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# Cost estimation of the use of low-carbon fuels in prospective scenarios for air transport

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**Using low-carbon energies is a major lever to reduce the $CO_2$ emissions of aviation. Some low-carbon energy carriers consist in fuels that are drop-in and require few modifications to current aircraft, like biofuels and electrofuels. Hydrogen is another low-carbon fuel that would be relevant in the long term only since it requires significant aircraft modifications (non-drop-in fuel). In both cases, several production pathways exist with radically different impacts in terms of cost of production and life-cycle $CO_2$ emissions. Literature is already exhaustive on prospective decarbonization scenarios for aviation and low-carbon fuel production cost estimates. In this paper, an open-source simulation framework named CAST is enhanced by a module that links low-carbon fuels production cost to their respective consumption in given scenarios. Hence, the cost of a custom decarbonization scenario is evaluated. Results show that the cost of the integration of low-carbon fuels in this scenario would represent around 40 % of airlines revenues in 2050, while the energy demand growth would necessitate important capital investments, regularly increasing to 130 Bn € in 2050. A sensitivity analysis shows that these cost estimates are subject to large uncertainties.**

## Nomenclature

*ATAG* = Air Transport Action Group
*ATJ* = Alcohol-To-Jet
*CAPEX* = CAPital EXpenditure
*CAST* = Climate and Aviation - Sustainable Trajectories
*CORSIA* = Carbon Offsetting and Reduction Scheme for International Aviation
*FT* = Fischer-Tropsch
*HEFA* = Hydroprocessed Esters and Fatty Acids
*IATA* = International Air Transport Association
*IEA* = International Energy Agency
*IPCC* = Intergovernmental Panel on Climate Change
*LCA* = Life Cycle Assessment
*MFSP* = Minimal Fuel Selling Price
*NPV* = Net Present Value
*NZE* = Net Zero Emission
*OPEX* = OPerational EXpenditures
*SAF* = Sustainable Aviation Fuel
*SMR* = Steam Methane Reforming

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# I. Introduction

Anthropogenic climate change is now a consensual topic and requires rapid and determined decarbonization action from all the emitters. The greenhouse gas emissions pathway of IPCC (Intergovernmental Panel on Climate Change) to limit global warming below + 1.5 degrees Celsius in comparison to pre-industrial levels requires an 84 % reduction in annual $CO_2$ emissions by 2050, meaning an annual decline of around 6 % [1]. Among those, aviation contributed to around 2.6 % of the global $CO_2$ emissions in 2019 [2]. Its overall contribution to the temperature change is higher, since other effects like persistent condensation trails also have a warming effect, despite higher uncertainties [3]. Aviation emissions continued to grow, with a 34.7 % increase between 2013 and 2019 [4, 5].

Therefore, more efforts are needed to curb the emissions and over the last few years, several industrial reports and forecasts were edited with the aim of providing a plan to reach ambitious goals in the long term [6–8]. While industrial stakeholders, via the voice of ATAG (Air Transport Action Group) and IATA (International Air Transport Association), share the ambition of $CO_2$ net-neutrality in 2050 [6, 7], governmental bodies agreed on CORSIA which is a program designed to ensure a carbon-neutral growth for most international aviation after 2020 [9]. Most of these scenarios require the use of carbon offsets to fulfill their goals [6, 9]. Academic research has also recently addressed this issue with the development of models specifically designed to simulate and evaluate the climate impact of given decarbonization scenarios [10–14]. Besides pursuing the continuous improvement of aircraft efficiency and pursuing efforts towards more efficient operations, using low-carbon fuels is a major action lever to reduce aviation climate impact. For instance, the so-called Sustainable Aviation Fuels (SAF) contribute to 55-71 % of the emissions reduction in 2050 in ATAG scenarios [7].

Two categories can be established among low-carbon fuels: drop-in fuels and non-drop-in fuels. The first category can be used in conventional aircraft without major modifications (blended up to 50 % SAF nowadays and to 100 % in the near-term [15]). Biomass-based kerosene, also called biofuel, and power-to-liquid kerosene, also called electrofuel or e-fuel, can be identified, the latter is produced using electricity and a source of carbon. Since carbon dioxide was captured during biomass growth, no additional carbon is released when biofuel is burned. However, production processes, land-use change, and other factors should be accounted for within a Life Cycle Assessment (LCA) methodology and the overall process is not necessarily carbon neutral. There are several chemical processes already approved by authorities to transform biomass into fuel, depending on the feedstock source [16]. The carbon dioxide abatement potential ranges from little or no benefits to more than 90 % reduction, depending on the conversion pathway, the feedstock source, and the accounting method [17]. On the other hand, non-drop-in fuels require substantial technological changes to the aircraft fleet. Hydrogen is an example of a non-drop in fuel studied for application to aviation. Unlike with biofuels and electrofuel, there are no carbon dioxide emissions during the flight with hydrogen but an LCA approach is also necessary to account for hydrogen production emissions. Several pathways exist to produce hydrogen with different $CO_2$ emissions during production [18, 19]. Hydrogen involves a relatively complex supply chain and a poorer volumetric density. Electrofuels allow to avoid this problem by combining hydrogen and $CO_2$ into a drop-in fuel [20].

Both non-drop-in and drop-in fuel generate substantial production costs. Fossil-fuel prices are mostly driven by exclusivity rents, with production costs well below trading prices [21]. Meanwhile, biofuels involve several transformation steps and most of the time feedstock needs to be produced. This leads to a Minimal Fuel Selling Price (MFSP), i.e. the fuel selling price ensuring a minimal profitability, between 1.5 and 9 times the cost of conventional kerosene in the mid-term [17]. There are three MFSP drivers: the capital cost, the operating costs, and the feedstock himself [22]. Hydrogen (and other non-drop-in fuels) involves another cost effect: since aircraft design is also modified, it could be more expensive to operate from 6 to 10 %, excluding the cost of hydrogen which is itself more expensive from 10 to 100 % [23]. Several other studies on biofuels or hydrogen production costs and environmental impacts were published [24–28].

Besides, aviation-specific integrated assessment models have been developed such as AIM2015 [29] or FLEET [30]. They simulate system-wide demand-offer equilibrium, based on various econometric models. It is possible to use such models to investigate how more expensive biofuels would affect passenger demand and eventually $CO_2$ emissions [31]. However, integrated models are computationally expensive which can lead to significant computation times sometimes not suitable for rapid decision-making. In addition, their ability to predict future events is conditioned by the fact that they are calibrated on past data. Consequences of individual events are less direct to understand since these models are built to represent all the interactions between air transport system stakeholders. Some decarbonization scenarios present abatement cost (expenses required to avoid $CO_2$ emissions) estimations associated with the use of biofuels or hydrogen but rely on more or less open-source models [6, 8].

In this paper, a simplified approach is presented to integrate the cost of switching to low-carbon energies into CAST (Climate and Aviation - Sustainable Trajectories), an open-source tool used for simulating aviation prospective scenarios [10]. CAST is used to estimate the energy consumption of aviation scenarios, with a parametric approach to tune various parameters such as growth rate, aircraft fuel burn evolution, or operational improvements. Simple cost models for biofuels, electrofuels and liquid hydrogen are built and integrated into CAST. Additional fuels costs and investments required to use low-carbon fuels are computed on a yearly basis, allowing the rapid cost evaluation of user-defined scenarios. Prospective prices for biofuels and hydrogen are matched with the amount of energy needed while financial parameters such as the discount rate are tuned by the user. Eventually, the abatement costs related to the use of low-carbon energies are computed.

To this end, the paper is organized as follows. In section II, the existing CAST tool is described. The methodology chosen to model low-carbon energy prices and match their supply volume to the aviation consumption is detailed in section III. In section IV, models are tested and some results are presented for a global scenario defined with CAST. Besides this central scenario analysis, the effects of selected parameters on $CO_2$ emissions and energy costs are presented. Conclusive remarks and prospects are given in section V.

## II. Methods and Tools

In this section, the CAST tool is presented and the existing gaps to develop a cost estimation module for the tool are presented.

As briefly introduced in the introduction, CAST is an open-source framework simulating and evaluating user-defined aviation emissions scenarios. Inputs such as traffic growth rate, aircraft efficiencies, and fleet renewal parameters as well as load factor and energy carbon content are used to feed the corresponding models. Air traffic is modeled via decennial exponential functions, while the integration of low-carbon fuels is modeled using incorporation rates and fuel characteristics such as production efficiency and emissions. Fleet renewal and aircraft efficiency improvements are modeled using two different approaches. On the one hand, a model based on annual efficiency gains allows simply estimating the fleet energy consumption. On the other hand, a bottom-up approach, based on logistic functions accounting for new aircraft market penetration, can be used to generate a more detailed estimation [32]. The results are used to compute worldwide civil aviation $CO_2$ emissions. Other environmental impacts are computed, such as the share of available bio-energy used by aviation. A schematic illustration of CAST architecture is given in Fig. 1.

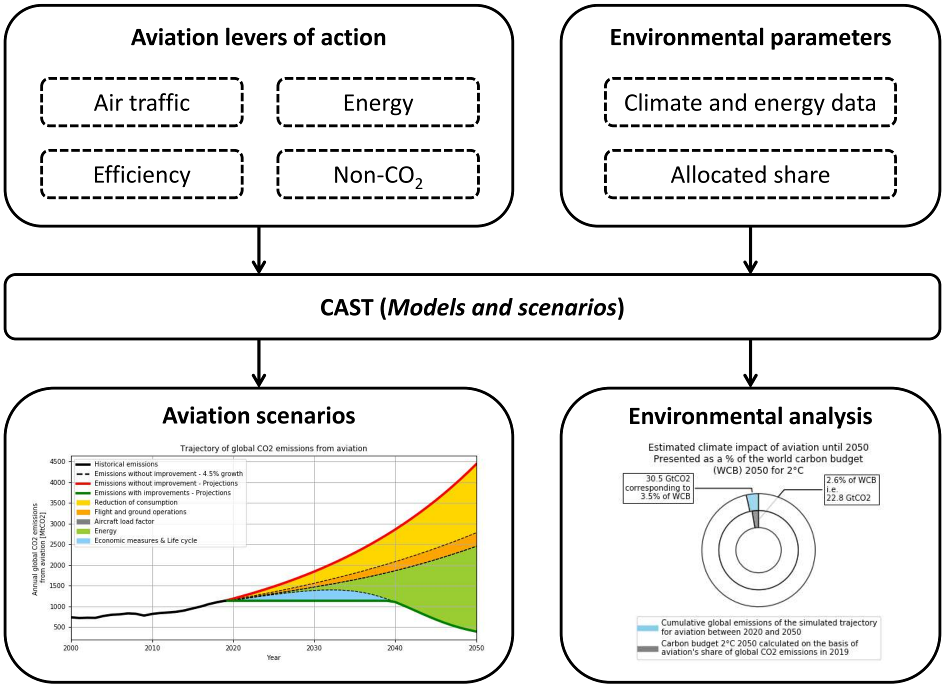

**Fig. 1 CAST schematic diagram**

Currently, the framework cannot link the cumulative $CO_2$ emissions of a given trajectory to an extra cost for the industry. Several cost models must be developed to predict the cost induced by each lever mentioned before. For instance, introducing unconventional aircraft to the fleet requires larges investments by aircraft manufacturers and might change the operating cost of the aircraft. Accelerating the fleet renewal implies a larger capital cost for airlines. Replacing fossil kerosene by low-carbon energies introduces on its side a straightforward cost: they reduce life-cycle $CO_2$ emissions but are more expensive than kerosene in the mid-tern [17], leading to higher system operating costs. This work is a first step to introduce cost models in CAST, focusing on this energy replacement lever.

The CAST user specifies several energy parameters (such as the incorporation rate of the different kind of fuels mentioned in the introduction, their emission factors and the availability of the corresponding resources) and CAST generates a yearly energy demand for each fuel category. The cost module presented in this paper matches this demand with a production scenario: each year, enough production capacity is built to ensure the adequate production in the following years. Two main parameters are computed each year: the (CAPEX - Capital Expenditure), the capital needed to build the various plants and a cost premium representing the additional cost generated for the companies through the purchase of SAF. This kind of approach can allow to search for optimal decarbonization scenarios, in which the cost is minimized while respecting some decarbonization objectives. Even if the present work does not follow this objective, the integration of cost models in CAST presented here aims at building the basis for such a work in the future.

## III. Cost models for fuel production

In this section, simple models to estimate the production costs and the investments needed for biofuels, liquid hydrogen and electrofuel are presented. Biofuels and electrofuels are jointly referred to as drop-in fuels, while liquid hydrogen is also designated as a non-drop-in fuel. In the context of this paper, all of these fuels are referred to as SAFs.

### A. Biofuels Production Modeling

Several biofuels production pathways have been identified and certified to be blended with fossil aviation fuels. Biomass used can be categorized into three groups: oil-containing biomass or used oils, lignocellulosic biomass, sugar or starch-containing biomass [16]. Three conversion pathways are modeled within CAST: Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT), and Alcohol-To-Jet (ATJ).

Pavlenko *et al.* present a harmonized evaluation of the production costs for various pathways [28]. Production cost is split between initial investment (CAPEX - Capital Expenditure), biomass cost (Feedstock, noted FEED), and other operational expenditures (OPEX). The latter is made up of various inputs required for production (in addition to feedstock), such as hydrogen addition or the electricity necessary for the conversion. Note that OPEX are often directly taken as a whole without considering its individual components. Therefore no links are modeled between the electricity generation models and hydrogen production models presented latter and the biofuels models of this section, despite existing links.

The overall production modeling approach is summarized in Fig. 2, which also lists the different variables of interest that are tracked. They will be discussed in more detail in the following.

It is a common practice to use *$n^{th}$ plant* analysis to calculate production costs. It evaluates production costs once processes are mature rather than during a more expensive initial phase [17]. In the real world, investments would likely further decline over time because of learning effects, and so would the cost of production. Taking into account those effects is beyond the scope of this paper.

In the literature mentioned above, a discounted cash flow analysis is used to estimate the minimal price at which a product should be sold to ensure a profitable production. To do so, the project $NPV$ is computed. It is the present value of a project whose benefits and expenses will span over $N$ years. Eq. (1) is used to estimate the $NPV$, where $P_t$ is the production at time $t$, sold at the price $FSP_t$, with production expenses $EXP_t$. Future benefits and expenses are discounted at the rate $r$ to reflect the fact that an economic agent would prefer a given amount of money immediately rather than having fixed assets, having to wait some years for benefits to come [33]. A positive $NPV$ means the project creates value for its investor, while a negative $NPV$ means it should invest its money elsewhere.

$$NPV = \sum_{t=0}^{N-1} \frac{P_t \times FSP_t - EXP_t}{(1+r)^t} \tag{1}$$

It is possible to obtain the MFSP, defined as the constant fuel selling price that will ensure a $NPV$ equal to zero. It can be decomposed in the three cost components mentioned before, as shown in Eq. (2). This standard methodology is

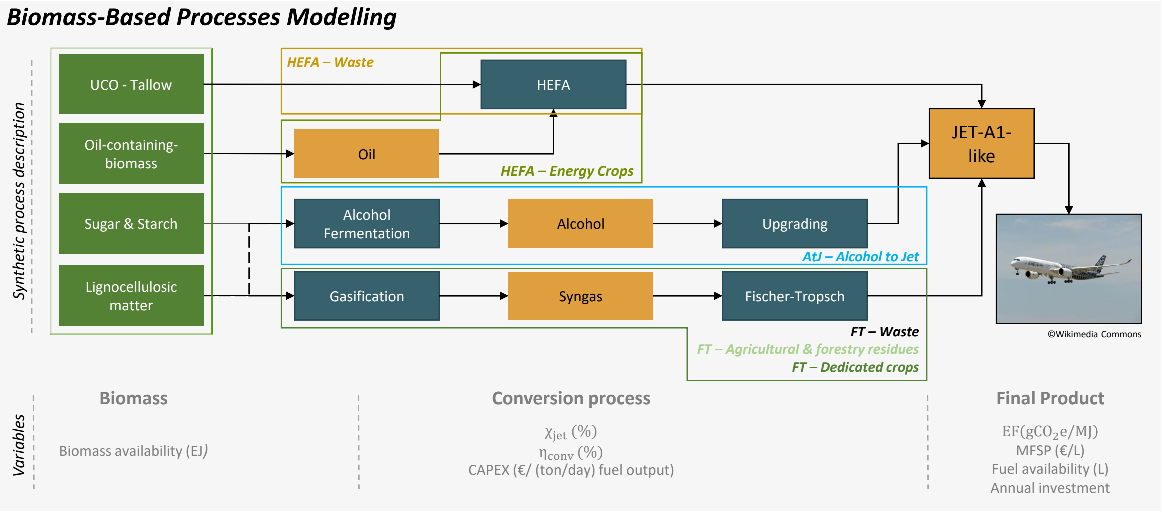

**Fig. 2 Biofuels production modeling: pathways and variables used**

adapted to the context of this work in the following.

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

If an aviation-only point of view is adopted, the annual investments needed to produce the required fuel output are supported by the oil and gas industry (despite being transferred to aviation through the fuel price). The additional annual cost $\Delta C_t$ for the aviation industry is then determined with Eq. (3), where $FC_t$ is the annual fuel consumption. $\lambda_{i,t}$ and $\Delta C_{i,t} = MFSP_{i,t} - FSP_{fossil,t}$ are respectively the market share and the cost differential of biofuel pathway $i$ in the year $t$.

$$\Delta C_t = FC_t \left( \sum_i \lambda_{i,t} \Delta C_{i,t} \right) \tag{3}$$

The extra cost for airlines is straightforward to implement into CAST by matching the biofuel demand with the supply and the selling price. Yet, the MFSP will not necessarily represent the actual selling price of biofuels to airlines. Indeed, scarcity effects could increase their price and/or marginal pricing mechanisms could be adopted. As a consequence, to ensure sufficient biofuel production, the market price might be at least as high as the MFSP of the most expensive pathway required to satisfy the demand. Besides, the annual investment (CAPEX) required to reach the necessary production output in time is another important metric, since these costs are relevant for policymakers or the oil and gas industry.

CAPEX values are often only presented as a fraction of the MFSP ($CAP_L$), therefore as an estimate of how the initial capital investment affect the fuel selling prices through the plant operating life. It is possible to reverse Eq. (2) to get the initial CAPEX. This value, noted $CAPEX^*$, is given in Eq. (4). It requires the knowledge of capital spending chronology $cap_t$ (and completion date $N_{CAP}$), of the production ramp-up schedule and of some financial parameters such as the discount rate $r$, the equity share of the investment $e$ and the loan duration $d$ and the loan rate $i$.

$$CAPEX^* = \frac{CAP_L \sum_{t=0}^{N-1} \frac{P_t}{(1+r)^t}}{e \times \sum_{t=0}^{N_{CAP}} \frac{cap_t}{(1+r)^t} + (1-e) \times \sum_{t=0}^{N_{CAP}} \frac{1/d + i \times (1-t/d)}{(1+r)^t}} \tag{4}$$

For the sake of simplification and given the purposes of this study, biofuel production modeling will be based on a literature review rather than on a detailed modeling of the biofuel production pathways. Three references [17, 22, 28] propose a detailed modeling of the production processes, which they compare to the literature. MFSP and CAPEX values are extracted from these sources and harmonized to €$_{2020}$. A statistical approach is then followed using the quartiles of the collected samples to derive pessimistic, optimistic and trend values for each of the production pathways and biomass types. The resulting values are represented on Fig. 3.

Only looking at their price is not sufficient to thoroughly evaluate biofuels. As mentioned in the introduction, they could have very different emissions factors when a life-cycle assessment is performed. A statistical study of literature on this topic is given in [34]. The results are represented on Fig. 3. Knowing the biofuel emission factor and its selling price, as well as those value for a reference (fossil fuel), one is able to compute the abatement cost related to a given biofuel production pathway. The abatement cost, given in Eq. (5), is defined as the cost of avoiding the emission of an amount (generally a ton) of $CO_2$ via a given technology. $CA_i$ is the cost of carbon abatement through pathway $i$ while $EF_i$ and $C_i$ are its emission factor and cost. Note that signs are tuned to be used with *positive* costs. A positive abatement cost means that the biofuel is more expensive but less carbon intensive. A negative abatement cost is possible if a solution is both cheaper and emits less than the reference. It is necessary to use this formula with caution since a more expensive, more carbon intensive fuel would also lead to a negative abatement cost.

$$CA_i = \frac{\Delta EF}{\Delta C} = \frac{EF_{fossil} - EF_i}{C_i - C_{fossil}} \tag{5}$$

A further parameter to be taken into account is the limited availability of the biomass. As for the emissions factors, a statistical analysis of the literature is presented in [34]. There are three parameters that influence the quantity of biofuel potentially available and therefore the $CO_2$ abatement potential: the raw biomass available for each production pathways, the fuel conversion efficiency and the refinery output fraction of jet fuel. The latter can be either set by technical reasons (inherent to hydrocarbon production or to maximize the energetic output of a biomass plant) or by the fact that many other product would likely be sourced from biomass. In 2019, jet-fuel represented below 10 % of the total oil final consumption [35]. The carbon abatement potential $\Delta E_{pot}$ is defined in Eq. (6), where $E_{bio}$ is the raw biomass energetic availability, $\eta_{conv,i}$ the conversion efficiency of the pathway $i$ and $s_i$ its selectivity (jet fuel output share).

$$\Delta E_{pot,i} = E_{bio,i} \times \eta_{conv,i} \times s_i \times (EF_{fossil} - EF_i) \tag{6}$$

Once this study is achieved, it is possible to combine all these parameters to study the interest of each production pathway. This will be detailed in section IV.

### B. Hydrogen Cost Modeling

Hydrogen has several usages in future sustainable aviation fuels. Hydrogen can also be directly used as a fuel, either burned or within a fuel cell to produce electricity. It could be combined with $CO_2$ to produce power-to-liquid fuels. Like biofuels, hydrogen can be produced via various pathways, including water electrolysis and Steam Methane Reforming (SMR) [19]. Those different pathways have widely different production costs and $CO_2$ emission factors. In this paper, only the electrolysis pathway is modeled.

Like biofuels, hydrogen MFSP can be calculated using Eq. (2). When hydrogen is produced via water electrolysis, two cost drivers can be identified: electricity price and electrolyzer CAPEX [36]. By analogy with biofuels modeling, electricity could be seen as a feedstock in this case, as it is the energy carrier converted to hydrogen. Hydrogen can be produced continuously using grid electricity or intermittently using only excess grid power or dedicated renewable sources. The first option allows high electrolyzer load factors hence low CAPEX but involves high electricity prices. The second option leads to the opposite.

As explained earlier, hydrogen can also be used to produce drop-in fuels. Electrofuels will also be modeled in this section. The modeling processes are synthesized on Fig. 4. All the values used during the modeling of all the processes described in this section are given in the appendix.

#### *1. Direct Hydrogen Usage*

As explained in the introduction, Hoelzen *et al.* estimates the operating cost of a hydrogen-powered aircraft to be between 6 and 10 % higher than a conventional aircraft, energy cost excluded. However, aircraft operating cost (other than energy) is not in the scope of this paper. When hydrogen is directly used as a fuel, the existing supply chain can not be used. Hydrogen has to be produced, transported, liquefied, and eventually stored before being supplied to the aircraft [23]. The total cost of hydrogen when supplied to the aircraft $C_{delivery}$ is the sum of the costs $C$ of all these steps:

$$C_{delivery} = C_{production} + C_{liquefaction} + C_{transport} + C_{storage} + C_{refueling} \tag{7}$$

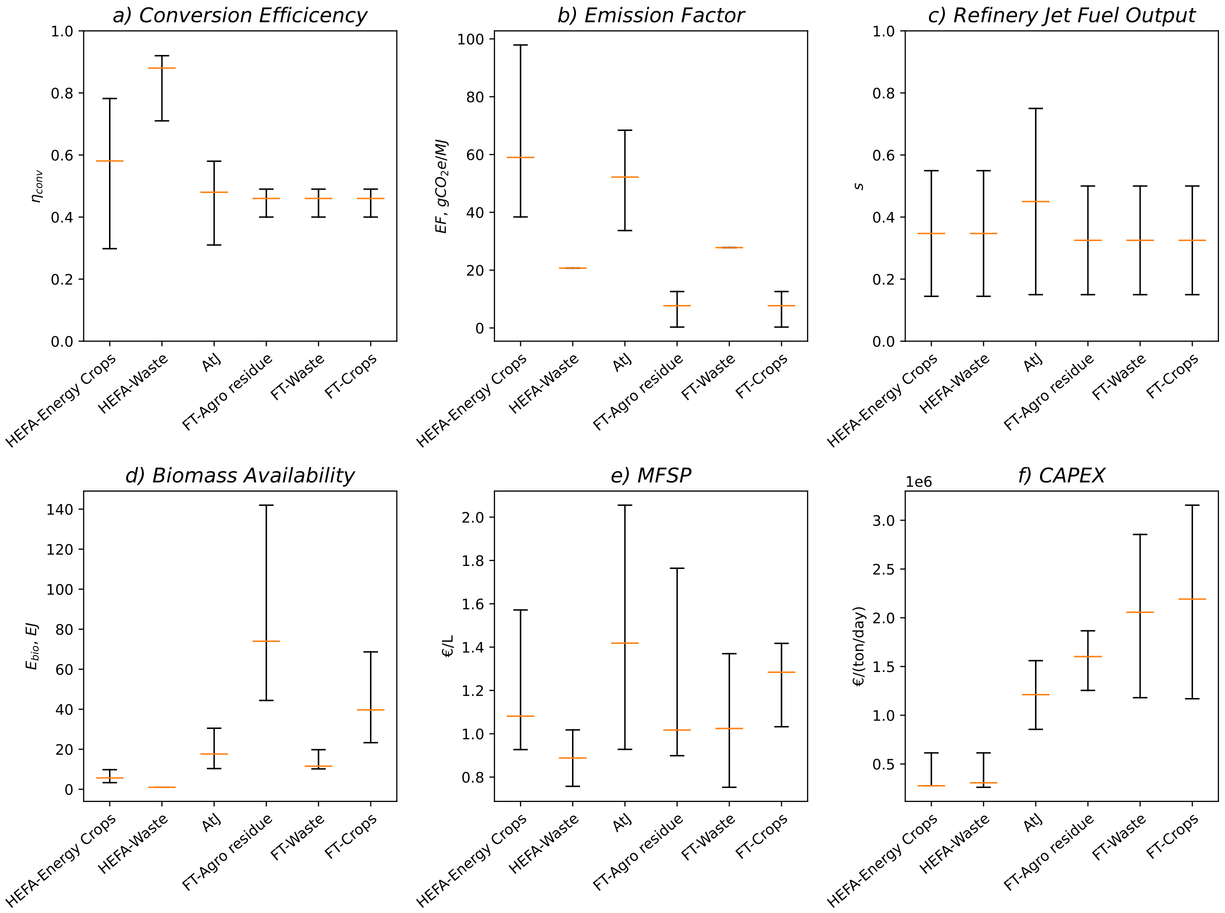

**Fig. 3** Results of a statistical literature review on essential biofuel production parameters. Data taken from [17, 22, 28, 34] and their related literature. The lower whisker is the first quartile, upper whisker the third quartile and the median is in between.

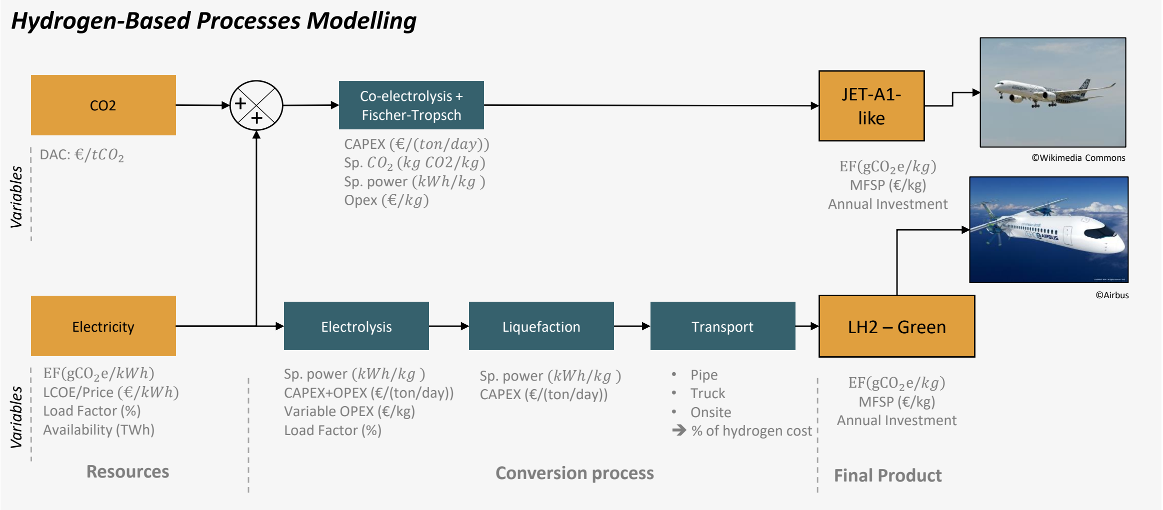

**Fig. 4** Hydrogen fuels production models used

For the production stage, an explicit hydrogen MFSP model is built with an adaptation of Eq .2. It computes the MFSP given the electrolyzer CAPEX, fixed and variable operating costs, its specific electricity consumption ($q_{el}$, in kWh/kg) combined to the electricity cost $C_{el}$. Hydrogen production CAPEX is expected to decline with time, to account for learning-by-doing and scale effects. The same is true for operating expenses as well as for specific electricity consumption which is expected to be improved with the years. Taking into account these effects makes the modeling more detailed than the one presented for biofuels, where these values are constant. This is a limitation of the current model, especially for comparing biofuels and hydrogen, but it could be corrected. To take these effects into account, 2020-2050 technological scenarios from the UK Department for Energy are used for Alkaline and Proton Exchange Membrane electrolysis pathways [36], completed by a reference database for CAPEX values [37]. Both production cost and emissions are highly dependent on the electricity characteristics. In the traditional way, the fuel MFSP is the constant selling price that would ensure a null NPV of the project. The option considered here is to index the fuel MFSP on electricity cost. Eq. (2) is therefore rewritten as Eq. (8), where $q_{el}$ and $MFSP_{CAPEX+OPEX}$ depend only on the plant electrolyzer commissioning year, but $C_{el,t}$ is allowed to change each year with a direct impact on the hydrogen selling price. This allows in particular to investigate the implications of some scenarios where there would be an important evolution of the electricity prices. If the cost of electricity and production output are constant from year to year, then $MFSP_t$ is the same that one would have obtained with Eq. (2).

$$MFSP_t = MFSP_{CAPEX+OPEX} + ELEC_t = \frac{\sum_{i=0}^{N-1} \frac{CAPEX_i}{(1+r)^i} + \frac{OPEX_i}{(1+r)^i}}{\sum_{i=0}^{N-1} \frac{P_t}{(1+r)^i}} + q_{el} \times C_{el,t} \tag{8}$$

Hydrogen production emissions are computed in a similar manner, assuming that emissions only occur during electricity production (therefore not accounting for electrolyzer manufacturing). This is consistent with specific electrolyzer literature [38, 39], but should be questioned if very low-carbon-intensive electricity is used.

$$EF_{H_2,t} = q_{el} \times EF_{elec,t} \tag{9}$$

The liquefaction process is modeled in a similar manner, without taking into account the technology evolution across the years. Data for liquefaction CAPEX and specific electricity consumption were taken from [23]. Liquefaction could be centralized, after which liquid hydrogen is transported to airports, or decentralized with gaseous hydrogen being transported or produced at airports. Hoelzen *et al.* estimate the cost of liquefaction between 0.2 and 3 \$/kg. Other costs (transport, storage, refueling) are supposed to add between 5 and 20 % to the total cost of hydrogen [23]. The global modeling process is described on Fig. 4.

Unlike with biofuels, the fuel is non-drop-in, and will therefore involve aircraft and potentially energy consumption modification. This must be taken into account while computing the fleet-wide cost $\Delta C_t$ for using hydrogen. Eq. (10) is used with $FC_{H_2,t}$ is the overall hydrogen consumption, and $C_{H_2,t}$ is the associated cost. It replaces a kerosene volume $FC_{fuel,t}$ at price $C_{fuel,t}$ for the same operations.

$$\Delta C_t = FC_{H_2,t} \times C_{H_2,t} - FC_{fuel,t} \times C_{fuel,t} \tag{10}$$

It is possible to compute a carbon abatement cost by adapting Eq. (5) to integrate the possible energy consumption modification.

### *2. Power-to-liquids*

To use hydrogen as a drop-in fuel, hydrogen can be upgraded with $CO_2$ through a Fischer-Tropsch synthesis [40]. Since more complex production processes can be involved, power-to-liquids are modeled as a single end-to-end process, as opposed to a two-step process (hydrogen production and then conversion). Indeed, hydrogen could either be produced through water and carbon-dioxide co-electrolysis or externally supplied and $CO_2$ can be either provided on-site from direct air capture or provided externally. Within this work, values from 5 studies were considered [20, 41–44]. CAPEX, OPEX, specific $CO_2$ use and specific electricity values were derived from this literature and the process is modeled with the same approach as the electrolyzer or the liquefier described before. Power-to-liquids are *drop-in* fuels, meaning that no additional infrastructure is required for their distribution. The process is described on Fig. 4. Estimates of direct air capture $CO_2$ cost are taken from [45] and range from 130 to 330 \$/ton. Industry capture is much cheaper (15-35 \$/ton), however the allocation of the original emissions could be questioned. Either only the original emitter takes on the emissions, or can share half with the fuel user. The latter case would seriously downgrade the power-to-liquid emission factor. To simplify, only direct air capture is modeled in this framework. To compute e-fuels MFSP and the fleet-wide cost, (Eq. 3 and 8) can be directly used.

Regarding the fuel emission factor, most of the impact comes from the electricity used during the e-fuel production. However, a significant fraction of the carbon footprint comes from the carbon capture phase, especially if oxy-fired $CO_2$ capture technology is used [46]. Electric heating could reduce this impact, which is interesting if the fuel is produced using low-carbon electricity. The end-to-end emission factor accounting for e-fuel production including electric direct air capture is given in Eq. (11), where $EF_{ptl,t}$ is the e-fuel emission factor, $q_{el}$ is the process specific electricity (taken as 29.3 $kWh/kg$ from [20, 46]) and $EF_{elec,t}$ is electricity load factor. Other life cycle emissions are neglected. Like with biofuels and liquid hydrogen, a carbon abatement cost can be computed using Eq.$\tilde{(}$5).

$$EF_{H_2,t} = q_{el} \times EF_{elec,t} \tag{11}$$

# IV. Applications: models testing and reference scenario evaluation

In the previous section, biofuels and hydrogen-based fuels were modeled at the plant level. The next step is to merge this work with the CAST environment. A first application will be a direct application of the models, estimating the cost and the emission factor of each pathway for median hypotheses. Then, a benchmark scenario will be defined using CAST to estimate a year-by-year decarbonized energy demand. The cost models are then used to ensure this demand is matched by enough supply. The total annual expenses of airlines to purchase this decarbonized energy are computed. Similarly, an estimation of the necessary annual investments is provided. Based on the results of this analysis, parameters with the greatest influence on costs will be challenged.

## A. Direct application of the models and influence of electricity for hydrogen-based fuels

Both liquid hydrogen production and liquefaction, as well as power-to-liquid processes are highly dependent on electricity in terms of cost and resulting emissions. On Fig. 5, the cost breakdown for both processes are represented for different electricity load factors. They are also compared to biofuels pathways modeled in the previous section, under median hypotheses for each parameter. As it can be seen on hydrogen and e-fuel production pathways, the cost of electricity is prevailing, especially when plants operate a high load factor, spreading the capital expenditures over more production. It motivates the investigation of several electricity generation scenarios. The carbon intensity of the grid electricity is high in 2022 in many countries (380 $gCO_2$/kWh in the US for instance [47]), but is expected to decrease with the deployment of low-carbon generation technologies. The environmental interest of electrolysis-based fuels (hydrogen or electrofuels) is conditioned to having a low-carbon enough electricity as it is illustrated on Fig. 6. Using hydrogen produced with either the US or EU average electricity is more emitting than using conventional kerosene for an aircraft. By definition, using grid electricity allows hydrogen plants to run at their full potential. Another scenario is to use dedicated renewable, hence a lower carbon intensity but also a lower load factor. This latter case makes sense to rapidly produce low-carbon hydrogen-based fuels, before grids are decarbonized enough. Very low-intensive electricity grids or dedicated renewable are necessary to match the carbon intensity of the least emitting biofuels. It should be noted that other scenarios exist: dedicated nuclear power would have both a low-carbon intensity and a high load factor profile, while in a grid with a lot of intermittent renewable, it might be possible to use generation curtailment to get cheap electricity. This would, however, lower the load factor of the plant.

Biofuels emissions factors presented are fixed: the effects of the electricity emission factor are not modeled with the simple approach presented in the previous section.

## B. Setting a benchmark scenario

The reference scenario on which the various costs are computed is defined using CAST to illustrate most industrial prospective scenarios. The most important parameters are defined in the following.

On the one hand, concerning the non-energy levers of action, simple models are used. First, the annual revenue-passenger-kilometers (RPK) growth rate is set to 3 %, which is close to ATAG Waypoint 2050 central forecasts [48]. This assumption is however below current industrial estimates, around 4 % [49, 50]. Then, for fleet energy consumption, optimistic assumptions are taken into account based on [10]. For instance, an average annual aircraft efficiency improvement factor of 1.5 % is taken. Moreover, operational improvements are modeled using a logistic function ensuring a global efficiency gain of 12 %, reached around 2040.

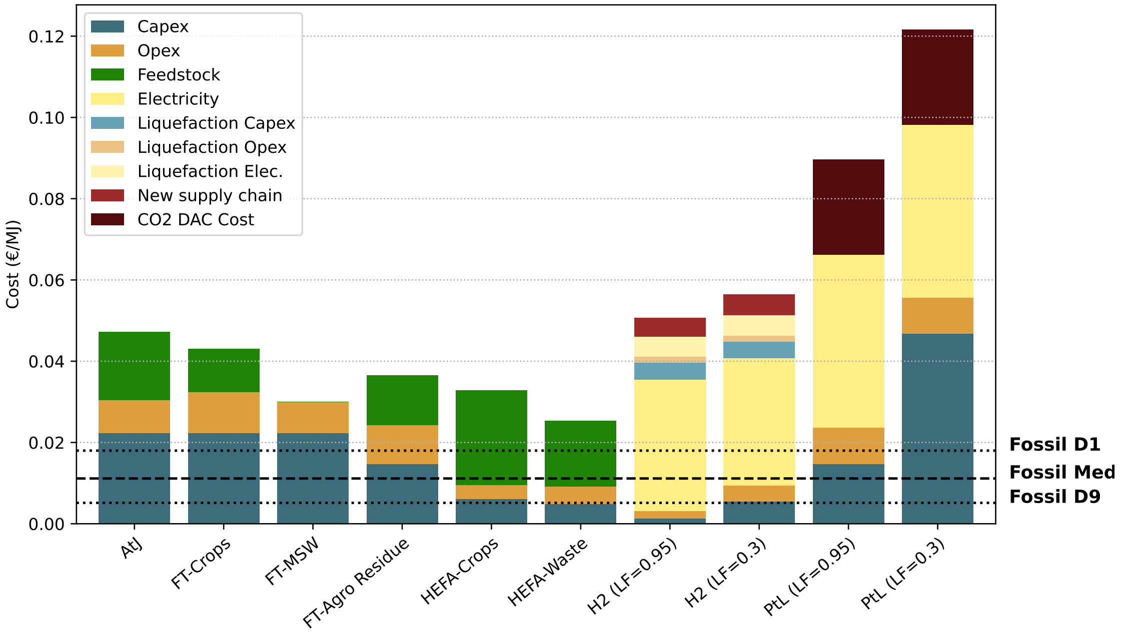

**Fig. 5 MFSP breakdown for pathways modeled in section III. Median technological and cost hypothesis, electricity cost: 80 €/MWh, $CO_2$ input cost (Direct Air Capture): 225 €/t. Reference year: 2040**

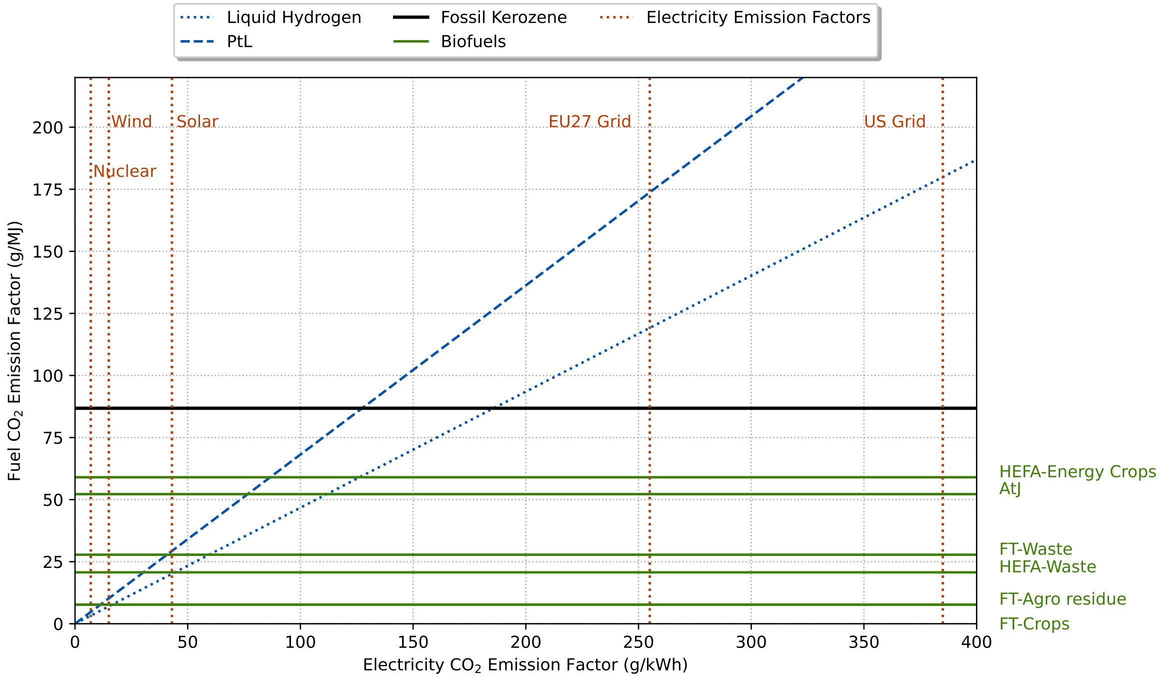

**Fig. 6 Emission factors of aviation fuel production pathways and evolution with the electricity emission factor. Biofuels emissions are constant due to the simplified models. Indicative values of electricity emission factors of selected grids or pathways are plotted vertically.**

On the other hand, concerning the energy levers of action with the use of alternative fuels, in a first simplifying approach, the distribution of the different production biofuels/hydrogen-based fuels production pathways is externally set. The ongoing legislative package of the European Union for aviation includes ReFuelEU Aviation, a specific law proposal to introduce blending mandates of low-carbon energies [51]. It consists in a progressive ramp-up of advanced biofuels and non-biomass based fuels (i.e. hydrogen and power-to-liquids) until 2050. These blending targets are applied to the world-wide energy consumption modeled by CAST. The share of biofuels in total energy consumption will increase from 4 % of energy in 2030 to 24 % in 2040 and 35 % in 2050. Over the same period, the share of electrofuels increases from 2 % to 13 % and then 50 % of energy consumption. In accordance to Fig. 6, electrofuels introduction is delayed to 2030 ensure the grid is less carbon intensive at the time of their introduction. Therefore the share of biofuels in 2030 is increased to 6 % to keep the same amount of low-carbon energies, but the other values are left unchanged. The resulting values for the fuel distribution are given in Tab. 1.

| | Biomass-based | Synthetic-fuels | Hydrogen | Fossil Kerosene |
|---|---|---|---|---|
| 2020 | 0 | 0 | 0 | 100 |
| 2030 | 6 | 0 | 0 | 94 |
| 2040 | 20.6 | 15.7 | 1.7 | 62 |
| 2050 | 30.8 | 44.1 | 11.9 | 13.2 |

**Table 1 Share of each production pathway in total energy use**

In this work, the direct use of hydrogen is modeled separately. It is considered that hydrogen-powered short-haul aircraft are introduced into the fleet from 2035, and that they eventually represent 50 % of the fleet in this segment. Their deployment is modeled by a logistic function, 98 % of the final value being reached in 2055. In the final version of ReFuelEU, hydrogen could be counted to satisfy the non-biomass-based blending mandate. An illustrative and optimistic grid electricity scenario is used to power hydrogen-based production pathways. Its starts at 429 $gCO_2$/kWh in 2019 [2], dropping to 160 in 2030, 60 in 2040 and 20 in 2050. The electricity cost starts at 80 €/MWh in 2020 and 2030, 100 €/MWh in 2040 and 120 €/MWh in 2050. These are ambitious targets, but they will be challenged in section IV.E. This scenario is in line with ambitious electricity decarbonization scenarios[52], but does not guarantee that this is the trajectory that will be followed.

The partition between biofuels production pathways is chosen to distribute resource consumption equitably; the share of each pathway is equal to the share of resource availability in the total available biomass. This is a major simplification and one of the limits of the model. Indeed, some fields, notably HEFA, are more mature and will logically be deployed first. Similarly, waste-based feedstock such as Used Cooking Oil (UCO) or Municipal Solid Waste (MSW) are sourced out of waste, and using them at their full potential might be an interesting option.

#### *1. Climate and energy results*

Before conducting an economic study, CAST allows the analysis of this scenario from an energy and climate perspective. The emissions trajectory of this scenario is represented on Fig. 7. The emissions reduction linked to the use of low-carbon energies is represented by the green area on the scenario. This scenario would use 3.0 % of the world carbon budget to remain below 2.0 °C of temperature increase, slightly above the 2.6 % current contribution of air transport to annual global $CO_2$ emissions. It would use around 6.4 % of the available biomass in 2050, under median availability hypothesis as defined in the appendix. Finally, it would use 20.3 EJ of electricity in 2050, which is to compare to around 100 EJ of electricity production in 2020 (27 EJ of renewables) and 250 EJ in 2050 in a deep-decarbonization scenario such as IEA NZE (International Energy Agency - Net Zero Emission) [52].

### C. Matching demand and supply

The previously described CAST scenario is used to estimate a yearly biofuel, power-to-liquid and hydrogen demand. Each year $n$, the production gap of the next year $\Delta P_{n+1}$ between energy demand $D_{n+1}$ and production supply $P_{n+1}$ is computed (Eq. (12))

$$\Delta P_{n+1} = D_{n+1} - P_{n+1} \tag{12}$$

This gap will be filled by plants built during the year $n$. Therefore, enough capacity $Q_n$ to fulfill the production gap

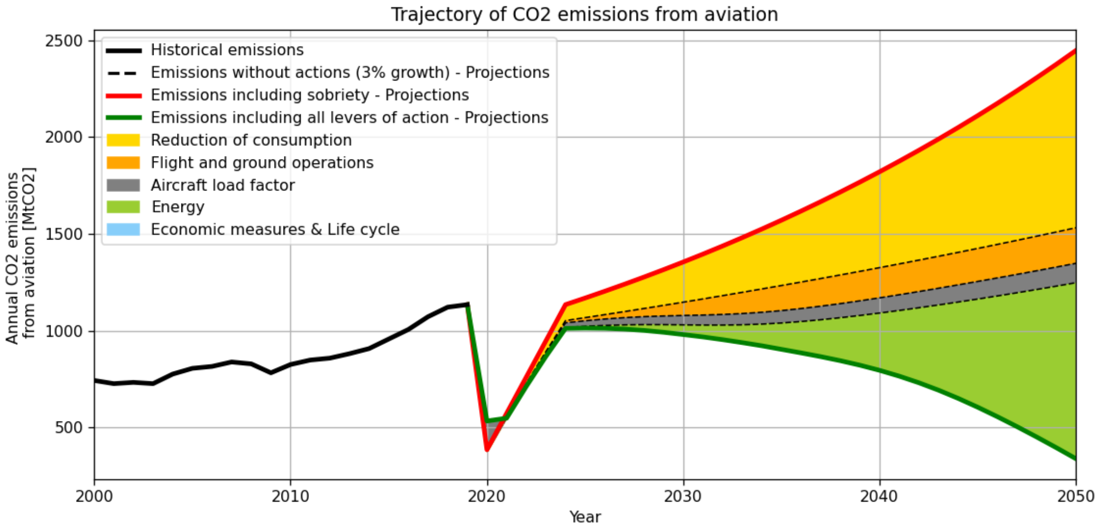

**Fig. 7 $CO_2$ emissions trajectory of the reference scenario.**

of year n+1 is built. The production of the newly commissioned plants is added to the production supply inventory for the duration of its operating life. The process is repeated each year in an iterative process. Annual CAPEX investment of the scenario is computed using the capacity to be built for each kind of plant and the relative CAPEX data. Fuels MFSP are obtained with either Eq. (2) or (8) depending on the fuel studied. The total cost of the energy produced is computed by multiplying the MFSP by the production quantity. To take into account the fact that the technological parameters are likely to evolve over the course of the scenario (the plants built become more and more efficient), the calculation is made at the level of each plant, then summed up at the scenario level. As biofuel and e-fuels models do not yet take into account a potential evolution of the different costs, this formulation is less relevant.

Some mechanisms are not yet modeled. For example, if a biofuel production line is used for less time than expected because deep decarbonization requires the use of lower-carbon energy, this would result in a loss of production revenue and therefore a cost to be passed on to the initial MFSP. These phenomena are known as stranded assets. The scenario analyzed in this section is not exposed to this effect because the energy quantity is strictly increasing for all considered production channels.

### D. Scenario Analysis

A cost premium is computed for each scenario year using the approach presented in section IV.C and a reference fossil fuel price of 0.4 €/L (median value of 2015-2019 weekly Gulf Coast Spot price for jet-fuel). Similarly, the annual investment in fuel production is computed using the previously described methodology.

The first significant finding is that electrofuels represent the major part of the investments needed in 2050, with around 110€ Bn annual investments out of 130 (Fig. 8). This is linked to two aspects. First, as shown on Fig. 5, e-fuels are a rather capital intensive production pathway, especially since the capital linked to $CO_2$ production or electricity generation are not included here (they are considered as external inputs to the system). The second aspect is directly linked to ReFuelEU blending mandate design. Indeed, biofuels are used rapidly but their ramp-up is limited to moderate the pressure on the ecosystems. Therefore, most of the increase in demand is met by these electrofuels, whose share is growing very rapidly to reach 50 % of the energy consumption of air transport in 2050. As a mean of comparison, the annual investments in the oil industry in 2019 reached 470 Bn \$ [53], while total annual capital investment in IEA NZE scenario [52] is estimated between 4500 and 5000 Bn \$ per year between 2030 and 2050. That means capital investment for developing low-carbon energy for aviation would be between 2 and 3 % of the total NZE investment. Note however that the additional electricity production investments required are not included in this figure nor modeled in CAST for teh time being.

From the point of view of an airline, on which these investments will be passed on via the MFSPs, it is interesting to look at how this additional cost compares to their expenses. Knowing that airlines expenses were around 10 cts/RPK in

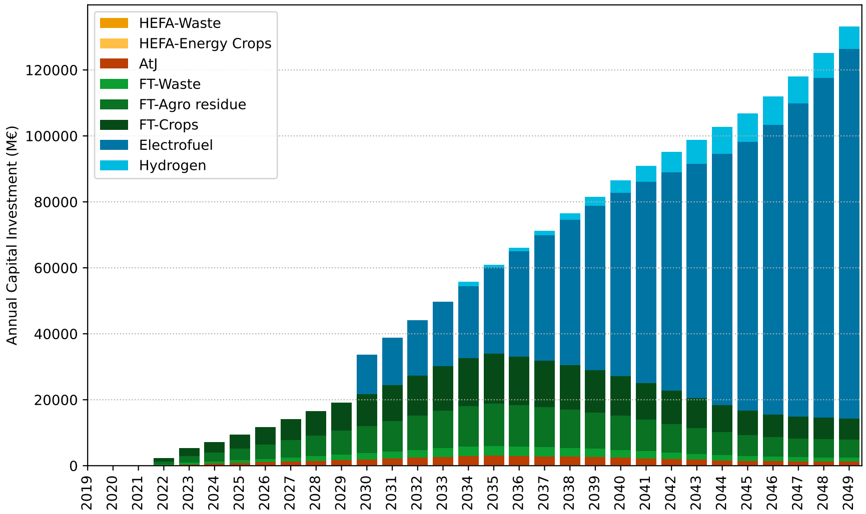

**Fig. 8  Annual capital investment required by production pathway**

2019 [5] (of which fuel expenses represent a quarter), the total expenses increase is computed and represented on Fig. 9. This figure also highlights the crucial role played by electrofuels in the cost increase in this scenario.

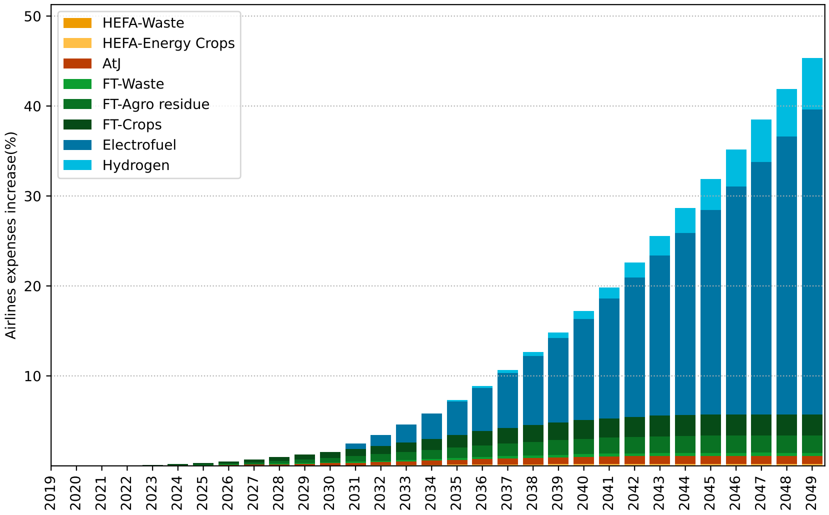

**Fig. 9  Share of low-carbon energy cost increase in airlines expenses. Reference airline cost structure for year 2019**

Lastly, it is possible to have a first idea of the impact that this could have on the demand for air transport by using a price elasticity via Eq. (13). $E_p$ is the price elasticity and $\Delta T/T$ and $\Delta P/P$ are the relative change in transport demand and ticket price. Under the hypothesis that airlines would transfer all the cost increase onto their consumers and using a price elasticity of -0.6 [54], air transport demand in 2050 would be 25 % lower than expected. Without taking this effect into account, the air traffic was multiplied by 2.2 between 2019 and 2050, while this value would fall to 1.6 taking into account the elasticity. Note that this is valid if we consider that the 3 % annual growth projected has not already taken this into account. This has no effect on the relative prices of low-carbon energies in this simplified model, since low-carbon energies are introduced as blending mandates. With a more detailed model, it would possibly allows the use of less expensive pathways, hence a loop to be modeled for more accuracy. However, the price elasticities are computed using prices and demand variations from the past and are therefore valid only for moderate price variations. This conclusion should be taken with the necessary caution.

$$E_p = \frac{\frac{\Delta T}{T}}{\frac{\Delta P}{P}} \tag{13}$$

### E. Sensitivity analysis

In the previous section, a reference scenario, based on ReFuelEU blending mandates extended for global aviation and reasonable technological assumptions, was presented. The simplified models used make the interpretation of the results subject to caution.

The very high costs related to the use of power-to-liquids fuels motivates a first sensitivity analysis on their MFSPs. Under the hypothesis used to run the scenario of the previous section, the MFSP would be 4.3 €/kg (10 cts/MJ) in 2040. The scenario considered the use of grid electricity. Should the plant run only on offshore wind electricity (and therefore at the related load factor, taken as 0.45), the electricity would cost around 23 €/MWh and its emission factor would be 8 $gCO_2$/kWh [55]. Using the optimistic plant parameters (see Appendix) and a low direct air capture price of 120 €/$tCO_2$, this would result in a 2.17 €/kg (5 cts/ MJ) MFSP, i.e. half of the original price. This value is in the same price range as the other low-carbon fuels in the reference case (Fig. 5). Improvements on the carbon intensity of the resulting fuel are also a important (Fig. 6). However, this relatively low price remains well above the fossil fuel price and requires the best-case scenario, with very low-carbon and cheap electricity.

To complete this analysis, the decarbonisation potential of each production pathway can be looked at using two essential parameters. The abatement cost should be completed with the decarbonisation potential of the pathway. This allow to draw full-potential marginal abatement cost curves. On x-axis, it represents the potential of each production pathway, given the resources availability and their carbon intensity. The y-axis represent the cost of carbon abatement of each pathway. Each step on the curve represents the switch to the next production pathway, having a higher carbon abatement cost. The best and worst case scenario for biofuels production pathways are displayed on Fig. 10. The worst case scenario combines a low biomass availability, low conversion efficiencies and high emission factors, as well as high production costs. On the other hand, the best case combines high biomass availability, intermediate jet fuel refinery output, low emission factors and low production costs. The Optimistic scenario only represent a theoretical maximal potential: aviation only uses 10 % of current oil production [35]. The jet fuel share of refinery output plays a very important role on the volume of biofuel available for aviation. Both worst case and median scenarios use a the first quartile (Fig. 3), slightly above the current share. The best case use the median value of the same figure, and multiplies the jet fuel share of oil product by 3 to 4 times. The third quartile, representing the technical maximal jet output, is not relevant in a multi-pathway analysis: most other fossil fuel users would also use this bio-energy. A very wide range can be seen between best and worst case marginal abatement cost trajectories since they are the combination of many parameters, each one having its own variation range. Some parameters, like the jet fuel refinery output share are also political levers; they are not linked to a technical uncertainty. This would motivate further investigations on the subject, since it could have major implications on the strategy to be adopted for the decarbonization of the air transport.

Particular attention must be paid to the fact that the fuels used have residual emissions: beyond the maximum potential of biomass, it is important to note that the cumulative volume of avoided emissions cannot exceed the one achieved at the total fuel use. This limit is marked on Fig. 10 by the intersection of the cumulative fuel produced by the various pathways and the horizontal black dashed line, representing the energy needs of aviation in 2050. In both worst case and median scenarios, not enough biofuel is produced to match the drop-in fuel demand of aviation in 2050. This comes mostly from the reduced jet-fuel share, and also from the limited biomass available for the pessimistic scenario. This curve could theoretically be used to select the best pathways to use, and therefore to use a merit order for biofuel pathways, contrary to the approach chosen in the previous section, which consisted in spreading the effort over all the pathways. Such curve could be used to derive a carbon price that would ensure the economic competitiveness of the pathways necessary to reach given decarbonization targets by increasing the fossil fuel price.

As a comparison, the abatement cost of the power to liquids in the reference case are much higher, at 1320 €/ton. In the very optimistic scenario described above, they fall at 470 €/ton of $CO_2$ abated. They are not represented on the same figure since maximal electricity availability and its share available to produce low-carbon fuels is much more harder to

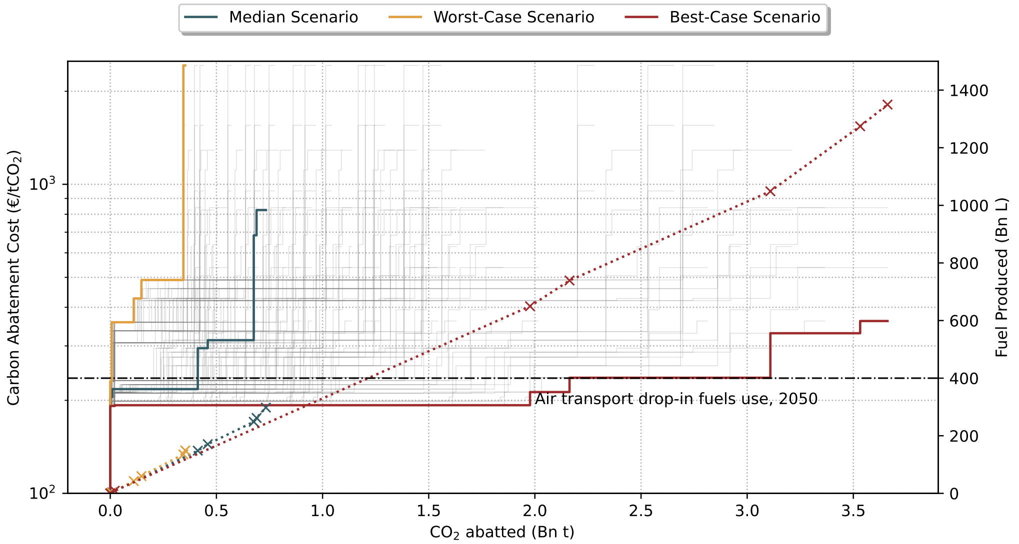

**Fig. 10 Biofuel production pathways sensitivity analysis. Marginal Abatement Cost in plain line, fuel volumes in dashed lines. Intermediate scenarios are plotted in grey. Air-transport drop-in fuel use (horizontal line) intersects cumulative fuel production (dashed lines), if there is enough fuel available. The intersection abscissa represents the amount of CO$_2$ abated if all the drop-in fuel used is biofuels. The marginal abatement cost at the same abscissa is read on the marginal abatement cost curve.**

estimate. Nevertheless, they are required to match the 2050 drop-in fuels demand in median and pessimistic scenarios of Fig. 10. Should the CAST scenario run with theses very optimistic electricity settings the investments would increase due to the low load-factor iduced by renewables, around 250 Bn € in 250, but the cost increase to airlines would be limited to 29%.

There are two other aspects that could modify the various abatement costs: first of all, all prices considered in this paper are minimal fuel selling price. Airlines could pay much more because of scarcity effects, if the demand exceeds supply. If one analyses the economic interest at the society level, the opportunity costs would also affect the analysis. For instance, using low-carbon electricity to decarbonize the grid may be more economically efficient than using it to make power-to-liquids. This remains beyond the scope of this paper.

Finally, this full-potential marginal abatement cost-curve could be used to select the best pathways with the goal to respect a given carbon budget such as provided by CAST. Otherwise, using an economic cost optimization principle, the least expensive pathways will be implemented first. It could lead in carbon-intensive lock-ins: least expensive pathways might be low-carbon enough in the short term but not enough in the long-term. Pathways having a higher carbon abatement cost but a lower emission factor should be started to ensure that they will reach enough production potential in the long term to allow a deep decarbonization scenario. Such considerations are discussed in [56].

## V. Conclusion

This article presents the work related to the introduction of low-carbon energies in the CAST tool and a case study on an aviation decarbonization scenario. CAST simulates medium-term decarbonization scenarios for air transport, using technological, operational and energy levers as well as traffic volume. In this context, it is used do define an annual low-carbon energy demand. Individual cost models for biofuels, liquid hydrogen and electrofuels are developed. In the case of biofuels, MFSP (Minimum Fuel Selling Price) values are taken from the literature and harmonized for several production channels. The same operation is performed for the availability of the required biomass and for the associated CO2 emission factors. A statistical classification of these values is performed to obtain optimistic, central and pessimistic values for each of the parameters influencing the cost of bio-energy. A simple model to estimate the required capital investments is developed. For hydrogen and biofuels, a similar but more detailed approach is followed, by directly estimating the MFSP based on industrial capital and operating costs, as well as on conversion efficiency values taken from the literature. The models are tested and the production pathways are compared in terms of price and $CO_2$ emissions. In general, biofuels are cheaper to produce than liquid hydrogen or electrofuels. Then, these models are linked to the CAST scenarios and to the demand in the different types of associated energy by making sure that the demand is equal to the supply. Cost trajectories (investment and company overhead) are presented for a reference scenario. Capital investments in the order of 120 billion euros per year (excluding electricity production) would be necessary in 2050 to meet the growth in energy demand. Airline expenses would increase by 40 % in the same time frame. This is mainly due to electrofuels, which are both the most used energy carrier in 2050 in the presented scenario and the most expensive. In a very favorable scenario using low-cost, low-carbon electricity, these become more competitive with biofuels. By comparing the costs of carbon abatement related to each pathway, it is possible to define an order of merit, ranking the decarbonization efficiency of the various pathways. While keeping a limited ratio of jet fuel (15 %) in biofuels production, it is difficult to satisfy the energy demand of air transport in 2050 without using electrofuels.

These analyses could be completed by a refinement of the data used: indeed, the statistical approach used to give values to each variable leads to many possible scenarios without it being possible to decide on the validity of each one. Links can exist between variables (for example, a low biofuel production cost could induce a high emission factor) and this is not taken into account by this approach. The exogenous approach used to allocate the energy used based on the availability of resources can be questioned. An optimization approach, allowing to minimize the societal cost of a scenario, under the constraint of decarbonization and biomass availability, would be relevant in the future. Finally, the non-CO2 environmental impact of the different energy carriers presented is not addressed at all in this work. An approach looking at the planetary limits and for example at the consequences of global warming on the production of these biofuels would be a good complement.

# Appendix

| Item | Unit | Scenario | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Max Load Factor | % | | 0.98 | 0.98 | 0.98 | 0.98 |
| Specific electricity | kWh/kg $H_2$ | Pessimistic | 60 | 56 | 54 | 53 |
| | | Medium | 51 | 49 | 49 | 48 |
| | | Optimistic | 49 | 48 | 47 | 47 |
| Operating lifetime | Years | | 30 | 30 | 30 | 30 |
| CAPEX | €/(kg $H_2$/day) | Optimistic | 499 | 338 | 303 | 294 |
| | | Medium | 588 | 459 | 434 | 420 |
| | | Pessimistic | 807 | 668 | 623 | 601 |
| | | Litt Review [[37]] | 533 | 355 | 261 | 210 |
| Fixed OPEX | €/(kg $H_2$/day) /year | Optimistic | 20.46 | 19.84 | 19.62 | 19.62 |
| | | Medium | 21.29 | 20.57 | 20.25 | 20.04 |
| | | Pessimistic | 25.05 | 23.38 | 22.55 | 22.13 |
| Variable OPEX | €/kg $H_2$ | Optimistic | 0.15 | 0.13 | 0.12 | 0.12 |
| | | Medium | 0.20 | 0.19 | 0.18 | 0.18 |
| | | Pessimistic | 0.30 | 0.27 | 0.26 | 0.25 |

**Table 2 Hydrogen alkaline electrolysis parameters. Data adapted from [36]**

| Scenario | Specific electricity (kWh/kgH2) | CAPEX (€/(kg H_2/day)) |
|---|---|---|
| Optimistic | 6.62 | 899 |
| Medium | 7.54 | 1457 |
| Pessimistic | 11.06 | 2248 |

**Table 3 Liquefaction parameters. Data from [23]**

| Cost Scenario | Specific CO2 (kg/kg jet fuel) | Specific electricity (kWh/kg jet fuel) | CAPEX (€/(kg/day) jet fuel) | OPEX (€/kg jet fuel @0.9 LF) |
|---|---|---|---|---|
| Optimistic | 3.19 | 21.9 | 1678 | 0.31 |
| Medium | 4.47 | 22.9 | 2311 | 0.38 |
| Pessimistic | 5.37 | 27.5 | 4548 | 0.51 |

**Table 4 Power-to-Liquids (Electrofuels) parameters. Data from [20, 41–44]**

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