# THE ROLE OF CARBON CAPTURE, STORAGE AND UTILIZATION TO ENABLE A NET-ZERO-$CO_2$-EMISSIONS AVIATION SECTOR

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## Abstract

This contribution presents a techno-economic analysis of feasible pathways for the aviation industry to achieve net-zero $CO_2$ emissions. These pathways are based (i) on carbon capture and storage (CCS), where conventional fossil jet fuel is produced and the corresponding emissions are offset by capturing $CO_2$, either via direct air capture (DAC-CCS route) or via point-source capture (PSC-CCS route), and permanently storing it underground; and (ii) on carbon capture and utilization (CCU), where synthetic jet fuel is produced by using $CO_2$ as feedstock, which is either captured from air (DAC-CCU route) or from a point-source emitter (PSC-CCU route). To ensure net-zero $CO_2$ emissions, the feedstock of the point-source emitter, both for CCS- and CCU-based routes, must be of biogenic nature. A comparative quantitative assessment of these scenarios and of a business-as-usual (BAU) scenario, where aviation emissions are subjected to a carbon tax, is performed based on jet fuel cost and carbon price projections until 2050. Cost reductions due to economy of scale of current low-maturity technologies are accounted for. An uncertainty analysis based on Monte Carlo simulations is performed to assess the effects of the uncertainty associated with the most relevant techno-economic quantities on the observed trends. Findings show that CCS-based scenarios consistently lead to lower jet fuel costs than CCU-based scenarios across the considered time scenarios and sensitivity analyses. This is mainly due to the fact that CCU-based routes result in an energy consumption more than 20 times higher than CCS-based routes, which also implies higher $CO_2$ emissions when considering the carbon intensity of current electricity grids. Overall, the PSC-CCS route represents the most cost-effective solution for decarbonizing the aviation industry and it is cost-competitive with BAU already today.

***Keywords:*** *aviation; net-zero emissions; carbon capture and storage; carbon utilization; renewable fuels.*

## 1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) scenarios, limiting global warming to 1.5°C implies reaching net-zero $CO_2$ emissions globally around 2050 [1]. To achieve this target, all anthropogenic emissions should be reduced as much as possible, with the remaining unavoidable fraction being balanced by an equivalent amount of carbon removal. The mobility sector, and especially the air transport sector, will face critical decarbonization challenges due to the limited availability of mitigation strategies (e.g., low-carbon fuels, aircraft energy efficiency, operational efficiency, etc.) and to the higher demand growth with respect to other transport modes [1].

Although alternative jet fuels (JF) and direct air capture (DAC) combined with permanent $CO_2$ storage emerge as promising strategies to achieve carbon-neutral aviation, their high costs are hindering their commercial deployment [2, 3]. The goal of this work is to provide a quantitative assessment of the current and future projected costs of possible strategies based on carbon capture, storage and utilization to decarbonize the aviation industry, and to compare them to the business-as-usual (BAU) solution. We follow a similar approach adopted in a recent paper on the role of CCS and CCU to enable a net-zero chemical industry [4], but we expand the focus of that work to include a full techno-economic performance analysis [5].

## 2. Scope of the work

Five scenarios are investigated. The BAU scenario (1) is based on the use of conventional fossil JF and relies on the extraction of crude oil. Since this results in $CO_2$-positive emissions, we consider these to be subjected to the payment of a carbon tax. The next four scenarios considered achieve net-zero $CO_2$ emissions through carbon capture and storage (CCS) or carbon capture and utilization (CCU) technologies, under the assumption that the processes are powered by carbon-free electricity, e.g., coming from carbon-free solar or wind. Scenarios (2) and (3) are based on Direct Air Capture (DAC), while scenarios (4) and (5) are based on Point-Source Capture (PSC). The DAC-CCS scenario (2) is still based on the use of fossil JF, but the corresponding $CO_2$ emissions are offset by $CO_2$ removal from the atmosphere through DAC and subsequent permanent storage. In the DAC-CCU scenario (3), carbon-neutral synthetic fuels are produced via Fischer-Tropsch reaction from $CO_2$ provided by DAC and $H_2$ supplied by water electrolysis. The PSC-CCS (4) and PSC-CCU (5) scenarios are symmetrical to scenarios (2) and (3), respectively, but they make use of biogenic $CO_2$ captured at a point-source emitter. Such an emitter may be a waste-to-energy (WtE) plant producing heat and electricity through the incineration of waste, where around 60% of the carbon contained in waste is biogenic.

The five scenarios are broken down into their corresponding technology routes, for which current costs are estimated based on available data. Future costs of low-TRL (Technology Readiness Level) technologies (i.e., water electrolysis, $CO_2$ electrochemical reduction, DAC, and PSC) are projected using learning curves, while trends in carbon prices are taken from literature [1]. The functional unit for the comparison is the synthesis and use of one tonne or liter of jet fuel (conventional or synthetic) with costs estimated from today to 2050.

## 3. Comparative assessment: current costs

Estimates of the current JF cost and of the total electricity consumption for the five aforementioned scenarios are summarized in Table 1. It is worth noting that the JF cost estimated for the BAU scenario includes the payment of a carbon tax. The CCU-based scenarios result in the highest cost and electricity input as they mostly rely on low-TRL, expensive, and energy-intensive technologies, i.e., water electrolysis and electrochemical conversion of $CO_2$. As expected, the lower cost of PSC with respect to DAC leads to a lower jet fuel cost for the PSC-based technology routes. In particular, the PSC-CCS scenario may be already cost competitive with BAU today.

Table 1. Current jet fuel cost estimated for the five aviation scenarios and corresponding electricity input.

| | JF cost | | Electricity input |
|---|---|---|---|
| | [€/t] | [€/L] | [MWh$_e$/tJF] |
| BAU | 670 | 0.53 | - |
| DAC-CCS | 2320 | 1.86 | 2 |
| DAC-CCU | 6610 | 4.89 | 50 |
| PSC-CCS | 750 | 0.60 | - |
| PSC-CCU | 3750 | 2.77 | 48 |

It should be noted that the investigated technology routes result in net-zero $CO_2$ emissions when considering carbon-free electricity to supply the energy required by the JF production processes and by the $CO_2$ capture technologies. However, operating the technology chains with currently available electricity would result in positive values of the $CO_2$ emissions. This is illustrated in Figure 1, which shows the amount of $CO_2$ emitted per unit JF as a function of the carbon intensity of the available electricity.

The BAU scenario results in about 3 $tCO_2/tJF$ and is nearly independent of the electricity mix, since the largest share of $CO_2$ emissions is due to the use of fossil carbon to produce and use JF, whereas the electricity required for the production process plays a negligible role. In contrast, the $CO_2$ emissions of the other scenarios increase with the electricity carbon intensity, with those of CCU-based scenarios growing about 22 to 24 times faster than those of CCS-based scenarios. This is proportional to the larger electricity consumption of the CCU scenarios, which is mostly due to the electricity required to produce hydrogen and to convert $CO_2$ into CO.

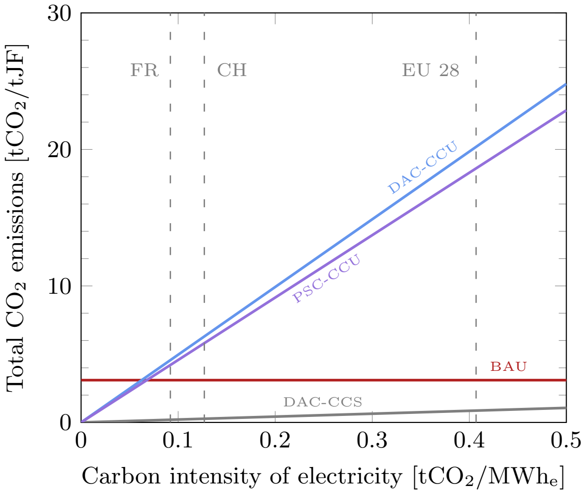

Figure 1. Total $CO_2$ emissions for the BAU (red), DAC-CCS (gray), DAC-CCU (blue), and PSC-CCU (purple) routes as function of the carbon intensity of electricity.

As an example, consider the electricity mixes of France (Fr, 0.09 $tCO_2/MWh_e$), Switzerland (CH, 0.13 $tCO_2/MWh_e$), and the average European Union (EU-28, 0.41 $tCO_2/MWh_e$). The CCU-based scenarios emit about 4, 6, and 18 t of $CO_2$ more than the CCS-based ones per tonne of produced JF (average of -PSC and -DAC routes), and more than the BAU case even for such low-carbon electricity grids as those of France and Switzerland.

For both CCS and CCU scenarios, the $CO_2$ emissions are higher when adopting DAC than PSC, due to the higher efficiency in capturing $CO_2$ from concentrated sources versus capturing it from air, hence to the larger electricity requirements of DAC compared to PSC.

## 4. Comparative assessment: future forecasts

Ranges of JF cost are estimated for several scenarios from 2020 to 2050. On the one hand, such scenarios consider the potential cost reductions for low-maturity technologies through learning-by-doing (i.e., DAC, PSC, H2 production through water electrolysis, and $CO_2$ electrochemical conversion); on the other hand, possible future evolutions (increase) of the carbon price are accounted for.

Figure 2 illustrates the future projections of JF cost for the considered scenarios. The shaded areas represent computed ranges, while the solid lines represent the mid-range values of JF cost estimated for each scenario.

Different factors determine the lower and upper bounds of JF cost for the different scenarios.

- BAU. The lower and upper bounds correspond to the extreme trends assumed for the carbon tax, namely to the 1.5°C high OS and to the Below 1.5°C pathways, respectively, of the IPCC report [1].
- Net-zero scenarios. The lower and upper bounds correspond to the maximum and minimum learning rates assumed for estimating the cost reductions of low-TRL technologies.

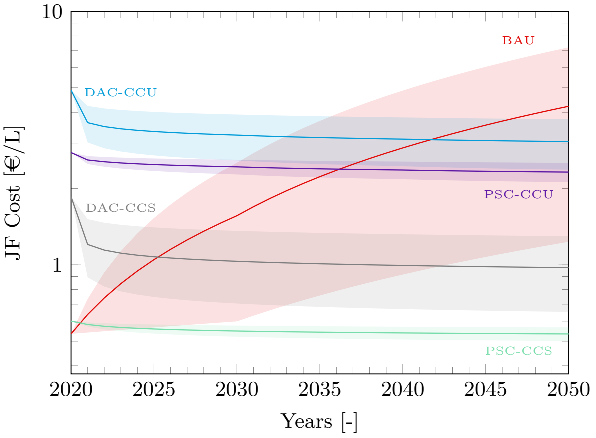

Figure 2. Cost ranges (shaded areas) and mid-range values (solid lines) of JF cost estimated for all scenarios from 2020 to 2050.

Various considerations can be made when comparing the different scenarios.

- CCS-based scenarios lead to lower JF costs than CCU-based ones across the entire time horizon, independently of the considered learning rates.
- Technology chains based on PSC result in lower JF costs and narrower cost ranges than those based on DAC. The lower JF costs are due to the lower capture cost of PSC with respect to DAC; the narrower cost ranges are because PSC is a more mature technology than DAC, hence relies less on future learning rates.
- Overall, PSC-CCS (green shaded region) represents the most cost-effective solution for a net-zero aviation going towards 2050. It is cost competitive with BAU already today, independently of the considered carbon tax evolution and learning rates.
- DAC-CCS will become cost competitive with BAU before 2035 provided that high learning rates are experienced. The higher the carbon tax, the earlier DAC-CCS becomes competitive.
- In case of high carbon taxes, CCU-based solutions become cost-competitive with BAU around 2030. The higher the carbon tax and the learning rates, the earlier CCU becomes competitive.

## 5. Monte Carlo analysis

Finally, we further discuss the uncertainty associated with our assumptions through a Monte Carlo analysis, which allows to determine the probability distributions associated with the JF costs of all scenarios.

The following quantities are randomly sampled between ±20% of their reference values: (i) the initial cost of DAC, hydrogen production, $CO_2$ conversion and PSC; (ii) the production cost of fossil jet fuel; (iii) the levelized cost of electricity (LCOE); (iv) the revenue resulting from the sale of diesel; and (v) the $CO_2$ transport and storage costs.

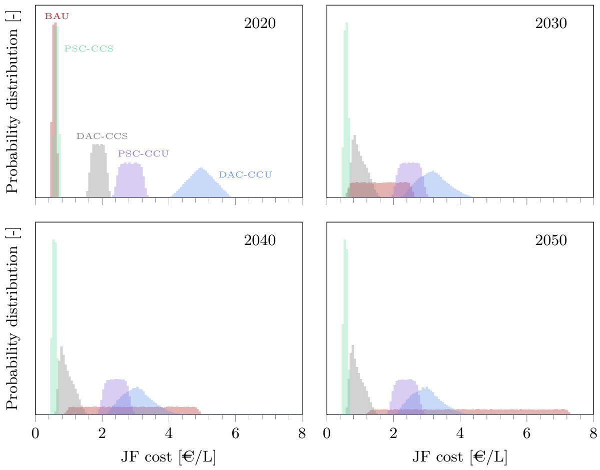

Figure 3. Probability distribution of JF cost obtained via Monte Carlo analysis for all scenarios, for years 2020, 2030, 2040 and 2050.

The carbon price during each year is randomly sampled within the range determined by the 1.5 °C high OS and the Below 1.5 °C curves [1]. The learning rate is randomly sampled between 5% and 20% and it is allowed to be different for each technology. All parameters are sampled according to a uniform distribution. Based on these, the probability distributions of JF cost for all scenarios are calculated from 2020 to 2050.

Findings are presented in Figure 3, which shows that the trends obtained for the baseline assessment, as well as considerations made in Section 4, are not significantly affected by the uncertainty and variability in the input quantities. This means that CCS-based technology routes represent the most cost-effective solutions (with PSC-CCS competing with BAU already today), and that PSC has an economic advantage over DAC.

Looking at the cost distribution, in 2020 the only scenario enabling a net-zero-$CO_2$-emissions aviation industry while being cost-competitive with BAU is PSC-CCS (mean JF cost of about 0.6 EUR/L).

By 2030, PSC-CCS becomes the most convenient route, DAC-CCS (mean JF cost of about 0.9 EUR/L) becomes on average more convenient than BAU, and PSC-CCU (mean JF cost of about 2.4 EUR/L) starts getting close to BAU.

From 2040 onward, all technology routes start being on average more cost-effective than BAU, whose cost increases due to the increasing carbon price.

Overall, while the cost distributions of the net-zero-$CO_2$-emissions scenarios maintain a similar width from 2020 to 2050 (and exhibit a slightly positive skewness), the cost distribution of BAU becomes remarkably wider because of the uncertainty associated with future values of carbon price (and it can be approximated by a uniform distribution).

## 6. Conclusions

This work defines, analyzes and compares possible scenarios to achieve a net-zero-$CO_2$-emissions aviation sector. These scenarios are based on (i) carbon capture and storage (CCS), where fossil jet fuel is produced and the corresponding emissions are offset by capturing $CO_2$, either from the air (DAC-CCS route) or from a point-source emitter (PSC-CCS route), and permanently storing it underground, and (ii) carbon capture and utilization (CCU), where synthetic jet fuel is produced by using $CO_2$ as feedstock, which is either captured from air (DAC-CCU route) or from a point-source emitter (PSC-CCU route).

A quantitative comparative assessment of these scenarios with a business-as-usual (BAU) scenario where negative externalities are subjected to an aviation carbon tax, is provided through estimates of jet fuel cost from today to 2050. The future cost of low-TRL technologies, such as DAC, hydrogen production, $CO_2$ conversion and PSC technologies, is estimated through learning curves. The analysis leads to the following conclusions:

1. A net-zero-$CO_2$-emissions aviation industry is possible, and can be accomplished by following the CCS and CCU scenarios discussed and assessed in this work. All scenarios are feasible and lead to net-zero $CO_2$ emissions under specific conditions, namely when considering carbon-free electricity to power the jet fuel production and the carbon capture processes.
2. A thorough assessment of the pros and cons of different technology routes requires a systemic analysis that (i) considers the key technical features of all involved technologies, (ii) covers the cost evaluation of the entire technology routes, (iii) accounts for the uncertainties associated with the quantities of interest.
3. General considerations, independent of such uncertainties, can be made concerning the techno-economic assessment of the technology routes.

   Overall, CCS-based routes result in an electricity consumption (with heat requirements also met by using electricity) more than 20 times smaller than CCU-based routes. This implies that, when considering increasing levels of the carbon intensity of electricity production, the $CO_2$ emissions of the CCU routes grow about 20 times faster than those of the CCS routes. Besides they are above BAU emission levels for a carbon intensity of electricity above circa 0.07 $tCO_2/MWh_e$ (for reference, France energy mix corresponds to about 0.1 $tCO_2/MWh_e$).

   Furthermore, the smaller electricity consumption and the simpler jet fuel production processes of the CCS routes lead to lower jet fuel costs and to a smaller impact of the uncertainty associated with the future deployment of low-TRL technologies.

   In fact, the CCS-PSC route is cost-competitive with BAU already today and technology-ready for wide deployment.
4. The transition to a net-zero-$CO_2$-emissions aviation industry based on CCS can be driven by carbon prices in the order of only 70-100 EUR/$tCO_2$, whereas the impact of electricity prices is limited (negligible in the case of PSC). In contrast, the transition to a CCU industry requires much higher carbon prices and/or a large increase in the availability of low cost carbon-free electricity.
5. A deep decarbonization of the aviation sector will most likely depend on a mix of different mitigation measures as there is no silver bullet for reaching this goal. In any case, it is becoming more and more evident that carbon capture, storage and utilization will be key in achieving net-zero $CO_2$ emissions.

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