

Sustainable aviation: Production of e-SAF



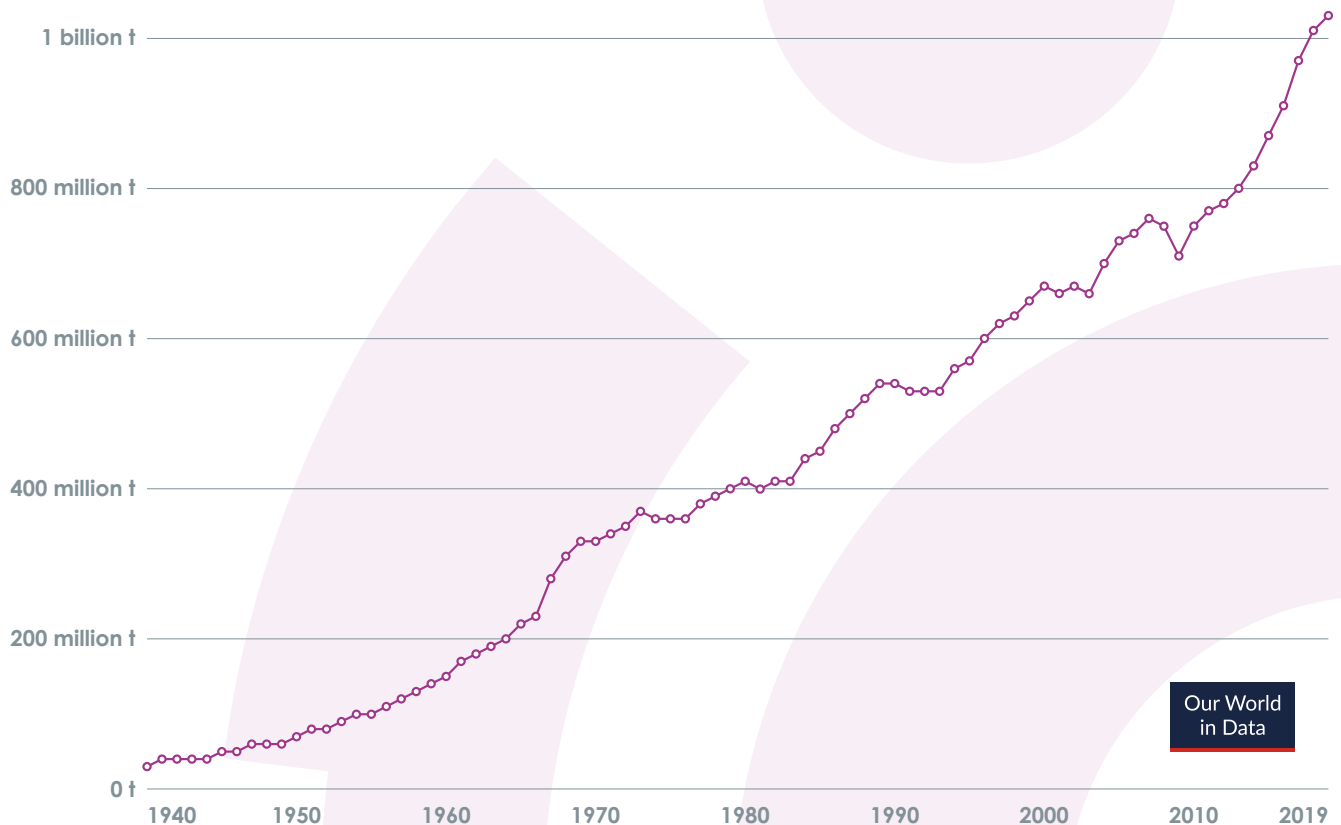
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Introduction

In recent years¹, the aviation sector has typically accounted for around 3% of global, energy related emissions of carbon dioxide [1,2]. While there has been a drop in total emissions from the sector due to the travel restrictions imposed during the COVID-19 pandemic, there is an expectation that demand will very soon return to and exceed pre-pandemic levels and that emissions from aviation will resume the consistent growth observed since commercial aviation took off after the second world war [3].

Figure 1-1: Global CO₂ emissions from aviation, 1940 to 2019



Data source: pre-1990 data from Lee et al. (2021); 1990 onwards Bergero et al. (2023)
Note: Does not include non-CO₂ forcings, and additional warming impacts at altitude.

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¹ Based on emission levels from prior to COVID-19 pandemic.

Since 1990, demand for aviation travel, in terms of passenger-kilometres has quadrupled and it is only through increased efficiency that emissions from aviation have only doubled [4]. There is some scope for demand side reductions, be those through encouraging alternatives such as high-speed rail or virtual meetings, banning flights over short distances where alternatives exist [5] or discouraging flying by applying taxes and carbon pricing to tickets. However, with living standards across the globe continuing to improve, the number of people who can afford to fly is expected to continue to rise and demand is set to grow further.

Given the increasing demand, how else can the emissions from aviation be addressed?

Two alternatives to conventional jet fuels are being proposed for aviation: hydrogen and batteries. However, even in the long-term it is anticipated that these technologies will be limited to short- to medium-range flights: hydrogen stores approximately four times less energy per unit volume than conventional aviation fuel and batteries are significantly heavier per unit of energy stored [1]. Kerosene is broadly recognised as the only fuel suitable for long range aviation.

Rather than eliminating emissions from the aviation sector, negative emissions technologies, such as Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS), could be deployed to offset the emissions from burning fossil-based jet fuel. These technologies are designed to remove CO₂ from the atmosphere, either directly (DAC) or indirectly (for example, capturing emissions of CO₂ from a power station burning biomass (BECCS)), and to store the captured carbon in geological formations. Despite their potential, scaling up these technologies presents significant risks and uncertainties. Technical challenges include the high energy requirements for DAC, sustainable biomass sourcing for BECCS (with the potential to compete with food production for available land) and the effective storage of the captured CO₂. Economic concerns revolve around the substantial costs associated with deployment and operation.

The final alternative being considered to address emissions from aviation is through sustainable aviation fuel (SAF). Unlike conventional jet fuel derived from fossil fuels, SAF is produced from renewable resources, leading to significant reductions in greenhouse gas emissions over its lifecycle. There are several types of SAF, falling broadly into two categories:

- ✓ Biofuel derived SAF comes from biomass such as used cooking oils, agricultural residues, and non-food crops.
- ✓ Synthetic SAF, also known as e-SAF or Power-to-Liquid-SAF (PtL-SAF), is produced by combining hydrogen (generated from renewable electricity) with CO₂ captured from the atmosphere or from industrial processes.

The frameworks of the EU ReFuel legislation and the UK SAF Mandate will drive the aviation sector towards greener practices by requiring a percentage of all aviation fuel to be SAF. Both require that a portion of the mandated SAF supply must be produced through power-to-liquids (PtL) processes. While e-SAF is expected to be more expensive than SAF produced from forms of biomass (primarily because biomass feedstocks inherently contain more energy than the raw feedstocks (water and CO₂) for e-SAF), the limitations on the availability of biomass feedstocks combined with the requirement for jet fuel to contain a certain portion of e-SAF are stimulating significant interest in e-SAF projects.

During our work on e-SAF projects, the team at io have explored various options available for producing SAF through a power to liquids route. In this article we'll describe some of the issues to be considered when sourcing the key inputs to the process (carbon dioxide and electricity) and the impact that choices made may have on the design and operation of the facility. A subsequent article will delve into the options available for converting the feedstocks to product.

Carbon Dioxide

CO₂, which is used as one of the feedstocks for e-SAF, can be provided from various sources with different levels of sustainability.

The least sustainable sources of CO₂ for use in production of SAF are industrial emitters burning fossil fuels or producing cement (releasing CO₂ from the decomposition of limestone), often referred to as anthropogenic CO₂ emissions. While reusing the CO₂ from these facilities is more efficient than emitting them directly to atmosphere, this CO₂ still ultimately leads to an increasing concentration and global warming effect. The EU have legislated that anthropogenic CO₂ originating from industrial processes cannot be used to produce e-SAF beyond 2040 (or 2035, if emitted from power generation). While the UK have not currently specified a timeframe beyond which CO₂ from these sources can be used as a feedstock to SAF, industrial decarbonisation brings into question the long term reliability of these sources of CO₂.

Biogenic CO₂ is a second source of feedstock. This is CO₂ captured from the processing of biomass, some examples of which include:

- ✓ Burning wood to generate electricity
- ✓ Fermentation of specific crops to produce ethanol
- ✓ Anaerobic digestion of specific crops to produce methane

In addition to purely biogenic sources, 'hybrid' sources exist, producing a combination biogenic and anthropogenic CO₂. These include cement production, where biomass can be used to provide the heat to the decomposition of limestone, and Energy from Waste production, where a combination of biomass and fossil-based waste is burned to produce electricity. This CO₂ could be used directly as feedstock to an e-SAF facility or split such that the biogenic portion is used to produce SAF and the anthropogenic portion is sequestered.

While, in the short-term, biogenic sources of CO₂ will be a good source feedstock for e-SAF, the quantity available will ultimately be limited; there is a finite area of land available for biomass production for use in processes that produce CO₂ as a waste stream. Therefore, in the long term, CO₂ will need to be captured directly from the atmosphere: Direct Air Capture. This nascent

technology is currently being developed at a scale that would meet the capacity of a small e-SAF facility [7] but the cost of the facilities, combined with the ongoing operating costs from the high power consumption, make the cost of CO₂ from DAC several times more expensive than that captured from more concentrated sources.

There are a number of factors to consider when selecting the source of CO₂ for an e-SAF facility, a couple of which are described in more detail below.

Capturing and transporting CO₂ requires energy and energy typically results in emissions of CO₂. While the carbon intensity of waste CO₂ streams (that would otherwise be emitted to atmosphere) is considered to be zero, the emissions associated with capturing the feedstock and delivering it to the e-SAF facility must be included in the GHG emissions intensity of the e-SAF. This, in turn, affects the emissions reduction of the e-SAF relative to conventional jet fuel. This is unlikely to be a 'deal breaker' in the EU, where provided the fuel produced achieves a 70% reduction in carbon emissions it can be sold as SAF. However, in the UK, the number of certificates that can be claimed for each litre of SAF produced and, hence, the price premium that the fuel will attract, is proportional to the reduction in emissions intensity of the fuel. Therefore, the efficiency of the capture process, the emissions intensity of the electricity used for the capture process and the complexity of transporting the CO₂ from source to the e-SAF facility, or the location of the e-SAF facility itself, should all be considered when identifying, assessing and selecting a feedstock supply.

Purity of the CO₂ feedstock also impacts e-SAF production. Regardless of the e-SAF production pathway selected, the processing facilities will involve catalytic or electrolytic processes. These are quickly damaged by impurities such as sulphur containing compounds or nitrous oxides. Therefore, additional processing units will be required to remove these compounds, involving increased costs both in terms of CAPEX and OPEX, plus further increases to the emissions intensity of the fuel from the energy used in these process steps.

Electricity

To qualify as e-SAF, the fuel must meet the requirements of Renewable Fuels of Non-Biological Origin (RFNBOs). While there are differences in the precise definition of the requirements for RFNBOs between different jurisdictions, the requirements for the source of electricity are broadly defined to require e-SAF facilities to take power from sustainable, low carbon generators. In the UK, the recent announcements on the SAF mandate have indicated that production of e-SAF from nuclear power will be permitted but for the purposes of this article, the term 'renewable' will be used, rather than 'renewable or nuclear'.

Looking more closely at the UK regulations, and how this might impact the design and operation of e-SAF facilities, there are essentially three categories of electricity to produce RFNBOs (defined under 5 scenarios in the Guidance for RFNBOs):

- ✓ **Scenario 1:** Power taken from a mix of generators from the national grid (not from a dedicated renewable generator). **Scenario 2** is a subset of Scenario 1, where electricity is taken from a regional grid (the criteria for demonstrating the regionality of the grid will not be explained in this article).
- ✓ **Scenario 3:** Additional (either new, renewable power generation or renewable generation that would otherwise not have been produced).
- ✓ **Scenario 4:** Renewable power generation, dedicated to the production of e-SAF, but not from new production capacity (**Scenario 5** is a combination of electricity drawn under Scenarios 3 and 4).

e-SAF producers will typically try to maximise the amount of power supplied to the facility by additional, renewable generators, since this electricity is considered to have zero greenhouse gas emissions intensity and, therefore, 'Scenario 3 e-SAF' will attract the most certificates. Electricity from additional renewable generation can either be provided to the e-SAF facility through a private wire / direct line from the generator or via the grid (in which case, transmission losses must be accounted for). In either case, the e-SAF facility can only consume power when the generator is actually producing power, and the power generated must be exclusively allocated to the e-SAF (i.e. it is not sufficient to demonstrate that a generator has produced more

electricity than the e-SAF facility has consumed but, also, that the electricity generated has been sold only to the e-SAF facility):

- ✓ This requirement is relatively easily demonstrated in the case of a direct wire between the generator and the e-SAF facility (although, in the case of a generator that is also connected to the grid, metering must be provided to demonstrate that electricity is never imported from the grid to be supplied to the e-SAF facility).
- ✓ Where additional, renewable electricity under Scenario 3 is supplied through the grid, consumption must be matched to generation for each and every 30 minute settlement period.

This requirement for 'temporal correlation' makes electricity supply for RFNBO production under Scenario 3 (or Scenario 4) different to other 'green electricity' tariffs where Renewable Energy Guarantee of Origin certificates (REGOs) can be used over a twelve month period (or longer) such that electricity generated during periods with high renewable generation, can be considered to have been consumed when neither the wind is blowing nor the sun shining.

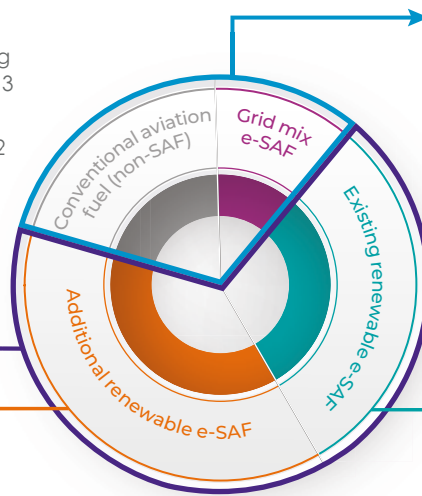
Where additional, renewable electricity is not available, electricity from existing renewable energy generation can be purchased specifically for use by the e-SAF facility. As with electricity provided to produce 'Scenario 3 e-SAF', this power can be provided via a direct line or the grid and the requirement for 'temporal correlation' applies. However, the GHG emissions intensity of the electricity supplied to produce Scenario 4 SAF is considered to be equal to that of the grid (this can be done on a real-time basis or using the annual average emissions intensity of the grid). Depending on the emissions intensity of the grid to which the e-SAF facility is connected, this can significantly increase the emissions intensity of 'Scenario 4 e-SAF', reducing the number of certificates for which the fuel is eligible and reducing the value of the fuel produced.

Finally, for fuel produced under Scenario 1, electricity is consumed from the grid with no agreement for that electricity to come from renewable generators. In this case, the portion of fuel produced that can be considered to be a RFNBO is equal to the portion of electricity supplied to the grid from non-biomass

Electricity types for production of Renewable Fuels of Non-Biological Origin and the implications for SAF production.

Scenario 5 Electricity

- Combination of additional and existing renewable electricity (mix of Scenario 3 and 4)
- GHG intensity = weighted average of 2 power supply scenarios



Grid Mix Electricity (Scenario 1 & 2)

- Grid electricity, no additionality
- RFNBO production proportional to non-bio renewable % of grid multiplied by portion of grid power used for RFNBO production
- Scenario 1 – no regionality, GHG intensity of power = national grid intensity
- Scenario 2 – regionality, GHG intensity of power = regional grid intensity

Additional Renewable Electricity (Scenario 3)

- Additional power that would not have been produced, or would have been wasted, if not consumed by RFNBO site
- Scenario 3 SAF production proportional to the share of Scenario 3 power consumed
- GHG intensity of power = 0 gCO₂e/MJ

3a Directly connected renewables

- New (or life extended) renewable capacity
- No grid connection

3b Directly connected renewables with grid connection

- New (or life extended) renewable capacity
- Power production site has grid connection
- Evidence that RFNBO facility has not consumed grid power through metering

3c Renewable power via green PPA

- New (or life extended) renewable capacity
- Temporal correlation of 30 minutes
- Grid transmission loss accounting
- No systematic grid congestion between renewables and RFNBO site
- Guarantees of Origin (GO) certificates (or equivalent) are retired following consumption

3d Curtailed power via PPA

- Excess renewable power that would have been wasted unless consumed by RFNBO site
- Temporal correlation of 30 minutes
- Grid transmission loss accounting
- No systematic grid congestion between renewables and RFNBO site
- GO certificates (or equivalent) are retired following consumption

Existing Renewable Electricity (Scenario 4)

- Power that would have been consumed elsewhere, if not by the RFNBO site
- Scenario 4 SAF production proportional to the share of Scenario 4 power consumed
- GHG intensity of power = national/regional grid intensity

4b Directly connected renewables with grid connection

- Existing renewable generation capacity connected directly to SAF facility
- Power production site has grid connection
- Evidence that RFNBO facility has not consumed grid power through metering

4c Renewable power via green PPA

- Existing renewable generation capacity
- Temporal correlation of 30 minutes
- Grid transmission loss accounting
- No systematic grid congestion between renewables and RFNBO site
- GO certificates (or equivalent) are retired following consumption

renewable sources (and this portion can be determined using either annual average or real time data) and the emissions intensity of the e-SAF is calculated using the GHG emissions intensity of electricity equal to that of the grid (again, using either annual average or real time data). Thus, 'Scenario 1 e-SAF' suffers a 'double hit' in terms of value: the emissions intensity is higher making it eligible for fewer certificates and only a portion of the fuel produced is considered to be a RFNBO.

How does this impact the design of e-SAF facilities? Clearly, there are different strategies that might be adopted for the design and operation of the facility, and provision of electricity:

✓ Design the facility to operate at steady-state

This strategy would typically minimise the capital expenditure associated with a certain capacity of fuel production, since each part of the facility can be optimised to deliver the correct amount of product. However, it is unlikely that a Power Purchase Agreement (PPA) for steady (baseload) additional, renewable electricity will be available and, even it is, a significant premium would be paid to guarantee power is delivered during periods of low renewable generation. Therefore, rather than producing Scenario 3 e-SAF, there will be periods where lower value Scenario 4 and 1 e-SAF (as well as a portion of non-RFNBO aviation fuel) will be produced, lowering the value of the product.

✓ Design the facility to consume only additional, renewable electricity

Maximising the flexibility of the facility such that it consumes only additional, renewable electricity and hence only produces high-value Scenario 3 e-SAF comes at an upfront cost. While the cost of a PPA for additional renewable electricity where consumption more closely follows generation will be less expensive than a baseload PPA of the same, meeting a particular production capacity over the course of a year will require the facility (either the whole facility, or at least some sections of the facility) to be oversized such that it can over-produce during periods of high electricity generation to compensate for the periods of low generation.

✓ Design the facility with some flexibility to match production to maximise the economic return from the project

An ultimate objective of an e-SAF project must be to maximise the economic return. This can be measured using various metrics (for example, maximising NPV, IRR, levelised cost of SAF over the duration of the project). This strategy would

maximise the production of high-value, Scenario 3 e-SAF (for example, by oversizing energy intensive elements of the facility to produce and store intermediate products during periods of high generation). However, some sections of the plant would operate on a continuous basis and, where flexibility in capacity is more expensive to build into the design, at reasonably high throughput. Therefore, there will be times when the facility will produce lower-value, higher emissions intensity e-SAF. Finally, this strategy could also consider incorporating energy (electricity) storage into the facility.

Assessing the type of electricity consumed by a facility, the cost of that electricity, the emissions intensity of the different consignments of fuel produced under different scenarios and the value of that fuel, while varying the throughput of the facility to maximise the value of the fuel, without incurring excessive capital costs to do so, is clearly a highly complex problem. To optimise the design of the facility requires a model incorporating not only the variation of electricity generation meeting the criteria for Scenarios 3, 4 and 1 over, for example, a twelve month period but also how the portion of generation supplying electricity to the grid varies over the twenty year lifetime of the project. Over this timespan, the portion of UK electricity supplied to the grid by renewable, non-biomass generators is expected to increase significantly, with a corresponding reduction in the associated GHG emissions intensity, which will reduce the 'penalty' associated with production of e-SAF under scenarios 1 and 4.

Conclusions

Production of e-SAF is a newly developing area focused on meeting the challenges of achieving Net-Zero in the aviation industry. Through our work at io consulting, we understand that these new Power-to-Liquid facilities will form part of a complex, multi-sector system with CO₂ being sourced from emitters across a range of industries and with the facility being integrated into a rapidly evolving electrical network. We've recognised that understanding how these different systems interact, how they are likely to develop over time, how that impacts the emissions intensity of the e-SAF produced and hence the revenue that will be generated is key to de-risking projects and unlocking investments. We're developing systems models and deploying our expertise in techno-economic evaluation of facility designs to assist our clients when making decisions early in the project lifecycle.

Look out for our second e-SAF article, in which we will delve into some of the technical options available for the facility itself and the trade-offs that need to be made within the design of the process

References

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