Collective reflection within the framework of the Energy et Environment Commission

ACTING FOR SUSTAINABLE AIR TRANSPORT

May 2023

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This text, in its current state, is not an official document of the Air and Space Academy. It was written, on a provisional basis, by several members of the AAE Energy-Environment commission who, in view of the very active political and industrial context on the subject (particularly in the run-up to the Paris Air Show) thought it advisable not to wait for the work to be completed in full:

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The document is based on the first year's work of the aforementioned commission as a whole.

Detlef Mueller-Wiesner, Gérard Théron, Xavier Fron and Jean-Louis Montel (AAE members), Edouard Freund and Bernd Kaercher (outside participants in the commission) as well as Daniel Iracane (Académie des Technologies) made important contributions to this document and are warmly thanked.

Table of contents

Introduction

Building upon studies on the future of air transport carried out for over ten years by the Air and Space Academy (AAE) and work accomplished by its recently formed "Energy and environment" commission in the past year, and in parallel with preparation of a formal AAE Dossier planned for late 2023, several members of the commission have taken up the pen in order to express an independent vision, supported by the knowledge of some sixty European experts and in cooperation with a number of organizations, learned societies and industrial players.

This document examines the issues that need to be addressed in order to achieve the goal of "Acting for sustainable, climate-neutral air transport" by 2050.

Our analysis today is that this goal is achievable but requires a long-term vision and the audacity to rapidly engage substantial new investment in the fields of energy.

These are just a couple of links in a long chain of actions that will only succeed if our European and global societies are capable of such a vision and willing to make the joint efforts and perhaps sacrifices that are required. Within this framework, energy sovereignty could be a crucial element.

Air transport has an active role to play in this context.

We will therefore examine how air transport is organized, the role it plays in society, its current impact on the climate, progress in energy efficiency, alternative fuels to kerosene, primary energy needs and the new ecosystem that needs to be built to sustain a "virtuous air transport system" in a society that will have to make considerable efforts in the main energy-intensive sectors, and even in those that are more modest such as… aviation.

How can aviation, this irreplaceable tool for connecting the peoples of the world, with its remarkably small footprint, drastically reduce its climate impact?

We propose to demonstrate, on the basis of scientific, technical and economic considerations, that aviation is almost a textbook case of all that awaits our societies in a collective effort that has only just begun. The crux of the problem lies in the awareness of what will have to be accepted to achieve a world that is more efficient in terms of energy and natural resources as well as to establish new sources of energy to replace the crushing domination for two centuries of a relatively inexpensive fossil fuel…

The chosen plan consists of four parts:

- **Air transport**, its organization, its climate impact
- **Technical solutions** that exist to meet the climate challenge
- **Systemic implications (**relating to air transport and energy)
- **Societal aspects** (an integral part of the overall problem).

1. Air transport, its organization, its climate impact

1.1. The international nature of air transport and its organization

A plane is by definition a fast, long-distance means of transport, and therefore air transport is international by nature. This requires a high degree of technical interoperability, if only for safety reasons.

On the other hand, international air service operations between two States bring into play the sovereignty of the States of departure and arrival and of any States overflown. It is a specific market that can only be exploited with the agreement of the States concerned.

These two specific features of air transport led States very early on to approve a general framework for its development (Chicago Convention in 1944, creation of the International Civil Aviation Organization), both in terms of technical aspects (with internationally recognized standards) and in economic and commercial terms. Environmental aspects, protection against unlawful interference (security) and the facilitation of traffic flows (health crisis) are also covered by ICAO, which today has 193 Member States. These rules apply to international traffic (65% of the total), while States, or groups of States (such as the EU) can apply specific rules to domestic traffic.

Within this overall framework, specific aspects, in particular traffic rights, are governed by diplomatic agreements between States. Unilateral decisions are only possible on condition that they do not call into question these agreements (in particular in terms of equal opportunities for market access, one of the basic principles of the Chicago Convention). The European Union has harmonized certain rules applied by its Member States within their bilateral aviation agreements with third countries, and in a few cases has directly signed open skies agreements (liberalized market access) with third countries. Within the EU, bilateral agreements have been replaced by a single sky policy open to operators from all Member States.

In environmental matters, ICAO has had a policy of limiting noise pollution for more than 50 years, has regulated local emissions since the 1980s, and has been developing a policy relating to CO2 emissions for 20 years, in accordance with the mandate conferred on it by the Kyoto Protocol (1997), unchallenged by the United Nations Framework Convention on Climate Change and its various COPs, including the Paris Agreement.

The strategy in question is based on four pillars:

- Technological innovation, stimulated by a system of CO2 emission and certification standards adopted in 2016;
- Improved flight operations and infrastructures;
- Development of sustainable aviation fuels (SAF);
- So-called "market-based" economic regulatory measures, which resulted in the adoption of the recently implemented CORSIA system.

CORSIA is a system that caps air transport emissions at 85% of their 2019 level. It is applied airline by airline. Emissions that go beyond the authorized threshold, according to a method of calculation accepted by all, must be financially offset. Each state is responsible for applying the system to airlines registered with it. Emissions are therefore not allocated according to country, but rather by operator. Indeed, attempts to calculate international emissions by country (see ADEME or "Shift project") have little chance of being validated by third-party States and could only lead to disputes that are difficult to resolve. In this regard, it is important to keep in mind the principle of « Common but Differentiated Responsibilities » (CBDR), appearing in the Kyoto Protocol and taken up by the Paris Agreement (Art.2), subscribed to by emerging and developing countries. This principle is also one of the pillars of CORSIA[1].

Not only therefore is air transport subject to internationally approved emissions limitation policies, it is the **only economic sector organized in this way at the global level.**

If a State or a group of States wished to put in place measures that went beyond the (sovereign) agreements signed, these agreements would have to be renegotiated. To achieve this, these projects should be shared before implementation and negotiations opened at ICAO level or country by country within the framework of bilateral agreements. Any unilateral application of measures perceived as restrictive and not in line with the agreements would not fail to cause blockages, or even retaliatory measures, such as those applied by China in 2012 when the EU wanted to apply the EU-ETS to international flights without negotiation. In this case, the EU had to backtrack under pressure from third countries. **It is therefore vital to prepare the ground diplomatically in advance, to convince our partners and forge alliances, otherwise the same causes will produce the same effects. Trying to impose unilateral rules on carriers from third countries would have very little chance of succeeding.**

With regard to ICAO, it is necessary not only to give this organization the means to speed up the process of preparing the policies under its remit, but also **to better control the work it has been carrying out on an identical model, for 15 to 20 years. The presence of a European in the Presidency of the Council should constitute an opportunity.**

Finally, it should be noted that emissions from domestic transport are fully covered by the Paris Agreement, and that intra-EU emissions can be dealt with by the 27 EU Member States. For example, two draft European regulations currently under discussion aim to contribute to the global goal of net zero emissions by 2050, adopted at the last ICAO Assembly:

- From 2026, by bringing intra-European aviation fully under the Emissions Trading Scheme (ETS). This measure will ensure that the emission quotas set by the European Union are respected by all the sectors covered, including aviation.
- Gradually, from 2030 to 2050 through mandatory low-carbon fuel minima in the composition of aviation fuels (Refuel EU) as is already the case for road fuels. A minimum of 70% SAF in 2050 (including a minimum of 35% "e-fuel" i.e., non-"bio" synthetics) has just been negotiated at the time of writing and should be enacted in the coming months.

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[1] We do not deal here with the application of CORSIA to developing countries, which would consider these measures to be unfair.

This will require sufficient production of low-carbon aviation fuels, which will be produced primarily from low-carbon power. We will return to this later.

1.2. The climate impact of air transport: perceptions and realities

The accumulation of carbon dioxide in the atmosphere is the main cause of global warming. Air transport currently contributes around 2.5% of this CO2. This average figure should not obscure the enormous disparities in emissions from one country to another: in terms of tonnes of "aeronautical" CO2 per inhabitant, we observe a ratio of 20 between North America and Africa (and of course, once emitted, CO2 does not stop at borders). The "non-CO2" atmospheric effects of aviation have been studied by many research centres for 20 years, all the very complex phenomena at work in the atmosphere being fully elucidated or their impact measured. This has given rise to divergent points of view that inevitably go beyond the scientific field (see 1.3 and 1.4).

Air transport is included in national inventories for domestic routes and therefore in international climate agreements such as the Paris Agreement. Under the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Paris Agreement, which did not call this into question, ICAO is responsible for defining and implementing a policy for international air transport aimed at combating climate change. The air transport system is therefore clearly invested in policies to fight climate change. However, communication in the sector has not always been very effective and, until recently, has not succeeded in highlighting the full extent of efforts undertaken or their strategic dimension.

Comparisons with other modes of transport, in particular rail, only cover a small part of air transport emissions, namely those over the shortest distances. Moreover, they are often biased, only taking into account the "immediate" emissions of a journey. The only way to correctly analyze and compare emissions from a sector is to think in terms of life-cycle analysis; when this is done, the perspective changes. Moreover, it is easy to forget that the environmental externalities of aviation are particularly low compared to other modes of transport (see § 1.3 below).

In fact, public perception in Europe of the impact of air transport on the climate is such that the proportion of press articles or social network activity devoted to it is much higher than its true representation among contributing human activities. Indeed (cause or consequence?) a survey[2] has shown that more than a half of the public, particularly in France, believe that this share of emissions exceeds 10%, far above the actual figure of 2.5 to 3%.

« Aviation, the main culprit?»

But there is something more important than the figures: the existence of representations of aviation that make it a "separate" human activity. The planetary nature of aviation,

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[2] Chiambaretto P., Mayenc E., Chappert H., Engsig J., Fernandez A-S., Le Roy F., Joly C. (2020). « Les français et l'impact environnemental du transport aérien : entre mythes et réalités », Les Carnets de la Chaire Pégase, n°1

its visibility in the truest sense of the word (much greater than that of electrons during streaming!), impress our retinas and our minds; CO2 emissions are felt as immediate and direct, as instantaneous as the sound of an aircraft taking off, as opposed to more diffuse emissions along a production chain in the clothing or food industry or others[3].

As well as being highly visible, aviation also retains, here and there, the image of "transportation for the rich", which contributes to its blacklisting. This must be put into perspective, **for while it is true that the higher socio-professional categories represent roughly half of the passengers in France, and probably throughout Europe, this is the same weighting as for long-distance trains[4], which are in no way more democratic than aircraft**.

The truth is that the liberalization of air transport, initiated some forty years ago in the United States and ten years later in Europe, has enabled less well-off social categories to access long-distance travel, and to travel easily by plane at affordable prices (low-cost companies). Indeed fares are often more reasonable than for high-speed trains, whose infrastructure, unlike that of air transport, is largely subsidized. The almost viral statement that "only 1% of people are responsible for 50% of global aviation emissions" results from a miscalculation[5]. This is not to deny, of course, that there are very strong global inequalities in the use of aircraft, but these are not specific to air transport, they are merely a reflection of major income inequalities, both between countries and also within a given country, which must therefore be tackled at a level other than that of air transport.

Admittedly, air transport communication campaigns have too often focused on dream destinations and first-class travel for us now to be surprised by this criticism, and the democratization of air transport is not yet effective enough to counter this perception (a democratization that would be the first to suffer from coercive measures… and also from the rise in ticket prices, undoubtedly inevitable as we will see below).

It is also important to bear in mind the somewhat arrogant growth prospects for global air transport: a doubling or even tripling of air traffic by 2050 would obviously increase either aviation emissions or requirements for carbon-free energy, even taking into account technological progress (see Chapter 2). But such strong growth will not be driven by the very wealthy, but rather by increased access to travel for the middle classes of developing Asia and Africa.

Moreover, there is no guarantee that this growth will be as strong as forecast by the airline industry, especially internationally. Between now and 2050, global instabilities, antagonisms between political blocs, pandemics and other economic crises are very likely to slow it down. Voluntarism at all costs, with the accompanying media coverage, does the environmental image of aviation a disservice. More caution and modesty would certainly be welcome.

Provided that it remains reasonable and constructive, media pressure can certainly be beneficial by encouraging air transport to play a role in the fight against climate

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[3] In particular the 'hidden' carbon in imports which accounts for half of the West European's carbon footprint

[4] DGAC, Enquête nationale auprès des passagers du transport aérien 2015-2016 (https ://www.ecologie.gouv.fr/sites/default/files/ENPA_2015_2016.pdf); Th. Le Gouezigou, Head of TGV Data and Performance at SNCF (https://fr.linkedin.com/pulse/le-tgv-est-il-train-des-riches-thomas-le- gouezigou?trk=article

[5] TMB Aéro, October 2022

change that is commensurate with its mission in contemporary civilization. But it is this mission that is often forgotten. It is indeed travel as such which is at issue in the debate (see the section on sobriety in chapter 4), and in particular long-distance travel, for which the plane is irreplaceable[6], and which is of considerable importance to society, having done so much to bring civilizations together and to open the minds of citizens individually and collectively. For while most goods are transported by land, human beings are carried by air. Awareness of this fact is certainly not enough, but can be compared with what the aviation sector represents arithmetically in world GDP.

« Aviation, the canary in the coal mine? »

Since air transport is the subject of so much media coverage, the same media pressure will inevitably lead to a greater interest than at present in the more general issue of primary energies, to which we will return later in this document. Indeed, the magnitude of the effort required to decarbonise aviation can, in principle, be generalized to most human activities. **What the aviation "case study" shows us is the unprecedented and underestimated nature of the economic, social and political effort required.**

1.3. Contribution of aviation to greenhouse gas emissions and other environmental externalities

The first, and by far the largest, contribution is the production of carbon dioxide resulting from the combustion of kerosene of fossil origin. It accounts for 2.5 to 3% of the anthropogenic production of this gas, which accumulates in the atmosphere over a period of one hundred years.

The second contribution is the continuous emission of nitrogen oxides ("NOx"), which is regulated in the vicinity of airports for air quality reasons and has a relatively small overall climate impact compared to CO2. Indeed, interacting at altitude with other atmospheric components, they contribute on the one hand to increasing the concentration of ozone, a greenhouse gas, but on the other, to reducing that of methane, a very powerful greenhouse gas.

Another probable contribution is that of cirrus clouds induced by contrails, which is the subject of the following section (1.4).

The next point to note is the extremely low average impact of air transport per passenger-kilometre in terms of environmental externalities and infrastructure costs. Fig. 19 of the report cited in the note below[7], from a study commissioned by the European Commission, ranks aviation better than all other modes of transport, even coaches. The externalities of air transport are therefore mainly greenhouse gas emissions, with all

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[6] What's more, in terms of lifecycle analysis, cruise ships emit significantly more than aircraft.

[7] Sustainable Transport Infrastructure Charging and Internalisation of Transport Externalities : Main findings. Commission Européenne 2019. (Study by TU Delft).

ground emissions, noise, infrastructure, damage to biodiversity, etc. being low and more closely related to the passenger-kilometre[8].

Thus, in a life cycle analysis, the construction of the aircraft, the ground infrastructure, and the ancillary activities do not weigh heavily in relation to the CO2 of the fuel... and will decrease as the general decarbonization of society progresses.

1.4. Contrails

Finally, let's talk about condensation trails (contrails) and the cirrus clouds (clouds of ice crystals) they induce in a cold and supersaturated atmosphere. Their effects on the atmosphere and climate are highly complex and can vary considerably in intensity and direction, depending on time, season, location, etc. In the current state of scientific knowledge (see the extremely cautious IPCC report, pp. 866-7 and 956 of IPCC, Climate change 2021, The Physical Science Basis), the level of uncertainty in the modelling of the phenomena involved is very high and the quantification of the climate impact associated with contrails depends very much on the metric adopted to quantify these effects (in particular the time horizon). **Comparing the effects of contrails-cirrus to those of CO2 and deciding on actions today, including avoidance manoeuvres in areas deemed critical in terms of ice cloud persistence, on the basis of such uncertain exchanges between the two pollutants could lead to results opposite to those sought**. It is therefore advisable to wait until scientists have succeeded in significantly reducing the level of uncertainty through research activities and dedicated experiments, before deciding on the issue.[9] It is also necessary for specialists to have a fairly accurate understanding of the environmental impact of new aviation fuels, particularly with regard to the formation of contrails.

Given the current levels of uncertainty about non-CO2 effects, the "Trilogue" agreement reached on 8 February 2023 "provides that the Commission will implement a monitoring, reporting and verification (MRV) system for non-CO2 effects in aviation from 2025. By 2027, the Commission will submit a report based on MRV and, by 2028, after an impact assessment, the Commission will make a proposal to address non-CO2 effects."

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[8] For example: an aircraft weighing a few dozen tonnes, whose production has contributed to the emission of 50,000 tonnes of CO2, will fly almost every day for 25 years or more, covering between 30 and 100 million kilometres – between 3 and 50 billion passenger/kilometres (pkt) – and will therefore have a construction carbon footprint per pkt of only one to a few grams, rather than the tens of grams of land and sea transport.

[9] The drastic reduction in traffic in 2020 due to Covid provided the opportunity for measurements by difference with "normal" traffic: five studies were done, inconclusive, some pulling the effect of contrails down the range of uncertainty cited by the IPCC

2. Faced with the climate challenge, technical solutions exist.

The question is one of stopping the addition of carbon dioxide to the atmosphere and reducing the other impacts of flight (emissions of gases and particles that can affect atmospheric composition).

2.1. *How can CO2 emissions from aviation be reduced?*

In addition to reducing traffic, other levers include (depending on local situations): increasing load factors, optimizing flight paths and air traffic control management and accelerating the renewal of airline fleets to take advantage of efficiency gains associated with latest generation aircraft. But we must also continue to support and intensify technological research to develop more efficient aircraft. Today, we know that the main means to do this will be to produce and use fuels with very low emissions, or even completely carbon neutral (sustainable aviation fuels, SAF).

Yield management[10] and cabin densification, accepted by passengers despite the associated loss of comfort, have led to enormous savings in CO2 emissions per passenger kilometre (pkt)[11]. Continuous descents, which are more economical, are beginning to be practised, waiting times for landing are becoming rare, but a further 5% in consumption could still be gained in Europe by further optimizing flight paths.

Aircraft produced since 2017 (A320-21 neo family, A350, etc.) consume significantly less per pkt than their predecessors, which still dominate the world, with an average fleet age of 12 years. Simply renewing the fleets with this new class of aircraft, therefore, will reduce consumption per pkt from 3-3.5 litres/100 to under 2.5 litres/100.

In 10-15 years' time, a new generation of lighter aircraft, with more efficient wings and more fuel-efficient engines, is expected to bring an additional 25% improvement in fuel consumption per pkt.

Modelling of this progress by AAE suggests that, given a sufficiently rapid rate of renewal, **consumption per pkt will be reduced by just over a third by 2050**. All of this will help to offset the significant increase in fuel prices in the ticket price.

2.2. *How to get rid of the CO2 footprint? Which "energy carrier" on board?*

Aircraft cannot fly without a strong input of energy. Aircraft such as Solar Impulse, the solar-powered gliders of flying clubs (prototypes) and the high-altitude drones with an endurance of several weeks are by no means suitable for mass transport. Possible onboard energies are batteries, hydrocarbons (organic or synthetic) and hydrogen.

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[10] Yield management is a business practice of the transportation and tourism industries. The prices of the services offered vary according to demand and consumer behaviour.

[11] There isn't much to gain from it although any improvement is welcome (1-2%?)

Hydrogen can be used in many ways: as a propellant in engines like kerosene, in a fuel cell that will power electric engines, or as an essential component of synthetic jet fuel. And indeed, the latter is no longer a dream. We know how to make synthetic jet-fuel from various bio resources or from hydrogen and CO2 extracted from the air.

Provided that these on-board "energy carriers" are produced using "carbon-free" primary energy (photovoltaic, wind, hydro, nuclear, etc.) and that the carbon atoms they may contain have been captured from the atmosphere or from biomass, **the flight will be CO2 neutral.**

To power an A320 by capturing all the solar energy illuminating it in good weather would require wings of a few hectares... or 50 tonnes of batteries per hour of flight... but an electric flying club plane, the Pipistrel, is certified with 1 hour of battery life! Start-ups are currently looking at slightly larger, short-range aircraft for niche markets, although this will not change the order of magnitude of fuel needs, as the proportion of very short-haul flights will be a very small minority.

2.3. Replace hydrocarbons? But with what?

Kerosene and the sustainable fuels replacing it, whether organic or synthetic, have quite a remarkable mass and volume energy content. In addition, they are easy to transport and store, and the kerosene remains liquid over the entire useful range (from -47°C to over 60°C), which explains why aviation has so far favoured their use. **If aviation was "born with oil", it will survive it** thanks to solutions that are already on its shelves. Hydrogen gas has three times the specific energy of kerosene, but is 3000 times bulkier at atmospheric pressure for the same energy. By compressing it to 350 or even 700 atmospheres, some space is recovered, but the size and weight of the tank remain significant. By liquefying hydrogen (at -253°C), we reach a density of 71 kg/m^3 which, for the same energy, puts us at about 4 times the size of kerosene, without counting the volume (and the mass) of the super-insulated tank required. Halfway between hydrogen and kerosene, we find methane (CH4), a fossil gas which can also be synthesised like e-fuels. Although quite tempting to use compressed or liquefied, it shows no obvious advantages for aviation[12].

We will come back in more detail to the two non-fossil fuel sectors likely to propel the planes of the future: for now, we can say that synthetic kerosene (produced from hydrogen and CO2 captured from the atmosphere, which mimics the physical and chemical properties of kerosene) is not easy to produce but can be used almost immediately, whereas hydrogen is produced quite easily by electrolysis but is very tricky to use afterwards... Moreover, **SAFs that are miscible ("drop- in") with current kerosene will allow a gradual transition that is much easier to manage (and faster!) than a technological leap**.

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[12] Methane is well known in the maritime environment by its LNG carriers which transport liquefied 10% of the world's natural gas production. It is also used in space by Elon Musk's Starship launcher.

2.4. Which primary energies and yields are used to produce these fuels?

For so-called "first generation" biofuels, mostly derived from oleaginous plants cultivated for this purpose, the chemical and collection sectors are well proven and require relatively little primary electrical energy. Waste oil has its physical limits (we are aiming for a few percent of demand) and, whatever happens, will remain far from being able to power a large proportion of the world's fleets. The energy (in terms of NCV[13]**)** to be added to the process is minimal.

Lignocellulosic biofuels use the whole plant. They can be produced from forest waste collected at a "reasonable"[14] distance or from fast-growing plants (miscanthus, bamboo, etc.) cultivated for this purpose. The fuel yield per tonne of dry matter is attractive: 1 to 1.5 tonnes of fuel per hectare for the most efficient plant, miscanthus, although this plant has limits of use as it requires marshy soils, 500-600 mm of rainfall between May and September and is vulnerable to frost).

The yield is multiplied by two if we intervene with a supply of hydrogen. It then takes 10 kWh of (carbon-free) power per kilogram of fuel. In this case we speak of “e-biofuel” to differentiate it from conventional biofuels.

The recent study by the French Academy of Technologies[15], whose conclusions we share, speaks of a maximum 20% coverage of aviation needs by « bio » resources, at least in Europe (see §3.1 below).

"Green" hydrogen is obtained by electrolysis of water. There are several variants, some of which are at high temperature. The energy efficiency of the electrolysis reaches 70% for alkaline and "PEM [16]" technologies but this hydrogen then has to be compress and/or liquefied. Liquefaction requires additional energy equivalent to 30% of the calorific value of hydrogen (in large liquefiers), which brings the energy efficiency of fuel production to 58% before transport, evaporation, etc. With “SOEC [17]” technology, the yield can be higher, up to 90% before liquefaction, but an additional source of heat is required… which is available "for free" if electrolysis is combined with SAF production.

PtL (Power to Liquid) requires the combination of hydrogen and carbon. The hydrogen comes from the electrolysis of water and the carbon comes from carbon dioxide directly captured from the air (DAC for "Direct Air Capture")[18]. A series of reactions called "Fischer-Tropsch", invented almost 100 years ago, makes it possible with these ingredients to build chains of hydrocarbon molecules CnH2n+2, precursors of hydrocarbons.

The heat released by the Fischer-Tropsch synthesis step can be used in the atmospheric CO2 extraction unit.

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[13] Net calorific value

[14] A hundred kilometres

[15] https://www.academie-technologies.fr/publications/la-decarbonation-du-secteur-aerien-par-la-production-de-carburants-durables-rapport-et-avis/

[16] Polymer electrolyte membrane electrolysis

[17] High temperature solid oxide electrolysis

[18] Using unavoidable CO2 emissions from another industry would have little economic interest.

Finally, a variant under development uses high temperature co-electrolysis of steam and CO2, leading almost directly to the desired hydrocarbons. The best current yields from these processes are just over 50%. This means that about 25 kWh of power is needed to produce one kilo of fuel.

Note: The kerosene selectivity of the process is about 60%. In other words, for 37 kWh spent, we get one kilo of e-fuel and 0.67 kilo of e-diesel[19].

The existence of commercial outlets for these co-products should be noted: they could be used as fuels (e-diesel, for non-electrified surface transport and maritime transport), but also (and mainly) as a low-carbon petrochemical base.

Accordingly, since decarbonization of aviation is analyzed as part of the decarbonization of all societal needs, in our needs study and economic analysis as well as in the study by the Academy of Technologies mentioned above, 25 kWh are allocated to e-kerosene and 12 kWh to co-products (see §3-1 for more detailed explanations).

"SAF"[20]: first generation bio, e-biofuel, PtL, are all kerosene variants miscible with jet-A1. Seven of them are ASTM certified for different blends, all limited to 50% to date[21]. Engine manufacturers and energy specialists are optimizing these fuels and any engine adaptations to achieve 100% use without loss of reliability, drastically reducing the small proportion of unburned fuel[22] conducive to the appearance of contrails.

NB: ASTM (ASTM International) is the only globally recognized organization for the certification of aviation fuels. It has been a US publisher of internationally recognized standards for 125 years; ICAO has also adopted sustainability standards (Annex 16 Volume 4 of the Convention) and a methodology for calculating the emissions of these fuels over their life cycles. These standards lag far behind European requirements.

2.5. *What about hydrogen?*

As indicated in 2.4, the production of liquid hydrogen requires essentially the same amount of primary energy as PtL and more than e-biofuel for the same on-board energy. A hydrogen-powered aircraft will have to be larger and heavier than a conventional plane[23] to carry out the same mission, and will be all the more disadvantaged in terms of fuel consumption the further it has to fly, a minor consequence for short-haul aircraft, but one which is already significant for medium-haul, and prohibitive for long-haul aircraft which will have to be of a radically different

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[19] At the lab stage, processes would exist providing higher selectivity, up to 80% See document from the 2023 Academy of Technologies on fuels

[20] SAF (Sustainable Aviation Fuel)

[21] But thousands of flights have already taken place with engines powered by pure bio or e-fuel.

[22] It may be that we maintain a share of "aromatic" compounds in SAF which would reduce this advantage (still uncertain)

[23] Volume and weight (gravimetric index) of cryogenic tanks Today, at the same on-board energy, with the best tanks either pressurized or thermally insulated for liquid hydrogen, the total mass containing + content is greater than that of kerosene

design (of the flying wing type for example?). Hence the far more distant prospects for entry into service of long-haul hydrogen aircraft (2060 or even beyond).

While the use of hydrogen in propulsion systems does not appear too difficult, the conservation of liquid hydrogen in the tank and its transfer to the engine pose difficulties that are still far from being resolved by major manufacturers possessing staff and significant test resources. These could decide on the feasibility of aircraft of whatever size within 3 to 4 years, a decision that will also take into account the availability of a sufficient refuelling network at the time of entry into service.

Reservations concerning the difficulties to be overcome in order to produce an aircraft with satisfactory reliability raise the question of the credibility of certain projects promoted by start-ups that do not have experienced teams to manage definition and certification.

We will soon see light aircraft with a few seats or "commuter aircraft" (less than 20 seats) with electric or hybrid propulsion, powered by fuel cells using hydrogen gas. Slightly more ambitious are projects such as "Universal Hydrogen", which plans to retrofit ATRs and Dash-8s with gaseous or liquid hydrogen propulsion, refuelling through a system of interchangeable cartridges. These innovations will provide hands-on experience of safety and refuelling issues.

The production, transport, storage and refuelling of liquid hydrogen at airports is a major challenge. **The ability of a large number of airports to refuel aircraft with liquid hydrogen will be a key decision factor, particularly due to the large investments required and the strategic orientations taken by the various players.**

Understandably, technological developments and ground and flight tests are being launched to answer the many issues raised. These developments will be useful in clarifying the long-term potential of liquid hydrogen fuel, provided they do not divert attention, or funding, from more powerful, faster-to-implement decarbonization solutions.

Given these difficulties that will need to be overcome, even though hydrogen could emerge as a viable solution on a large scale in the long term, SAF will have been developed and taken their place on the market, especially since **the possible fleet mix between hydrogen aircraft and aircraft using sustainable fuels (drop-in SAF) will limit interoperability, complicate airline operations, and require duplication of investments**, already considered very substantial for SAFs which are a priority.

As we will see later, the place of SAF is limited only by the capacity to produce carbon-free power, which is also the case for hydrogen fuel.

It should be noted that even in the roadmaps that currently include liquid hydrogen as an aircraft fuel, its contribution to reducing CO2 emissions will remain modest compared to technical and operational improvements and the use of SAF "drop in" biofuels and e-fuels.

Consequently, in view of the many challenges to be overcome, the prospects for liquid hydrogen as a fuel for aircraft engines by 2050 appear very poor, and uncertain beyond that date.

We won't say more here. Certain 'unlikely' R&T successes experienced by many of us make us cautious of saying 'never'

2.6. What about the use of fossil kerosene whose CO2 would be fully offset?

Just as we capture CO2 to make SAF, we can capture atmospheric CO2 to bury it and thus "authorise" (offset) the CO2 emissions of a fossil fuel tonne for tonne.

We can also capture and concentrate the CO2 emitted in industrial processes at the factory outlet. Captured CO2 can be sequestered in a variety of ways:

The combination of a CO2 absorption process using only moderate temperatures and burial in basaltic subsoils where the CO2 quickly binds to the rock should make the whole process safe and simple. The technique has been at the demonstration stage since 2021 at a rate of 4,000 tonnes, using geothermal energy as the main source of energy.

Oil companies have been storing CO2 for decades in abandoned or endangered coal or oil reservoirs as well as in saline aquifers, because these geological formations are well known to them and present very little risk of leakage. On the other hand, CO2 sedimentation there is very slow, unlike in the basaltic environment.

Since CO2 pipeline networks exist here and there, transport and sequestration are not very expensive.

The technique is currently mature, with 45 megatonnes of CO2 stored worldwide each year, a flow which is expected to increase more than tenfold by 2030 (IEA estimates).

According to the IPCC and the IEA, the storage potential of these two techniques is considerable (some gigatonnes of CO2 for the world as a whole) with, according to ADEME, around fifty megatonnes for metropolitan France.

Proponents of these technologies see them as a way of decarbonizing air transport, complementary SAF, for at least part of the fuel consumed.

Quoted costs are extremely variable and depend on the maturity of the processes. They depend on the type of CO2 capture.

The current cost of processing concentrated CO2 captured leaving the factory ranges from a few tens to a hundred euros (or dollars) per tonne.

The cost of capturing and treating CO2 from the atmosphere by prototype plants is currently much higher, ranging from several hundred euros up to a thousand euros per tonne.

In view of these figures, some oil-producing countries might wonder what proportion of fossil kerosene they could still consume in their country, to be offset by direct air capture and storage (DACS).

Indeed, at a rate of 3.15 kg of CO2 to be stored for 1 kg of kerosene burned, if the price of CO2 stored by DACS did not exceed one or two hundred euros per tonne, and if the price of crude and therefore of fossil kerosene has not rocketed, such a route could be tempting at least for extra tonnages and in specific geographical cases.

The industrial energy cost of a fully optimized process is not yet known to us and will not be discussed further in this document.

3. Systemic implications

Given the many uncertainties, we have tried to give an order of magnitude of the main factors, their relative weights and the main trends, and then to identify the conditions for achieving decarbonisation goals by 2050.

In a later report, the analysis will focus on the kinetics between 2023 and 2050, taking into consideration all carbon emissions over this period.

As mentioned above, the two main levers influencing the success of decarbonisation targets for air transport are:

- fleet modernisation, which should reduce unit consumption by 36% by 2050;
- the development of the SAF production chain, which can reduce unit emissions by ~90%.

The fuel-efficient solutions (electric and hybrid) used by other players, such as ground transport, will remain limited to specific markets in air transport (short-haul, small aircraft), which account for only a small proportion of emissions. They are therefore not considered in this chapter.

The main ideas are as follows:

- **According to the IEA (NZE, Net Zero Emissions scenario), society will be decarbonised by electrifying as many usages as possible.**
- **The need for new decarbonised power generation capacity is huge and its implications in terms of acceptability by the public may require nothing less than a new social contract.**
- **The decarbonisation of aviation cannot be considered in isolation from the challenges of decarbonising society as a whole.**
- **A major step towards CO2-neutral fuels by 2050 will only be possible if decarbonised power is available in the European Union in significant quantities relative to the already considerable needs of its society, and if we agree to rely on some imports.**
- **There will still remain a significant residual share of fossil fuels in the overall consumption of the decarbonised society (NZE) in 2050, with CO2 emissions from fossil fuels being subject to CCUS (Carbon Capture, Utilization and Storage).**
- **Aviation fuels will not escape this rule.**
- **Biofuels (in all their forms) could mitigate this decarbonised power demand to some extent, but there are still uncertainties about the physical and societal limits to aviation's access to sufficient quantities of biomass.**

In this chapter we show that **efforts to improve the efficiency of air transport**, combined with the impact on demand of the increase in ticket prices reflecting the increase in cost due to the use of SAF, which is more expensive than kerosene, **will make it possible to maintain total fuel consumption in 2050 at the 2021 level.**

After examining the limits of biofuels arising from problems of access to biomass, and then focusing on access to the required quantities of decarbonised power we bring into perspective the needs of air transport in relation to those of the rest of society.

Finally, we identify a possible path and the conditions for achieving it, so that air transport can come as close as possible to its decarbonisation targets by 2050.

3.1. How much energy is needed to produce all these fuels? Orders of magnitude...

3.1.1. Air transport fuel requirements (in Mt/year)

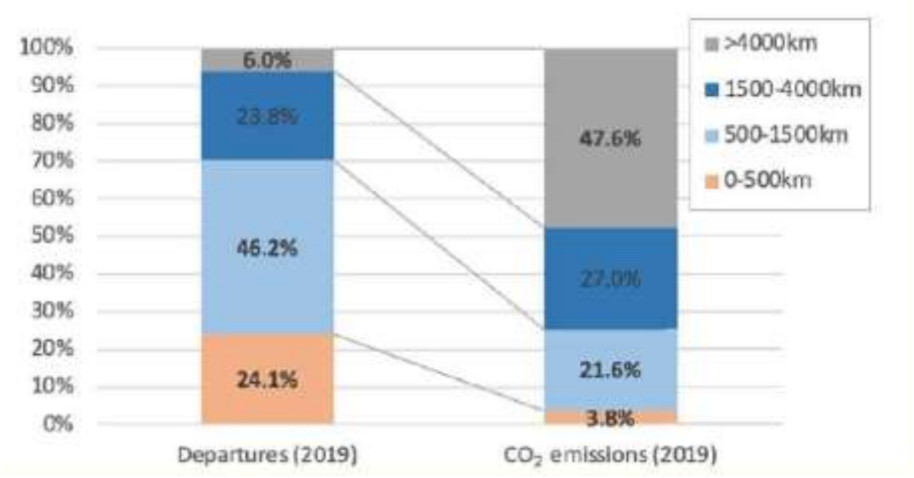
We begin by estimating (see also Annex I) traffic in 2050 in pkt on the basis of the trend increase in traffic from 2021 to 2050 in %/year, corrected for the effect of higher ticket prices (resulting from the use of more expensive SAF) to obtain an estimate of traffic in 2050 in pkt.

After estimating unit consumption in litres/pkt in 2050, i.e. in kg/100pkt, we arrive at an estimate of fuel consumption in 2050.

Consumption and structure of current uses

Current fuel consumption in European airports[24] is about 62 Mt, of which 42 Mt in the European Union.

As Figure 1 shows, only 6% of flights departing from Europe go further than 4,000 km, but they account for almost half of the emissions attributable to Europe and therefore of the fuel consumption.



Source : Eurocontrol Think Paper 10

FIGURE 1 : SHARE OF FLIGHTS AND EMISSIONS BY FLIGHT DISTANCE

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[24] In the following, the term Europe will be applied to the scope of the European Civil Aviation Conference (ECAC), which brings together 44 countries, including the 27 countries of the European Union, plus in particular the United Kingdom and Turkey, and we will use EU to refer to the Europe of 27.

Given the many uncertainties surrounding the development of air transport, societal changes, fuel costs and the relationship between ticket price and traffic (elasticity of demand), we have attempted to assess future demand and its implications based on the scenario that seems most likely today.

Assumptions and scenarios considered

SAF incorporation rate in the fuel mix 2050

We have examined two base cases for the rate of incorporation of SAF by 2050, respectively, which are the two extremes resulting from the draft European ReFuelEU Aviation regulation:

-- Scenario A : 100% SAF;

-- Scenario B : 70% SAF;

Biofuel content of fuels in 2050

The draft EU regulation requiring 70% SAF by 2050 requires a minimum of 35% e-fuel by 2050 and assumes a 35% biofuel share. In our view, 35% biofuels is excessive (cf. §31.12).

We therefore examined two variants of Scenario B:

-- Variant B1 with 20% biofuels (in line with the recommendations of the Académie des Technologies) and 50% e-fuel (maintaining 30% kerosene);

-- Variant B2 with 35% biofuels (in line with the Refuel EU project) and 35% e-fuel (maintaining 30% kerosene).

Estimation of traffic (pkt) and total fuel consumption (Mt) by 2050

As for the key assumption regarding traffic growth trend, we have chosen the WAYPOINT 2050 central scenario used by ATAG and adopted by the aviation industry, which forecasts an average current growth rate between 2021 and 2050 of 3.1% for the world and 2.2% for Europe.

We then adjusted the growth trend figure to take account of the negative impact of higher ticket prices due to the inclusion of more expensive SAF in the fuel mix, to obtain the traffic (pkt) in 2050 (cf. Appendix 1).

To obtain the fuel consumption in 2050, we multiply traffic (pkt) by estimated consumption in 2050 (litres/pkt), which takes into account fleet renewal and therefore an efficiency gain of 36%[25].

- In Scenario A, annual traffic growth would drop to around **1.3% per year** between now and 2050. Improvements in energy efficiency combined with this slow-down in traffic growth would bring fuel consumption from **42 Mt to 39 Mt**.

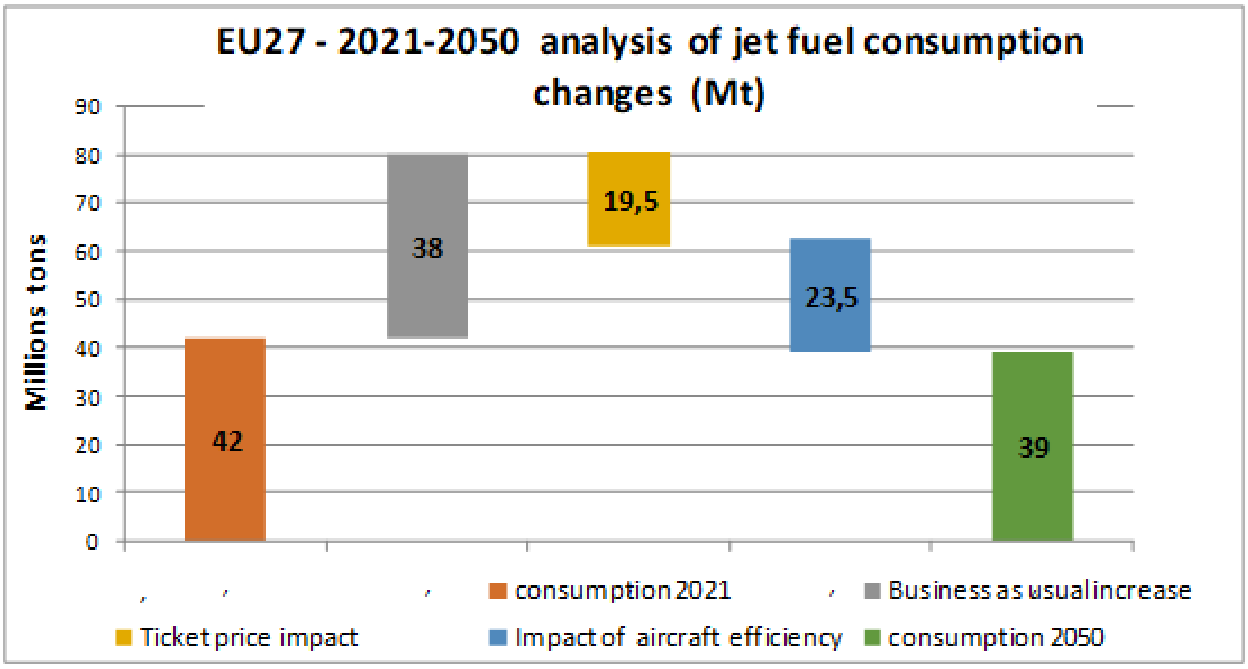
---

[25] Multiplier of 0.638 between litres/pkt 2021 and 2050 reflecting efficiency improvements from 2021 to 2050. Based on the historical average efficiency improvement rate of 2% per year still valid today, the PPA has assumed that this rate will gradually decrease from 2% per year to 1% per year between 2021 and 2050 in a linear fashion over 29 years.

- In Scenario B and its variants, assuming a uniform SAF price, annual traffic growth would be **1.5% per year**. Improved energy efficiency combined with a shallower slow-down in traffic would bring fuel consumption at **40 Mt** in 2050.

Details of the above calculations can be found in Appendix I. The graph below shows the different impacts in Mt of fuel for Scenario A.

FIGURE 2



3.1.2. Bio-input requirements and their limits

Biofuels in all their forms (traditional biofuels and e-biofuels) are subject to specific constraints.

The proportion of biofuels in SAF is restricted

Many factors limit the production potential of each type of SAF: some are purely physical, such as the availability of land for growing crops or collecting biomass for bios, or the availability of sufficient quantities of water for electrolysers for e-fuels and e-bios.

Others relate to the industrial and economic maturity of processes such as the capture of CO2 from the atmosphere (DAC), electrolysers and floating photovoltaics at sea.

Limitations of a different kind, specifically concerning biofuels, result from trade-offs in use and above all from future trade-offs which, in the current climate, are likely to be unfavourable to aviation.

The importance of trade-offs in use

- The IEA's World Energy Outlook 2021 predicts that the amount of bioenergy available in the world in 2050 will be 2100-3000 Mtoe/year.

  Given that generally accepted estimates of global aviation fuel production in 2050 are ~300-400 Mtoe/year, and assuming a bioenergy-to-biofuel conversion efficiency of 50% and a SAF selectivity of 60%, it would be necessary to mobilise **~1000-1300**

Mtoe/year, i.e. between 30 and 50% of total global bioenergy production, to meet aviation demand alone!

- We will see in §3.1.4 that the implications of realistic scenarios for SAF in the European Union in terms of biomass area requirements lead to similar conclusions.

- **Trade-offs between usages will therefore have a significant global impact on the biomass resources available for aviation.**

Hypotheses on the share of biofuels in SAF

- The availability of biofuels in all their forms seems to be, along with the availability of decarbonised power (cf. 3.1.4), the factor limiting SAF that most escapes determined action.

- We agree with the Académie des technologies that the use of biofuels is limited by the trade-offs between usage, and in the physical constraints which are more prevalent in Europe than in the rest of the world (available land use, but also the economics of collecting forestry waste).

This is why, in our estimates, we start by setting as a fundamental assumption the absolute quantity (Mt/year) of biofuels available in all their forms.

We have therefore assumed a 2050 production potential of 8 Mt/year (20% of the ~42 Mt/year currently required by aviation) for the EU, based on the very detailed calculations of the Académie des technologies[26].

Our figure of 20% is halfway between the figure, which we feel is optimistic, of 35% quoted by certain studies[27] and retained in the EU Refuel targets which have just been negotiated, and the estimates we have seen recently in the press, which we feel are too pessimistic.

Robustness of qualitative messages

In any case, we will see in § 3.1.4 (and in Appendix II) that the needs in Twh/year of decarbonised power are not fundamentally modified by assumptions concerning the percentage of bios, whether it is zero, 20% or 35%.

Section 3.1.4 presents the results of calculations based on 100% e-biofuels.

(Annex IIII shows that when the opposite assumption is made, i.e. 100% conventional biofuels, the need for **decarbonised** power **generation capacity is 10 to 20% lower, but at the cost of double the biofuel acreage).**

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[26] Academie-technologies.fr/la-decarbonation-du-secteur-aerien-par-la-production-de-carburants-durables-rapport-et-avis/

[27] ADEME in 2022; roadmap for decarbonising air transport in France

3.1.3. The energy needs of society in the European Union (in Mt/year)

Let us recall some orders of magnitude often misunderstood by the general public:

- According to the BP Statistical Review of World Energy 2022, the European Union currently consumes ~ 16,000 TWh/year of primary energy, of which, according to the IEA, a minority is used for power generation, with the remainder of primary fossil fuels used mainly in buildings (heating/cooling/kitchen), transport (mainly road transport) and industry.
- According to the IEA's Net Zero Emissions (NZE) scenario, which we believe is most consistent with society's decarbonisation goals, primary energy consumption is expected to fall despite population growth, thanks to improvements in energy efficiency.

At the same time, power **consumption would rise considerably, going from ~3000 TWh/year (of which 1700 TWh decarbonised) to ~6000 TWh/year in 2050 in the EU**.

In this scenario, significant efforts will be needed to:

- decarbonise the energy consumed, in particular by electrifying as many uses as possible in the building, transport, industry and agriculture sectors;
- decarbonise the production of this power proportionately.

Usages that do not lend themselves to electrification, particularly in industry, would have to rely to as great an extent as possible on capture/sequestration/reuse of CO2 emitted (CCUS).

- A major objective is therefore to produce this 6,000 TWh of decarbonised power by 2050, which requires:

  - **adding ~3000 TWh/a of additional low-carbon generation by 2050;**
  - **replacing ~1300 TWh/a of current carbon-based generation** with decarbonised units, i.e. adding **a total of ~4300 TWh/a of decarbonised production**.

- In addition, to compensate for the intermittent nature of renewable generation (periods without wind or sun when production is not at full capacity), it will be necessary **to build excess capacity of 24%[28] (1100 TWh/year)**.

In total, therefore, we will need to add around **5,400 TWh/year (4,300 + 1,100)** of new decarbonised generation capacity.

To give some idea of the resulting footprint, assuming 20% nuclear[29], 40% solar and 40% offshore wind in the European Union, we would need to build **~110-120 EPR units** plus ~1100 Saint Nazaire-type offshore wind farms (~80km2 each) plus ~12,000 km2 of photovoltaic fields (~4,200 solar farms of 2.6 km2 each, supplemented by distributed solar power)[30].

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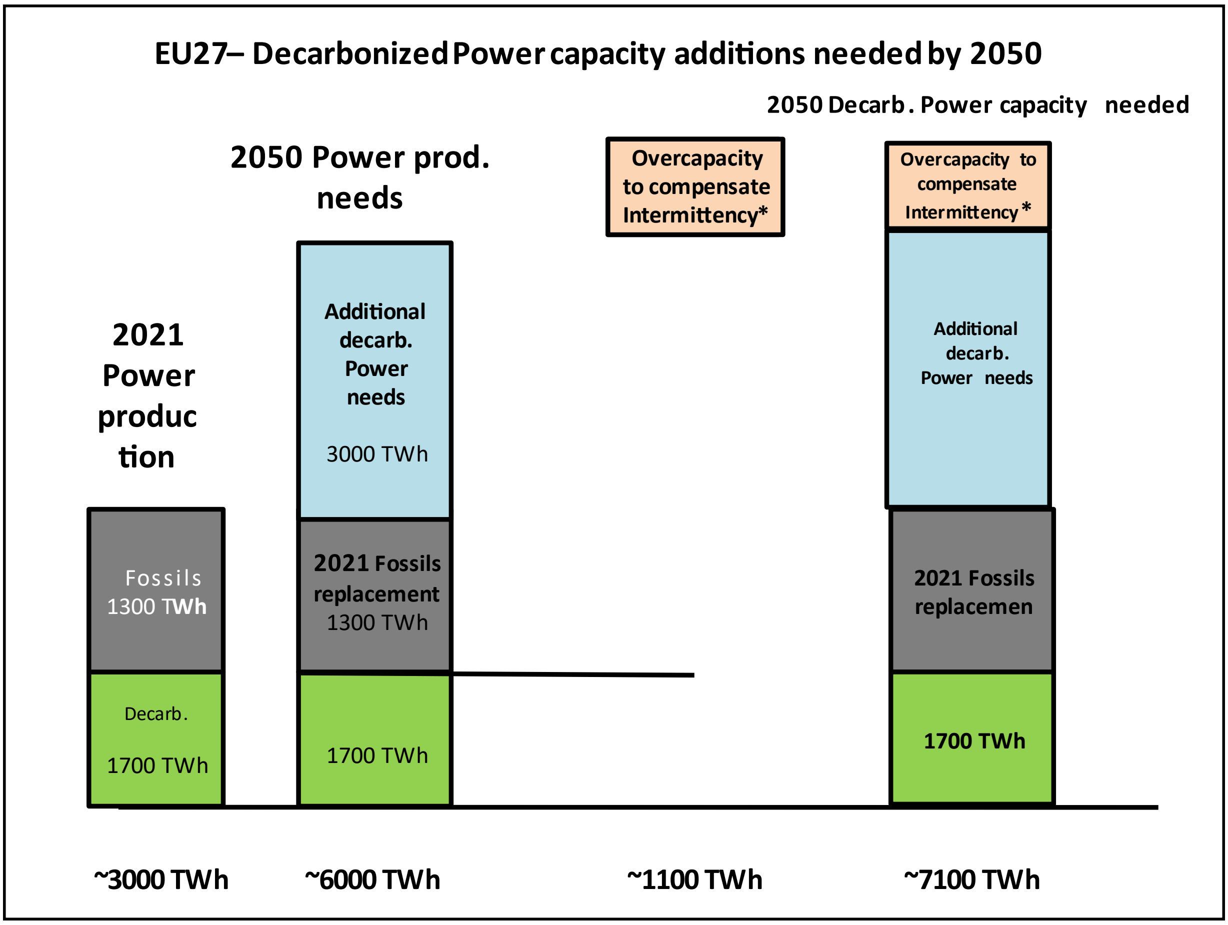
[28] Compensating for intermittency requires an overcapacity of 30% for renewables, but none for nuclear and hydro, which are controllable (i.e. 24% of the total).

[29] 30% nuclear power, except in countries where it is "out of scope", such as Germany, etc.

[30] Annual capacity. Source RTE and EDF

Figure 3



The need for additional decarbonised power generation capacity to decarbonise power generation in the European Union in 2050 (~5,400 TWh/year) should be compared to total primary energy consumption of around 12,000 to 15,000 TWh/year (NZE).

It should be noted that this 12,000-15,000 TWh/year includes a residual share of fossil fuels with recourse to CCUS.

These targets are very ambitious, both in material terms and in terms of the social acceptability of expanding the nuclear fleet and the territorial coverage of the renewables required.

They are also ambitious in terms of the investment required: whether nuclear, wind or photovoltaic, the production of decarbonised power requires physical investment (CAPEX) of around €1 to €1.25 per kWh of annual production capacity, or €1.25 billion per TWh per year.

Therefore, if we plan to invest to increase decarbonised power production capacity by ~5,400 TWh/year over 25-30 years across the European Union, **we will need to mobilise almost €7,000 billion, or more than €250 billion per year, assuming we start immediately.**

Given that the annual rate of productive investment in the European Union as a percentage of GDP is around 20% for a GDP of around €18,000 billion, i.e. ~€3,600 billion per year, we are talking about **an increase in investment flows of ~7% by 2050**. It is therefore important to act quickly and massively.

Failing this, to meet our goals we will have to import this energy in the form of an intermediate fluid (methane, ammonia, liquid hydrogen or SAF!), which will multiply yields losses, will therefore be costly and will have its limits (see 3.3 below)!

- Faced with this colossal challenge at both European and national level (even though some countries, such as France, will be a little less constrained thanks to their nuclear power stations), society as a whole, which has to respond to the climate emergency, **is already up against the wall in terms of energy.**

It is to be hoped that, as with the post-war reconstruction effort, this challenge will be met.

But in view of the land and sea surface required for renewables and the number of nuclear reactors needed, it is nothing less than **a new social contract**!

Given the importance of the political, social, industrial and financial stakes involved, we can only recommend moving forward the debate between the relevant public and private actors.

3.1.4. The need for "decarbonised power" for Air Transport

It should be noted that the following considerations also apply if we are interested in hydrogen as a fuel, since e-fuels and hydrogen share 80% of production processes.

The constraints of the laws of chemical thermodynamics

Synthetic fuels are chemically very similar to kerosene (except for the aromatics).

The difference in terms of carbon footprint comes from the fact that the CO2 absorbed from the atmosphere during the production of synthetic fuels is re-emitted during their combustion, so that the carbon footprint of synthetic fuels is in principle zero (zero life-cycle emissions).

However, this decarbonisation comes at a price: the energy efficiency of synthetic fuel production (e-fuel) is currently estimated by the Académie de Technologies, ONERA and DENA to be at best 50-55%, assuming a fully optimised industrial process.

As mentioned above, it takes about **25 MWh of decarbonised** power **to produce 1 tonne of e-fuel** (whose carbon comes directly from atmospheric CO2) with an energy content of 12 MWh. **10 MWh of e-biofuels** (similar, but whose carbon comes from vegetation) are sufficient to produce 1 tonne of SAF. Moreover, in practice, the intermittent nature of the renewable energies that will largely supply the electrolysers means that the **electrical capacity will have to be oversized by about 10%** to supply the continuous equivalent of 25 TWh (therefore 27.5 TWh/tonne) of e-kerosene or 10 TWh (11 TWh/tonne) of e-biofuels.

Estimation of needs for decarbonised power

On this basis, let us look at the scenarios from section 3.1.1, which reflect the extreme assumptions for SAF blending resulting from the draft RefuelEU regulation, and which can be broken down as follows:

Scenario A:

100% SAF in the 39 Mt/y required in 2050, consisting of:

- ~8 Mt/y of **e-biofuels as postulated (~20% of total fuel)**
- 31 Mt/y of e-fuels (~80%)

Scenario B:

70% SAF and a residual 30% of fossil kerosene in the 40 Mt/y required in 2050 (~12 Mt/y, **to be addressed by offsets** - see §2.6) with:

- ~8 Mt/y of e-biofuels as postulated (**~20% of total fuel)**
- 20 Mt/y of e-fuels
- **12 Mt/y of fossil kerosene to be offset as indicated in §2.6.**

Results of simulations

In Scenario A, the need for additional decarbonised power production capacity (including the 10% oversizing required for electrolysers to work properly through the off-on cycles) is **~925 TWh/a for the European Union, i.e. ~16%[31] of its total power production in 2050**, a share of total investment and, above all, a share of land use with the resulting difficulties of social acceptance that make it difficult to propose.

The needs of aviation are so high because, unlike most other sectors, electrification cannot be achieved directly, but through the use of power (25 MWh) to produce 1 ton of fuel,(12 MWh energy content).

As for the implications in terms of territorial footprint, see the impressive figures for EPRs, wind turbines and photovoltaic fields quoted at the beginning of the chapter!

For the remainder of our analysis, Scenario A is therefore discarded in favour of Scenarios B1 and B2.

- In Scenario B1, new decarbonised power generation capacity is required at a rate of ~625 TWh/y for the European Union, or ~11% of total power production in 2050, a less disproportionate, but still substantial share.

  To summarise, for 8 MT of e-biofuel and ~20 MT of e-fuel produced in the EU, the territorial footprint in the EU would be:

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[31] We had a choice between three different ratios to measure the proportion of aviation's needs in relation to those of society as a whole: relating needs to what production will actually be in 2050, relating them to the production capacity to be put in place in 2050 after taking account of intermittency, relating them to the addition of decarbonised capacity. (We chose the ratio yielding the figure in the middle)

- 11 EPRs plus ~120 Saint-Nazaire-type offshore wind farms (~10,000 km2) plus ~4,800 km2 of solar power, including ~500 very large solar farms and additional distributed solar power;
- as well as … **~2.7 to 5.4 million hectares for e-biofuels** at a rate of 1.6 to 3.3 tonnes[32] of biofuel per hectare, **representing 8 to 16% of the area currently used for industrial biomass in the EU[33].**

Such proportions underline the importance for aviation of the trade-offs involved in allocating biomass resources.

- In scenario B2 (35% biofuels), the European Union's energy requirements would fall by around 100 TWh/year to ~525 TWh/year.
- **The weight of air transport needs in relation to society's total power production in 2050 would fall to around ~9% (*instead of 11% in the 20% biofuel scenario*), but would mobilise biomass land use of between 5 and 9 million hectares (i.e. between 14 and 28% of the areas currently devoted in the EU to the production of biomass for industrial use),** a goal which has not yet shown to be realistic.
- Assuming that we also accept to import 1/3 of total needs, these figures would become ~285 TWh/a for the EU, or ~5% of the needs of society as a whole.

<u>Importing so as to help resolve the power conundrum?</u>

- In order to help resolve the power conundrum, we could consider, by partially giving up the strategic autonomy of SAF supplies, agreeing to import part (~ one third) of the fuels, while remaining aware of the risks and limitations (cf. § 3.3) of imports.

It should also be noted that importing merely shifts the problem of limits and allocation of scarce resources geographically.

- We have assumed that imports are made at prices comparable to local production and that therefore neither ticket prices nor traffic are affected. As a result, if EU bio production is set at its maximum (8 MT/year), the mobilisation of power resources would decrease by 27.5 TWh/MT[34] of imported e-fuel and 11 TWh/MT of imported biofuel[35].

- Thus, for a third of the imports (~10 MT), 240 TWh less would be required from power producers, with the need for additions **falling to 385 TWh, or about 6.5% of EU** power **production in 2050, a figure that is much easier to propose from a societal point of view.**

The fact of aviation pursuing these partial imports in order to reduce its dedicated share relative to the rest of society from 11% to 6.5% would of course signify the European Union giving up part of its energy autonomy[36].

---

[32] The upper end of the yield per hectare range assumes miscanthus, which is very efficient and yields at least twice as much as other plants, but is tricky to use (frosts are a problem and it requires 500-600 mm of rainfall from May to September), while the lower end assumes a mix of other possible plants.

[33] Approximately 60 M ha for the EU according to the WVW Institute in Vienna (2020)

[34] 25 TWh/ MT for continuous production of e-kerosene + 10% excess capacity to compensate for intermittence (on-off cycles)

[35] 10 TWh/ MT for continuous production of e-biofuels + 10% excess capacity to compensate for intermittence (on-off cycles)

[36] Purchase of additional SAF imported: €35 billion/year, investment avoided in Europe €450 billion/year €.

3.1.5. Required investments

Scenario B1

- The **CAPEX required upstream for the SAF** sector, i.e. investment in decarbonised power generation to supply the ~625 TWh/year required for aviation, will be carried out by the power producers and will cost ~**€800 billion** at a rate of ~€1.25 billion per TWh/year (see above).
- **The CAPEX to be carried out in the SAF** sector consists of CO2 capture (DAC), electrolysers, the Fischer-Tropsch reactor, hydrocracking and reforming facilities.

According to the data available to us, mainly from the leading German studies (Ralf Peters et al, 2022 and Concawe -2019), as well as the work of the Académie des Technologies mentioned above, the corresponding investments are estimated to decrease from €9.6 billion/Mt of SAF to €3.6 billion/Mt of SAF by 2050.

Assuming an average value of €6.6 billion/Mt of SAF over the period, we arrive at a budget of €200 billion for the EU over 30 years, i.e. €7 billion/year on average.

The total amount to be invested in SAF (over ~30 years) in the European Union is therefore €200 billion + €800 billion, i.e. **~€1,000 billion**.

We will see in section 3.2 how the long-term supply contracts we recommend ("simili PPAs") can shift the burden of these investments to SAF producers in a win-win transaction.

Scenario B2

CAPEX invested locally in the European Union would follow in due proportion.
It should be noted, however, that the overall need for CAPEX would not decrease. Investors would therefore be needed for those countries that would equip themselves to export 40[37].

Reminder

CAPEX will be €1,200 billion in Scenario A.

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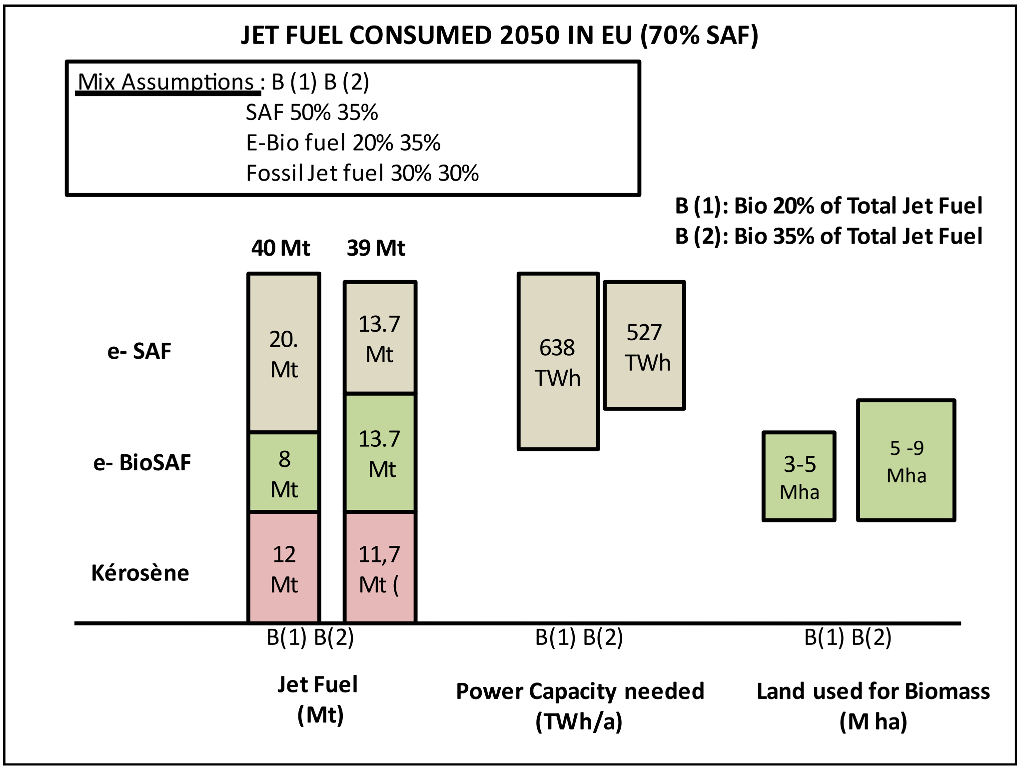
[37] Is SAF's Neste plant in Singapore, planned to produce 1 million tonnes of biofuel a year, the first sign of such a trend?

FIGURE 4



SUMMARY OF RESULTS

100% e-biofuels in bios									
EVALUATED HYPOTHESIS				**Needs (TWh/y)**	**% of total needs**	**Equival. EPR**	**M ha biomass**	**% vs present bio surfaces**	**CAPEX (G€)**
Scenario	% SAF/ % Kero fossil	% Bios in total	% SAF imported						
A	**100%**	**20**		925	**16%**	85	3 to 5	**5-9%**	1200
B1	**70 /30**	**20**		625	**11%**	57	3 to 5	**5-9%**	800
B2	**70 /30**	**35**		525	**9%**	48	5 to 9	**9-18 %**	650
B1 with imp.	**70/30**	**20**	33%	385	**6,50%**	35	3 to 5	**5-9%**	700
B2 with imp.	**70/30**	**35**	33%	285	5%	26	5 to 9	**9-18 %**	550

3.2. What can and should aviation do, especially in Europe?

3.2.1. Strategic uncertainties

- **Is 100% success in achieving society's decarbonisation goals certain?**
- **How many countries in the world will adopt similar policies to the EU?**
- **What volume of physical offsets can be achieved through massive deployment of atmospheric CO2 capture and sequestration?**
- **To what extent will the automotive industry's** new appetite for synthetic fuels change global input requirements?
- Under what conditions and with what guarantees of stability could biomass use allocations become more favourable to aviation?
- How many TWh/year will be included for aviation in decarbonised power generation investment plans for 2050, and under what conditions?

If decarbonised power becomes a scarce resource:

- In which countries would low-carbon power be allocated through a liberal system with a classic auction mechanism?
- In which countries would there be quotas?
- **If there were quotas, what criteria would they be based on: weight of the sector in CO2 emissions? Weight of the sector in the economy? Abatement costs? Tonnes of CO2 saved?**

3.2.2. Limits to be taken into account

The specific characteristics of aviation

- **Air transport is not a single entity with a single decision-making power.**
- Fuel issues are primarily the responsibility of the airlines, in technical and logistical coordination with the airports for the related infrastructure.

However, the interests of all players are interlinked, as any negative impact on traffic would firstly affect airlines, then airports, and later aircraft manufacturers through a reduction in orders.

The idiosyncrasies of the power wholesale market

In order for the power producers to be able to plan its production and, even more so, their investments, large consumers must always sign multiannual contracts defining the volume of purchases and the price conditions.

The power producer does not have to supply beyond its production (or supply) capacity.

When demand exceeds supply, wholesale contracts are auctioned, leading to higher contract prices.

In extreme cases of shortage, some customers may not find a counterparty.

The need to start building an industrial sector for SAF

- Aviation is at the end of the transformation chain from inputs (biomass, decarbonised power CO2) for the production of SAF.

- Without secure outlets, the power company would have no interest in investing on the scale and within the timeframe desired by the aviation industry, and neither would the aviation fuel producer have any interest in investing and committing to the power company, except on the basis of secure outlets.

- Since air transport is not the legitimate partner to place orders with the power company, the industry will therefore have to find a way to encourage the fuel producer to do so on its behalf and initiate the process of creating a SAF industrial sector.

3.2.3. A possible action plan

- Aviation should position itself very early on as one of the demand sectors in the collective process of building new decarbonised power generation capacity.

This would ensure its place in any prioritisation process, given the uncertainties surrounding the decarbonisation of society.

A wait-and-see approach would be a mistake. The risk would be to end up as a last-minute candidate jumping the queue, with a disproportionate demand in decarbonised power *compared to other uses.*

- Given the need to create and structure a SAF industry, it is also in the interest of the aviation industry to act without delay to ensure that all the elements are in place in a timely and coherent manner.

- An action plan for the air transport industry could consist of the following measures:

1. **Rapidly publicise its needs to** power **suppliers and potential synthetic fuel producers.**
   Publicising these needs might risk reviving familiar opposition to air transport... but inaction risks ostracising the sector for not having anticipated its needs, with the consequences of authoritarian traffic reduction, for example through dissuasive taxes.

2. Move closer to SAF producers and other upstream players through European coordination structures.

   - For example, through their three major alliances, airlines could seek long-term supply agreements with aviation fuel producers, who could then do the same with their own suppliers. In this way, all players in the branch would be able to secure their supplies and outlets in terms of volume and price.

   Such an approach would also have the advantage of shifting the burden of financing investment to an upstream sector with secure outlets.

   At the same time, it would give the hydrogen producer an interest in dealing with the power producers.

   - We can expect pressure on investment by the power producers to meet demand for all uses, which will drive up prices: for example, the price of long-term renewable supply contracts has already doubled in a year and is trading at more than double the cost of production.

- The introduction of priority processes or even quota mechanisms cannot be ruled out.

- It is very likely that some SAF producers will consider integrating upstream into the clean production of decarbonised power. In this case, we can expect them to ask air transport to participate in the capital of production consortia set up on an ad hoc basis.

3. At the same time, set up an industrial SAF network to ensure timely access to the required tonnages of e-fuels at the best price.
   For example, a number of plants are emerging that produce e-fuels for the automotive industry (e.g. Porsche in Chile), and e-fuels have just been officially introduced for the post-2035 period following an agreement between the European Commission and Germany.
   A SAF production industry still needs to be established and structured.
4. **Take concerted action at European level to obtain more favourable conditions for access to biomass for aviation.**
5. **Take early action to secure the necessary import volumes (see §3.3 below), especially as competition for access to the resource is expected.**

3.3. To import or not to import?

- As mentioned above, it is possible that **aviation will need to import sustainable fuel from countries that are better off in terms of climate, space ... and cost factors** in order to make its demand for decarbonised power generation capacity more acceptable.

  We might note that, given the very low efficiency (~30%) of a "power to liquid to power" cycle[38], only importing *ready-to-use* liquids such as SAF makes sense.

- **Beyond the specific problem of aviation, this question arises for all societal needs, whether for green hydrogen or SAF (e.g. the plans envisaged by Germany).**
  - In the short term, imports are inevitable. But if this were to happen on too large a scale, it would **replace our current energy dependence with another and expose the European Union to the emergence of a green OPEC**.
  - There is a huge discrepancy between the total power production of ~1,300 TWh/year in the Middle East, ~900 TWh/year in Africa and ~1,400 TWh/year in Central and South America, and the potential demand of European society as a whole, which is 5,000 TWh/year for the Union and ~7,000 TWh/year for Europe.

3.4. The dynamics of aviation decarbonisation

The question of the industrial and political capacity to achieve the 2050 targets (whatever they may be) must not overshadow the immediate question of the dynamics of progress towards decarbonisation. The urgency of climate change is well known. It is therefore important not only to achieve 70% or 100% decarbonisation by 2050, but also

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[38] It should also be remembered that the problems of intermittent energy supply will be much the same in the candidate countries for such production.

to do so on the most favourable trajectory, minimising all emissions between now and then.

However, by its very nature, the creation of a decarbonised primary energy/electrification/SAF sector will take time before, as we hope, accelerating in a way that we cannot quantify today. This reinforces the need to start quickly with the massive investments that the aviation sector needs to support.

Air transport is not specific in this respect; it is simply part of a general "race against time".

Of course, this question of dynamics applies to all the vast decarbonisation challenges facing society: the speed at which electric vehicles will become widespread and the availability of green power needed, whether for heating or agriculture.

Similarly, the level of decarbonisation of energy used by air transport in 2050 will still be less than 100% and the sector will therefore have to make up the difference, a problem that, once again, will not only concern air transport.

4. Societal aspects

4.1. Sobriety

The energy challenges mentioned above contribute to the need for a frank approach to "air sobriety".

But in order to evoke it, it is essential to place it in a wider context.

Sobriety is a concept with variable contours, which we must endeavour to distinguish from energy efficiency, even though the two concepts are linked: the first concerns behaviour and uses, the second technical and operational solutions (for aviation: performance improvement, alternative fuels, flight optimization). The first is more complex and more controversial…

It can result from two opposite but converging approaches: on the one hand, a societal choice aimed at curbing the runaway energy consumption of recent decades; on the other, a necessary complement to decarbonization.

It can be voluntary, even spontaneous, highly individual or, on the contrary, organized at the level of society or market-driven. For air transport, all of these modes can co-exist. Apart from a change in behaviour (which is likely to be marginal, at least initially), the most likely scenario is one of induced "sobriety", if we can still call it that, (as we have already assumed in the forecast of fuel needs) through an increase in ticket prices as a result of the use of alternative fuels, despite the opposite effect that technological and operational performance improvements will have.

This debate on sobriety, which has recently been greatly intensified by the geopolitical energy crisis, is essentially European. For air transport, which is essentially global, this is a serious inconvenience. However, this situation, which may be temporary, should not prevent us from thinking about a truly European model of society and transport: air transport is not a “groundless” activity. In particular, the development of virtual meetings is having an impact on the frequency of business flights, and "mass" tourism, in its current form, is experiencing the beginnings of challenge - although the return to normal post-pandemic life shows a thirst for travel that must be quenched, and that long-distance travel, the prerogative of the plane, is in any case a fact of civilization whose beneficial social effects must be taken into account.

The search for sobriety is therefore almost a simple matter of common sense although, once again, it cannot replace the "technological" search for efficiency, which is the most urgent and ardent obligation.

The most important thing is to get rid of postures and preconceptions on both sides. Aviation bashing is unfair and ridiculous. Conversely, the technocratic, conservative refusal to question the energy voracity of contemporary societies, including aviation (in its rightful place, no more, no less) is a dead end. One has to choose between drunkenness and sobriety; sobriety and efficiency, though, are not rivals but partners, in a ratio no one can yet predict. It is a great and noble subject for public debate, a political subject if ever there was one…

4.2. Complexities and uncertainties

The issue of decarbonization in general is extremely complex, given the mix of technological progress, financial and human investment, regulatory decisions, social acceptance, democratic priorities, etc. This is particularly the case for air transport which is essentially international in its function and economy.

This is especially true when we add to these multiple parameters the time requirement linked to the climate emergency: in other words, not just the hopes or promises of thirty years from now, but what we are capable of doing, in terms of all emissions, between now and then.

All the above-mentioned approaches are feasible, none are easy, and none of them immediate, but the longer we delay the harder the effort will be.

Performance improvements in this sector are by nature long-term. Fleet modernisation at odds with airline profitability, regulatory efforts require international negotiations, whose difficulty is well known, synthetic fuels need to reach the industrial stage, the enormous primary energy needs will be met in a very gradual way with many obstacles to overcome.

Finally, sobriety, in the form of an evolution of uses which raises political and civilizational questions, is no easier than the rest.

Consequently, we must agree to reason and act in a vague context. Everything that is feasible may not be done, or not quickly enough. But the physical constraints will remain. Decarbonizing the world is a huge, unprecedented and uncertain task.

This complexity and this uncertainty must not lead us to give up, or to wait for answers to all questions, to all interactions. Quite the opposite. It must reinforce the need to act immediately, without further procrastination and in a focused way.

5. Conclusion

After this call to action, we need to ask: what is the path to climate neutrality by 2050?

As we, the authors of this situation analysis, publish our findings, we have the feeling that the decarbonization of air transport by 2050 will not be easy, but that it is possible, at least in Europe and probably in some of the regions of the world that emit the most aeronautical CO2.

But we must stop procrastinating! The climate can't wait, one year of emissions is one year too many! It will "cost" more in CO2 than it will take to fix one imperfection.

Given that long-distance flights are the raison d'être of aviation and the biggest consumers of fuel, and that plant resource are limited by competition and/or regulation, it is clear that the SAF obtained by capturing atmospheric CO2 and hydrogen from electrolysis will be the "heavyweights" of the market by 2050 and in the long term.

Adapting aircraft engines to new kerosene can be done in time and does not worry us.

The accelerated renewal of aircraft fleets already underway will make it possible to go part of the way quickly, provided that airlines have the resources.

The prospects for improving aircraft efficiency will require bold solutions which, without going to the extremes of liquid hydrogen concepts, will require serious maturation. There is still a lot of work to be done by design offices but we can already expect a new major step towards optimized energy efficiency around 2035+.

It's the rise of the energy industry that will be the biggest problem! In some European countries, the carbon-free electrical energy available should make it possible to meet the challenge of SAF integration in the 2030-2035 timeframe, but beyond that, unless a significant increase in industrial power has been initiated, with advances in know-how and training of personnel, it will be difficult to invest at the level required by society in those European countries which no longer have a strong industrial base.

Countries that do not make this investment effort will pay a high, long-term price for their fuel imports, if indeed they ever find enough.

Financial resources are a key to the problem, an essential tool, as is building a social consensus on the acceptability of new rights of way, but there is a more fundamental need for commitment at the highest level to guide and support efforts over time, to initiate, implement, regulate, and manage effective processes in all relevant areas, and to win public support. This is not just about aviation, and not just about Europe! It also requires strong international coordination.

That is why it is important to start work immediately. The longer we delay, the greater the risk that the energy wall will exceed the industrial capacity of our countries.

It is the duty and the interest of air transport to be a driving force in this modernising of industrial policy.

APPENDIX I

IMPACT OF TICKET PRICE INCREASE RESULTING FROM THE INCREASE IN FUEL COSTS DUE TO THE INCORPORATION OF SAF.

Key findings from simulations

It is interesting to note that the estimated demand for carbon-free power is relatively insensitive to variations in the parameters tested (rate of SAF, rate of bio in SAF, distribution of classic bio / e-bio, cost of SAF, compensation, etc.).

This can be explained by a triple "shock absorber" effect:

- The impact of the increase in the cost of fuel on the cost of transport is mitigated by the fact that fuels represent only about 27% of the total cost. Consequently, a doubling of fuel costs leads to an increase in total costs limited to 27%, a tripling to an increase limited to 54%, etc.
- Negative traffic/price elasticity: around -0.75
- ~ 36% improvement in unit consumption (aircraft efficiency).

Key data and assumptions

1- Unit fuel consumption 2021 and 2050

- Unit consumption 2021: **3.21 l/100pkt** [39]

- Unit consumption 2050: 2.05 l/100 pkt
(Multiplication factor vs 2021: 0.638 after aircraft efficiency improvements)

2) Price of fossil Jet fuel including ETS (*prices in constant 2023 euros - net of inflation*)

	2021	2023 Q1	2050
Kerosene Vols extra-EU	0,56 €/l *(700€/t, source FNAM)*	0.65 €/l	**1 € /l** [40]
ETS Intra -EU flights (+UK+ CH dès 2024)	~40 €/t CO2, - of which 130 €/t kerosene **i.e., ~ 0,01 €/l kerosene** exemptions taken into account	100 €/t CO2, of which 315 €/t kerosene, i.e., 0,25 € /l kerosene (0% exemptions after 2026)	200 €/t CO2,[41] hence 630 €/t kerosene, i.e. 0,50€ /l kerosene
Total intra-EU flights	~0.57 €/l kerosene	0.9 €/l kerosene	**~1,50 €/l kerosene**

Given the 40/ 60 split of intra-EU/ extra EU flights, we will retain an average 2050 cost of kerosene of €1.20/l (40[42]%@1.50/l + 60%@€1.00/l) including cost of compensations.

3) 2021 carrier costs

-Total carrier cost 2021 **€7.00/100pkt**
(Public sources)

- Of which fuel cost 2021: 3.21 l/100pkt x €0.57/l = **€1.83/100pkt**
(i.e., 27% of total carrier costs)

4) Elasticity of fuel consumption/ticket price estimated by AAE = - 0.75

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[39] IATA
[40] Académie des Technologies February 2023 Report (based on decreasing energy efficiency index of E&P)
[41] AAE Assumption
[42] Eurocontrol

Impact on carrier costs and traffic assuming a 70% SAF incorporation rate

Impact on the net price of fuel used in 2050 (including offsets)

SAF 2050 Production cost *(Central value)*	**2,0 €/l**[43]
Vendor's profit margin (15%)[44]	**0,30 €/l**
ETS *intra-EU+UK+CH flights*	**0,04 €/l for 90% decarbonised SAF** [45]
ETD *(Energy tax)*	**Supposedly applicable to aviation at the reduced rate of sustainable energy**[46]
Total cost SAF 2050	2.34 €/l SAF intra -EU 2,30 €/l SAF extra EU **2,32 €/ l (Weighted average intra EU flights : 40%)**
SAF 2050 incorporation rate	70% (*RefuelEU mai 2023)*
Weighted average cost of fuel used 2050	**2,0 €/l** (70% SAF@ €2.32/l / 30% kerosene @ €1.20/l)

Impact of fuel price increases on carrier costs (70% SAF)

- Fuel unit cost of transporter 2050: 2.05l/100pktx2.0€/l = **4.10 €/100pkt**

- Carrier fuel cost increase 2021-2050[47]

4.10 € /100pkt - 1.83 €/100pkt **=** **2.27 €/100pkt**

- Total carrier cost increase in %

2.27 €/100pkt / 7.0 €/100pkt = **33%**

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[43] Académie des Technologies report - February 2023 - with decarbonised electricity costing €30-50/MWhh

[44] AAE assumption

[45] 10% net CO2 emissions vs. kerosene; taking into account the proportion of intra-EU flights and ETS assumption: €200/tonne CO2

[46] European Commission - Revision of the Energy Taxation Directive (ETD), Q&A, 14 July 2021

[47] Cf. previous page

Based on Traffic / price elasticity estimated at "- 0.75" *(source AAE)*

A 33% increase in ticket prices (70% SAF) would thus result in a 19% reduction in traffic (pkt).

Impact on carrier costs and traffic assuming a 100% SAF incorporation rate

Carrier fuel unit cost 2050

2,05 l/100pkt x 2,32 €/l = ***4,76 €/100pkt***

Increase in carrier fuel unit cost 2021-2050

4,76 €/100pkt– 1,83 €/100 pkt = ***2,93 €/ 100pkt,***

Percentage increase in carrier costs 2021-2050

2,93 €/100pkt / 7,00 €/100pkt = ***41%***

Impact in terms of reduced consumption (100% SAF)

A 41% increase in ticket prices (100% SAF) would result in a ***23%*** *reduction in traffic (pkt)***.**

APPENDIX II

SENSITIVITY TO "BIO- SAF-FOSSIL KEROSENE" MIX

assuming 100% e bios within bios mix

KEY ASSUMPTIONS TESTED				Power needs (TWh/an)	% vs society needs	EPR Equival	M ha biomass land	% vs Current Bio land used	CAPEX (G€)
Scenario	% SAF/ fossil fuel	% Bios vs total fuel	% SAF imported						
A	100%	20		925	16%	85	3 to 5	5-9%	1200
"B with NO BIOS"	70/30	0		800	13%	75	0	0	1000
B1	70 /30	20		625	11%	57	3 to 5	5-9%	800
B2	70 /30	35		525	9%	48	5 to 9	9-18 %	650
"B with NO BIOS «and with imports	70/30	0	33%	500	9%	45	00-janv	0	625
B1 with imports	70/30	20	33%	385	6,50%	35	3 to 5	5-9%	700
B2 with imp.	70/30	35	33%	285	5%	26	5 to 9	9-18 %	550

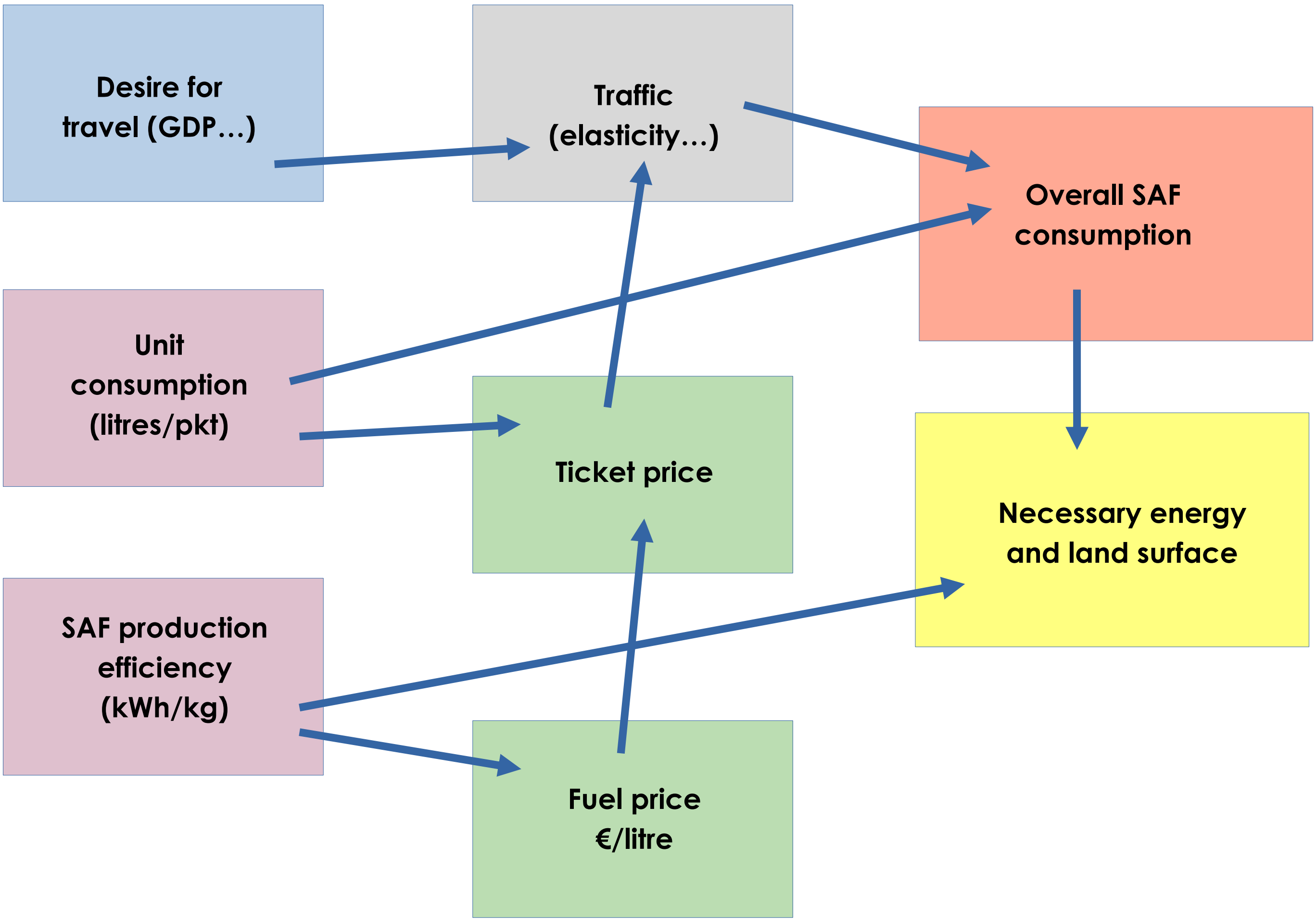
APPENDIX III

SENSITIVITY ANALYSIS TO E-BIOS % WITHIN BIOS MIX

KEY ASSUMPTIONS TESTED									
Scenario	% SAF/ fossil fuel	% Bios vs total fuel	% SAF imported	Power needs (TWh p.a)	% vs society needs	EPR Equival	M ha biomass land	% vs Current Bio land used	CAPEX (G€)
A	100%	20		825	15%	75	6 to 11	9 à 18	1000
B1	70 /30	20		525	9%	48	6 to 11	9 à 18	650
B2	70 /30	35		375	6%	34	10 to 19	16 à 32	475
B1 with imports	70/30	20	33%	275	5%	25	6 to 11	9 à 18	350
B2 with imports	70/30	35	33%	110	2%	10	10 to 19	16 à 32	150

APPENDIX IV

METHODOLOGY FOR ESTIMATING SAF AND INPUT NEEDS



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