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FOREWORD

Ten years after its Dossier No. 38 "Flying in 2050", and following the March 2021 conference "Air transport in crisis and the climate challenge: Towards new paradigms", which gave rise to its Opinion No. 13, the Air and Space Academy (AAE) is publishing this Opinion No. 20 "Decarbonising air transport", the fruit of two years' work by its "Energy and Environment" commission (C2E) comprising more than 60 participants, including 20 from outside AAE, from eight European countries, collectively at the highest scientific and technical level in the fields of climate, energy and aeronautics.

This opinion puts the spotlight on the essential components of the strategy to decarbonise air transport. Why this new publication, when AAE has already expressed its views on the subject several times and the topic is dealt with in a number of publications from a variety of sources? The main reasons are the extremely rapid rate of change of the general context of decarbonisation in the sector. The scale of the challenges to be met is increasingly apparent, and raises new questions. These challenges concern three areas:

Technology

Technological innovation will be a key condition for success; firstly, by taking full advantage of what already exists (fleet modernisation) and improving performance (aerodynamics, new configurations, reduced weight, etc.); then by developing the use of very low-emission fuels (SAF, Sustainable Aircraft Fuels), whose production processes are already familiar, but whose synthetic version will require a large quantity of decarbonised electricity, and will be more expensive than kerosene, at least in the initial period. Other types of propulsion are possible (electrification, hybridisation, hydrogen) but for limited aircraft sizes.

Both operational and technical optimisation of air navigation systems could also reduce air transport emissions by up to 5 % in Europe.

Once all these technological solutions have been implemented, any residual emissions will be able to be offset by CO_2 capture and storage (CCS).

In all these areas, a **general acceleration strategy** will need to be put in place: incentives to modernise fleets and use SAF, support for research, investment in SAF production and CCS techniques.

Energy

The main new contribution of this opinion is a detailed analysis of energy requirements in terms of SAF, based on new European regulations (ReFuelEU). It is not enough to possess the technological solution, we need to be able to implement it, i.e. to have a sufficient share of decarbonised electricity. We estimate air transport needs to be at least 11% of the total amount required to meet all the needs of the European Union (650 TWh versus 6,000 TWh). As for the investment needed to produce SAF, including electricity production, this is estimated to be at least € 40 billion a year for 25 years.

These figures are very high and demand reflection as to the policy to adopt. We cannot rule out a scenario involving a shortage of decarbonised electricity, which will raise the question of how to allocate this resource to the various sectors of activity. Airlines could be forced to increase their foreign supplies, a development they already seem to be anticipating. The political strategy of decarbonisation could thus become difficult to reconcile with the search for European energy independence.

The public authorities will therefore have to encourage the massive investment needed and/or raise the issue of regulation. Investors will need **regulatory stability** to give them greater visibility on future markets. Regulations should **take into account the respective technological decarbonisation capacities of the various economic sectors and therefore give priority to air transport**.

Sobriety and regulation

Uncertainties surrounding policies call for in-depth reflection on the societal changes affecting air travel in its international context.

The Covid crisis led to a change in attitudes, particularly within companies, with a noticeable drop in business travel. However, tourist travel has resumed its growth, and IATA (International Air Transport Association) is forecasting a record year in 2024. AAE believes that this is not just a cyclical phenomenon, and that air travel professionals must start thinking now about the air travel of tomorrow.

The temptation to impose regulatory constraints on traffic is a very real one. Whatever the arguments, such a policy applied unilaterally to international air transport would, in our view, have no chance of success, as illustrated in several past examples. Instead, European countries should implement cooperative strategies with third countries and join forces to support policy developments at ICAO (International Civil Aviation Organization) level.

Another idea sometimes advanced is that of artificially increasing costs by applying taxes, and thus exerting a downward pressure on traffic. In addition to its uncertain impact, this type of policy would, in our view, run counter to the policy of European and global liberalisation that has been pursued for over 30 years, which aimed to facilitate access to air transport for the less well-off.

In conclusion

This opinion raises many political questions, highlighting both the certainties, but also the uncertainties relating to the various possible courses of action. It attempts to provide some points of reference and to open up a debate that can only move forward with in-depth analysis of the different prospective scenarios. The Air and Space Academy will continue its analyses theme by theme, and is ready to contribute to any wide-ranging reflection. It is also currently publishing an in-depth dossier on the various themes raised here: Dossier No. 55, entitled "Decarbonising air transport by 2050: a question of energy".

Michel WACHENHEIM

President of the Air and Space Academy

SUMMARY

Air transport has played an important role in improving access and supporting the economic development of many countries and territories. It has driven an incredible expansion in relations between the peoples of the world. The combined effect of liberalisation and fuel and cost reductions has opened up access to long-distance travel for a large proportion of the population in developed countries, and this will continue in the rest of the world.

In the coming years, the European air transport sector aspires to be sustainable in the face of the climate challenge, and is aiming for carbon neutrality by 2050.

Decarbonising aviation requires: (a) a sharp reduction in aircraft fuel consumption; (b) the use of alternative fuels to kerosene[1] [2]; (c) carbon capture and storage to “neutralise” emissions from the remaining fossil kerosene; (d) sobriety.

a) The acceleration in the replacement of aircraft fleets by recent aircraft (average age 12 years) and the appearance of a new generation of aircraft around 2035 will provide successive gains of 30 % and 25 % respectively in fuel consumption per passenger-kilometre-transported (pkt). Given that medium- and long-haul flights of more than 1,500 km departing from Europe generate over 70 % of CO_2 emissions, it is on these flights that action must be taken as a priority.

b) Various SAF variants compatible with current aircraft are in the early stages of industrial production and will enable a safe transition thanks to their drop-in capability. SAF from bio-based sources

1 *These alternative fuels are called Sustainable Aviation Fuels (SAF). They are produced either from bio sources (bio-SAF), or from CO_2 and hydrogen... and a large amount of electricity (e-SAF/e-fuel).*

2 *For general aviation and short-haul aircraft with less than 100 seats, “all-electric” or “hybrid” or “hydrogen” alternatives seem interesting (see below).*

have many advantages, but the quantity available in Europe for aviation will amount to only 20 % of requirements[3]. *Consequently, the use of a large quantity of e-fuels is a necessary step, and will call for a great deal of decarbonised electricity*.

c) Measurable, certifiable carbon capture and storage operations will generate "negative emissions" that offset the emissions from the remaining use of fossil kerosene on a tonne-for-tonne basis.

d) The notion of sobriety in usage and behaviour will become more accepted, depending on the country, indeed this is already the case for business travel.

Hence the recommendations below:

Recommendation 1

Public authorities should introduce incentives to speed up fleet renewal.

Recommendation 2

Public authorities should give immediate priority to supporting the development of air transport using SAF.

Recommendation 3

The European airline industry and public authorities should encourage massive investment in SAF production, with a stable regulatory strategy and greater visibility as regards future demand.

Recommendation 4

European and national public authorities should arbitrate for access to biomass on the one hand, and to "sustainable" fuel imports on the other, in line with the social and economic value of aviation.

3 *This 20% figure is confirmed by a report by the French Académie des Technologies, June 2023: "La décarbonation du secteur aérien par la production de carburants durables" – https://shorturl.at/xGIKW*

Recommendation 5

Industry and public authorities should accelerate the deployment of CO_2 capture and storage needed to achieve carbon neutrality by 2050.

Recommendation 6

Economic and regulatory measures taken within a national or European framework will only be fully effective if they are accepted and applied by the rest of the world. To this end, they should be negotiated within the framework of existing international agreements (ICAO and bilateral agreements).

Recommendation 7

The European air transport sector should adapt its outlook, embracing a spirit of sobriety and "best use", whilst promoting the irreplaceable nature of travel.

What are the conditions for success?

- **Fleet renewal?** No major obstacle here: it is known to be in the best interests of the airlines. Any limit will be that of aircraft manufacturers' production rates.
- **Developing new aircraft?** Here too, market forces and fuel efficiency gains will be motivating factors for aircraft manufacturers and airlines. Among the various projects, the development of medium- and long-haul liquid hydrogen-powered aircraft raises doubts, as numerous technical, operational and commercial obstacles would have to be overcome, including the setting up of dedicated airport facilities around the world.
- **SAF production?** The adoption by the European Union (EU) of the ReFuelEU regulation, requiring greater incorporation of SAF by 2050, removes many uncertainties for investors. There are no major technical obstacles, but energy investment outside of aviation needs to move up a gear to avoid a potential shortage of low-carbon energy for society as a whole. This represents a huge industrial and economic challenge. Social obstacles will have to be overcome in order to accelerate the construction of facilities producing decarbonised electricity.

- **Carbon capture and storage?** Initiatives are underway for industries where this process is unavoidable, according to the IPCC (Intergovernmental Panel on Climate Change). The aviation sector should play a greater role.
- **Acceptance of a certain sobriety?** Aviation bashing is unfair, but open debate is to be welcomed: better, more reasoned uses should gradually be defined by all stakeholders.

A fundamental point

European air transport is not totally in control of its own destiny. It will rely on the supply of a sufficient quantity of decarbonised energy, i.e. a significant proportion of Europe's electricity. Yet the energy transition has barely begun: for EU society as a whole, the investment needed simply to produce enough low-carbon energy would amount to around €6,500 billion, or €250 billion a year until 2050. With 26 years to go, and given the time needed to set up such an industrial complex, this represents an investment programme unrivalled since post-war reconstruction.

Explanation

By 2050, European airports will be required to supply a minimum of 70 % SAF, i.e. ~ 28 million tonnes/year (order of magnitude).

This will call for more than 10 % of Europe's decarbonised electricity[4], i.e. around 650 TWh per year, a quantity equivalent to the total current electricity consumption of countries such as Germany and France.

The amount of decarbonised energy in 2050 is likely to be insufficient to meet the needs of society as a whole[5].

Hence a reflection that goes far beyond the aviation sector: both national and European "energy transition" plans seem to us to be very optimistic in terms of society's capacity to reduce its energy consumption and to invest. It would be a shame to miss out on such an opportunity to reindustrialise our regions and, in so doing, save € 100 billion a year in "sustainable" fuel imports.

4 *In fact, while road transport gains 50% energy by switching to electric power, synthetic kerosene doubles electrical energy requirements. The availability of sufficient quantities of carbon-free electricity is therefore key.*

5 *The United States, with its Inflation Reduction Act (IRA), has created a momentum commensurate with the challenge.*

Note

In this short executive summary, we make no recommendations concerning contrails and induced cirrus clouds, other than to continue research with a view to gaining a better understanding of the phenomenon and proposing measures to mitigate the effects in due course. We would point out that this effect, which is as difficult to measure as it is to model, is not cumulative and therefore cannot be directly added to the cumulative CO_2 emissions linked to combustion. The doubling of emissions often claimed today is a scientifically dubious shortcut. **Explanations are provided in the body of the document** (see § 4.1)**.**

A few orders of magnitude for air transport[6]

World air traffic (in 2019)

- **46.8 million flights** operated by 1,478 airlines.
- **8,680 billion** passenger-kilometres transported (pkt) and **57 million** tonnes of freight.
- **115 accidents**, including **6** fatal accidents causing **239 casualties**.

Number of jet aircraft

- **23,000 aircraft** in service consuming on average **3.4 l/100 pkt**.
- **6,500 aircraft** post 2017.
- **15,000 recent aircraft** on order (firm + options), consuming **2.5 l/100 pkt**.
- Production rates: **2,000 to 2,500 aircraft/year from 2025**.
- The emergence of **new types of aircraft in 2035** consuming **1.8 l/100 pkt**, i.e. almost half the average consumption recorded in 2019.

Kerosene consumption in 2019[7] [8]

- **290 Mt** (world) including 20 % for freight – **50 Mt** (from EU) including freight.
- Only 30 % of flights departing from Europe exceed 1,500 km, but these flights emit 75 % of the CO_2 attributable to European air traffic.

6 *ICAO "Presentation of 2019 Air Transport Statistical Results" – https://shorturl.at/hosU7*

7 *EASA EEA Eurocontrol "European Aviation Environmental Report 2022" – https://shorturl.at/bfqIU*

8 *FNAM "Feuille de route de décarbonation de l'aérien", March 2023 – https://shorturl.at/mtPZ5*

A few orders of magnitude for air transport (cont.)

CO_2 emissions

- **915 Mt** (World) – **156 Mt** (from EU).

Annual consumption in 2050 from the EU

- "Base case" based on a moderate increase in traffic from Europe and reductions in unit consumption.
- **40 Mt** of fuel, including **28 Mt of SAF (8 Mt bio-SAF + 20 Mt e-SAF) + 12 Mt** of kerosene (made neutral by capture/storage).

Electrical energy to produce SAF used by air transport in the EU

- Electrical energy to produce 1 kg of e-SAF: ~25 kWh.
- Electrical energy to produce 1 kg e-bio SAF: ~10 kWh.
- Electrical energy for the European aviation mix in 2050: **~650 TWh/year** (including 10 % to take account of the intermittent nature of renewable generation), **in addition to** other investments in decarbonised electricity in the EU, i.e. between **~11 %** and **~12 %** of a total of **~6,000 TWh/year** (see insert p.34).

Investment in air transport

- Production of SAF (EU) including the necessary energy: **~€ 1,000 bn**, i.e. **€ 40 bn/year** until 2050.

Estimated fuel costs in 2050

- Cost of producing 28 Mt of SAF: **~€ 70 bn/year**
- Cost of eliminating CO_2 for 12 Mt of kerosene: ~€ 10 bn[9]
- Cost of SAF in 2050: **around € 2/l** (today **€ 0.8/l**) with electricity at € 50/MWh.

9 *CCU (Carbon Capture and Utilization) should not be confused with CCS (Carbon Capture and Storage), DACS (Direct Air Capture and Storage) and CDR (Carbon Dioxide Removal). CO_2 captured on leaving the factory and reused (CCU) is not a genuine "negative emission". The others are!*

1- INTERNATIONAL AND ECONOMIC SPECIFICITIES OF AIR TRANSPORT

The raison d'être of air transport is to travel fast and far, so it is by its very nature an essentially international mode of transport. Its characteristics mean that it can only exist if it guarantees its customers a very high level of safety. It is easy to understand that for this to be the case, a high level of technical standardisation and interoperability is required. Meeting these requirements relies on agreements between States, which remain sovereign over their airspace and free to establish their own national regulations.

These requirements were perfectly identified even before the end of the Second World War, when the future development of civil air transport was anticipated by the Americans and Europeans. An international convention signed in Chicago on 7 December 1944:

- defined the operation of a unique international standardisation system in that it is open-ended and legally enforceable against Member States;
- adopted a set of rules by which States accept the use of their airspace by aircraft from other Member States and the operation of commercial traffic to or from these States, under certain conditions;
- created the International Civil Aviation Organization (ICAO), which is responsible for managing and developing this body of regulations and proposing changes to the policies concerned to the Member States.

ICAO is therefore an organisation of States and not a supranational agency. By signing the Chicago Convention, the 193 ICAO Member States have accepted its rules and undertake to comply with them.

1.1 Environment

In environmental terms, ICAO has had a policy of limiting noise pollution for over 50 years, has regulated local emissions since the 1980s, and has been developing a policy on CO_2 emissions for 20 years, in accordance with the mandate it received from the Kyoto Protocol (1997), which has not been called into question by the various COPs of the United Nations Framework Convention on Climate Change, including the Paris Agreement.

Its strategy is based on four pillars:

- technological innovation stimulated by a system of CO_2 emission standards and certification adopted in 2016;
- improving flight operations and infrastructure;
- the development of sustainable fuels (SAF);
- so-called "market-based" economic regulation measures, resulting in the adoption of the recently implemented CORSIA system.

So not only is air transport subject to internationally-agreed emissions limitation policies, it is also **the only economic sector organised in this way at global level**.

It is clear that in this context, unilateral measures incompatible with our international commitments cannot be taken without consultation and agreement with third countries. Several precedents have led Europe to abandon projects that were not accepted by the majority of states. We must therefore work diplomatically upstream, if we want to avoid a similar outcome, to convince our partners of the merits of our projects and forge alliances.

It should also be noted that emissions from domestic transport are fully covered by the Paris Agreement, and that intra-EU emissions can be handled by the 27 members of the EU. Two draft European regulations currently in progress are designed to contribute to the global objective of zero net emissions by 2050, adopted by the last ICAO assembly (see Chapter 2):

- from 2026, all intra-European aviation will be subject to the carbon market (Emissions Trading System – ETS). This measure will ensure that the emissions quotas set by the EU are met by all sectors concerned, including aviation;
- progressively, from 2025 to 2050, minimum levels of low-carbon fuel will be mandatory in the composition of aviation fuels (ReFuelEU). A minimum of 70 % SAF will be required by 2050 (including a minimum of 35 % synthetic fuels).

1.2 Air transport policy

In the past, air transport was entirely regulated by national governments, under bilateral diplomatic agreements. The market was dominated by the major international airlines. In Europe, the majority of airlines were state-owned. In the past 30 years, although the system is still governed by diplomatic agreements, liberalisation changed all that. The networks were reorganised around major hubs with coordinated schedules between feeder and long-haul routes, in order to optimise transits and increase the density of long-haul connections. This system, which still exists, has had the effect of lowering costs (economies of scale) and increasing the range of possible destinations. European airlines have been privatised and so-called "low-cost" airlines have emerged to boost new market segments. The number of routes served has increased considerably. Today, the intra-European air transport market is organised like a domestic one.

Air transport has thus become accessible to less well-off sections of the population, even in developing countries, where the process is ongoing. It is a factor for development in a great many countries, including some of the poorest ones, sometimes due to mass tourism. It would seem difficult to dial back this kind of development without raising social issues.

This is why we believe that cost-based regulation policies (including taxes) would only result in a regression to the previous model, especially as wealthy customers would be impervious to such increases. The most effective way out of the dilemma is to act first to reduce emissions, without hindering development where it is useful. The objective of reducing emissions does not automatically mean curbing traffic growth.

1.3 The need for in-depth, prospective analysis

Who can claim that similar major changes will not occur within the next thirty years? The question we should be brave enough to ask is: "*Should this liberalisation policy be called into question?*" This question does not only concern air transport: the very principles behind the policy of liberalising international trade could be challenged. But of course, no one wants to ask this question.

Estimating the volume of air traffic over the long term is a key factor in calculating trends in CO_2 emissions. Conventional econometric models do not adequately account for the impact of disruptions and structural changes. Only strategic foresight methods are suitable for constructing very long-term scenarios.

The Air and Space Academy believes that such a study is necessary to give meaning to the various predictions and to inform the strategic choices that need to be made now to achieve the 2050 objectives. Such a project requires significant resources, and above all considerable know-how, which needs to be clearly identified. AAE could contribute via the expertise of its members, as and when required. Obviously, the contribution of many other players would be required.

Opinion

- The legal and technical framework of the Chicago Convention requires a consideration of the international impact of local, European or national decarbonisation strategies, and a securing of their implementation diplomatically.
- Regulatory policies based on costs (including taxes) or supply would clearly run counter to the policy of European and global liberalisation that has been pursued for over 30 years, in addition to hampering carriers' investment capacity and hence the modernisation of their fleets.
- The period we are going through of multiple disruptions should encourage us to carry out in-depth strategic prospective analyses so that political decisions can be based on scenarios that take account of structural and societal changes.

2- THE FOUR LEVERS OF DECARBONISATION

In the coming years, air transport intends to become "sustainable" in the face of the climate challenge, and is therefore aiming for carbon neutrality by 2050.

The "levers" that will enable this decarbonisation will be:

a) energy efficiency in air transport;
b) sustainable fuels;
c) carbon capture and storage;
d) sobriety.

2.1 Energy efficiency in air transport

2.1.1 Accelerating fleet renewal

Recent aircraft (post-2017 generations) consume considerably less fuel per passenger kilometre than the average aircraft in service (2 to 2.5 litres/100 km compared with 3 to 3.5 litres/100 km, i.e. -30 %). The benefits are such that it is clearly in the interest of airlines themselves to anticipate replacements.

Of the 23,000 aircraft in daily use, around 6,500 are recent[10] (post 2017) and therefore 17,000 are candidates for replacement. Added to this are the aircraft purchased by airlines in emerging countries (India, South-East Asia and also Africa) which are expanding their fleets. To date, almost 15,000 firm orders + options have been placed. In fact, fleet renewal will be limited by the production capacity of the main aircraft manufacturers, even though they plan to manufacture around 2,000 to 2,500 aircraft a year from 2025 (plus potentially around

10 *A320neo, A350, A330neo, B787 and B737max.*

300 to 400 aircraft a year in China[11]). It will therefore take a dozen years for this gain to come fully into effect.

2.1.2 Launch of the next generation (entry into service 2035?)

Fuel consumption (jet fuel or SAF equivalent) is expected to be 25 to 30 % lower than for the 2017 generation (A320neo, A350).

Fuel consumption savings relate to:

a) aerodynamics, with very high aspect ratio or truss-braced wings, requiring innovation in structure design;

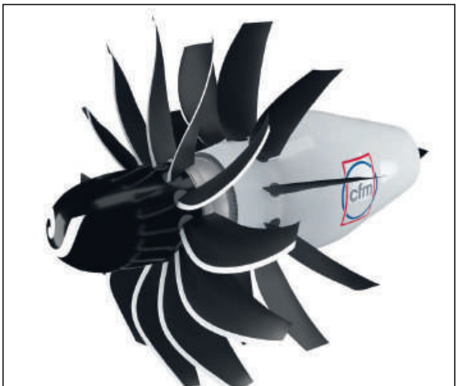
b) engines, with vastly improved bypass ratios thanks to open rotor concepts (CFM RISE open rotor) or huge variable-pitch fans (Rolls-Royce Ultrafan), which will require a rethink of the aircraft's overall geometry;

c) weight gains from multiple sources (additive manufacturing, etc.).

These savings relate to aircraft with "conventional" engines powered by SAF (neutral in CO_2 emissions).

It will take a dozen or so years to develop a formula that incorporates so many innovations: in the meantime, this timeframe should encourage fleet renewal, which will be achieved at the rate mentioned above.

All in all, this points to a reduction in fuel consumption **of more than 40 %**. However, we'll have to wait ten years or so after 2050 for the entire world fleet to have moved on from the (already excellent) 2017 generation!



Safran CFM RISE concept. © Safran

Airbus very high aspect ratio wing. © Airbus 2020

11 *COMAC C919 and its successors.*

Module loading and unloading test at Toulouse-Blagnac airport. © Universal Hydrogen

Pipistrel Velis Electro, the world's first certified all-electric aircraft of this type. © Pipistrel

2.1.3 Breakthrough solutions

At the same time, innovations currently being developed for short-haul, modest-capacity aircraft (light aircraft with a few seats, commuters with fewer than 20 seats and regional aircraft with 50 seats), using battery-powered electricity and/or hybridisation with internal combustion engines (SAF or hydrogen) or fuel cells, are silent, energy-efficient and reduce CO_2 emissions from infrastructures[12]; these represent new, direct competition for ground transport, even in developed countries. Some projects involve retrofitting regional aircraft with gaseous or liquid hydrogen propulsion, refuelled by a system of interchangeable capsules.

The low investment and operating costs of these "decarbonised" aircraft could lead to modal shifts in the opposite direction to the one some people are advocating today!

These aircraft will significantly reduce emissions for very short flights, although these only emit a very small proportion of aviation's CO_2 (less than 5 %).

2.1.4 Flying "differently"?

To reduce fuel consumption in air transport, two changes to air travel conditions have been suggested: reducing speed and cutting flight range, leading to a segmentation of long-haul flights, with one or two stopovers.
Reducing cruising speed can lead to a significant reduction in energy consumption only if it is combined with a change in the propulsion system: replacing jet engines with propellers. Significantly longer long-haul flights could have a negative impact on passengers.

12 *Short-haul flying and sustainable connectivity – prepared for ERA, ACI EUROPE, ASD Europe, CANSO, and A4E, 24 March 2022 – http ://www.oxera.com*

Adding two stopovers[13] to a 15,000 km flight would **reduce** fuel consumption by **up to a quarter**. The result would be an increase in the number of aircraft and an additional burden on airports.

Airlines could offer flights with stopovers with an "incentive": CO_2 savings in the short term, and economic gains later on...

2.1.5 What about hydrogen-powered aircraft?

For the same mission, a hydrogen-powered aircraft is bigger and, above all, heavier than a conventional aircraft. The greater the distance it has to cover, the greater the penalty in terms of fuel consumption. This is a minor consequence for short-haul aircraft, but it is already significant for medium-haul aircraft, and becomes prohibitive for long-haul aircraft.
While the use of hydrogen in propulsion systems does not seem too difficult, the storage of liquid hydrogen in tanks[14] and its transfer to the engine pose difficulties that are still far from being resolved. Major manufacturers could be in a position to give their opinion on the feasibility and economic relevance of hydrogen-powered aircraft within the next three to four years.
Faced with the challenges to be met to achieve satisfactory reliability, there is an issue of credibility with certain projects driven by start-ups lacking the experienced teams to carry out design and certification.

Producing, transporting, storing and refuelling liquid hydrogen at airports raises major challenges. **The ability to refuel aircraft with liquid hydrogen at a large number of airports will be a key factor in the decision, not least because of the major investment required and the strategic directions that the various players will take.**

Technological developments and trials on the ground and in the air can provide answers to the many points that need to be studied and can be useful in clarifying the long-term potential of liquid hydrogen fuel. **However, they must not divert attention, or funding, from decarbonisation solutions that are more robust and quicker to implement: notably reducing consumption and increasing availability of SAF.**

13 *But the route has to be suitable!*

14 *Cryogenic tanks must be large in volume, thermally insulated and of non-penalising mass.*

Once these difficulties have been overcome, the widely available SAF will have taken their place on the market, and **any "fleet mix" between hydrogen-powered aircraft and aircraft using sustainable fuels (drop-in SAF) would limit interoperability, complicate airline operations and duplicate investment**.

Liquid hydrogen's contribution to reducing CO_2 emissions will therefore remain modest in 2050, compared to technical and operational improvements and the use of Sustainable Aviation Fuels (SAF): biofuels and e-fuels, which are drop-in compatible.

Until the work in progress is completed, the prospect of liquid hydrogen as a fuel for aircraft engines appears very slim by 2050, and uncertain beyond that. However, unlikely R&T successes over the last few decades mean that we should never say never.

Assuming that R&D funding is not unlimited, the priority would seem to be to invest in developing new aircraft using SAF, and in the availability of these SAF, rather than in the development of hydrogen-powered aircraft and their airport infrastructure.

2.2 Sustainable fuels

The European Union has adopted the ReFuelEU Aviation regulation, which requires that a growing proportion of CO_2-neutral Sustainable Aviation Fuels (SAF) be used to replace kerosene (2 % by 2025, 20 % by 2030, 70 % by 2050).

It should be noted that although the obligation to use SAF does not exceed 70% for the time being in Europe, most airlines will probably strive to reach 100% whenever the fuel is available. If it is not, they will still have the option of exactly offsetting their CO_2 emissions (caused by the use of fossil kerosene) by certified capture of atmospheric CO_2, a subject discussed below.

What are SAFs?

1. Current biofuels[15] miscible with jet fuel reduce emissions by more than 90% when used in their pure state. Their use is planned in increasing proportions. Factories to produce them are up and running, with others

15 Including those resulting from the use of waste oils.

under construction. The resource is limited.

2. E-biofuels use all the carbon in the plant, with the addition of "green" hydrogen, and therefore require half the surface area of bio-cultures. The processes exist, but the transition from laboratory pilot to mass production still needs to be made.
3. E-fuels use "green" hydrogen (produced by electrolysis using decarbonised electricity) and CO_2 captured directly from the atmosphere. The process has been perfected, with a factory in Chile using it exclusively for automotive fuel. This is the most promising route, but it requires twice as much "green energy" in electrical form as is stored in the fuel produced.

2.2.1 Biofuels (bio-SAF)

These are practically the only ones currently in use. Their price is currently four times higher than Jet-A1, but is not prohibitive given the small quantities of blend, and should fall significantly as production increases.

They have been widely used in land transport (bio-diesel, etc.) for some time, with their oleaginous variants. A so-called second-generation version that uses the plant more fully (lignocellulosic) is gradu-

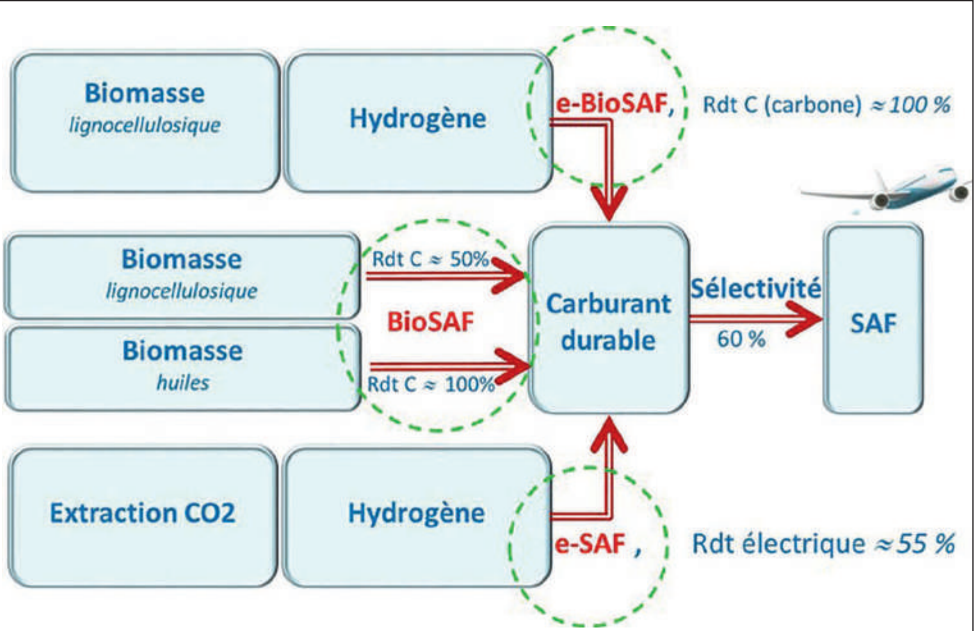


Figure 1 : The different production methods of SAF © Daniel Iracane / Académie des technologies

ally being developed. According to a study by the Académie des technologies[16], given the surface area of bio-cultures required for their production and competition with other user sectors, the volume available for aviation in Europe will barely reach **20 % of needs**[17]. The ReFuelEU objective is 35 %…

Do more? If bio-cultures are not enough, the (collected) agricultural and forestry waste which already supplies a growing number of methanisers could become more available. Since the transition from methane to liquid fuel is possible efficiently, this little-cited path deserves a second examination. But we should not expect miracles...:

- the “hand of the market” will not be enough. Political choices will have to be made, taking into account the lack of alternatives for air transport, to swing the use of this biomass away from applications (like road transport) that would be more energy efficient through direct electrification;
- there are still problems with the industrialisation of second-generation biofuels, which will delay their availability.

Therefore: One must not expect to obtain more than 20 % of biofuels for flights departing from Europe. On the other hand, this quantity must be secured through very long-term contracts.
However the route of waste and methanisers should be more fully explored.

2.2.2 E-biofuels (e-bioSAF)

This is a variant of biofuels that is “doped” with hydrogen, making fuller use of the carbon in plants but requiring external energy (10 kWh/kg). It would seem advisable in terms of land use to substitute e-biofuels for the biofuels mentioned above, since they require **two to three times less land**… on the other hand “low-carbon” energy is needed, and the proper investment must therefore have been made in it.

Therefore: The pressure for land occupation in Europe and the availability of “green” hydrogen should encourage the transition towards the development of e-biofuels.

16 Académie des Technologies, June 2023: “La décarbonation du secteur aérien par la production de carburant durable” – https://shorturl.at/qAQV7

17 This 20% comes from an assessment of the ratio of bioenergy that could be captured by aviation: 10%.

2.2.3 E-fuels (e-SAF)

For the **medium and long term**, it is essential to develop **e-fuels**, complementary alternatives to biofuels.

Completely synthetic, derived from carbon dioxide taken from the atmosphere and electrolytic hydrogen, they “only” require energy, but the 50-55 % efficiency between the energy required and the energy stored in the e-fuel leads, on the one hand, to a considerable demand for “green” electricity and, on the other, to a high cost of two to three euros per litre (for a cost per MWh of € 50). Now that the EU has decided that a minimum of 35 % incorporation will be required by 2050, the biggest difficulty today is ensuring a sufficient supply of green energy.

The manufacturing processes exist, but mass industrialisation has not yet begun.

2.2.4 Hydrogen as an input

Derived from electrolysis or other processes using “green” energy, hydrogen is present in e-fuel and e-biofuel plants. It is also used in land transport and in many industrial processes. So, as in other sectors, its availability for making e-fuels depends on the investment in energy that powers these plants.

All these fuels, with the possible exception of current biofuels[18]... will require considerable amounts of energy.

2.3 “Negative” emissions from carbon capture and storage

The energy cost of capturing and burying CO_2 from the atmosphere or from industrial sources is already lower than that of synthesising fuels, and still seems far from the minimum achievable[19]. Hopefully the economic cost, currently not very encouraging, will drop with massive industrialisation. This process, mentioned in the IPCC reports, has sufficient (geological) potential to play a complementary role, at least locally and/or temporarily, in decarbonisation, once it has reached the necessary level of maturity.

A pilot plant has been operating for two years in Iceland for the extraction of atmospheric CO_2 and another larger plant is under construction there, with others being built in the United States. CO_2 transport and storage processes appear to be at Technology Readiness

18 We don’t often talk about the carbon footprint of the crops dedicated to these biofuels!

19 Académie des Technologies, private communication.

Levels TRL 6 to 9, depending on the method used, and some are already being employed on a scale of millions of tonnes by the oil industry.

Other ways of creating "negative emissions" include one original method being tested on the Moroccan coast: seaweed cultivation with burial of dry seaweed. More traditional measures[20] involve reforestation, biochar[21], biomass recovery, rock mineralisation and weathering, etc.

Some players in the sector have begun advance purchases[22] of hundreds of thousands of tonnes of CO_2 sequestration to offset their aircraft emissions on a tonne-for-tonne basis.

Carbon capture and storage could therefore be a lever for "de-constraining" air travel. However, costs need to be cut, long-term storage sites confirmed and quantities estimated.

These CO_2 capture/storage techniques, which can be described as "negative emissions" to distinguish them from the less precise term "offsets" (sometimes assimilated to "green washing") are quite similar to the process of capturing atmospheric CO_2, using it to synthesise e-fuels, with the CO_2 then being re-emitted by engines, the whole process taking place within the "chain". These "negative emissions" will have to be measurable, verifiable and politically acceptable.

An additional 12 million tonnes of fossil kerosene could still have to be "neutralised" beyond the 70 % SAF required by ReFuelEU. The most promising avenue today, supported by the IPCC and increasingly "visible", is that of capturing and storing atmospheric CO_2.

Therefore: Support investment in carbon capture and storage facilities.

2.4 Sobriety

Sobriety, which has become a social issue in Europe, is a concept with varying contours that must be distinguished from energy efficiency, even if the two options are closely linked: the former relates to behaviour and uses, the latter to technical and operational solutions. The former is more complex and more controversial. But it seems unavoidable.

20 *"Elimination of atmospheric CO_2, Introduction to negative emission processes", 07/2022, CarbonGap, Mines Paris – https://shorturl.at/jGW14*

21 *Or "agrichar": soil amendment using a plant-based powder similar to charcoal.*

22 *In the United States, in particular.*

The most important thing is to do away with posturing and preconceptions on both sides. **Aviation bashing is unfair**; conversely, a technocratic refusal to question the energy voracity of contemporary societies, including aviation (in its rightful place, no more, no less), would be a dead end.

Sobriety can be voluntary, spontaneous, highly individual or, on the contrary, organised on a level of society as a whole or driven by the market.

Driven by the market? Perhaps **more** important than the price of fuel alone, the increased price of decarbonised energy compared to today's easy fossil fuels will have inevitable repercussions on consumption *in general*, and consequently in transport.

This represents a forced sobriety. Taxes on air travel would have the same effect. Anything seems to be on the table, even the proposal (which has actually been made) of an authoritarian rationing of air travel....

However, rather than focusing on mechanical or authoritarian levers, it is worth looking at a possible evolution in mentalities, given that this can also be accompanied by economic restraint. Encouraging the general public in the form of education, positive incentives, infrastructures, etc., is certainly a prerequisite for this.

It would be foolish to see habits we have become accustomed to, but which have only existed for one or two generations, as irreversible.

In fact, changes in patterns of behaviour often come faster than one might imagine, and are sometimes quite unexpected. To think that the enthusiasm shown for air travel by Europeans, especially young people, in the summer of 2023, puts an end to the debate once and for all, consigning the advocates of flight moderation to the dustbin of history, would be naive.

It is true that **long-distance tourism** (for which air travel has virtually no substitute) is an integral part of our global civilisation, despite the inequalities characterising it. Becoming familiar with other countries and other cultures, however superficially, is an essential part of our sense of belonging "to the planet". Without the ability to travel far and wide, environmental awareness might not be where it is today. You only feel concern for the planet when you leave your back garden!

However, the question of *what really matters*, this time from a societal point of view, cannot be avoided. Like all our actions, the decision to fly includes the superfluous and the pointless. European society must decide between the intemperance of its current mental models and a chosen sobriety, and air transport is part of that choice. Not by means of rationing, but rather through a gradual change in mentalities that is already visible.

This is the case for **business travel**, which is clearly not going to disappear entirely, but which does have an established substitute in the shape of teleconferencing that satisfies both company management and the employees concerned. In this case, the trend is not just European, but global.

It is clear, however, that for the time being, reflections around sobriety are taking place mainly in Europe. The United States is traversed by very diverse currents of thought, among which concern for the environment plays an important role. China is following its own path, with the most urgent priority being the fight against pollution. Asia in general and Africa are in a phase where air transport growth, seen as a condition for development, is being encouraged. **For Europe to act alone, without considering the rest of the world, would make no sense. Rather than seeing itself as the climate Messiah, it must be able to discern developments in other countries and act accordingly**.

In fact, aviation sobriety is not so much an additional lever for decarbonisation as a new framework, a socio-political environment whose contours we must try to anticipate. **It would be wise if the airline industry as a whole were to take this squarely on board**, as some of its players have already done, rather than focusing solely on achieving the highest possible growth.

Therefore: Like all economic activity, air transport is likely to move towards greater sobriety in both its professional and private uses (in Europe at least initially): given this perspective, it should actively contribute to redefining tomorrow's travel. This element should be considered in the foresight study of scenarios recommended above.

Adopting such an attitude can only help show that the same sincerity governs the decarbonisation actions to be undertaken and the call for the corresponding heavy investment.

3- THE QUESTION OF ENERGY

3.1 The needs of the aeronautics industry

3.1.1 What requirements in terms of aviation fuel and carbon-free electricity?[23]

Whatever the scenario, CO_2 emissions will remain directly proportional to two key factors: traffic – expressed in passengers x kilometres carried (pkt) – and average fuel consumption per pkt.
AAE has therefore focused on these two factors and built up a "base case" that corresponds to published assumptions and forecasts that seem most likely to us, with sensitivity studies including both upward and downward variations in these two parameters in order to identify the main trends in primary energy requirements.

3.1.2 How can we produce the quantities of SAF required by 2050?

According to this "base case", the European Union will need to supply around 40 million tonnes of fuel for flights taking off from its territory by 2050.

The ReFuelEU Aviation regulation stipulates that by 2050 the minimum incorporation rate for SAF should be 70 % *(the availability of biofuels for air transport, as seen above, should peak at around 20 % and not 35 % as stipulated by ReFuelEU, so e-fuels will be needed at a level of around 50 %)*.

23 Full details of the calculations and assumptions are available on the AAE website.

We show below that, unless there is a technological breakthrough in the production of green hydrogen that would replace water electrolysis by a less electro-intensive process, the pressure on the availability of decarbonised electricity will make it difficult to exceed this 70 % incorporation rate, without massive recourse to imports from countries with better conditions in terms of natural areas, climate and costs.

In the European Union, **a SAF-producing industrial sector would have to be built up**, supplying the EU with at least 70 % of the 40 million tonnes needed for flights taking off from its territory, i.e. 28 million tonnes/year... at competitive prices.

The base case and sensitivity analyses (*see note 21*) indicate that to produce these SAF (with the target of 70 % SAF in the fuel mix, the remaining 30 % being offset by carbon capture and storage) would likely require **~650 TWh/year** of decarbonised electricity, within a range of 450-900 TWh/year. These orders of magnitude correspond to **considerably more than the current total electricity consumption of major countries such as Germany and France**.

The scale of these requirements is explained by the fact that e-fuel production requires twice as much electricity as the energy it contains[24].

Massive availability of low-carbon electricity will therefore be key to decarbonising air transport.

We show in section 3.2 that **such requirements for decarbonised electricity would represent around 11 % of the total requirements for society, which are already difficult to meet**.

As a result, **fierce competition can be expected between users** for access to the low-carbon electricity resources available on the market.

Left to its own devices, the market would allocate the scarce resource of decarbonised electricity to the highest bidding sectors and users, which would be politically and socially difficult to accept.

Political trade-offs will be necessary **in which air transport, via its SAF supplier, will have to play an active role in any decisions on priorities in order to safeguard its supplies**.

24 *Land transport, on the other hand, can switch directly to electric engines, with immediate primary energy savings of over 50 % (because "direct" electricity avoids the low efficiency (30-40 %) of combustion engines), so there would be no point in favouring the use of synthetic fuels.*

3.1.3 What costs, what investment?

The cost of SAF will depend essentially (~80 %) on the cost of electricity. If we assume 50 €/MWh, the price of SAF in 2050 could be around 2 €/litre, i.e. ~ three times the price of fossil jet fuel in recent years, but less than twice the **currently forecast** price of fossil jet fuel in 2050, taking into account the cost of offsets and a likely change in the price of oil[25].

In the EU, investment in the production of electrical energy would be ~€ 800 billion in the base case, while investment in SAF production plants would be ~€ 200 billion. This means that for a production of ~28 million tonnes/year of SAF, the investment would be ~€ 1,000 billion in the base case, and between € 600 and € 1,200 billion depending on the scenario.

3.1.4 What impact will these additional costs have on traffic?

It is tricky to predict how fares will evolve, as air travel usage is already changing, starting with business travel. The numerous current forecasts rarely point to a decline in traffic, although a certain sobriety is often evoked.

Under current conditions, the average full cost of a passenger kilometre is around 7 centimes[26] . On **average**, fuel accounts for a third of this cost[27]. Consequently, if the cost of fuel were to triple (quadruple) and consumption per kilometre fell by 30 %, the cost per kilometre would increase by "only" 40 % (60 %). The impact of fuel costs on carriers' costs by 2050 is therefore subject to a strong "cushioning" effect, which reduces the impact of uncertainties about SAF costs.

It is likely that with increased production and advances in methods, the unit cost of SAF will fall. In addition, the economic model of air transport could evolve further, slightly reducing the impact of tariffs.

In any case, the impact on very long-haul flights[28], which generate the most emissions, would be in the region of € 1 to € 1.5/100km, i.e. € 120 to € 180 for a round trip between Europe and New York[29] .

25 *Due to the decline in the energy rate of return on exploration and production investments.*

26 *All airline business models combined (unit costs ranging from 4 to 12 cents).*

27 *Between 27 % for medium-haul and 40 % for long-haul, all airline business models combined.*

28 *The impact on short-haul flights is not expected to be significant, as the full cost remains close to or even lower than that of land transport.*

29 *So it is relatively marginal in terms of the total cost of a trip, hotel, etc.*

3.2 The availability of "green" energy outside of air transport[30]

From the perspective of decarbonisation, the needs of air transport are set against a backdrop of huge requirements for additional production of renewable/decarbonised energies for society's needs as a whole.
This observation is shared by France's electricity transmission system operator RTE[31], even though France is the most decarbonised country in the European Union thanks to nuclear power.

At the level of the EU as a whole, this will require the construction of "decarbonised" electricity production facilities supplying 5,000 to 6,000 TWh/year in 2050 (see insert below), **i.e. a doubling of the current total**, while replacing 60 % of the current fossil fuel energy mix with decarbonised production, in a way that is acceptable both in economic terms and by society as a whole.

A few broad figures concerning energy in the European Union

Total energy consumption in the EU today is 16,000 TWh/year, including 3,000 TWh/year in the form of electricity.
Reducing this by a quarter, as forecast in the Net Zero Emissions (NZE) scenario of the International Energy Agency (IEA), to around 12,000 TW/year, would be a major achievement.
By 2050, electricity consumption is expected to double from 3,000 TW/year (1,700 TW/year of which is already decarbonised) to 6,000 TW/year.
In order to supply these 6,000 TW/year of decarbonised electricity, 3,000 TW/year of additional renewable energy (wind, solar and nuclear) will need to be produced, and the current 1,300 TW/year of non-decarbonised electricity replaced with decarbonised electricity, i.e. a total of 4,300 TW/year of additional decarbonised electricity.
If we add the additional production capacity of around 1,100 TW/year needed to compensate the intermittent nature of solar and wind power, we arrive at a need to build a new decarbonised electricity production capacity of 5,400 TW/year, compared with the current 1,700 TW/year!

30 Detailed calculations are available on the AAE website.

31 As well as by the French Académie des Sciences and Académie des Technologies.

Assuming, **for the sake of illustration**, a 33/33/33 split between the different modes of generation, the European Union would need to build or rebuild **110 to 120 EPR units in around fifty power stations by 2050, plus ~1,100 offshore wind farms of the Saint Nazaire type (~80 km^2 each) plus ~12,000 km^2 of photovoltaic panels, i.e. thousands of 2 to 3 km^2 solar farms supplemented by a lot of solar energy scattered on roofs, car parks, etc**.

NB: *these figures are quoted only to give an idea of the scale of the* **effort**. *They are rightly impressive. Some would dismiss them out of hand as utopian. We have given them some thought and hope that solutions exist that are acceptable to the regions and the public. But this goes beyond air transport! It is up to the electricity producers to find and show the way to do this.*

The decarbonisation of society as a whole will therefore have to overcome considerable challenges:

3.2.1 Industrial challenges

Sites will be difficult to find for renewable generation units, and possibly for nuclear reactors.
The necessary qualified personnel and physical resources (including energy) will be hard to obtain to **build** such a large number of low-carbon electricity production units.

3.2.2 Financial challenges

The capital needed to finance the required investments will need to be found.
At a rate of 1.25 G€/TWh per year to build the facilities needed to produce the 5,000 to 6,000 TWh per year mentioned above, around 6,500 billion euros would have to be invested, or 250 billion euros per year until 2050. This energy project will absorb more than 10 % of the European Union's productive investment. *And not included here are all the ancillary costs of these installations: electricity grids to reinforce, network management in terms of quality and quantity, access roads, investment on the part of users...*

With 26 years left until 2050, and given the time it will take to set up such an industrial complex, **we are facing an investment programme unrivalled since post-war reconstruction**.
Such investments cannot be made by governments alone, already struggling to make ends meet. And the longer we wait, the higher the energy wall will rise... or the more it will retreat!

3.2.3 Societal challenges

- *Nuclear power:* The expansion of nuclear power could be restricted or slowed down in Europe by 2050 due to very strong reservations on the part of some sections of society, not just in Germany. The current revival of nuclear power in a number of countries is still suffering setbacks.
- *Renewable energies:* In theory, the potential for "green" energy (photovoltaic, wind and even hydraulic) is enormous. But capturing, transforming and concentrating this energy in economically and socially acceptable conditions comes up against yield limits, despite technological advances (offshore wind and photovoltaic...).
  Wind power has been criticised by society for its impact on the landscape, among other things, and this criticism has sometimes led to strong opposition in principle, especially in France... This indirectly feeds into cumbersome bureaucratic procedures for the installation of any wind farm, for which authorisation takes from 18 months to ... much longer!

  Offshore wind farms seem to pose less of a problem, as they have the added advantage of greater efficiency despite higher investment costs. However, they take up 40 km² to produce just 1 TWh/year (0.2 % of the consumption of a large EU country)...

  It remains to be seen as to whether these offshore windfarms can be multiplied (by an enormous coefficient) and whether they can all be located in "acceptable" maritime zones[32].

  Photovoltaic farms benefit from more leniency in principle, although this does not prevent an almost universal reluctance to locate them in one's own vicinity.

  In the long term, floating solar farms on the high seas could make a significant contribution.

  In addition to these industrial resources, distributed professional or individual photovoltaics and agrivoltaics have a number of advantages, and will feed into large-scale collective needs.

  In the case of both wind power and photovoltaics, if nuclear and hydro power were insufficiently developed to manage intermittent power generation, we would need to increase capacity (by 15 %?) to provide the storage capacity needed to cope.

32 *The consultations and authorisations for the offshore test wind turbine 16 km off the coast of Roussillon will have taken seven years.*

The NIMBY syndrome ("Not in my backyard") has grown stronger over the decades for absolutely every type of industrial project, and has a bright future ahead of it!

Given the scale of deployment of these new low-carbon electricity generation units, it seems clear that the authorities, and particularly the State, will have a central role to play in convincing and leading citizens towards the equivalent of a new "social contract".

But whatever the level of availability of decarbonised energy over time, the question of lifestyles in this new context is also acutely raised.

The efforts required of society as a whole to decarbonise by 2050, even without taking into account the needs of air transport, will therefore be very substantial.

Over and above the considerable financial effort required of industry, citizens will have to understand and accept that the price of maintaining our advanced societies is the proliferation in their environment of low-carbon, renewable and nuclear means of production. This will enable public authorities to take robust decisions in a climate of social calm.

Some European countries have little concern for energy independence and intend to import a large proportion of their decarbonised electricity. Others are discussing energy sovereignty and would like to dispense with the oil rent that is "weighing down" their balance of payments. Quite apart from the associated risks of geopolitical dependence, there is likely to be strong competition between countries for access to these resources.

3.3 What should air transport do to ensure its SAF supplies?

In the most likely case[33], the need for decarbonised electricity should be around 650 TWh/year, or ~11% of society's total production. This is a high figure, both in absolute terms and as a proportion of society's total needs.

The problem for air transport is not so much the relative importance of its needs compared with others as the fact that this ~11% represents a considerable quantity in **absolute terms, added to** a

33 *Our conclusions are invariable throughout the field covered by the sensitivity analyses (see details on the AAE website).*

huge mass of needs which we can see will be difficult to satisfy, not only financially but also physically and in terms of acceptance by society as a whole.

In our view, this point is essential if air transport is to structure and steer its action in the face of the general effort to decarbonise society as a whole.

Possible courses of action are suggested below.

In 2022, the United States, with its Inflation Reduction Act – which, incidentally, recognises the social interest of aviation – committed to "green" fuels by subsidising manufacturers through tax credits, so as to kick-start a virtuous cycle of production and consumption, **which can already be observed** (2023).

In Europe, it would appear that the air transport industry has an interest in being proactive:

- **Plan A: the preferred approach would be to encourage the creation of an industrial e-fuels and e-biofuels sector, and the development of the biofuels sector in the European Union.**

Contractual approach: air transport should move closer to SAF producers and other upstream industrial players, through Europe-wide coordination structures[34].
In order to guarantee access to sufficient quantities of biofuels, European airlines are already signing long-term supply contracts with distant suppliers, as they are unable to find any locally.
In terms of e-fuels: since no e-fuels industry yet exists, we need to start building it in Europe.

The higher price of e-fuels presupposes that the European institutions introduce measures, particularly tax measures and other transitional aids, to avoid distortions of competition with airlines from countries that have not adopted the same approach in terms of decarbonisation.

Like the PPAs[35] common in the energy sector, a contractual approach, with a chain of long-term supply contracts between airlines, refiner-chemists and electricity producers, should be used to speed up the creation of an e-fuels industry in Europe.

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34 *"The Renewable and Low Carbon Fuel Alliance" (RLCF), an EU-level initiative, is to launch a working group whose objectives are consistent with this recommendation.*

35 *PPA: Power Purchase Agreement.*

Now that the need for millions of tonnes of e-fuels and e-biofuels and TWh/year has been identified[36], airlines could, through the three major alliances, seek long-term supply agreements with aviation fuel producers.
In this way, these producers, assured of their outlets in terms of quantity and price, could launch investments in e-fuel production on the scale needed for 2050, after committing themselves in turn to electricity producers who would invest proportionally in the production of decarbonised electricity, thus constituting a chain of “generalised PPAs”.
Such an approach would also have the advantage of shifting a large part of the investment burden to an upstream sector with secure outlets.

Therefore: The European airline industry and public authorities should encourage massive investment in SAF production, in particular through a clear statement of air transport needs, a stable regulatory strategy and greater visibility of future demand; and encourage long-term contractual agreements between airlines, refiners and energy suppliers.

At the same time, it is to be hoped that, in the **face of competition from other users**, arbitration on biomass will recognise that aviation requires access commensurate with its irreplaceable economic and societal advantages, which need to be much better known, demonstrated and defended.

Even so, it is possible that a proportion of e-fuels will have to be imported, with the attendant risks of dependency. Here too, we need to plan ahead to ensure that aviation fuels find their rightful place, **especially as we can expect competition for access to the resource**.

Therefore: European and national public authorities will have to arbitrate for access to biomass and green fuel imports, in line with the social and economic usefulness of aviation.

Therefore: If such arbitration is to be favourable (via regulations? like the incorporation of biofuels into road fuels today?), political leaders and society as a whole must be much more convinced than they are today that this is justified by the economic and societal advantages procured by air transport.

36 *The RLCF (Renewable and Low-Carbon Fuels) Alliance is beginning to publish figures that are consistent with our own.*

The air transport industry must also act to encourage the development of alternative technologies for the production of green hydrogen, which would significantly reduce the amount of TWh needed of carbon-free electricity.

This could be achieved through active involvement, including financial support, in current and future research and development (plasmalysis and other forms of turquoise hydrogen, white hydrogen, etc.).

► **Plan B: if air transport cannot find enough decarbonised fuels in Europe, it will have to consider importing them on a massive scale.**

This approach would mean replacing geopolitical and economic dependency on imported hydrocarbons with a similar dependency on imported decarbonised energy, and still putting up with the oil rent that is "weighing down" the sector's balance of payments: (up to) 40 million tonnes at € 2.5 per kg, so **€ 100 billion a year**.

In any event, there will be **competition between users and between countries** for access to these imports.

4- THE NON-CO_2 IMPACT OF AIR TRANSPORT

Air transport's impact on the climate, and more generally its environmental impact, has four components:

- CO_2 emissions, chiefly from the combustion of fossil fuels, the main subject of this document;
- emissions of nitrogen oxides (known as "NOx") and traces of other gases;
- condensation trails (contrails) and induced cirrus clouds;
- other effects: noise, pollution, land use, accidents, etc.

As a reminder: CO_2, a greenhouse gas, is the main, most confirmed contributor of air transport to climate change. Air transport accounts for between 2.5 % and 3 % of global emissions of this gas.

Emissions of nitrogen oxides, unburnt fuel and traces of other combustion products are of a much lower order of magnitude. Their levels are continually being reduced by engine manufacturers, and therefore do not require the kind of effort that is needed to stop the accumulation of CO_2 in the environment.

Condensation trails (contrails) are caused by the passage of an aircraft through an area of very cold, over-saturated air.

Other environmental effects or "externalities" include accidents, air, noise and other pollution, environmental damage, etc. They have been identified for all means of transport in a study commissioned by the European Commission from CE Delft in 2019.

4.1 Contrails

The "non-CO_2 effects" of contrails and the cirrus clouds they induce result from the difference between a "parasol" effect and a "warming" effect. This difference is as difficult to measure as it is to model. Unlike CO_2, which accumulates in the atmosphere for decades, its effect is ephemeral (a few minutes to a few hours), non-cumulative[37] and therefore cannot be directly added to the accumulations of CO_2 linked to combustion. The doubling of emissions often claimed today is therefore a scientifically questionable shortcut.

A little physics

The contrails caused by aircraft passing through an area of very cold air at an altitude over-saturated with humidity have **complex but temporary** climatic effects. These contrails are mainly due to water vapour emission from fuel combustion by the engines, but also to carbonaceous micro-particles (unburnt combustion products) which trigger the formation of micro-crystals of ice which either reabsorb very quickly (ephemeral contrails with no significant impact), or propagate this effect to form high-level clouds (cirrus clouds) of varying sizes and durations[38].

These clouds are similar in appearance to the natural cirrus clouds (of various types) which cover more than 20 % of the Earth's surface and which have a complex effect on the climate: they block (during the day) part of the sun's rays, creating a cooling effect known as a "parasol", but they also block (during the day and night) some of the infra-red (thermal) rays which rise towards space, creating an additional "greenhouse" effect.
These two antagonistic effects are of the order of tens of watts per square metre each, for natural cirrus clouds, but it is their difference of the order of two or three watts per square metre that counts!

Measuring this difference is difficult, and estimating it via calculation is just as tricky. Most researchers attribute a "warming" effect to contrails, with the greenhouse effect outweighing the albedo effect[39]. Radiation measurements from the ground or by satellites,

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37 *Although the calories absorbed by the Earth during the life of a cirrus cloud do not disappear instantly... As for the accumulated CO_2, it will permanently warm the planet for decades or even longer...*

38 *Using hydrogen as a fuel would increase the amount of water vapour but reduce unburnt carbon to zero. We do not yet know what would happen to these contrails.*

39 *Albedo: reflective proxy for solar radiation, maximum for fresh snow, minimum for matt black paint, ocean or forest. The effect of contrails is partly an albedo effect.*

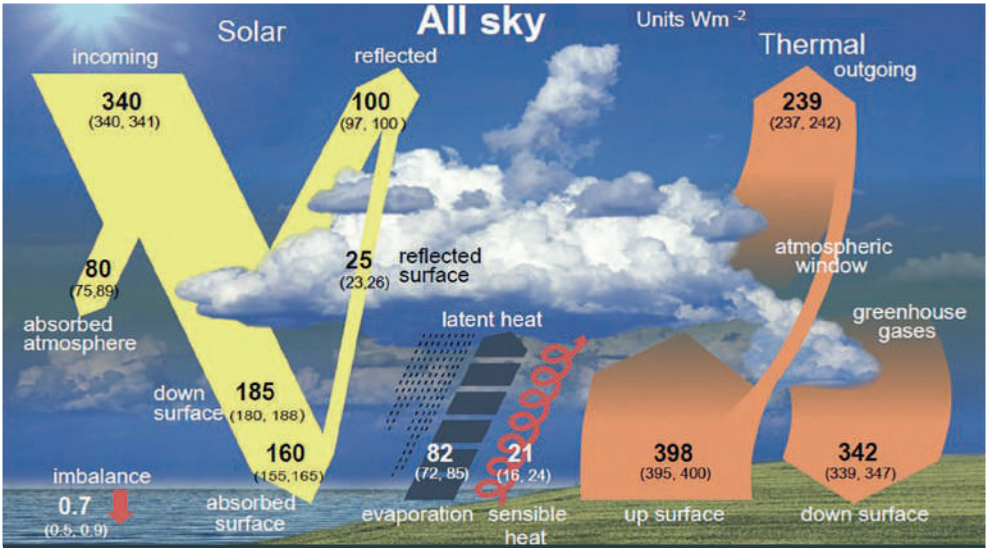

Figure 2 : Overview of global energy exchanges © IPCC

as well as *in situ* samples taken during airborne measurement campaigns, are used to cross-check calculations, but to go any further we would need a huge amount of data on the dimensions and shapes of ice microcrystals, which are highly varied and difficult to obtain. What is more, these effects depend on latitude, ground albedo, the presence of other cloud layers, etc.

Cirrus clouds induced by contrails (0.1 % of the Earth's surface) would have an effect similar to that of natural cirrus clouds, with the same signs, 40 times weaker overall (~50 mW/m² instead of around 2 W/m²)... but locally five times more "effective" given the surface area concerned.

The studies compiled by the IPCC give a wide range of results, from a very small effect to an effect double or triple that of aeronautical CO_2... Some rather reassuring clues were gathered during the virtual suspension of flights during the Covid period (four important references in the note below[40]). The general trend is towards a reduction in the impact.

40 ***See Schumann (February 2021)*** *"Aviation signals become discernible in the observed differences of these data between 2019 and 2020"; **Gettelmann (March 2021)** "no significant annual averaged ERF from contrail changes in 2020; **Digby (September 2021)** "our analysis suggests that its warming effect from cirrus changes may be smaller than previously estimated"; **Qaas (+ Boucher, March 2021)** "The change in cirrus translates to a global radiative forcing of 61 ± 39 mW m-2. This estimate is somewhat smaller than previous assessments".*

But direct measurements are still lacking, although a method for obtaining them was proposed as early as 1984[41]. We are tracking a few tens of milliwatts/m² in a climate system, as shown above in the IPCC "All sky" figure, where the uncertainties on the main terms are as high as ten watts!

Research on this subject has been active for more than twenty years, including, recently, research into the remedies that should be applied if the "greenhouse" effect clearly outweighs the "parasol" effect. For example, it may be possible to avoid contrail zones using extremely accurate **real-time** weather forecasting[42]… but doing so a priori could be counterproductive if the total effect is small and if avoidance leads to over-consumption and therefore over-emission of CO_2.

We could also imagine deliberately triggering contrails where they have a cooling effect! Another avenue is also being explored: "SAF" fuels that are low in aromatic compounds seem to generate 80 % fewer contrails than conventional kerosene. We can therefore hope

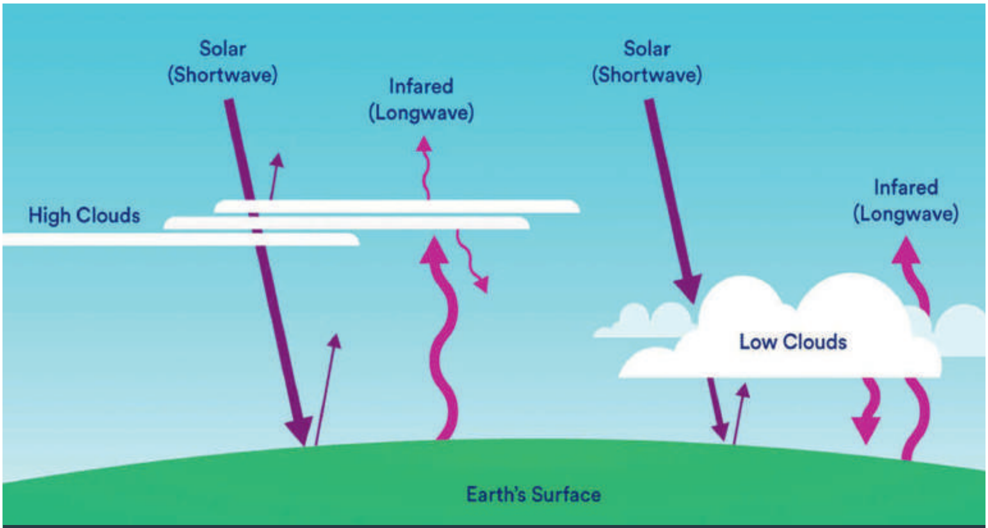

Figure 3 : Cirrus clouds and low clouds. © Clean Air Task Force

41 *Anne-Marie Mainguy (1984). Proposal of a principle for absolute measurement of the radiation budget based on spatial accelerometry. Demonstration of its feasibility using the results of the experiment. Castor/Cactus. Thesis, University of Paris VI.*

42 *This is because these pockets of moisture-saturated air change and move.*

that within ten years or so, this ephemeral effect will have all but disappeared.

A recent document co-authored by David Lee, one of the most respected researchers on contrails, is in line with our findings, i.e. a certain over-evaluation of their effects[43]. Another renowned specialist, Bernd Kaercher, was a member of the AAE commission which produced this report: he urges caution until more precise experimental results are available.

With regard to the metrics used: most publications present the non-CO_2 effects of air transport in "CO_2 equivalent", unhesitatingly taking the value adopted by the IPCC within its wide range of uncertainty[44] and roughly doubling and sometimes tripling the CO_2 effect of flights. **This combines cumulative effects with others that are not**. Without launching into major calculations, it is easy to illustrate the strangeness of the method: let's imagine that next year traffic drops by 10 % everywhere in the world with the same aircraft. There will be 10 % less climate impact from the contrails, but the CO_2 will continue to accumulate in the atmosphere, only a little more slowly! Decrease in one, growth in the other!

Therefore: To legislate on contrails at the current level of knowledge seems to us to be irrational and inconsistent with the way in which all other anthropogenic sources with similar effects, apart from CO_2, are dealt with, such as the change in albedo of territories accompanying a change in use and/or the artificialisation of land.

We should encourage scientists to use measurements to refine their models. If the amplitude of this effect is confirmed, there would seem to be robust ways of preventing the formation of these cirrus clouds (or even provoking them where their effect is cooling).

4.2 Other effects on the environment

These were identified for all modes of transport in a study commissioned by the European Commission from the CE Delft consultancy firm in 2019: "*Sustainable Transport Infrastructure Charging and Internalisation of Transport Externalities*". A cost is assigned to each "externality" (accidents, air pollution, climate impact,

43 *Keith P. Shine & David S. Lee, "Contrails Avoidance Challenges", 7 Nov 2023: "*Understanding of contrail climate effects is evolving; we are not confident that they are the biggest current contributor to aviation-induced climate change*".*

44 *50 milliwatts/m² in a distribution of calculated values from 20 to 150 mW/m².*

pollution, noise, environmental damage, etc.). Per passenger x kilometre, because of the very low proportion of its infrastructure, aviation ranks remarkably well. And without even taking infrastructure into account, excluding CO_2, aviation would still be the leading mode of transport.

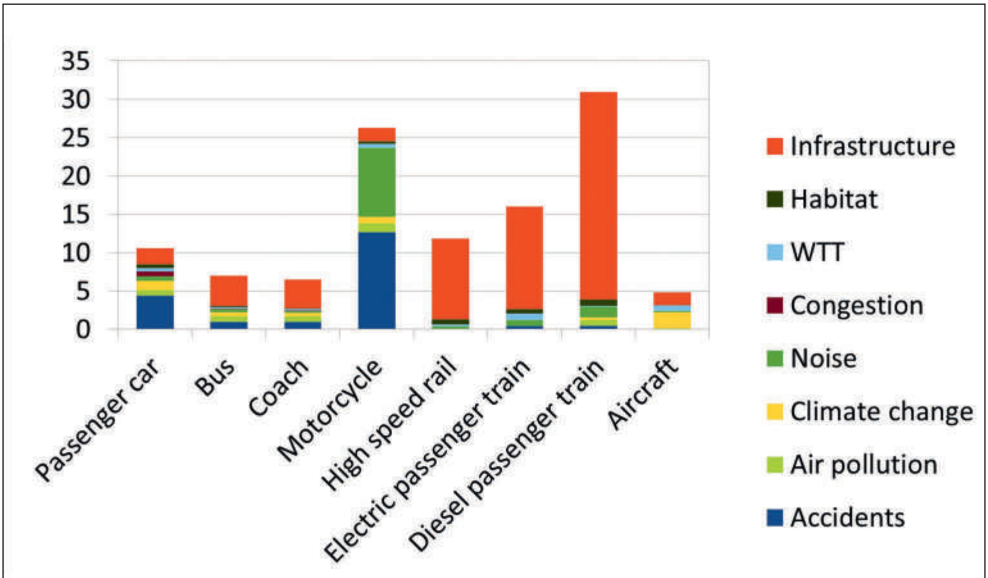

Figure 4 : Diagram taken from the detailed data in the above-mentioned CE Delft report (Annex D, Final Total Average Cross Modal Comparisons).

NB : "climate change" means ~ scope 1 emissions, not Life cycle analysis of the effects. Costs cent-€/pkt. Average External & Infra costs Road & Rail for EU28, aviation for selected 33 airports (WTT : Well to tank). © CE Delft, May 2019

The accumulation of CO_2 in the atmosphere is THE problem that needs to be tackled without delay. As far as non-CO_2 effects are concerned, we need to:

1) Continue work on contrails and, if necessary, legislate only in a way that is consistent with the appropriate metric.
2) If it turns out that contrails have a significant effect on the climate, implement the proposed reduction procedures: use of new SAF fuels and, if necessary, with a minimum of extra consumption, practical trajectories to avoid atmospheric zones conducive to these phenomena.

5- CONCLUSION

This analysis shows that air transport, which is the only solution for long-distance travel and is also highly recommended for a wide range of short journeys because of its low environmental "externalities", can technically be "decarbonised" but risks running into a shortage of low-carbon energy, like much of society. Aircraft efficiency and some sobriety of usage will reduce this shortfall.

A huge amount of European investment is needed in energy production between now and 2050 (€ 250 billion per year), of which around 10 % will be for aviation. Failing that, sustainable fuel will have to be imported at a cost of almost € 100 billion a year.

A heavy industry has to be set up in a short space of time! Are we ready?

This investment will also have to contend with local and political opposition if awareness of the climate challenge is not raised in society as a whole. Dark scenarios are looming if decarbonised energy is too scarce. The issue goes far beyond air transport, which could be compared to "the canary in the coal mine".

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