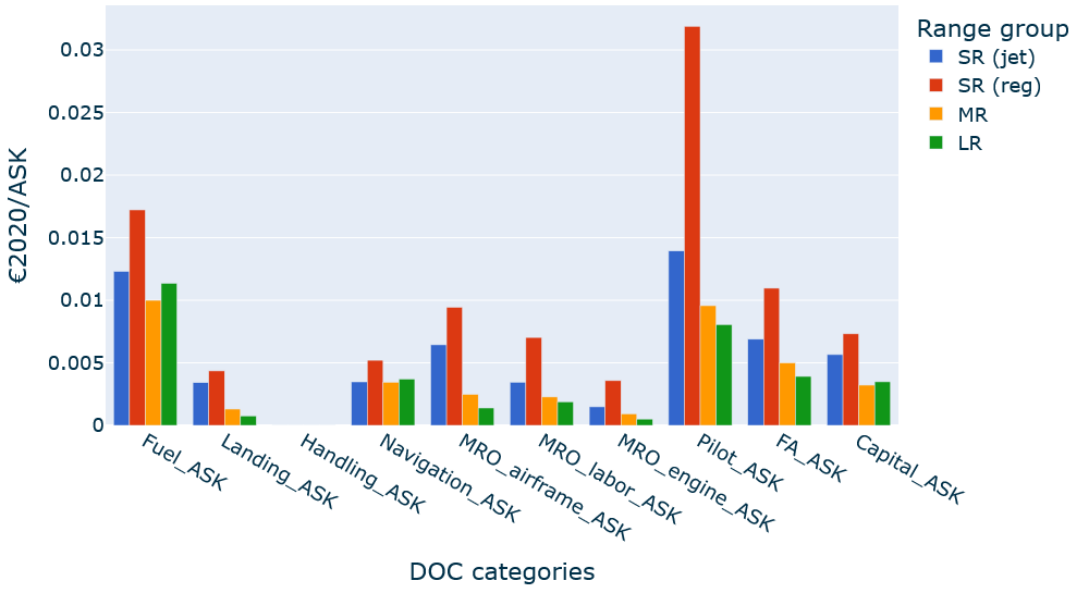

Figure 3: Average cost per available seat kilometre for US-based airlines in 2019.

Introducing new aircraft into the fleet could result in significative changes in direct operating costs. Switching to low-carbon fuels would increase the fuel DOC as it was highlighted in Section 3.1. To balance this, one could think about abatements on landing or navigation charges. Single pilot operations concepts are also studied [37] and could significantly impact the DOC as it can be seen on Fig. 3. Since DOC are directly related to the aircraft type, they are handled via the fleet renewal model mentioned in Section 2. First, aircraft are defined within categories. When a new aircraft is introduced in a category, its market share is modelled via a logistic function that takes into account the final market share of the aircraft being introduced, and the renewal speed of the fleet. More details are given in [25].

The flexible nature of AeroMAPS suggests that the reference values used for DOC excluding fuel, which are calibrated on the previous values by default, should be left free for the user to choose to adapt to different contexts. For the sake of simplicity, a single category for total non-fuel DOC is considered. The non-fuel DOC of each aircraft DOC_{NF_i} introduced into the fleet is expressed as a relative change to this reference Eq. (5).

$$\Delta \mathrm{DOC_{NF}} = \frac{DOC_{NF_i} - DOC_{NF_0}}{DOC_{NF_0}} \tag{5}$$

Thus, on a given year, the fleet level non-fuel DOC is then simply obtained via Eq. (6) by multiplying each aircraft *i* value per the number of ASK performed by this aircraft type in the scenario.

$$DOC_{NF_{fleet}} = \sum DOC_{NF_i} \times ASK_i \tag{6}$$

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Concerning the fuel DOC, it is directly linked to the energy cost module described in Section 3.1. Indeed, the fuel consumption of each new aircraft is defined by the fleet renewal model; and the fuel cost is simply obtained by multiplying this energy consumption by the average fuel price from the energy cost module. For the moment, each aircraft type in the drop-in fleet is considered to use a blend of all the pathways of the scenario (for example, a situation in which a new generation aircraft uses 100% SAFs while the older generation uses only fossil kerosene is not considered).

3.3 Manufacturing cost model

The last cost category covered so far in the AeroMAPS framework is the manufacturing and development cost related to a new aircraft. There are empirical cost models using several Top-Level Aircraft Requirements (TLARs) to estimate the development costs (Non-Recurring Costs - NRC) and production costs (Recurring Costs – RC) of a new aircraft [38]. They have been implemented by [39] with the addition of a model to split the NRC expenses over the development period [40]. The TLARs required by these models include the maximal takeoff weight, the operational empty weight, and the sea-level static thrust of the aircraft. They might not be known in every use case of AeroMAPS which could make using these models tedious. Therefore, these models were used to perform a regression on a set of recent commercial aircraft from Airbus, Boeing, Canadair, and Embraer. TLARs for the calibration aircraft were found in [41] and completed using manufacturers data sheet for modern aircraft models not included in the previous reference. A relatively linear relation is found between both aircraft RC and NRC and the standard number of seats onboard according to the model from, as it can be seen on Fig. 4.

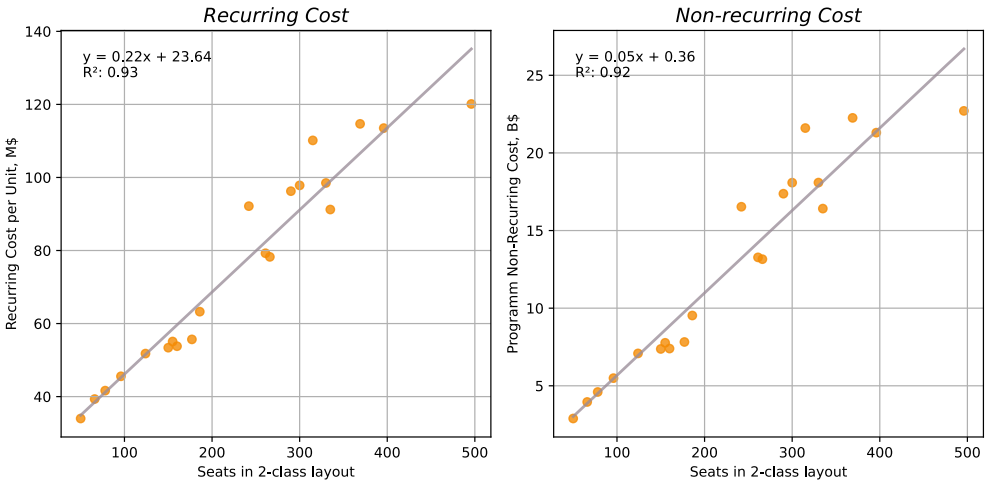

Figure 4: RC (per aircraft) and NRC for selected airliners using [38] and regression in relation to the number of seats.

Two comments are necessary at this point concerning these models. Despite the very good accuracy of the regressions when compared to models from [38], it should be reminded that they are conceptual phase models, and any value taken from this regression should be used for an order of magnitude only. Second, in case an aircraft is derived from a pre-existing aircraft either by stretching/shortening the cell, or by a re-powering, development costs are reduced. A methodology to estimate the NRC from a derivative program is proposed in [42] and could be easily adopted to the method presented here to manage this case.

Since the model from [40] requires the detailed outputs (different NRC categories: tooling, engineering, testing,…) of the NRC model, a simplified model is used so that a total NRC value C_0 can be used as an input. A gaussian-like distribution is used, centered around x_{peak} (the year with most expenses) while σ is adjusted to match the shape of the original distribution. The weights $w^*(x)$ are scaled by a factor WF to ensure the sum of the annual costs $C(x)$ matches the total cost C_0. When $x_{peak} = x_T/2$ (x_t being the total development time) and $\sigma = 1/6$ the model fits relatively well the original distribution, as illustrated on Fig. 5 for various development times x_T.

$$w^*(x) = \exp\left(-0.5.\left(\frac{x - x_{peak}}{\sigma}\right)^2\right)$$
$$WF = \frac{\sum C_0 * w^*(x)}{C_0} \quad (7)$$
$$C(x) = w(x)^*.WF.C_0$$

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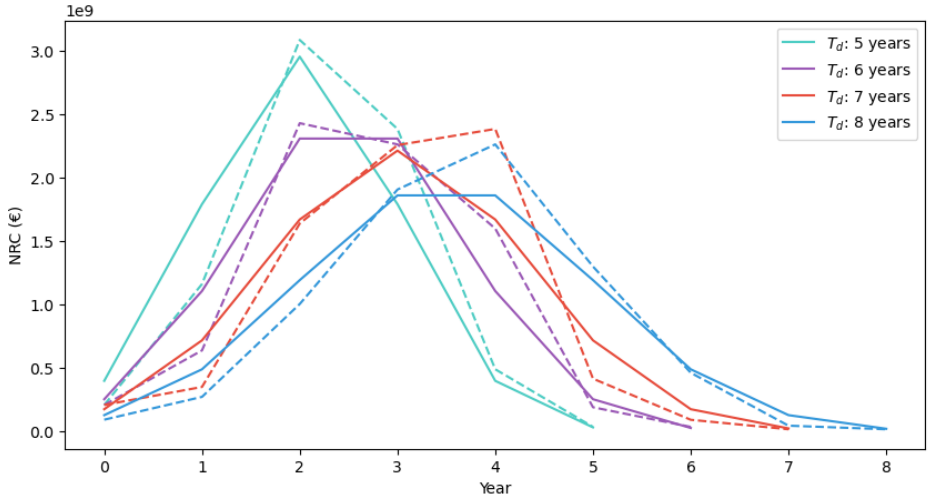

Figure 5: Single-parameter NRC distribution function (plain) compared to [40] distribution (dashed).

The actual user of AeroMAPS should provide a C_0 global value for the NRC of a new program, while the previous function will distribute it. It could come from user knowledge or from the regressions provided in Fig. 4. Once NRC and RC are known, these costs are integrated into a scenario using the fleet renewal model. Each time a new aircraft type is introduced, a NRC distribution is initiated at a user-defined year before the aircraft entry-into-service.

Lastly, to compute the total recurring costs of a scenario, one needs the number of aircraft of each type produced each year. It is obtained using the total distance flow per year by each type of aircraft divided by average distance flown by this type of aircraft each year. This gives a required number of aircraft of each type each year to satisfy the traffic. This number is compared to the available fleet. When the available fleet is insufficient, ΔA_t additional aircraft are manufactured (at year *t-1*) and added to the fleet, using Eq. (8). This method requires a detailed knowledge of the existing fleet, and particularly the ages (and thus the remaining life) of aircraft in fleet at t_0, the year at which the prospective scenario starts. This is obtained using a particularly simplified approach so far, assuming that the n_0 aircraft in fleet at t_0 have been introduced in the previous year t, ($t < t_0$) with an initial number X_i on year t_i and a compound annual growth rate g, as shown in Eq. (9). The lifespan of all aircraft is stored in $A_{available,t}$ which is then used in Eq (8). Similarly, when an aircraft is manufactured at $t > t_0$, its lifespan is stored in the same vector for the next iterations. Recurring costs (RC) are then calculated yearly by the multiplication of X_t by RC.

$$\Delta A_t = A_{required,t} - A_{available,t} \tag{8}$$

$$X_t = X_i(1+g)^{t-t_i}$$

$$\text{where } X_i = \frac{n_0}{\frac{1-(1+g)^{t_0-t_i}}{-g}} \tag{9}$$

3.4 Methodology for comparing costs

Different scenarios involve different cost chronologies, and therefore comparing them requires taking into account the impact of time on costs. This is achieved using a social discount rate. It is a value used to convert future costs (and benefits) into present values, considering both the expected future of the economy and the human preference for the present. In other terms, under the common hypothesis of a future growth and a positive preference for the present, future values should be positively discounted. Therefore, an investment happening in the future appears less expensive in current value than if it was realized today. Choosing this discount rate is a controversial economic research topic, especially when uncertainties about the future are added in the equation [43]. These issues being way beyond the current scope of AeroMAPS, a social discount rate *r=3%* is used by default to discount future costs. In practical terms, Eq. (10) is applied to every cost C_t to obtain the corresponding discounted cost C'_t.

$$C'_t = \frac{C_t}{(1+r)^t} \tag{10}$$

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4. Case study: comparing regulatory measures

The public policies evaluation capacities of AeroMAPS are explored considering two illustrative cases in this document. The first subsection evaluates the cost and sustainability consequences of blending mandates at a global scale and explore two different options to design the blend either by lowering the abatement cost or maximizing the carbon abated. This study is inspired by the fact that the European Union is about to adopt ReFuelEU for aviation legislative package, which aims at implementing blending mandates for the supply of alternative fuels in Europe [22]. The second subsection provides some answers to a practical question: as a regulator (such as the EASA in Europe or the FAA in the United States), how can the trajectory for improving fleet energy efficiency be enforced? Starting from a scenario with the blending mandate defined in the first point, a relationship will be established between the year of entry-into-service of a new aircraft type and the efficiency gains required to comply with a given decarbonization scenario.

4.1 Defining a blending mandate

The first application deals with blending mandates. With a disadvantage in terms of production costs, as explained in Section 3.1, the introduction of SAFs requires incentives or binding mechanisms. This could be, for example, the introduction of volume or blending mandates [44]. The European Union has chosen the second option [22]. In the corresponding proposal, a proportion of SAFs in the total energy consumed by aviation is specified for different time horizons. Of these SAFs, a proportion must be of non-biological origin (synthetic fuels). The exact details will be known when the text is finally adopted at the end of the legislative process of the EU. The organic origin of biofuels is not laid down in this proposal, which nevertheless stipulates that they must not compete with feed or food stock.

Three illustrative scenarios to design these blending mandates are presented. It is first assumed that the resource pressure is distributed equally across all biofuel production pathways, according to feedstock availability. This means that the pathway distribution is fixed over time. This option is designated as ‘homogeneous’ in the following. Therefore, 0.7% of biofuels are produced via the HEFA-FOG pathway (Hydroprocessed Esters and Fatty Acids - Fats, Oils and Greases), 3.8% via the HEFA-others pathway (mostly oil crops) and 7.4% via the FT-MSW pathway (Fischer-Tropsch - Municipal Solid Waste). The majority, 76.3%, comes from the FT-others pathway (agricultural and forestry residues, lignocellulosic crops). The remainder is made up of fuels originating from the AtJ (Alcohol to Jet) process. The values for biomass availability and the yields associated with each pathway are taken from [30]. Concerning synthetic fuels, they are derived exclusively from a Fischer-Tropsch synthesis with direct CO_2 air capture in this illustrative example. The direct use of liquid hydrogen should likely be included in this category in the final legislative text. Here, it is considered separately, via the introduction of a hydrogen aircraft into the fleet in 2035, eventually occupying 50% of the short-haul market (<1500km). Lastly, assumptions are also made on the other main scenario characteristics. It is assumed that traffic grows at a constant rate of 3% per year, and that energy efficiency improves by 1.3% per year. Operational efficiency is improved by 8% between 2025 and 2050, while the average load factor of the fleet reaches 89% in 2050.

The corresponding evolution of CO_2 emissions from aviation is given in Fig. 6. The scenario uses 6.3% of the available biomass in 2050 (164 EJ, before conversion in fuels) according to the estimation of [30] and 6.6% of the projected available electricity (250 EJ). Moreover, it uses 3.5% of the word carbon budget to remain below +1.8°C of global warming with 67 % of probability with 250 $GtCO_2$ of carbon dioxide removal.

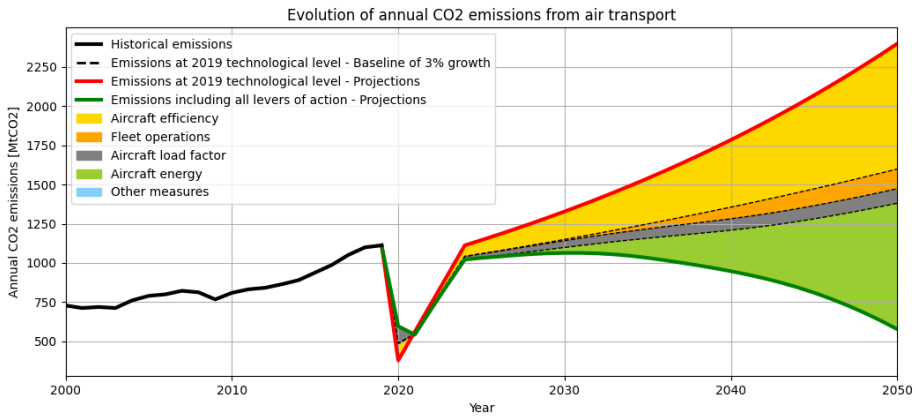

Figure 6: CO_2 emissions trajectory of the ‘homogeneous’ blending mandate scenario.

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Besides this 'homogeneous' scenario where no production pathway is favored, two alternative options for designing the blending mandates are studied. The methods and results are described in the following.

On the one hand, the first option explored to design a blending mandate is to use Eq. (3) to rank the different energy carriers by abatement cost. This option is designated as 'low carbon abatement cost' in the following. The abatement cost measures the monetary intensity of decarbonization, i.e. the additional cost associated with an action that reduces emissions compared to a reference scenario. The abatement costs of the various drop-in fuels considered here are shown on Fig. 7, with the abatement potential on the x-axis, to form a Marginal Abatement Cost Curve (MACC). For a given financial budget, the maximum emissions reduction will be achieved if decarbonization actions are carried out from the left to the right of the MACC ('cheapest first'). However, this curve is static and valid for a given time horizon. It does not guarantee the economic optimality of global decarbonization trajectories to meet a given carbon budget [45]. For instance, in our case, we can see that AtJ or HEFA-Others are used before electrofuels, following this logic, even though their emission factors are higher. Choosing them without considering the dynamic aspect of decarbonization trajectories would lead to make investments that would not enable long-term objectives achievement (carbon lock-in). In this simplified scenario, these considerations are set aside. To design this blending mandate, it is required to constrain the available biomass by sector. Indeed, the volumes of biomass available worldwide would make a reasoning based on MACC curves complex, as only the most interesting pathways would be used, without taking inter-sectoral competition into account. A value of 10% of the biomass of each pathway is allocated to aviation in this illustrative example.

Overall, this scenario based on the marginal abatement cost curve uses 3.5% of the carbon budget, 3.5% of the electricity budget and 10% of the biomass budget as defined previously. From a climate perspective, the two previous scenarios are very similar. Less electricity is used because as highlighted by Fig. 7, electrofuels have the highest carbon abatement cost. All the biomass pathways are used, until the allocation threshold of 10% of the resource, meaning that the availability constraint set to enable a MACC reasoning is active.

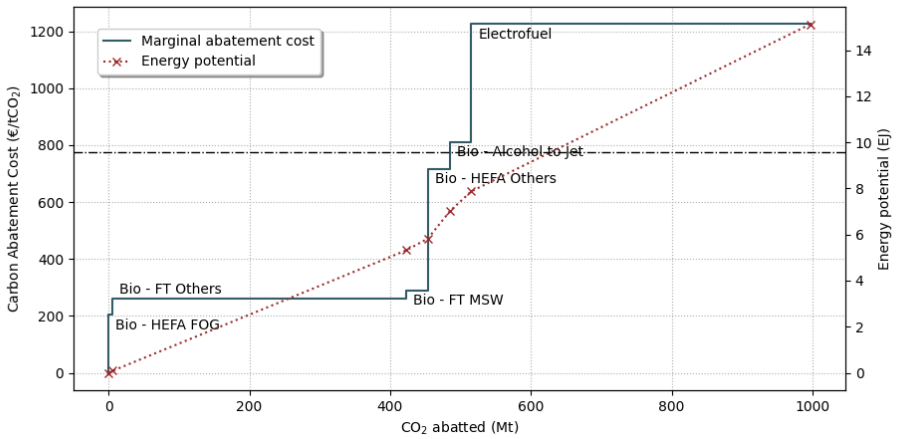

Figure 7: Marginal Abatement Cost Curve with 10% biomass availability constraint. The horizontal dashed line represents the drop-in fuel consumption of the aviation sector in 2050.

On the other hand, another option to refine the blending mandate would be to select the least carbon intensive options regardless of the cost. This option is designated as 'low carbon' in the following. With the same 10% availability constraint, only the FT-Others, the HEFA-FOG and finally the electrofuels are used, with respectively 80, 66 and 66% emissions reduction compared to fossil kerosene (in 2050). It uses also 3.5% of the carbon budget, 6.1% of the electricity and 7% of the biomass. All the allocated biomass for the previous 2 pathways is used, while none is used for the more carbon intensive pathways.

In order to compare the scenarios, the cost and the detailed abatement trajectory of the three proposed blending mandates can be seen on Fig. 8. As explained before, the MACC curve used to design the low carbon abatement cost and the low carbon trajectories was designed for 2050 values. It means that any cost or emission value between 2020 and 2050 might be suboptimal. For instance, in the 'low carbon' trajectory, the electrofuels are introduced quicker than in the two other trajectories, at a period where the electricity mix is still too carbon intensive to provide carbon emissions reductions through electrofuels usage. This explains the relatively similar carbon budget consumption between the 3 scenarios. However, in the long term, the trajectory is as expected the least carbon intensive, but not necessary in terms of carbon budget consumption. In terms of expenses, all the trajectories triple at least the annual energy expenses of a 'business as usual' scenario with 100% fossil kerosene. In the long term, it is mostly the use of electrofuels that drives the cost, as it is the most expensive alternative energy investigated here (Fig. 2). The average abatement cost (sum of the discounted costs over the sum of avoided emissions) of each trajectory is also insightful.

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With a 3% social discount rate, the ‘low carbon abatement cost’ scenario is at 708€/tCO_2, while the ‘homogeneous’ scenario is at 791€/tCO_2 and the ‘low carbon’ scenario at 841€/tCO_2. Overall, the extra cost linked to the use of alternative fuels is between 1846 and 2659 Bn. € (discounted at 3%). Note that this is not a certain value, and rather lower bound, since minimal fuel selling prices were used during the reasoning. They do not reflect the future market prices, which could be as high as the most expensive decarbonization option necessary to reach decarbonization targets.

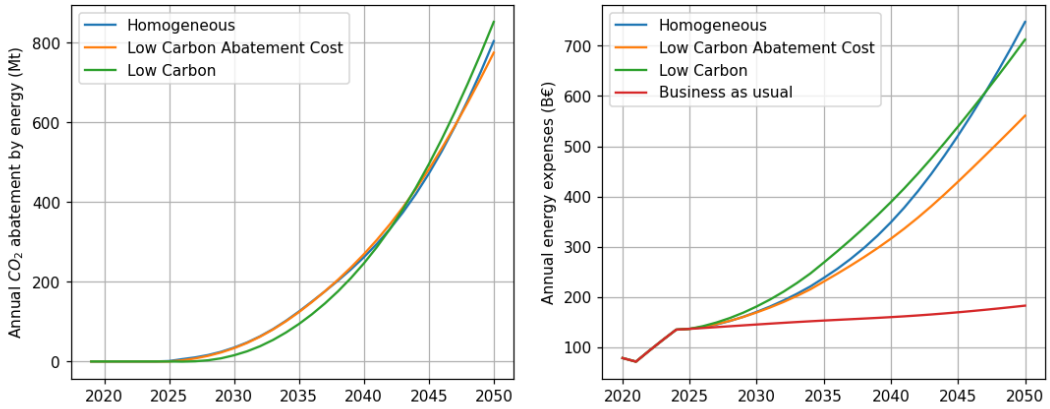

Figure 8: Abatement (left) and cost (right) trajectories for three blending mandates studied in Section 4.1.

In a nutshell, the blending mandate design process presented in this section clearly illustrates the difficulties of choosing between deep decarbonization, particularly in the long term, and shorter-term constraints, such as the budget available for the investments needed to launch the production of those energy carriers.

4.2 Driving the fleet efficiency with regulatory measures

The second application proposed in this section concerns the practical implementation of targets for the energy efficiency or CO_2 emissions of the global aircraft fleet, through explicit regulations on the energy consumption of new aircraft. This involves linking the top-down approach presented in the previous section with fleet renewal models. The starting point chosen is the ‘homogeneous’ scenario of the previous section. As mentioned before, this scenario used 3.5% of the remaining carbon budget to limit the global warming to 1.8 °C, corresponding to 28.0 GtCO_2. This share is greater than the current contribution of aviation to annual CO_2 emissions (2.6%). The exogenous parameters (such as the growth rate) used for this scenario make it difficult to achieve this objective. In what follows, an intermediate target of 27.0 GtCO_2 will be set. The aim of this section is to present a methodology to estimate the fuel efficiency gains required for a new aircraft in order to meet this target, depending on its entry-into-service year.

First, three aircraft categories are considered in the fleet renewal model: short, medium, and long-range. In all categories, an ‘old’ reference aircraft is being replaced by a ‘recent’ reference aircraft as the prospective scenario begins. In the real world, it could be for instance the replacement of A320s by A320neos or B767s by B787s. Then, the simultaneous introduction of a new aircraft in each category is simulated by the fleet renewal model of AeroMAPS. For the sake of simplicity, each aircraft introduced features the same fuel efficiency improvement compared to the category’s reference aircraft. A manual approach is used to find the efficiency/entry-into-service year trade-off that makes the scenario match the 27.0 GtCO_2 target. Since the fleet renewal duration (or aircraft lifespan) also affect the fleet renewal, three values of this parameters are tested: 25 (reference), 22.5, and 20 years. Besides, a hydrogen aircraft is introduced in 2035 for short-range flights, with a 50% nominal market share and a 10% energy consumption increase compared to the recent reference aircraft.

The result is shown on Fig. 9 (left). The first thing to note is that the objective is not always achieved. Indeed, from 2040 onwards, the introduction of aircraft whose efficiency has been improved by 60% is no longer enough to make up for the delay in reaching the target, even for the accelerated fleet-renewal option (20 years). Logically, the higher the rate of fleet renewal, the easier it is to achieve the target: the introduction can be delayed, or the necessary performance revised downwards. Note that the renewal rate parameter also affects the renewal of the ‘old’ reference aircraft by the ‘recent’ reference aircraft, hence an increased impact of this measure.

For this first analysis, the target was the cumulative CO_2 emissions, because of the relevance of this parameters from a climate point of view as explained in the introduction. Another solution is to consider the final CO_2 emissions in 2050. Both green curves (‘ref’) from the left and right plots of Fig. 9 are related to the ‘homogeneous’ scenario in terms of blending mandate of the previous section: one takes 96.5% of its cumulative CO_2 emissions while the other 96.5% of its final year CO_2 emissions as reference. In order to study the influence of the target choice, a simplified

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sensitivity analysis is also performed. Should the final CO_2 emissions criteria be used instead (as it is the case with 'net zero by 2050' plans [8]), the introduction can be delayed. Indeed, after a sufficient time, the aircraft is well established into the fleet and will contribute to the final year CO_2 emissions reduction no matter its entry-into-service year. This is not true with cumulative emissions where the introduction date is always important. One interesting point to note on the right curve is the existence of tipping points especially with loose targets. For example, to reach the reference 576.8 $MtCO_2$ target in 2050, the aircraft energy consumption reduction required is relatively moderate until 2033-2035. After this date, there is not enough time for the aircraft to be sufficiently deployed into the fleet to actually contribute to its global decarbonization, requiring therefore fast-growing energy efficiency improvements.

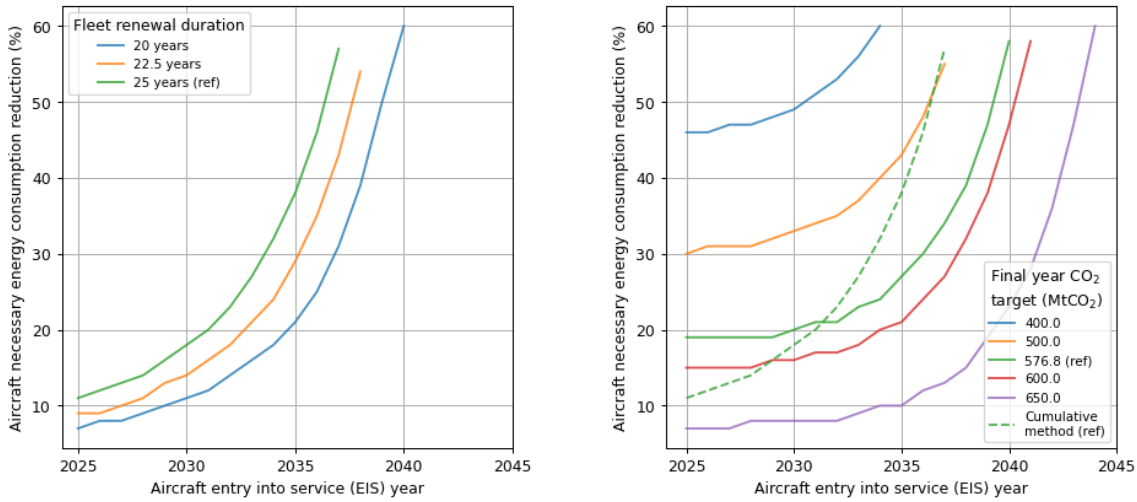

Figure 9: Performance & entry-into-service trade-off for CO_2 emissions targets.
Left: Performance & entry-into-service trade-off to respect a 27.0 $GtCO_2$ cumulative emissions target.
Right Performance & entry-into-service trade-off to respect various 2050 emissions targets (25 years fleet renewal).

The last method considered in this section concerns the use of non-climate targets. Indeed, cumulative or final CO_2 emissions targets were chosen. In a configuration where one would like to drive its energy efficiency regulation by adequately selecting a cumulative energy consumption (because of biomass or electricity availability for instance), Fig. 10 analysis could be used. The comments inherent to this figure are relatively similar to those made for Fig. 9: an over-ambitious target for reducing energy consumption can only be achieved by introducing ultra-efficient aircraft very quickly, which could be unrealistic depending on the energy consumption reduction required. Conversely, an unambitious target would have no effect on the fleet, as highlighted by the red curve. The same divergence after a threshold period is observed. Despite being centered on energy instead of CO_2 emissions, both approaches are complementary.

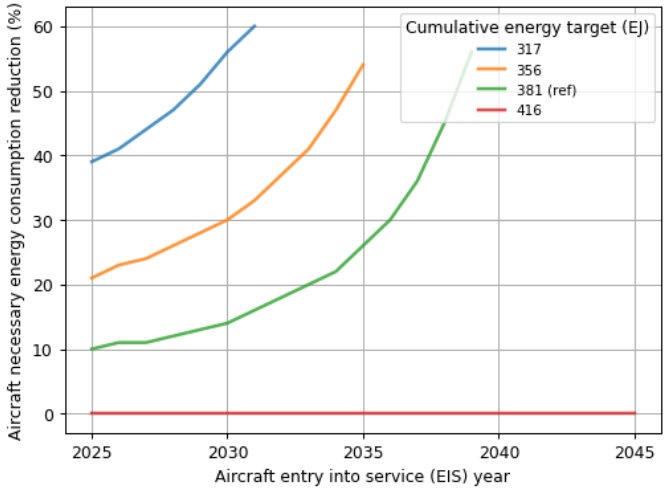

Figure 10: Performance & entry-into-service trade-off for various cumulative energy budgets.

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Lastly, analyses on manufacturing costs and airlines direct operating costs are performed, studying in particular the effects of the fleet renewal speed. There is currently no model to capture the cost of technological complexity on AeroMAPS. It is therefore considered that the same aircraft is introduced at three different dates in order to achieve the same objective for the three fleet renewal rates examined. As read from Fig. 9 (left), an aircraft offering 30% gains over the last generation of aircraft is introduced in mid-2033, 2035 and 2037, for a renewal period of 25, 22.5 and 20 years respectively. This makes it possible to achieve the cumulative CO_2 target discussed above.

In terms of non-recurring costs, the same number of aircraft types are introduced in all options. According to Fig. 4, it is assumed a 10 B€ NRC for both short and medium range narrow-body aircraft type and 20 B€ NRC for the long-range aircraft and the short-range hydrogen aircraft. For the latter, this choice is motivated by the novelty of hydrogen architecture. These values are doubled under the hypothesis that two aircraft manufacturers develop concurrent models for each category. The total NRC costs over the 2025-2050 period are therefore of 120 B€. To compare the present value of each fleet-renewal rate option, a 3% discount rate is applied. The late, but quick, renewal benefits from this since later development costs are squeezed by the discount. Indeed, the NPV of the NRC is of 99.7 B€ in the quick renewal option and 105.6 B€ in the slow renewal option. The difference remains relatively small. In terms of recurring costs, the rapid renewal option logically implies a higher aircraft production output. The recurring costs are at 5336 B€, 5208 B€, and 5040 B€ for the three scenarios, from the fastest to the slowest. In terms of NPV, the gap is smaller but still significant (3470 B€, 3407 B€, 3317 B€). Note the difference in order of magnitude between NRC and RC. The beneficial effect of NRC on NPV is therefore not offset by the extra cost associated with faster production, even if it is late. From an economic point of view, the scenario of early introduction of a high-performance aircraft with a conventional service life is therefore preferable. Using a discount rate of 7%, typical of the private sector, the slow renewal is still more efficient, but this trend is reversed using a very high discount rate (15% for instance).

Finally, it is proposed to look at DOCs using the models presented in Section 3. The non-energy DOCs for each aircraft type are calibrated on the values of Fig. 3, while the energy DOCs are obtained by multiplying the MFSP outputs of AeroMAPS by the energy consumption per ASK of each aircraft type. The impact of fleet renewal rate on DOCs mentioned in the previous paragraph has not yet been directly modelled. Nevertheless, it is proposed to use a simplified approach, assuming that the production cost of aircraft does not depend on their lifespan. The impact on DOC is therefore proportional to the reduction in lifespan. As illustrated by Fig. 12, the impact of fleet renewal rate on non-energy DOC (dashed lines) is very limited due to the moderate contribution of capital cost to DOC (Fig. 3). The effect of the hydrogen aircraft, whose non-energy DOC is arbitrarily set to 1.2 time the conventional short-range aircraft DOC, can be seen after 2040. By accelerating its entry into the fleet, the quick renewal option increases this effect. The most notable observation on Fig. 12 is the evolution of energy DOCs in all the scenarios. Between 2020 and 2026-2028, the energy DOCs are reduced thanks to the fleet renewal and the low share of SAFs in the scenario used. After this period, the rapid deployment of SAFs into the fleet rapidly increases the energy DOCs. In 2050, in this scenario, they would represent more than the half of the operating costs for medium and long-range categories, while non-energy DOCs would still drive short-range operating costs. The effect of the new aircraft introduction is seen with a curve inflexion after 2045, due to the improved fleet average efficiency. Because the slow deployment option requires an early entry-into-service to respect the cumulative CO_2 target, it is able moderate the energy DOC increase, while the effects diminish with time when the renewal happens as well in the two other options.

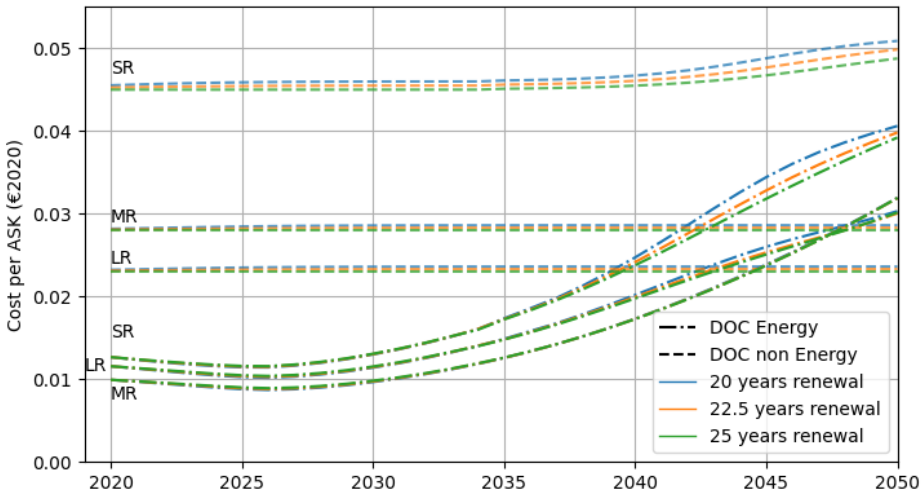

Fig 12: Average energy (top group) and non-energy (bottom group) DOC evolution per aircraft category. Accelerated renewal rate has moderate impact on non-energy DOC, while SAFs introduction increases energy DOC.

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To summarize, this section has presented a way of using AeroMAPS to define the annual performance evolution of new aircraft types required to meet given transition targets. Different options for the speed of fleet renewal are explored, showing the need to consider the full chronology of costs involved.

5. Conclusion

This paper presents the continued work to implement cost models in the AeroMAPS framework, as well as an illustrative case study to design two types of policies using the capacities of the tool. AeroMAPS simulates prospective scenarios for the future of air transport by matching the future demand for air transport with a fleet and an energy mix. Environmental and economic impacts are evaluated and a comparison with environmental limits is performed for assessing the sustainability and interest of various scenarios.

This paper specifically introduces a simplified direct operating cost model as well as aircraft manufacturing non-recurring and recurring cost models. The direct operating cost model capitalizes on AeroMAPS fleet renewal model as well as on energy cost model to evaluate the impact of both detailed fleet renewal scenarios and sustainable aviation fuel deployment scenarios on the average and total direct operating costs. The aircraft manufacturing cost model derives an annual aircraft production capacity for a given scenario by matching the demand from the scenario with a supply trajectory. Non-recurring costs are evaluated at the introduction of a new aircraft type thanks to a surrogate model built on literature data and spread over a time window prior the aircraft entry-into-service. The recurring costs are simply estimated by multiplying the aircraft production by the unitary production cost.

Two illustrative examples are given. First, three sustainable aviation fuel blending mandates are designed following three different objectives: equal strain on each resource (based on ReFuelEU assumptions), low carbon abatement cost and finally lowest emissions. They are compared both in terms of total CO_2 emissions and in terms of cost. Total energy expenses are at least tripled compared to a business-as-usual scenario, with significant difference between the three blending mandates in the long-run. This illustrates the need to find a compromise between deep decarbonization over time and economic efficiency. Then, the fleet renewal module is used to perform a trade-off study between a new aircraft type year of entry-into-service and the required efficiency improvement to match a given cumulative CO_2 emissions target. It shows that after a certain time threshold, the efficiency required is unrealistic. Alternative targets such as the final year CO_2 emission or the cumulative energy use are also presented, with a similar trend. However, it should be noted that the final year emission objective is less restrictive than the original target, making targets such as net zero in 2050 less restrictive than cumulative emissions targets. From a cost perspective, a slower but anticipated renewal requires less aircraft to be built each year to achieve the same targets, resulting in a smaller total cost for the air transport industry. The fleet renewal speed only affects moderately the DOC, contrary to the deployment of more expensive sustainable aviation fuels as expected from the results of the first illustrative example.

These applications underline the difficulties for considering simultaneous environmental and economic analyses. As a consequence, multidisciplinary tools such as AeroMAPS could therefore help decision-makers to evaluate different strategies quickly, in order to enlighten the necessary trade-offs.

Furthermore, these analyses could be enriched by considering also the impact of all the aforementioned costs on the demand side of the air transport. The cost increase impact on the demand is not modelled, making any comparison between different scenarios potentially incorrect. Besides that, the interaction between the different modules could be reinforced to capture, for example, the sector's limited investment capacity, making certain combinations impossible (e.g. combining both a rapid sustainable aviation fuel deployment and an accelerated fleet renewal). Finally, the analyses are yet conducted on a global scale. It allows rapid computation time, but also affects the reality of the scenarios that can be tested. For instance, ReFuelEU blending mandates were implemented at a global scale rather than at the European level. The points raised above are prerequisites for setting up optimisation processes that would allow determining in greater detail the scenarios that enable achieving fixed climate objectives at minimum cost, or decarbonizing as much as possible within a fixed financial budget.

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