NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE

For a reasoned, chosen, and shared progress

Decarbonisation of the aviation sector through the production of sustainable fuels

Report by the Academy

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REPORT BY THE NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE

DECARBONISATION OF THE AVIATION SECTOR THROUGH THE PRODUCTION OF SUSTAINABLE FUELS

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Académie des technologies
Le Ponant — Bâtiment A
19, rue Leblanc
75015 PARIS
+33(0)1 53 85 44 44

secretariat@academie-technologies.fr
www.academie-technologies.fr

Front page : KARSTEN@ADOBE STOCK

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NOTICE

This document is part of a series of studies and publications by the National Academy of Technologies of France on the subject of biofuels, in particular, the report published in 2015 entitled “Quel avenir pour les biocarburants aéronautiques ?”, the result of a joint study with the French Air and Space Academy.

The present paper discusses sustainable and substitutable fuels without the need for major infrastructure changes, with hydrogen as a key intermediate in the production processes of these fuels. More generally, the role of hydrogen in a decarbonised economy has been examined by the National Academy of Technologies of France (report "The Role of Hydrogen in a Decarbonised Economy" published in 2021) and has recently been addressed in a joint study with the Chinese Academy of Engineering (2022): "Hydrogen, fundamentals, and strategies in China and France/Europe for decarbonising the economy".

SUMMARY

In October 2021, the Energy Division of the National Academy of Technologies of France launched a study on the decarbonisation of aviation, and more specifically on the large-scale production of sustainable fuels.

The relative share of greenhouse gas (GHG) emissions from the aviation sector has been growing steadily for the past 30 years, despite significant improvements in technological performance. There are a limited number of options for the aviation sector to decarbonise its operations. Sustainable Aviation Fuels (SAF) is the measure that will contribute the most for decarbonising aviation, while its compatibility with existing infrastructure facilitates its penetration.

The next ten years are decisive for setting up a realistic industrial trajectory to ensure the effective availability of SAF, on the scale needed and with the right momentum. The concrete implementation of this trajectory from the beginning of the next decade will be critical for the achievement of the decarbonisation objectives by 2050, as set by the players in the aviation sector and soon to be imposed by the European directive currently being debated on the subject.

The scope of the study is therefore to examine the first steps of an energy and industrial policy that will enable the production of SAF on the scale needed in the next decade.

The production of SAF requires the harnessing of a considerable amount of biomass and low-carbon electricity. Given the limited availability of biomass, the growing need for SAF will be met by synthetic jet fuel production in the first half of the next decade. The critical resource then becomes low-carbon electricity.

Because of its already decarbonised electricity mix, France is one of the few countries that can consider rapidly deploying an industrial SAF production chain on its territory, and this beyond the limits imposed by the availability of biomass. Without requiring a major discontinuity in the evolution of its mix, France will be able to meet its SAF needs until 2040, with, however, a significant increase in electricity generating capacity beyond that time frame.

The associated production costs, at technological maturity, could be close to €2500 per tonne of synthetic jet fuel, i.e. a carbon abatement cost of around €300 per tonne of CO_2.

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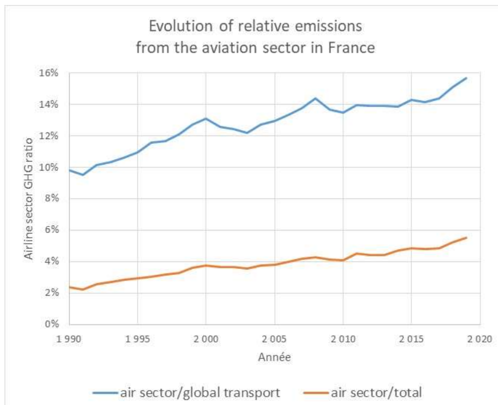
INTRODUCTION

The relative share of greenhouse gas (GHG) emissions from the aviation sector has been growing steadily for the past 30 years, despite significant improvements in technological performance. Today, global GHG emissions from civil aviation account for 3.1% of global energy-related emissions[A] and could double by 2050 if no concrete efforts are undertaken. The effects of air transport other than CO_2 could increase the climate impact of the aviation sector, but more research is needed to determine more precisely in which way and by how much[1]. The growing share of the aviation sector in greenhouse gas emissions is evident in France:



In France[2], the aviation sector's share of national emissions has doubled in 25 years.

There are a limited number of options for the aviation sector to decarbonise its operations. Sustainable Aviation Fuels, hereafter referred to as SAF, is the measure that will contribute most to the decarbonisation of aviation; its compatibility with existing infrastructures is an important factor in facilitating its uptake.

Given its growth projections, the aviation sector must implement decarbonisation measures to avoid 21 $GtCO_2$ in the period 2021-2050. The cost of this considerable effort is estimated at $1550 billion. These figures[3] illustrate the scale of the challenge and the urgency of the measures to be taken.

The next ten years are decisive for establishing a realistic industrial trajectory ensuring the effective availability of SAF, on the scale needed and with the right momentum. The implementation of this trajectory from the beginning of the next decade will be critical for the 2050 decarbonisation objectives, as adopted by the aviation industry and soon to be imposed by the European ReFuelEU[4]directive currently being debated on the subject.

The purpose of the study is to examine the first steps of an energy and industrial policy that will enable the production of SAF on the scale needed in the next decade.

This document extends the report[5] "Quel avenir pour les biocarburants aéronautiques ?" published by the Académie des Technologies in 2015, which outlined the technical characteristics associated with the use of biofuels and the different production branches; these

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[A] Based on International Energy Agency data, the aviation sector produced 1.3 Gt of CO_2 in 2019, or 3.1% of the 33.4 Gt of CO_2 emitted by energy consumption. This ratio does not include the CO_2 emitted in the life cycle of the fuel (production, transport, ...) nor the non-CO_2 effects of aviation.

factual elements are not repeated in this report. The issues identified in the 2015 report remain at the heart of the problem of decarbonising the aviation sector: the problem of mass production to meet demand in a context of proliferation of biofuel branches and pathways, mastering the effective environmental gain of biofuels, predictability of prices and volumes of biomass that can be made available for aviation in the face of intersectoral competition, the role of public authorities in national arbitration and in international convergence. In addition, the following analysis has an in-depth look at the central issue of the low-carbon electricity needed to produce SAF, particularly in relation to the specific situation in France.

Chapter 1 illustrates the variety of processes and associated inputs (biomass, waste, atmospheric CO_2, low carbon electricity) that exist on an industrial or pre-industrial scale.

Chapter 2 specifies the trajectory of SAF requirements at global, European, and French levels. It sets out the orders of magnitude of the problem and the associated time scales, as reflected in recent commitments by the aviation sector or in emerging European regulations. Given the urgency of action in the face of a dwindling carbon budget, these orders of magnitude make it necessary to examine the establishment of industrial sectors enabling the massive production of SAF from the beginning of the next decade.

Biomass is the primary resource used for SAF production. Chapter 3 analyses the availability of this biomass and identifies the limits of associated SAF production.

These limits are at a low level and the relay for growth will have to be taken quickly by technologies that harness large volumes of electricity for the production of SAF, either by adding hydrogen to biomass or as a synthetic fuel. Chapter 4 quantifies the electricity consumption associated with these technologies and consolidates the resources needed to satisfy SAF production in France over the next decade.

Chapter 5 shows that France, thanks to its decarbonised electricity, is in a unique position to consider the deployment of an industrial sector at the scale of requirements as early as the next decade.

Fuel accounts for 30% of aviation operating costs and many projections indicate a three to ten ratio between the price of sustainable fuels and fossil fuels. The technical analysis of the processes used, and the associated inputs will allow this cost range and the associated assumptions to be more narrowly specified in Chapter 6. The resulting CO_2 abatement cost attests to the validity of the SAF strategy.

The following synthesis summarises the main findings of the paper.

TECHNICAL SUMMARY

The need for sustainable fuels for decarbonising the aviation sector is a worldwide and European issue. The production of these sustainable fuels relies on resources whose quantitative and economic characteristics are, however, local. Therefore, the adequacy of needs and resources will be analysed in the French context only.

> **The decarbonisation of aviation requires the establishment of a large-scale industrial sector and will have to harness considerable and rapidly growing low-carbon energy resources.**

Today, the aviation sector is responsible for 3.1% of global greenhouse gas (GHG) emissions, a percentage that could double by 2050. The complete decarbonisation of the sector by 2050 is a stated objective of both airlines and manufacturers. Technological improvements and optimising procedures will contribute to this decarbonisation, but the main measure (60% of the objective) will be based on the use of low-carbon fuels, known as "SAF" for "*Sustainable Aviation Fuel*".

While facilitating its adoption by using existing infrastructures, the substitution of fossil jet fuel by SAF raises considerable economic, industrial, and energy challenges. These challenges need to be analysed in order to determine the best path towards the objective of limiting carbon emissions from the aviation sector. The non-CO_2 effects of aviation on the climate are still under active research and will not be detailed here.

The first challenge directly engages the physical feasibility of the objective of achieving decarbonisation of aviation through SAF and concerns the availability of significant quantities of bioenergy and/or low-carbon electricity. The aviation sector anticipates a global need for SAF in the order of 400 Mt (4800 TWh) per year by 2050. As an illustration, meeting the energy requirements for SAF, with an efficiency of 35%, would use the equivalent of half of all the electrical energy produced in the world each year (27000 TWh).

Importing these primary resources, by one energy vector or another, cannot be considered as an exclusive solution to the global problem unless it reproduces energy dependency patterns that carry a great deal of uncertainty in a world where all countries share the same challenges of decarbonised energy and competition for bioenergy and low carbon electricity. The analysis will therefore focus on the design of policies to enable domestic production of SAF.

Such a need for SAF responds to a growth in the air transport sector of around 3.1% per year, driven mainly by emerging economies, i.e. a doubling of traffic between 2020 and 2050. However, fuel consumption would only increase by a factor of 1.3 due to efficiency measures in propulsion and operations management. In the following, fuel consumption for Europe and France will be considered stable at 50 Mt/year and 10 Mt/year respectively.

Based on both aviation sector forecasts and the emerging EU ReFuelEU directive for sustainable air transport, the targets, in order of magnitude, for SAF production are as follows:

Besoin en SAF	2030	2035	2040	2050
Monde	20 Mt	70 Mt	185 Mt	400 Mt
Europe	2.5 Mt	10 Mt	16 Mt	30 Mt
France	0.5 Mt	2 Mt	3 Mt	6 Mt

Table 1: SAF demands arising from the stated objectives of the aviation sector and, for Europe, the Commission's regulatory proposals.

The scale and acceleration of the change illustrated by this table make it necessary to reason in orders of magnitude and put into perspective the uncertainties that weigh on the trajectory of demand. Such a trajectory also implies a large-scale effort to establish the first level of significant industrial production at the beginning of the next decade.

The use of biomass allows the efficient start of the growth trajectory of SAF. However, competition between the uses of biomass leads to policy arbitrations that will be complex and possibly shifting as knowledge and perceptions evolve.

The building blocks of SAF are carbon and hydrogen, which can be efficiently supplied by biomass. However, the harnessing of biomass raises several critical issues:

- Its overall impact depends on the nature of the biomass considered and the processes implemented (direct carbon footprint, land use changes, etc.). In Europe, first-generation biofuels are gradually being banned in order to avoid competition with food. SAF will have to be produced essentially from lignocellulosic biomass, used cooking oils, and urban waste.
- The corresponding resources are large but physically limited. Estimates for the bioenergy that will be available in 2050 vary by a factor of 1 to 2 for the coming decades. Academic studies, however, converge on the stability of this bioenergy and this is the assumption that will be retained here.
- Finally, biomass resources are subject to strong competition in terms of use with the historical sectors (construction or furniture wood, energy wood, biogas) and between sectors of the economy that must meet the same decarbonisation requirements (industry, air and non-air transport). This competition will require complex social and economic choices. This reality sets the dimensions and brings important structural uncertainties on the quantity of biomass that will ultimately be allocated to aviation.

Biofuel production is traditionally based on the oleochemical route and the so-called ATJ (Alcohol To Jet) route:

- The volumes of SAF currently available are mainly derived from the production of biodiesel for road transport. The inputs here are used cooking oils and animal fats that cannot be used in the food chain, in accordance with the European directive on renewable energy. The oleochemical processes used are mature and efficient. Oleochemical SAF volumes currently represent less than 1% of biodiesel produced; this could rise to 50% if incentive policies shift the market from road transport (assumed to be electrifying) to air transport. Oleochemical SAF could then represent 3% to 5% of the 2050 fuel requirement worldwide, 2 Mt/year (4%) for Europe and 0.25 Mt/year (2.5%) for France. The allocation of half of the oleochemical resources to aviation in 2050 is, however, a major societal choice between the economic sectors linked to air, sea, and road transport.
- The so-called ATJ (Alcohol to Jet) route converts biomass into alcohol by fermentation, and then the alcohol into fuel. However, the gradual abandonment of first-generation

fuels in Europe will limit the volume of production associated with this route. In Europe, the input will thus have to be lignocellulosic material, which adds a costly step of transforming cellulose into glucose. In the US, the ATJ route will remain important and grow rapidly in a different regulatory context.

The oleochemical and ATJ routes are therefore likely to be limited in scope in the European context. Other SAF production routes must therefore be harnessed to ensure that the growth resulting from the objectives is achieved. These are, on the one hand, the transformation of biomass by the thermochemical route and, on the other, the production of synthetic fuels.

The thermochemical route offers flexibility in terms of inputs by accepting different types of lignocellulosic material, and even urban waste. The efficiency of converting bioenergy into biofuel is around 50%. The addition of hydrogen can increase this yield to values close to 100%. Since biomass is a precious and coveted resource, it is strategically important to systematically combine the addition of hydrogen with the thermochemical route. This is known as e-bioSAF, as the hydrogen comes from both biomass and water electrolysis.

According to the SNBC (French National Low-Carbon Strategy) corrected by the latest analyses of *France Stratégie*, France could have access to 30 Mtoe of bioenergy (or 67 Mt of dry biomass). In its impact assessment in support of the ReFuelEU directive on sustainable aviation, the European Commission assumes that 10% of available bioenergy will be used for SAF production. Applying this assumption leads to 6.7 Mt of dry biomass (i.e. 3 Mtoe of bioenergy) for France. With a selectivity of 60% of the jet fuel portion in biofuel production, this allows for maximum production of e-bioSAF in France equal to 1.8 Mt per year.

If oleochemical SAF and e-bioSAF are added together, France could thus have a maximum of 2 Mt/year of SAF, i.e. around 20% of its consumption.

The uncertainty surrounding these figures is significant. Firstly, there is technical uncertainty about the conversion efficiency of biomass into fuel and the maximum selectivity of jet fuel in the total converted fuel. But the uncertainty is even greater and structural on the socio-economic level. Indeed, the assumption that 50% of oleochemical biofuels and 10% of bioenergy will be devoted to aviation requires a complex political arbitration between sectors that can legitimately compete for this resource. These ratios are at best a target and not an entry point. However, while these figures underpin the Commission's regulatory proposal for sustainable aviation ReFuelEU, they do not appear in the legislative text, which poses a problem of consistency between the objectives and the resources to be harnessed to achieve them. The debates in the European Parliament has illustrated this difficulty by focusing on both an increase in the SAF production target and a decrease in the associated resources by excluding forest residues.

The mobilisation of biomass for the production of SAF is an opportunity that must be seized, both with oleochemical SAF and e-bioSAF, which offer an initial opportunity for growth. This is a natural strategy to start the trajectory of SAF by allowing the necessary technologies to mature, normative frameworks to be put in place and a significant market to be established.

However, even in a proactive vision, these two production routes will only achieve 20% of the 2050 requirement. The uncertainties associated with both the political choices between competing uses and the regulatory framework, which is evolving as knowledge increases, may limit investors' appetite in this area and thus reduce the contribution of these biochemical routes to a level significantly below 20%.

The challenges associated with biomass collection, assuming collection radii of the order of 100 km for facilities producing 0.2 Mt/year of e-bioSAF, are another limiting factor, the local nature of which does not allow for an accurate assessment. Only regions with a high concentration of biomass will allow economic viability. Thus, in France, the number of viable e-bioSAF projects might be limited to a few units in the 0.2 Mt/year range, mainly in the southwest and northeast regions.

> **From the very beginning of the next decade, the share of the demand covered by synthetic jet fuel, known as e-SAF, will have to be significant in order to become dominant before 2045.**

Even if biochemical pathways contribute to 20% of the 2050 requirement, by the beginning of the next decade it will be necessary to marshal a new production pathway to ensure the growth of SAF's share of aviation fuel. This pathway is one of synthetic fuels without biogenic carbon and is referred to here as e-SAF.

This pathway is based on the direct capture of CO_2 from the air (DAC), the production of syngas (H_2+CO) by electrolysis of water for hydrogen and for CO by co-electrolysis of CO_2 and/or the reverse water gas shift reaction (with additional hydrogen consumption). The syngas is then converted into fuel by Fischer-Tropsch synthesis or by the methanol route. Finally, the jet fuel fraction is optimised by standard petrochemical techniques with a selectivity of up to 60%. The use of high-temperature electrolysis technologies is appropriate to exploit the heat released by the exothermic reactions of the process.

The technologies used are at a good level of maturity, with the exception of the direct capture of CO_2 from the air and high-temperature electrolysis, which is currently being industrialised on a significant scale[B]. CO_2 can be extracted more efficiently from the gaseous effluents of large industrial sites, such as cement plants (the concentration of CO_2 is greater than 10% in these effluents, compared with 400 ppm in the air). However, here again, the associated regulatory uncertainties do not allow this approach to be considered as a reference for the scaling up of SAF production.

In its proposal for a directive on sustainable aviation, ReFuelEU, the Commission sets a production target for e-SAF, which, for France, is of the order of 0.1 Mt in 2030, 0.7 Mt in 2040 and 2.8 Mt in 2050. This objective, reinforced by the uncertainties mentioned for the biochemical route, makes the production of e-SAF a strategic priority to be considered now in order to ensure the necessary boost to growth in 2030-35.

While the e-SAF pathway has the merit of decoupling SAF production from complex biomass issues, its development raises new challenges.

Technologically, the e-SAF and e-bioSAF pathways have important synergies with respect to the system integration of Fischer-Tropsch reactors, hydrocarbon distillation and cracking units, and high-power electrolysers. The optimisation of this integration, especially in the management of heat between exothermic and endothermic processes, is central to the energy and economic performance of both e-bioSAF and e-SAF. This confirms that the deployment of e-bioSAFs is a no-regrets option due to the efficient combination of biogenic carbon and hydrogen from electrolysis, but also due to the technical synergy between the e-bioSAF and e-SAF pathways. In France, the BioTJet[6] project is opening up this technological avenue.

Most of the energy consumed by e-SAF production processes is related to the production of hydrogen and CO. The use of high-temperature (HT) electrolysis technologies appears to be a preferred option here. Indeed, the exothermic Fischer-Tropsch reaction releases 20% of the

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[B] Examples include Climeworks and Carbon Engineering for CO2 capture, Genvia and Sunfire for high temperature electrolysis.

injected chemical energy in the form of heat. It is therefore imperative to use this heat in the process. HT electrolysis makes it possible to use this heat effectively and thus achieve electrical efficiencies close to 100%.

In the most recent studies, the use of HT electrolysis and an optimised integration of the system favouring the recirculation of heat flows appear to be the key to the development of the e-SAF sector.

Industrial advances in the direct capture of CO_2 from the air are significant. The energy cost to date is in the order of 7 to 10 GJ per tonne of CO_2, whereas the thermodynamic limit is 0.5 GJ, suggesting significant room for optimisation. A gain of a factor of 2 on the cost of this energy would make it possible to cover the heat requirement for the direct removal of CO_2 from the air by the heat extracted from the exothermic Fischer Tropsch reaction, and this after supplying heat to the high-temperature electrolysers. The strategic advantage of removing CO_2 from the air is that it frees us from the limitations and uncertainties associated with biogenic CO_2 or industrial effluents. It allows the integration of e-SAF production infrastructures everywhere in the country, as soon as low-carbon electricity is available.

The emerging regulatory requirements at EU level in the ReFuelEU proposal imply an acceleration of SAF consumption by a factor of 6 over the next decade. As a consequence, the gap between a rapidly growing demand and the supply of biogenic SAF could become apparent at the beginning of the next decade if the production of biogenic SAF falls below the level of 20% of demand. The increase in production will then have to be ensured by e-SAF, which will rapidly provide the bulk of demand. For this to be made feasible, it is necessary to promote the emergence of an e-SAF technological and industrial sector as of now.

In addition to the issues of scaling up industrial investments, the limiting factor for the production of e-SAF is the availability of a sufficient volume of low-carbon, low-cost electricity.

> **To meet its needs for SAF until 2040, France will have to make available around 50 TWh and 6 to 7 Mt of dry biomass.**

With existing DAC technology, an electrolysis efficiency of 90%, and a jet fuel selectivity of 60%, the production of 1 Mt of e-SAF (and concomitantly 0.67 Mt of e-diesel) will require 37 TWh. The vast majority of this energy is consumed by electrolysis (31 TWh), which will require just under 5 GW of electrolysers (with a load factor of 80%).

This compares with the production of 1 Mt of e-bioSAF (and concomitantly 0.67 Mt of e-diesel) which will use around 3.6 Mt of dry biomass and 10 TWh of electricity (to ensure the right proportion of hydrogen).

The insight into the e-bioSAF and e-SAF technologies allows us to choose the best combination of bioenergy/electricity resources for the production of SAF by selecting a region of interest for France in the following figure:

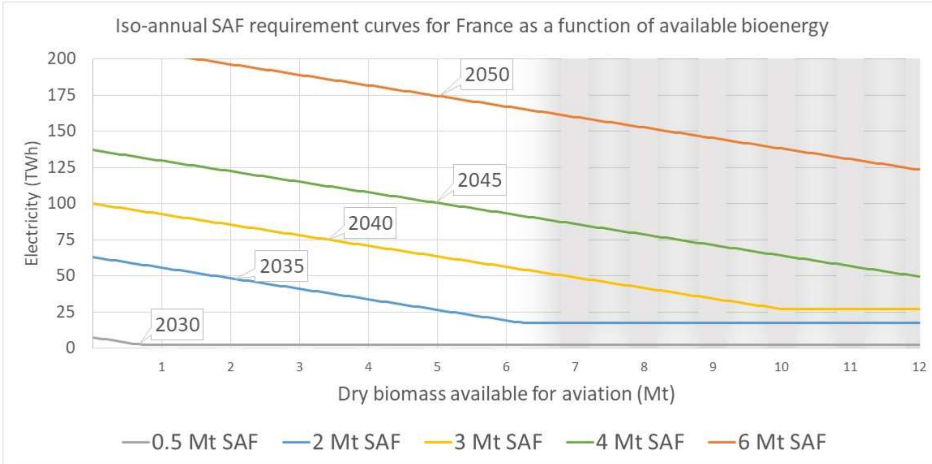


Figure 1: Each curve reflects a quantitative SAF target to be compared with the progression of demand defined in Table 1. The operating points in the shaded area would imply the allocation of more than 10% of the available bioenergy to the aviation sector alone.

The quantities of electricity and biomass to be used for SAF production are considerable and will need to be addressed by public policy to secure them over time. The optimum would be to keep the amount of low-carbon electricity required to a minimum, within the limits of the available biomass. Figure 1 shows that the availability of 50 TWh and 6.7 Mt of dry biomass would meet the SAF requirement for 2040, i.e. 3 Mt of SAF (30% of consumption). If only half of this biomass were available, 75 TWh of electricity would have to be used for the same amount of SAF production.

The challenge is then to identify a low-carbon electricity resource of several tens of TWh in a time frame that does not permit profound disruptions in the evolution of the electricity infrastructure.

> **The increase in wind and photovoltaic power combined with stable nuclear power provides France with the opportunity to launch a new large-scale industrial sector for the production of SAF in the next decade.**

The scaling up of strategies to decarbonise aviation as well as other sectors of the economy requires the availability of a significant amount of low-carbon electricity above current consumer usage. Therefore, there is a challenge in all countries to define the dynamics for reaching the decarbonisation target of the economy and the constraints on the dynamics for the growth of decarbonised electric power.

For countries whose electricity mix has a carbon footprint of more than 200 gCO_2/kWh, the direct injection into the grid of any low-carbon electricity produced avoids more CO_2 than its use for SAF production. France, with its already largely decarbonised electricity mix, is one of the few countries where it is climate-efficient to rapidly consider the production of e-SAF.

The challenge is then to determine the availability of low-carbon electricity for France in excess of existing uses. Two periods can be distinguished.

The first period concerns the next decade. The pace of deployment of electricity infrastructures and the uncertainties specific to the new electro-intensive sectors (hydrogen, SAF, etc.) do not allow us to envisage a significant reinforcement of the electricity mix for the production of SAF in this period. The reference mix that applies is based on the current consumer grid. In the spirit of maximising the available low-carbon electricity, this reference mix can be based on the extension of the lifetime of existing nuclear reactors to 60 years (i.e. a level of 63 GW) and on the continuous development of the installed wind and photovoltaic capacity up to 115 GW in 2040 and 135 GW in 2050; this corresponds to scenario N03 in the RTE report " Futures énergétiques 2050" [7].

The second post-2040 period will be characterised for France both by the replacement of reactors at the end of their operating life and by the growth of electricity demand. The integration of the need for decarbonising the economy will justify a doubling of electricity production, which will require ground-breaking decisions on additional generating capacity and in particular the commissioning of new nuclear reactors.

It is relevant to focus attention on the 2030 to 2040 period, which should allow the setting up of industrial sectors and the SAF market based on an electricity mix whose trajectory is practically known. Analysing the capacity for decarbonising the economy in 2050 is less relevant at this stage, as there are so many unknowns about the effective launch of an SAF sector in the 2030-2040 timeframe and about future decisions regarding electricity investments.

In the above-mentioned reference mix for the period 2030-2040, due to intermittency on the one hand and variability of demand on the other hand, a significant amount of additional electricity is produced beyond the grid requirement of the usual consumers. This additional electricity can be used for new electro-intensive economic applications such as the production of hydrogen and thus SAF, without jeopardising the supply for the usual consumers. By construction, this additional electricity supply is characterised by a guaranteed availability rate of less than 100%. It appears that the above reference mix allows for a low-carbon electricity mix (at 20 gCO_2/kWh), over the next decade, equal to 80 TWh with an availability factor higher than 80%, and to 100 TWh with an availability rate higher than 70%. It is important to note that this additional electricity does not require the addition of any generator specific to the SAF application; it is the natural by-product of a mix dimensioned for peak consumption and with a strong intermittent component.

This of course implies an electricity mix that is sufficiently robust to avoid consuming the additional electricity supply as a contingency to the weaknesses of the mix.

Moreover, this perspective implies a political trade-off between an export strategy that helps decarbonising the European mix and the development of new sectors of activity at the heart of France's reindustrialisation. In view of national commitments and because it prepares the future for the benefit of both France and Europe, the use of the national low-carbon mix for the accelerated development of industrial sectors such as the production of SAF seems a relevant option.

> **Political arbitrations on the allocation of available biomass and electricity resources, as well as on their stability over time, will ultimately determine the capacity to meet SAF needs until 2040.**

The electrical resources needed to ensure a level of SAF production on the scale needed over the next decade are available in France, provided that a proactive industrial policy is implemented to develop the additional electricity identified in the previous paragraph.

The low substitutability of liquid fuels in the aviation sector argues for a significant share of biomass and low-carbon electricity resources to be devoted to this sector. The table below illustrates the trade-offs that would be compatible with the decarbonisation objectives of the aviation sector:

	SAF Production in France e-SAF + e-bioSAF + oleochimique SAF	Electricity at 80% availability (e-bioSAF and e-SAF) 25 TWh	50 TWh	80 TWh	100 TWh
Biomass for ebioSAF	2.0 Mtdb	1.4 Mt	2.0 Mt	2.9 Mt	3.4 Mt
	4.0 Mtdb	1.8 Mt	2.4 Mt	3.3 Mt	3.8 Mt
	6.7 Mtdb	2.3 Mt	3.0 Mt	3.8 Mt	4.3 Mt
	8.0 Mtdb	2.6 Mt	3.2 Mt	4.0 Mt	4.6 Mt

Reminder of the need for SAF	2030	2035	2040
France	0.5 Mt	2 Mt	3 Mt

Table 2: The comparison between what is required and the quantities of SAF that can be produced (cumulatively from oleochemical SAF, e-bioSAF and e-SAF) indicates the relative quantities of low-carbon electricity and biomass (expressed in Mtdb - million tonnes of dry biomass) that need to be reserved for SAF production.

The SAF production targets, in the process of being set at European level, translate into the necessary choices between biomass and low-carbon electricity resources in Table 2. It should be recalled that 6.7 Mtdb represent 10% of the bioenergy deemed available in France. Moreover, the additional electricity with 70% to 80% availability (in the order of 80 to 100 TWh) is a specific product, which is not called for by conventional sectors that require a continuity of electricity supply, thus limiting competition between uses.

For every 10 TWh of SAF production, the installed capacity of high-temperature electrolysers is 1.5 GW, confirming that the deployment in France and/or Europe of a GW-scale industrial sector for high-temperature electrolysers is a central issue of an industrial policy for SAF production.

The production cost at maturity of e-SAF can be in the range of 2000 €/t to 2500 €/t.

In order to analyse the economics of SAF, only the e-SAF route will be considered in the first instance, as it has the largest cost and it will eventually be dominant.

At maturity, capex could be as low as €3.6 billion for the production of 1 Mt of diesel equivalent per year (€3 per l/year), from which 0.6 Mt/year of SAF is extracted. The weight of electrolysers in the capex is 50%.

With a high temperature electrolysis of 90% efficiency and a thorough optimisation of the heat flows in the system, an overall electrical efficiency called "PtL" (Power to Liquid) of 55% can be envisaged, thus using 37 TWh of electricity to produce 1 Mt of e-SAF and 0.67 Mt of e-diesel. With a PtL efficiency of only 45%, the same amount of production will require 45 TWh.

In a post-2030 equilibrium market, the jet fuel and diesel fractions produced will be valued at the same price in order to ensure a stable jet fuel to diesel ratio. With an efficiency of 55%, state-of-the-art Direct Air Capture (DAC) of CO_2 and electricity at 30 €/MWh, the production cost of an e-SAF would be 1.7 €/l (i.e. 2034 €/t). The following diagrams, in €/l and €/t, illustrate the sensitivity with respect to the important parameters.

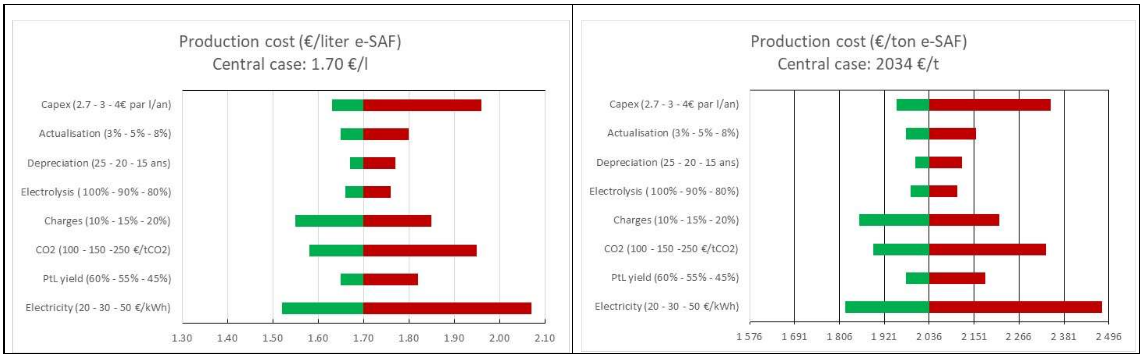


Figure 2 : The diagrams illustrate the sensitivity of the production cost of e-SAF to the different cost components, in € per litre on the left and in € per tonne on the right.

Unsurprisingly, the price of electricity is a significant part of the production cost of a SAF and should be kept to a minimum. Orders of magnitude of around €20/MWh are often quoted for projects based on wind or photovoltaic generators for e-fuel production in countries with optimal conditions. In the United States, the Department of Energy arrives at a price of 30 €/MWh by coupling e-fuel production with depreciated nuclear power plants, the price of electricity being a local and effective cost price and not a market price.

The French mix offers the opportunity until 2040 of an additional electricity supply with a guaranteed availability of 70% or 80%, the volume of which is of the order of 80 to 100 TWh/year. The value of this product cannot be equal to the value of 100% guaranteed electricity, as it implies an extra investment in capex for the user of this supply for a given annual production. The price of electricity with reduced availability is necessarily lower than an equilibrium price between the benefit of cheaper electricity and the additional capex cost that goes along with reduced availability. Starting from an electricity price in long-term and large volume contracts equal to 50 €/MWh (respectively 80 €/MWh), this equilibrium price for 80% available electricity is 41 €/MWh, and 34 €/MWh if the availability is 70% (respectively 71 €/MWh and 64 €/MWh). These equilibrium prices are obtained with a discount rate for the extra investment project of 12%.

It is in the collective interest to make use of the surplus electricity production capacity resulting from intermittence and variability of demand. Valuing the additional electricity at a price lower than the above-mentioned equilibrium prices brings a collective and strategic benefit by encouraging the anticipated development of new industrial sectors such as e-SAF, even before the electricity infrastructures are significantly reinforced to support the growing electrification of the economy.

This makes it possible to consider the possibility of producing e-SAF and e-bioSAF in France with an electricity cost close to 30 €/MWh (respectively 50 €/MWh) if the long-term contracts are at 50 €/MWh (respectively 80 €/MWh). The mature cost for SAF production is then around 1.7 €/l or 2034 €/t (respectively 2.07 €/l or 2479 €/t).

The important technological element here is the ability of high-temperature electrolysers to accept operations perturbed by the intermittency of electricity. This is made possible by keeping the electrolysers warm, and by switching the operation of the electrolysers on the scale of a few minutes to an inert gas with a power consumption of the order of one percent of the nominal consumption.

It is possible to produce synthetic jet fuel in France with a direct abatement cost of between €200 and €325 per tonne of CO_2 avoided, thus justifying the investment needed to develop e-SAF.

In order to establish the strategic viability of the SAF industrial sector, it is necessary to have a reference for comparison: fossil jet fuel. From 2017 to 2021, the price of jet fuel was around €0.5/l (with the exception of 2020). But it is not relevant to compare the price of a future SAF with a past price of fossil jet fuel. The continuous decrease in rates of return on energy justifies taking, as a conventional reference over the next two decades, a trend price of fossil jet fuel at €1 per litre (€1200/t).

Moreover, the increasing efforts required to adapt society to energy and climate issues are singularly reinforcing the questions of social equity in the distribution of constraints and priorities. Aviation fuel is not currently taxed, unlike the fuels used by other transport sectors. This is a matter of debate and may change shortly in Europe. Whether or not a carbon tax is introduced for the aviation sector, the evaluation and comparison of decarbonisation strategies require a carbon penalty to be associated with fossil jet fuel. The strategic interest of developing SAF will thus be measured via a carbon abatement cost calculated from the above trend price excluding tax.

The direct abatement cost is the extra cost of the SAF option compared to the fossil reference divided by the volume of emissions avoided by the SAF option compared to the fossil reference:

$$CA(eSAF) = \frac{1.7\text{ €} - 1.0\text{ €}}{3.45\ kgCO_2 - 0.371\ kgCO_2} = 227\text{ €}/tCO_2$$

This direct abatement cost rises to 324 €/tCO_2 for an e-SAF cost of 2 €/l (e.g. if electricity is valued at 50 €/MWh). More generally, the abatement cost depends on the cost of e-SAF, but also on the carbon footprint of the electricity used:

Reference fossil cost:	1.00 €/liter				
	carbon abatement cost	Electricity carbon footprint			
	€/tCO2	10 gCO2/kWh	20 gCO2/kWh	50 gCO2/kWh	100 gCO2/kWh
e-SAF cost	1.55 €/liter	168	178	218	344
	1.70 €/liter	214	227	277	438
	2.00 €/liter	306	324	396	626
	2.50 €/liter	459	487	594	939

Table 3 : With a decarbonised mix and by investing some of the additional electricity in the production of SAF, France can produce SAF with a direct abatement cost of around 200 to 300 €/tCO_2.

The notion of "carbon budget abatement cost" is introduced by France Stratégie to evaluate long-term strategies from the point of view of the community. This carbon budget abatement cost is the ratio of discounted SAF incremental costs to the sum of CO_2 gains, using a socio-economic discount rate of r=4.5%. The discounting makes it possible to determine the relative effectiveness of decarbonisation efforts in different areas, regardless of the date of the carbon emissions. The abatement cost in terms of carbon budget of e-SAF would be 132 €/tCO_2 for a production cost of 1.7 €/l and 189 €/tCO_2 for 2 €/l (the carbon footprint of electricity being assumed at 20 gCO_2/kWh). This result should be compared with the cost of converting thermal cars into electric cars, estimated by the Criqui[8] Commission at between €300/tCO_2 and €400/tCO_2. This establishes the relevance of the e-SAF option for society.

The production of SAF in France in the next decade is realistic. However, such a result is based on assumptions that embody as many objectives to be achieved.

Technologically, the key elements are the large-scale deployment of high temperature electrolysis and DAC technology. Optimisation of system integration, especially with regard to heat flows, will also require further technical investment. The parallel deployment of e-bioSAF and e-SAF plants offers the dual benefit of optimising the biomass/low-carbon electricity mix and a synergistic learning curve for the key technologies involved.

In terms of biomass and electricity resources, the competition of uses imposes complex but necessary political arbitrations. If only the market arbitrates, the price of resources could rise without taking into account the criteria of overall efficiency and social equity. Only a clear visibility of available resources in the long-term will allow investors to launch SAF production activities on the scale needed and in the desired timeframe.

The specificity of a mix that is already largely decarbonised offers France a unique opportunity to deploy an industrial SAF production sector in the country as early as 2030. At the same time, countries with a still largely carbon-based mix will have to develop import strategies that raise other sensitive issues. In an international market for fuel production technologies and energy carriers such as hydrogen, the early deployment of the SAF sector on the national territory would give France a strong industrial position in this new market.

The concomitance until 2040 of a stable nuclear power (through the life extension of the existing reactors as long as authorised by the safety authority and the construction of new units) and the announced growth of the wind and photovoltaic installed capacity induces an additional electricity volume characterised by an important but limited availability. The strategic allocation of this volume to new electro-intensive industrial sectors such as SAF production gives great value to this electrical overcapacity by contributing to both the reindustrialisation and decarbonisation of the French economy.

Beyond 2040, the scaling up of SAF production necessary to meet the decarbonisation commitments implies, for France as well as for other countries sharing this ambition, a significant reinforcement of low-carbon electricity production infrastructures.

Chapter 1

WHAT ARE SAF'S?

"Sustainable fuels" produce lower net CO_2 emissions than fossil fuels because they are produced by taking carbon from the environment.

Liquid fuels are essentially composed of C_nH_{2n} alkane chains of different lengths. Jet fuel, for example, is a mixture of hydrocarbons containing alkanes for "n" between 10 and 14.

For its production, the availability of three critical inputs is necessary: carbon, hydrogen, and energy which can be provided by biomass or low-carbon electricity. Aviation fuel requirements are considerable, currently around 300 million tonnes per year worldwide, including around 10 million tonnes for France. The challenge posed by the availability of the inputs required for such production is already apparent.

Several combinations of "technological processes/nature of the inputs" for the production of SAF are available today.

A first classification into large families is structured by the nature of the inputs used:

- **BioSAFs:** the terms BioSAFs and more generally biofuels are used when carbon, hydrogen and energy are provided by biomass:
  - this concerns, for example, so-called first-generation biofuels, which are in competition with food use and are gradually being restricted by regulations in Europe,
  - used cooking oils provides a good example of bioSAF. This technology is mature and benefits from growing production; but the availability of inputs is very limited compared to the needs;
- **e-SAF**: the terms e-SAF, or more generally e-fuel or synthetic fuel, are used when carbon is extracted from the atmosphere or from industrial effluents and hydrogen is produced by electrolysis with low-carbon electricity:
  - the associated technological building blocks exist on an industrial scale, but some are at an intermediate level of maturity. These processes make it possible to overcome the complex limitations posed by the biomass resource; the availability of low-carbon electricity then becomes the determining factor,
  - synthetic fuels also drastically reduce sulphide contents, aromatic hydrocarbons and particles that condense aircraft trails and generate non-CO_2 global warming effects;
- **e-bioSAFs** : the term e-bioSAF is used when biomass is used to provide carbon and part of the hydrogen, the other part being produced by electrolysis[C]. This combination maximises the efficiency of the use of carbon and energy from the biomass, thus ensuring the best use of this biomass.

[C] The addition of exogenous hydrogen in a biomass process makes it possible to obtain the ideal proportion '1:2' between the carbon and the hydrogen of the fuel - CH_2 -, whereas it is of '2:3' in the biomass of average formula $C_6H_9O_4$. This addition of exogenous hydrogen increases the yield (ton of biofuel per ton of dry biomass) from 20% for biofuels to 40% for e-biofuels.

The technological building blocks used for the production of e-SAF and e-bioSAF have significant synergies, making it possible to optimise the deployment of these two approaches according to the national context.

The nature of the biomass used is the subject of a growing regulatory effort in Europe in order to determine the channels that are truly profitable for society, in particular by prohibiting competition with food crops or the use of land that would involve deforestation. In this respect, a second classification is used:

- first-generation biofuels are derived from crops that are potentially food crops or have low energy yields. These technologies are being deployed but are already subject to a regulatory cap in Europe, which will decrease from 7% today to 0% in 2030. Crops with a risk of indirect land use change are also excluded;
- 2nd generation biofuels are mainly produced from organic waste. This is the path favoured by Europe, for example, with used cooking oils, animal fats unsuitable for food use, municipal waste or lignocellulosic forestry or agricultural waste;
- 3rd generation biofuels concern more prospective processes using algae and whose industrial maturity is low. The development prospects seem limited in relation to the necessary inputs (potash, nitrogen) and to the issues of location and mobilised surface area.

The interest of this segmentation of biomass resources into generations is firstly to express the European intention to eliminate so-called first generation fuels and to set out in detail the resources approved for second generation fuels through Annex IX of the RED II directive 2018/2001[9].

Finally, a third classification distinguishes the main families of technological processes:

- oleochemical processes of oil transformation by hydrogenation (HEFA);
- thermochemical processes by gasification and Fischer-Tropsch (FT);
- biochemical processes transforming sugar into alcohol (ATJ);
- synthetic processes (PtL, 'power to liquid') mobilising Fischer-Tropsch or methanol synthesis from CO2 and hydrogen.

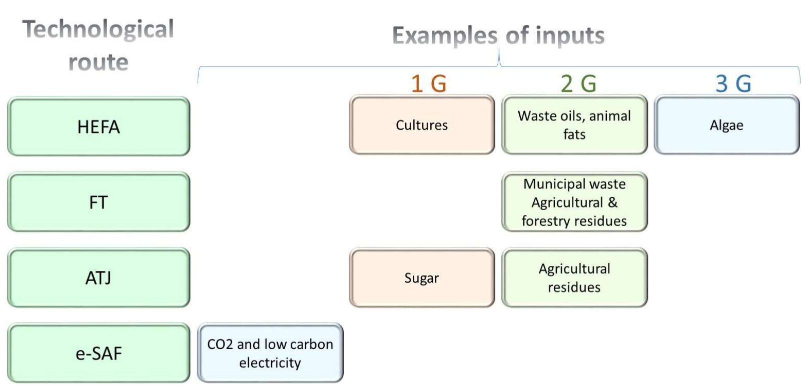


Figure 3 : Typology of processes and resources for SAF production

The HEFA technology is mature and deployed on an industrial scale, notably by the companies Neste and TotalEnergies[D]. In France, the Fischer-Tropsch pathway is implemented by the French "BioTfuel" project and its follow-up "BioTjet" and the ATJ pathway by the "Futurol" project.

Regardless of their nature, SAFs must be certified both:

- by standardisation bodies such as ASTM International for safe and efficient use in aviation,
- and by the ICAO (International Civil Aviation Organisation[E]) or the European Commission with regard to their environmental performance.

The concept of SAF is therefore normative in nature.

By the end of 2021[10], nine SAF streams have been qualified with maximum incorporation ratios ranging from 10% to 50% depending on the technology. This concerns in particular the following families of processes, with variations depending on the type of input:

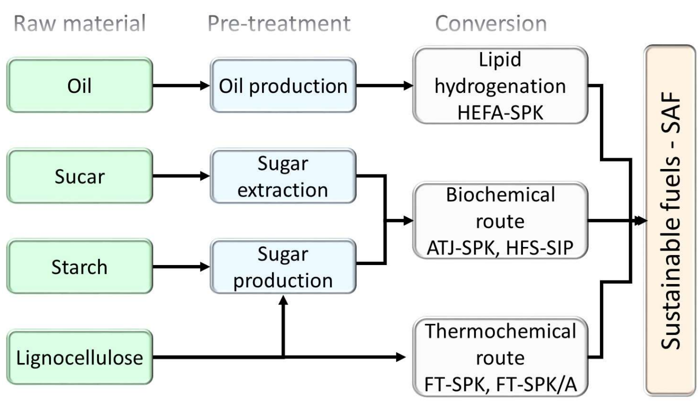


Figure 4 : Schematic diagram of ASTM-certified bioSAF

To date, the maximum incorporation ratio of SAF into aircraft fuel is 50%. The main factor limiting this ratio is the insufficient content of aromatics. For example, the FT-SPK process has been modified to FT-SPK/A to incorporate more aromatics[F], and the standard could move towards 100% incorporation.

The first sustainable fuels were certified in 2009 and 2011 for the FT and HEFA process and have been delivered to airports since 2015. They are used on a growing number of flights (250000 flights to date) and are now distributed by 46 airports worldwide.

In terms of environmental performance, ICAO manages the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). This programme, to which airlines are subject (currently on a voluntary basis), relies on the purchase of carbon credits to offset CO_2 emissions in excess of the 2020 baseline. Fuels eligible for CORSIA sustainability criteria, allowing for a reduction in offsets: To date, a fuel is eligible for CORSIA criteria if it allows for a reduction

[D] The Grandpuits site will produce 210 kt/year of SAF/HEFA from 2024 (https://totalenergies.com/fr/medias/actualite/communiques-presse/plateforme-zero-petrole-grandpuits-totalenergies-saria).

[E] ICAO, UN intergovernmental organisation responsible for the production of international standards and conventions in the field of aviation, without supranational authority.

[F] These aromatics are needed in older generations of aircraft for leakage performance. Newer generations of aircraft could accept low aromatic content SAF with 100% incorporation rates.

in carbon emissions of at least 10% compared to its fossil[11] analogue. The ambition at the international level remains very modest at this stage.

In Europe, the definition of "sustainable fuel" is spelled out in the RED II Directive 2018/2001[9], which stipulates that the reduction in greenhouse gas emissions must be greater than 65% for biofuels and 70% for synthetic fuels[G].

Therefore, the criteria refer to a life cycle analysis which should show that the associated investments lead to a significant reduction in CO_2 emissions.

Regarding carbon performance, this report is in line with the European requirement for the definition of SAF, i.e. a minimum carbon footprint reduction of 65%. While underlining the progress made under the aegis of the ICAO in the establishment of compensation mechanisms and in the standardisation of carbon emissions associated with the biogenic fraction of fuels[12], eligibility for the CORSIA programme from the 10% GHG reduction threshold onwards cannot be the only objective for a decarbonisation policy. Indeed, the use of resources of high value for many economic sectors, as well as the scale of the necessary investments, can only be justified by the prospect of a significant gain in terms of carbon emission reductions.

The use of SAF will contribute 60% to the reduction of aviation-related CO_2 emissions, with the remainder being achieved through the optimisation of technologies and operational processes.

The effects of aviation other than CO_2 on the climate are not addressed in this report. These effects are the subject of active research. The chemical and physical dynamics of the trails behind the aircraft are complex and induce processes that have a positive or negative impact on the radiative forcing. The dominant process is contrail-induced cirrus clouds under certain atmospheric conditions. The production of NOx and its effect on the chemistry of greenhouse gases is a second process with a significant impact. To date, there is still considerable uncertainty in the quantification of these effects. Furthermore, the radiative consequences of the non-CO_2 effects of aviation are profoundly different in nature from the direct effects of emitted CO_2. While emitted CO_2 accumulates over long timescales ($\gg$ 100 years), non-CO_2 effects have a short lifetime (< a few days for the dominant terms). This short-lived characteristic determines strategies for eliminating non-CO_2 effects, such as avoiding areas conducive to cirrus cloud creation (2% of flights would be responsible for 80% of cirrus clouds) and minimising NOx and soot emissions through the use of SAF.

[G] The European reference value for fossil fuel is 94 gCO_2eq/MJ, or a footprint of 4 $kgCO_2$/kg of fuel. It is 89 gCO_{2eq}/MJ in the CORSIA programme.

Chapter 2

SAF REQUIREMENTS FOR DECARBONISING THE AVIATION SECTOR

The databases of the International Energy Agency (IEA) confirm the strong growth of aviation fuel consumption, +40% every 15 years since 1990:

Kerosene	World - Mt	evolution
1990	153	
2005	222	145%
2019	314	141%

Table 1. Evolution of world jet fuel consumption

In the same period, the various improvements made by the airline industry have led to a 54% decrease in CO_2 production per passenger.km: between 1990 and 2018, the footprint per passenger fell from 240 gCO_2/passenger.km to 110 gCO_2/passenger.km on a global scale. It is now 96 gCO_2/passenger.km in Europe. The efficiency gains are therefore significant, but largely offset by the increase in traffic.

As early as 2009, the aviation sector adopted a sectoral benchmark for the reduction of CO_2 emissions with a target of 325 $MtCO_2$ in 2050, i.e. 50% of the emissions emitted in 2005. Due to the increase in air travel, reaching the 2050 target decided in 2009 would require a reduction in emissions of a factor of 3 between now and 2050.

In 2021, the sector strengthened its ambition by committing the world's civil aviation industry to a goal of zero net carbon emissions by 2050. This commitment was made by the International Air Transport Association (IATA[13]) and the Air Transport Action Group (ATAG[14]) following a "Waypoint 2050"[15] master plan assessing the pathways to achieve this goal. SAF production was identified as the most important factor in this development.

In its median scenario, the airline industry forecasts traffic growth of 3.1%/year (i.e. a 2.5-fold increase in traffic by 2050) and global jet fuel consumption, excluding measures to reduce CO_2 emissions, on the following trajectory

Consumption (without effort)	2 025	2 030	2 035	2 040	2 045	2 050
Mtoe/an	310	400	440	490	550	625
MtCO2/an	977	1260	1386	1544	1733	1969

Table 2. Projected global fossil jet fuel consumption and emissions if no efforts are made to curb it.

The median traffic growth scenario (3.1%) is framed by two scenarios where this growth is 2.3% (impact of the Covid crisis and protectionism) and 3.3% (return to globalisation with a residual impact of the Covid crisis). Even under the most restrictive assumptions, the expected growth is therefore sustained until 2050.

In the median scenario (3.1%), Europe and North America have a moderate traffic growth rate (2.1%), while the rate is higher (3.8%) in the Asia Pacific region.

In order to maintain such traffic growth while achieving zero emissions in 2050, the sector will have to implement measures that will enable it to cut a cumulative 21 $GtCO_2$ between 2020 and 2050.

Figure 5 illustrates the strategy pursued by the aviation sector. It is taken from the Waypoint 2050 Master Plan and concerns the median scenario studied by ATAG. It shows the four tools at the heart of the decarbonisation strategy: technology development, improved operations and infrastructure, sustainable fuels and offsets.

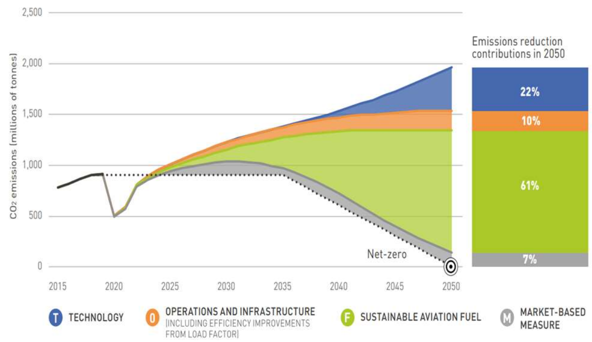


Figure 5 : Illustration of the decarbonisation strategy of the aviation sector

In view of the many uncertainties about how to achieve such an ambition, ATAG has studied several scenarios (variations in aircraft performance, infrastructure, operations and fuels) leading to different trajectories for the development of SAF:

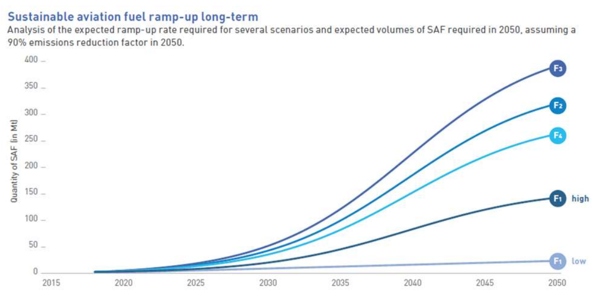


Figure 6 : Scenarios maximising SAF production are preferred, as they reduce the need for compensation measures (<10%).

The F1 curves correspond to scenarios where current trends are extrapolated without any particular effort; these scenarios give the majority role (>50%) to offsetting measures. Only more ambitious scenarios in terms of SAF availability allow the decarbonisation of the sector with the use of offsetting measures lower than 10%; the annual need for SAF is then considerably higher: between 45 and 60 Mt in 2030 and between 330 and 440 Mt in 2050. In its intermediate scenario, ATAG anticipates a SAF requirement of about 50 Mt in 2030 and 380 Mt/year in 2050.

In its communication[16], IATA has chosen a scenario where the 2050 target is achieved through a SAF utilisation rate of 65%, new flight technologies (13%), operational and infrastructure improvements (3%) and the remainder through compensation schemes. Compared with the ATAG scenarios, IATA's SAF growth path shows more moderate growth in the short term (19 Mt/year in 2030 and 73 Mt in 2035 compared to 50 Mt and 115 Mt respectively for ATAG), but leads to the same levels of SAF consumption in 2050 (363 Mt/year). The absolute values in terms of SAF volume envisaged by the aviation sector are based on traffic growth assumptions that are not discussed here.

Regardless of the assumptions on the evolution of traffic, it is necessary to ensure the production of SAF at the level of several hundred million tonnes, which raises systemic questions on the availability of resources and the accelerated deployment of industrial sectors which are at the heart of the present analysis.

Europe's share of world air fuel consumption (11% in 2019) is declining due to the growth of emerging countries. In the following, 50 Mt will be used as a stabilised reference for European consumption over the next decades (compared to 45 Mt today). Traffic growth is therefore assumed to be offset by efficiency measures.

SAF penetration will be driven by advanced economies. In its ReFuelEU regulatory proposal, the Commission sets a target of 5% and 20% SAF in aviation consumption in 2030 and 2035 respectively, converging to 63% in 2050. On the basis of the consumption of 50 Mt/year, Europe will therefore have to produce or purchase SAF up to 2.5 Mt in 2030 and 10 Mt in 2035. The objectives set by IATA and the Commission for 2030 and 2035 are consistent with Europe's share of world traffic (11% today) and its status as an advanced economy.

The ReFuelEU regulatory proposal is currently going through its legislative process, with a clear trend in the European Parliament towards reinforcing the incorporation targets without the feasibility of such a reinforcement being clearly established. For the sake of consistency, the numerous references to the EU framework used in the following refer to the Commission's text as published in July 2021 and do not take into account developments under discussion in the EU legislative process. This makes it plausible to rely on the impact assessment produced by the Commission to access the rationale for the ReFuelEU proposal.

In France, the Ministries of Ecological Transition and Transport have set a roadmap[17] for the deployment of sustainable aviation biofuels in air transport, with a deployment of 2% in 2025, 5% in 2030 and 50% in 2050. These targets will be aligned with the EU ReFuelEU directive when it is adopted. French jet fuel consumption is expected to reach 9 Mt by 2030. As an order of magnitude, France's share of Europe's aviation fuel consumption is 20%, i.e. a stabilised consumption of 10 Mt/year.

On the basis of the above elements, we can establish an order of magnitude reference for the SAF requirement for the world, Europe, and France: the following decarbonisation trajectory for aviation will be used as a reference:

SAF requirements	2030	2035	2040	2050
World	20 Mt	70 Mt	185 Mt	400 Mt
Europe	3 Mt	10 Mt	16 Mt	30 Mt
France	0.5 Mt	2 Mt	3 Mt	6 Mt

Table 4 : Order of magnitude of SAF requirements

Two important points emerge from the above table[H]

- The acceleration of SAF production puts the uncertainties on these figures into perspective, as a change in the target results in a very limited change in the date when the target is reached.
- The priority is to examine the conditions for establishing a 2030-2040 production plateau with a functioning market and effectively deployed large-scale industry branches. Therefore, the following analysis focuses on the 2030-2040 timeframe.

The decarbonisation of aviation requires the rapid establishment of a large-scale industrial sector, which will have to count on considerable and rapidly growing low-carbon energy resources.

[H] The table is based on a stabilised consumption of 10 Mt/year for France and 50 Mt/year in Europe (compared to 8.8 Mt and 45 Mt today). The figures are rounded off to their significant value.

Chapter 3

BIOMASS FOR SAF PRODUCTION, A LIMITED RESOURCE

The first stage of sustainable fuel production, and more specifically SAF, is provided by biomass, which provides the necessary carbon and hydrogen resources.

The constraints that determine the availability of biomass are sustainability criteria, competition for use, particularly with food, and technical and economic performance, notably in the area of collection logistics.

The sustainability criteria for biomass concern the carbon performance evaluated by life cycle analyses, the preservation of carbon stocks (forests, peat bogs, etc.), the protection of ecosystems, particularly with regard to biodiversity, and the maintenance of soil quality.

Thus, first generation biofuels do not offer any real prospects for development because of competition with food and/or poor energy and environmental performance. In Europe, these fuels are currently limited to 7% and will be phased out by 2030. In the rest of the world, the situation is still open for this category of biofuel, notably in Brazil (with sugarcane), in part of Asia (with palm oil) and in North America (with corn). The life-cycle analysis of these crops shows that the CO2 gain is limited; these biofuels could perhaps play a role in the global jet fuel supply, but will have a limited impact on the decarbonisation trajectory.

The following analysis therefore only considers second generation biofuels. This is the pathway favoured by Europe (ReFuelEU and RED II) with, for example, used cooking oils, animal fats unsuitable for food, municipal waste and lignocellulosic waste.

MACROSCOPIC ASSESSMENT

The demand for bioenergy far exceeds its availability

In the IEA's World Energy Outlook 2021[18], global bioenergy production, all uses combined, is multiplied by 2 and 2.7 respectively in the "*Stated Policies Scenario*" and "*Net Zero Emissions by 2050 Scenario*" between now and 2050. Taking a median value of the two IEA scenarios mentioned, the bioenergy available in 2050, all forms combined, would be of the order of 2100 Mtoe/year ±15 %.

The target for global SAF production is around 400 Mt/year. Assuming a bioenergy to biofuel conversion efficiency of 50% and SAF selectivity of 60%, 1333 Mtoe/year of bioenergy will be required to meet aviation needs alone, or 63% of the 2100 Mtoe estimated by the IEA. The demand of the aviation sector combined with that of other economic sectors far exceeds the available bioenergy.

With demand for bioenergy exceeding available resources, competition between sectors of the economy will require public policies to set the framework for the operation of markets for access to biomass.

The trend in available bioenergy over the next few decades is uncertain

The institutional bodies foresee growth in bioenergy by a factor of almost two between now and 2050. This is also the case for the IEA quoted above.

In its impact assessment for the proposed ReFuelEU directive, the European Commission considers an 82% increase in bioenergy potential between 2015 (140 Mtoe) and 2050 (255 Mtoe).

In France, the SNBC 2020 anticipates a growth in bioenergy of a factor of 2.5 between 2016 (180 TWh) and 2050 (450 TWh). This 2050 target is divided into 250 TWh for agricultural biomass, 100 TWh from waste and 100 TWh from forest biomass.

But more academic studies conclude that there will be no growth in available bioenergy.

For Europe, the "Material Economics[19]" study quantifies the use of biomass in 2019: 13 EJ for food, 4 EJ for biomaterials, and 6 EJ (144 Mtoe) for bioenergy. The outlook for bioenergy in 2050 is in the range of 3.9 to 7.7 EJ, or 90 to 185 Mtoe, thus remaining at a significant level, but without significant growth.

The Imperial College[20] study also concludes that the biomass available for bioenergy will remain stable between 2030 and 2050.

For the share of agricultural biomass alone, the France-Stratégie[21] analysis concludes that there is a maximum availability of 125 TWh/year, or 50% of the SNBC reference.

The volume of bioenergy in 2050 therefore has a robust share equal to its current value and a significantly more hypothetical share beyond this value.

The bioenergy withdrawal rate for aviation

In its impact assessment in support of the ReFuelEU proposal, the European Commission defined SAF incorporation targets in 2050 on the basis of a withdrawal rate of 10% of the envisaged bioenergy potential (255 Mtoe).

Such a withdrawal rate should be considered as a target. It should be noted that this objective, which determines the trajectory of SAF production, is not explained in the ReFuelEU legislative proposal by the European Commission. Thus, in the European debates on the quantities of SAF to be produced, it is not certain that the coherence between these quantities and the rate of bioenergy withdrawal that they imply for the sole benefit of aviation and therefore to the detriment of other economic sectors is taken into account.

With reference to the ReFuelEU impact assessment, a withdrawal rate of 10% of available bioenergy for the aviation sector is assumed below.

It should be noted that if the physical availability of bioenergy in Europe were reduced to 150 Mtoe as indicated by academic studies, the offtake rate, necessary to produce the level of SAF foreseen in the ReFuelEU proposal, would increase to 17% for the same SAF production.

Uncertainty about the growth of bioenergy obviously weighs on the potential rate of uptake by a given economic sector and could complicate trade-offs.

THE BIOMASS RESOURCE FOR THE PRODUCTION OF SAF BY THE OLEOCHEMICAL[4,22] ROUTE

The oleochemical treatment of biomass using the HEFA (hydrotreated esters and fatty acids) process has reached technological maturity and is widely commercially deployed for the production of biodiesel. The associated resources are used cooking oils and animal fats that cannot be used in the food chain; this corresponds to Part B of Annex IX of the European RED II Directive.

The conversion efficiencies are high, which allows for long-distance transport of the feedstock. For example, one litre of used cooking oil can produce about 0.9 litres of biofuel with a proportion of SAF that can be as high as 0.7 litres.[23]

It is therefore logically the main production route for SAF today and until 2030.

The share of jet fuel produced in HEFA processes is naturally around 15%. It could rise to 50% if the objective was to maximise SAF production, with the added cost of optimising the infrastructure.

In 2018, out of 5 billion litres of biodiesel produced worldwide, only 8 million litres were actually marketed as SAF, a ratio of 0.16% far below the natural share of SAF production in the HEFA process (15%).

SAF molecules are therefore currently consumed as biodiesel for the road sector, thus meeting current market conditions. Without the need for major technical changes, the share of commercial SAF production could increase significantly and rapidly if incentive policies are put in place to orient the market towards this objective.

SAF-HEFA's global production is growing rapidly and could reach 1 billion litres (0.8 Mt) by 2023, given the announced new infrastructure and SAF's production statements[I].

The uncertainty on the future volume of SAF-HEFA results from

- firstly, the evolution of biodiesel production under the pressure of the regulatory evolution with the obligation in Europe to consider only second generation biofuels[J] ;
- secondly, the percentage of SAF extracted during biofuel production. Increasing this percentage does not require major investment but does require incentivising policies to shift the market from the road sector to the aviation sector.

According to the World Economic Forum's report "Clean Sky for Tomorrow[23]", used cooking oils and animal fats could represent around 40 Mt/year and would make it possible to produce 20 Mt in SAF (including 3 Mt for Europe), i.e. 5% of the need in 2030. This estimate is based on a strong hypothesis: the infrastructures are optimised to produce 50% jet fuel and 50% biodiesel, compared to the current proportion of 0.16%. The challenge here is to create the market conditions for jet fuel's share of HEFA biofuels to increase by two orders of magnitude.

According to the Commission's ReFuelEU document, the share of SAF/HEFA in the aviation fuel mix would be 1.6% of the requirement in 2030 (i.e. around 0.8 Mt) and 4% of the requirement in 2050 (i.e. around 2 Mt). In this assessment, SAF production is assumed to mobilise 30% of used cooking oil in 2030 and 50% in 2050.

According to an initial study of the biomass deposits available in France to produce SAF[24] within the framework of the commitment to green growth (CGG), 0.3 Mt/year of oils and fats are collected today with a potential of 0.5 Mt/year to produce 0.25 Mt of SAF-HEFA. Normalised to a consumption of around 10 Mt/year, the maximum potential of SAF-HEFA for France is 2.5% of what would be needed.

HEFA processes are mature and efficient. Taking the above data as a rounded order of magnitude, the production potential for SAF-HEFA is limited to 3% to 5% of the need, i.e. 20 Mt/year worldwide, 2 Mt/year (4%) in Europe and 0.25 Mt/year (2.5%) in France.

[I] In 2021, the two main suppliers, Neste and World Energy, had a combined production of 0.2 Mt.

[J] SAF/HEFA offer an emission reduction factor of more than 75% if produced from waste and less than 30% if produced from vegetable oils (soybean or rapeseed oil). In Europe, the HEFA process is reduced to waste cooking oils and animal fats to ensure an emission reduction factor of over 65%.

The growth of SAF production requires limited adaptations in the infrastructure that currently gives priority to the production of over 99% road biodiesel.

The growth dynamics and the actual production ceiling of bioSAF-HEFA will therefore be driven primarily by future incentives that will shift the market significantly from the road sector to the air sector.

The challenge of these measures is to increase the selectivity factor of the jet fuel actually marketed from less than 1% today to 50% in the future in order to satisfy 3% to 5% of air transport needs.

This constitutes a major societal trade-off between the economic sectors of air, sea and road transport. The low substitutability of jet fuel in the air sector and the electrification of road transport provide a rational basis for a significant increase in jet fuel selectivity in HEFA biofuels.

THE PRODUCTION OF SAF BY FERMENTATION

The biochemical route for the production of SAF is based on the fermentation of sugars from biomass and is known internationally as "ATJ" for "Alcohol to Jet". This pathway is certified by ASTM for ATJ fuels produced from ethanol and isobutanol. Current developments involve a wide variety of processes and alcohol types[25].

Bioethanol production amounts to 5 Mt in Europe and 1 Mt for France (2019)[26]. Worldwide[27], biofuel production is 125 Mt in 2019. The global share of bioethanol is 85 Mt, including 50 Mt in the US. The inputs are mainly beet molasses in Europe and maize in the US (maize's share is 64% worldwide). The biochemical route is therefore currently based massively on first-generation fuels whose role in food prices and deforestation is the subject of growing criticism.

The European RED II/2018 directive has brought about a paradigm shift in this respect by prescribing a decrease in the contribution of first-generation fuels to 0% by 2030. Consequently, in order to take off in Europe, the ATJ route will have to be based on so-called second-generation processes, since they use lignocellulosic material.

The process for producing a second generation ATJ fuel (ATJ/2G) within the meaning of the RED II Directive then consists of three steps:

- step 1: after pre-treatment of the lignocellulosic biomass to make the cellulose accessible, the cellulose polymers are broken down into glucose molecules,
- step 2: the glucose molecules are fermented and produce alcohol,
- step 3: the alcohol is transformed into fuel by distillation.

Step 2 is at the heart of the production of first generation fuels and is therefore largely mastered in terms of large-scale industrial production.

Step 3 is also very industrially mature. It is carried out in refineries with some adaptations. The ATJ/2G route is therefore attractive to the petrochemical industry.

Step 1 represents a limiting step in the conversion of lignocellulosic biomass into fuel. The numerous recent research theses on the conversion of lignocellulosic material into alcohol show both the interest of the subject, but also the need for maturation before the ATJ/2G pathway can be taken to industrial scale.

Due to its structure, cellulose is very resistant and insoluble in most conventional solvents. Its depolymerisation into glucose is therefore a major challenge which is the subject of numerous pre-industrial developments. A certain number of pilot units exist, on a demonstrator scale (notably Futurol and Iogen) or on an industrial scale.

The historical routes for cellulose hydrolysis involved the utilisation of acids and had many drawbacks on an industrial scale. Enzymatic hydrolysis is now the reference route. Its large-scale industrial development involves improving yields and acceleration of reactions (through the use of catalysts and/or non-conventional media), and finally minimising the cost of enzymatic cultures.

The transformation of cellulose into alcohol is therefore the first limiting factor for the rapid development of ATJ/2G, with the understanding that ongoing efforts will bring this technology to full maturity within two decades.

Economically, ATJ/2G will be more expensive than ATJ/1G. They will only be able to develop within a regulatory framework that excludes first-generation fuels, such as the one prevailing in Europe. The situation could therefore be different in other parts of the world, and in particular in the United States, raising complex issues of regulatory fairness in commercial competition.

But beyond the issues of technological maturity and economics, the ATJ/2G route has a second, more structural limitation.

The mass share of cellulose is around 50% for wood and 35% for straw and grass, with the remainder being made up of hemicellulose, lignin and minerals.

The average formula of the biomass is $C_6H_9O_4$, so the mass share of carbon in the biomass is $\frac{72}{145} = 50\,\%$. On the other hand, the formula for cellulose is $(C_6H_{10}O_5)_n$, so the mass ratio of carbon to cellulose is $\frac{72}{162} = 44\,\%$. As the proportion of cellulose in wood is 50%, an ATJ/2G process will not be able to recover more than 50% * 44% = 22% of the mass of biomass in the initial material (instead of 50% for other processes). If we consider straws and grasses, at most 15% of the initial carbon mass could be recovered as carbon in ATJ/2G processes.

A thermochemical process such as gasification and Fischer Tropsch can recover 50% of the carbon from the biomass used (without hydrogen input), which is twice as much as an ATJ/2G process. We can therefore see that, for lignocellulosic biomass, the biochemical pathway will have to consume 2 to 3 times more biomass than the thermochemical pathway for the same service provided.

Of course, it is necessary to take into account the technological yields which will depend on the effective maturity of the different building blocks implemented in the biochemical and thermochemical processes. Nevertheless, at maturity, the respective technological efficiencies of the ATJ/2G and thermochemical processes will not compensate for the difference in principle of a factor of 2 to 3 in biomass consumption.

Lignocellulosic biomass is a valuable material that is legitimately coveted by many socio-economic actors. The technology that provides the majority of SAF production must ensure optimal use of the biomass mobilised. In this respect, it is likely that the ATJ/2G sector will only develop in niche opportunities, without making a significant contribution to the scaling up of SAF production.

THE SOLID BIOMASS RESOURCE FOR THE PRODUCTION OF SAF BY THERMOCHEMICAL AND BIOCHEMICAL MEANS

The processes used by the thermochemical and biochemical routes are technologically mature, but industrial experience is limited.

In France, the BioTFuel demonstrator and its evolution towards BioTJet are steps towards maturing the gasification + Fischer-Tropsch technology at the industrial level; the Futurol commercial process for producing lignocellulosic ethanol is the first valuable phase in the production of so-called "alcohol-to-jet" SAF.

The associated biomass resources are defined in Part A of Annex IX of the RED II Directive. They include :

- agricultural biomass: livestock effluents, crop residues, intermediate crops, dedicated perennial crops, agroforestry, etc. ….,
- forestry and wood industry residues,
- municipal waste, and industrial waste not suitable for use in the food chain.

In its impact assessment for the ReFuelEU proposal, the Commission anticipates a level of bioenergy availability in 2050 equal to 255 Mtoe/year and an offtake rate for the aviation sector equal to 10%, i.e. 25 Mtoe of bioenergy available for the production of SAF by thermo/bio-chemical means. Also in 2050, the ReFuelEU regulatory proposal aims at a minimum coverage of 35% of aviation needs (50 Mt) by bioSAF technologies, i.e. 17.5 Mt of bioSAF. To reconcile the availability of bioenergy with the production target, the conversion efficiency from bioenergy to biofuels must be 100% and the selectivity of the jet fuel portion in the biofuel must be 70%.

In line with the impact assessment of the ReFuelEU proposal, the following elements that affect the performances of the proposal will be retained:

- The bioenergy offtake rate for the aviation sector is 10%. This offtake rate is by nature a societal arbitrage and should be seen as a target and not an input.
- The conversion efficiency of bioenergy to biofuel for thermo/biochemical processes should be close to 100%, allowing maximum use of the available biomass. This implies a significant addition of hydrogen to the processes to establish the right ratio between hydrogen and carbon. According to the terminology adopted in this document, it is therefore a question of considering e-bioSAFs (with a conversion efficiency of bioenergy into biofuel close to 100%) and not bioSAFs (with a conversion efficiency of less than 50%).
- The selectivity of jet fuel in the biofuel is 60%, (see Annex 2).

With a bioenergy ratio of 0.45 toe per tonne of dry biomass, the idealized yield chain is as follows:

Idealized yield chain	
bioSAF pathway	**e-bioSAF pathway**
1 tonne of dry biomass	1 tonne of dry biomass
≈0.45 toe of bioenergy)	≈0.45 toe of bioenergy)
↪ 0.22 tonne of biofuel *without H2 input* (conversion efficiency 50%)	↪0,45 tonne de of biofuel *with H2 input* (conversion efficiency 100 %)
↪ 0,135 tonne of **bioSAF** (selectivity 60 %)	↪ 0,27 tonne of **e-bioSAF** (selectivity 60 %)
Conversion efficiency bioSAF/bioenergy : 30 %	Conversion efficiency e-bioSAF/bioenergy : 60 %

Table 5 : Biomass to SAF yield chain for thermo/biochemical pathways

On this basis, it is now possible to examine to what extent France can meet its SAF needs with an offtake rate of 10% of available bioenergy as defined in part A of Annex IX of the RED II Directive.

Under the SNBC, 450 TWh (39 Mtoe) of bioenergy would be available in 2050. Using the assumptions made in the ReFuelEU impact assessment, i.e. a 10% offtake rate for SAF production, France would use 4 Mtoe of bioenergy, or 9 Mtbs of dry biomass, for SAF production. The physical potential of e-bioSAF production in France would then be 2.4 Mt.

A study[21] by France-Stratégie concludes that the agricultural potential, announced at 250 TWh in the SNBC, is more likely to be close to 150 TWh, thus reducing the bioenergy potential by 100 TWh (or 9 Mtoe). With this reduction, the French bioenergy potential is 30 Mtoe. For SAF production, France would then use 3 Mtoe of bioenergy, requiring 6.7 MT dry biomass. France would have a physical potential to produce e-bioSAF of around 1.8 Mt. The realisation of this potential will require 6.7 MT dry biomass and the addition of hydrogen, which is assessed in the next chapter.

The ECV study[24] already mentioned provides an initial assessment of the lignocellulosic resources collected to date and their evolution. A crude addition of the different deposits leads to about 100 Mt of biomass. Nevertheless, this consolidation concerns biomass with multiple purposes: return to the soil with or without composting, recycling in the form of materials, and finally bioenergy. With a harvesting rate for SAF of less than 10%, the quantity of SAF that could be used is less than 2.7 Mt. The assessment of a production potential of 1.8 Mt of e-bioSAF is therefore not inconsistent with the ECV study.

The logistics of collecting biomass can significantly limit access to this resource and reduce the production potential of SAF to less than 1.8 Mt.

<u>The challenges of biomass collection</u>

As an illustration, the forest resource that could be mobilised for bioenergy[28] would be of the order of 6 Mtoe/year. Still considering a 10% offtake rate, it would be possible to produce 0.3 Mt of e-bioSAF on this basis. However, of the 13 French regions, only 3 have a forest biomass density of more than 25 t/km² and 7 more than 20 t/km². In a region with 25 t/km², a 0.2 Mt e-bioSAF production facility would require 0.75 Mt dry biomass, i.e. a collection area with a radius of 100 km. The economic as well as the environmental cost of collection is therefore significant and can become limiting in practice.

Municipal waste is a source of biomass that has the advantage of already having a collection circuit and large volumes in highly urbanised areas. For example, the area of Paris and its inner suburbs can be considered to have a bioenergy resource of 0.4 Mtoe[K], allowing the production of 0.24 Mt of SAF if it were entirely devoted to this purpose. Again, the potential may be limited by the small number of sites with high biomass concentrations.

Industrial investments will be concentrated in regions where biomass collection is cheapest. As a result, the entire physical production potential estimated above at 1.8 Mt may not be realised. Only local studies will determine the viability of collection processes.

[K] The annual production of municipal waste in France is 530 kg/capita, of which 150 kg/capita is fermentable. With 7 million inhabitants, Paris and its inner suburbs produce 1 Mt of biomass, or 0.4 Mtoe of bioenergy.

SUMMARY OF THE POTENTIAL FOR THE PRODUCTION OF SAF FROM BIOMASS IN FRANCE

Uncertainty about bioenergy potential, in France as elsewhere, is high due to (i) uncertainty about the evolution of available biomass, (ii) the rate of harvesting for SAF, and (iii) collection logistics, the viability of which depends on local realities.

The oleochemical route (SAF-HEFA) allows an initial acceleration of SAF production to a maximum potential of 0.25 Mt/year, i.e. 2.5% of the 2050 requirement. The realisation of this potential requires incentives to shift the market significantly towards the aviation sector at the expense of the road sector.

For thermo/bio-chemical pathways, with a 10% bioenergy offtake rate for SAF (consistent with the elements adopted by the Commission in its ReFuelEU impact assessment), with a national biomass resource of 67 MT of dry biomass, with a bioenergy-to-biofuel conversion efficiency of 100% and a jet fuel selectivity of 60%, the annual e-bioSAF production potential is around 1.8 MT. The criterion of viable collection could significantly reduce this potential.

With the assumptions made in the previous paragraphs, the production potential in France, cumulated in SAF-HEFA and e-bioSAF, would be 2 Mt/year, or 20% of consumption.

Compared to the demand trajectory, this production potential will peak in the period 2030-2035, at which point e-SAF synthetic fuel production will have to take over in providing growth.

It is important to note that, while the uncertainty on the potential of SAF production from biomass is significant, its impact on the transition date from which synthetic fuels should take over is small. This is due to the quickly increasing future demand (0.5 Mt in 2030 and 2 Mt in 2035).

Uncertainties of a technical nature (e.g. knowledge of bioenergy potential, viable local collection opportunities and conversion efficiencies) will gradually be addressed through feedback via experience. However, the uncertainty about the rate of bioenergy offtake for SAF production is more structural. It is up to public policy to set a stable framework over time to limit the risk factor associated with biomass availability and thus enable large-scale industrial investment and deployment.

Given the inability of biomass alone to ensure the growth of SAF production beyond 2030-35 and the significant uncertainties surrounding the availability of biomass, it is important to start the industrial scale-up of synergistic e-bioSAF and e-SAF technologies as soon as possible.

Chapter 4

THE POWER REQUIREMENT OF THE E-BIOSAF AND E-SAF ROUTES

In Chapter 3 it was shown that biomass is a valuable resource and subject to competition between economic sectors. It is, therefore, necessary to maximise its conversion efficiency by transforming it into e-bioSAF. This requires the supply of hydrogen, which in turn requires a critical new resource: low-carbon electricity.

Chapter 3 also concluded that e-SAFs will have to take over the growth of SAF production by 2035 at the latest. This will involve considerable amounts of carbon extracted from CO2 in the air and hydrogen extracted from water by electrolysis. The critical resource here is more than ever low-carbon electricity.

This chapter assesses the electricity requirement for the production of e-bioSAF and e-SAF. This requires a technological process and an examination of the material and energy flows.

At first order, the energy balance is determined by the enthalpy balances of the chemical reactions involved in a process, and, in this "perfect yield limit", all processes will have the same energy balance as long as they have the same initial and final states. On this basis, the effective technological efficiencies of the different processes will lead to different performances. Nevertheless, at technological maturity, the different processes should approach perfect efficiencies.

The processes considered in this chapter are thermochemical, with a combination of gasification plus Fischer-Tropsch for the production of e-bioSAF and a combination of Direct Air Capture plus Fischer-Tropsch for the production of e-SAF..

TECHNOLOGICAL BUILDING BLOCKS AND INTEGRATED PROCESS

Much research is devoted to optimising processes or technological building blocks for sustainable fuel production. However, in order to meet the decarbonisation agenda and aim for large-scale deployment at the beginning of the next decade, we must consider technological building blocks that are at least in the process of being industrialised.

The following mature technology building blocks or bricks will be considered here:

- the gasification brick for the production of syngas,
- the "Reverse water gas shift - RWGS" brick for the production of CO,
- the brick *« Fischer Tropsch – FT »* for fuel synthesis,
- cracking, reforming, and distillation bricks for the optimisation of the jet fuel fraction in the alkanes produced.

In addition, we will consider technologies in the industrialization phase, given their importance:

- the "Direct Air Capture - DAC -" building block for the extraction of CO2 from the air,
- high temperature electrolysis - HTE - for the production of hydrogen and possibly CO.

With these technology bricks, the following process with three variants for syngas production can be evaluated:

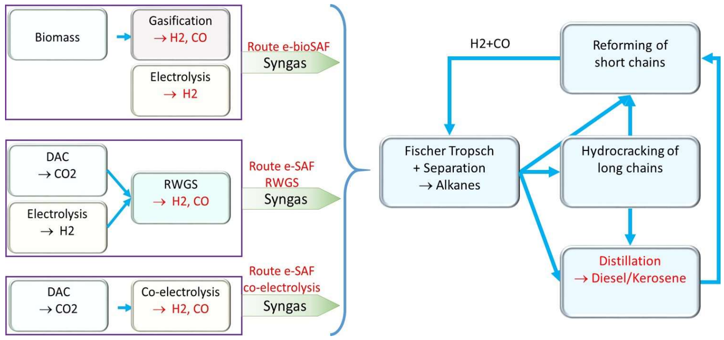


Figure 7 : Process diagram for the production of e-bioSAF or e-SAF by the thermochemical route

The integration of the process is a key issue for the economic viability, or even the feasibility, of the projects. Indeed, the effective yield of the process depends to a large extent on the looping of the material and heat flows, a yield that must now be evaluated.

THE LIMIT OF PERFECT YIELDS

As a first step, it will be useful to evaluate the energy quantities involved in the process at the limit of the perfect efficiency, resulting directly from the enthalpy balances of the different reactions involved. Apart from its illustrative value, this exercise determines the overall efficiency of the process at first order. Technological yields will degrade this efficiency, however, at a second order for mature processes.

Unsurprisingly, at the limit of perfect yields, the energy cost of producing syngas is independent of the reaction pathway chosen.

Since the combustion of one kg of octane delivers 12.3 kWh and the production of CO+H_2 syngas upstream of the FT costs 15.5 kWh/kgoctane, the efficiency of the process is 80%, which is identical for the RWGS/FT and HTE/FT processes.

It is therefore unnecessary to differentiate between RWGS and co-electrolysis processes at order 1. Only contingent technological realities will push projects in one or the other direction. But at the end of the industrial maturation processes, both routes should be equally competitive.

> The quantities involved can be illustrated by a case study: the synthesis of octane by a co-electrolysis + Fischer Tropsch (HTE/FT) process and by a RWGS + Fischer Tropsch (RWGS/FT) process. The following quantities are standardised to the production of 1 kg of octane:
>
> - For the e-SAF/co-electrolysis route, 0.3 kg of hydrogen (i.e. 17 moles of H_2 per mole of octane) and 2 kg of CO must be electrolysed from 3 kg of CO_2; the cumulative cost of CO and H_2 electrolysis is 15.5 kWh.
> - For the e-SAF/RWGS pathway, 0.44 kg of hydrogen (25 moles of H_2 per mole of octane) must be electrolysed and 3 kg of CO_2 consumed; the cost of H_2 electrolysis is 15.5 kWh.
>
> Combustion of one kg of octane delivers 12.3 kWh, thus the efficiency is $\frac{12.3}{15.5}$=80 %, identical for RWGS/FT and HTE/FT processes at the limit of perfect yields.

The FT reaction is exothermic and provides 3.2 kWh/kgoctane, or 20% of the energy input (the rest goes into the fuel). Even at the limit of perfect yields, 20% of the injected energy is found in the heat released by the FT brick. It is therefore a question of recovering this heat in the process through a carefully optimised integration of the energy flows.

Technologies in the industrialisation phase

The production of hydrogen by electrolysis requires 33.3 kWh/kgH2. Access to commercial hydrogen is often valued at 55 kWh/kgH_2 taking into account the intermediate operations of change of state, storage, transport, leaks, etc.

The integration of the process is again a key element. In an installation integrating hydrogen production and consumption, the energy cost of hydrogen is linked to the efficiency of the electrolysers alone (including cooling), i.e.[29]:

- for PEM technology in 2030: 48 kWh/kgH_2, or an efficiency of 69.4%,
- for SOEL technology in 2030: 37 kWh/kgH_2, i.e. an electrical efficiency of 90.1% requiring a heat input of 8 kWh/kgH_2.

Although the SOEL technology is still in the process of industrial maturation, it is made necessary by the obligation to recover the heat produced (20% of the energy invested) by the Fischer-Tropsch reaction.

Furthermore, the thermodynamic cost of extracting one tonne of CO_2 from a carrier gas is 490 MJ, 180 MJ and 20 MJ respectively, if the concentration of CO_2 is 400 ppm (air), 10% (industrial effluents) and 90% (biogas purification) (see Annex 1).

To date, the energy consumption of DAC installations is between 7 and 10 GJ/tCO_2 of which ¾ is heat. **The current performance of DAC is therefore 15 to 20 times the thermodynamic minimum cost. The performance of the DAC building block could benefit from significant improvements with industrial maturation.**

ENERGY COST FOR E-SAF FUEL PRODUCTION

The FT exothermic reaction allows heat to be supplied to the HTE electrolysis to achieve an efficiency close to 100%. Another part of the heat available in the process can contribute to the capture of CO_2[L]. Based on recent process research[30], the process efficiency[M] could be as high as 55% at 90% HTE (and 60% at 100% HTE).

Such a level of performance is based on the use of high efficiency electrolysis accompanied by a thorough effort to optimise heat flows through system integration. This militates in favour of the deployment of installations integrating on the same site the functions of CO_2 capture, hydrogen production by HTE electrolysis and production by FT of liquid fuels.

Achieving an efficiency of more than 50%, between the electricity consumed and the energy of the fuels produced, requires a proactive policy of maturation and industrial deployment on a GW scale with

- Fischer-Tropsch installations with optimised integration with respect to heat flows,
- high-temperature electrolysis or co-electrolysis HTE technologies (90% efficiency and higher),
- DAC technologies; it is reasonable to assume that their mass deployment will be accompanied by a continuous improvement in their performance, which is not taken

[L] The energy required for CO_2 capture is equal to 1.8 GJ electrical and 5.4 GJ thermal, i.e. a total of 7.2 GJ in accordance with the current state of the art of the Climeworks company.

[M] Efficiency here is the ratio of the energy value of the sustainable fuel produced (regardless of its composition) to the electrical energy to produce it.

into account here. An improvement in extraction efficiencies by a factor of 2 would allow both the HTE and DAC functions to be powered by the heat produced by the FT function[N].

Such an industrial policy is ambitious, but it is important to note that no solution, on the scale of requirements, will offer a significantly easier path.

Jet fuel selectivity depends on the optimisation of the overall system and in particular the looping of the different streams. Thus, by using both a hydrocracking step for the long chains and a reforming step for the short chains, it is possible to optimise the process in favour of jet fuel production.

Another strategy is possible. A Fischer-Tropsch reactor can be optimised to maximise the production of long chains before feeding a hydrocracking phase allowing maximum selectivity on diesel and jet fuel type chains. Selectivities of 75% to 85% have been obtained on diesel/jet fuel chains, of which 2/3 are jet fuel and 1/3 are diesel (see Appendix 2). On this basis, a selectivity of 60% in jet fuel can be envisaged.

In summary, for an optimised installation to produce e-SAF, an electrical efficiency of 55% and a selectivity of 60% can be envisaged. Thus, electrical energy of the order of 37 MWh will enable the production of 1 tonne of e-SAF and 0.67 tonne of e-diesel.

ENERGY COST FOR E-BIOSAF PRODUCTION

The energy input required for the production of e-bioSAF is of course reduced by the energy content of the biomass.

The inset on the right illustrates the effectiveness of adding hydrogen in terms of biomass savings. For a given fuel production, each tonne of exogenous hydrogen added saves 16 tonnes of biomass.

The energy cost of one tonne of hydrogen is less than 40 MWh if the best technologies are used and if hydrogen production is fully integrated into the process (so as to minimise intermediate steps and transformations).

Effect of adding hydrogen

Considering a basic model (see Appendix 3), the simple conservation of carbon and hydrogen mass shows that without adding hydrogen, the energy conversion efficiency of bioenergy into fuel is less than 40%, whereas it rises to 100% with the addition of hydrogen, the mass of which is 17.9% of the fuel mass. The amount of biomass required to produce 1 tonne of fuel is reduced by more than a factor of 2 thanks to this hydrogen input:

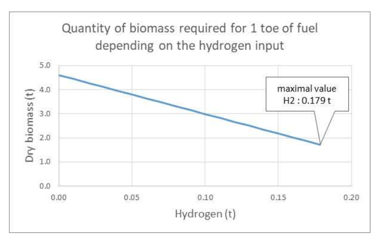


Figure 8 : Hydrogen injection reduces biomass consumption per unit of biofuel produced.

The energy content of one tonne of dry biomass is about 0.45 toe, or 5.2 MWh.

[N] Today, 75% of the energy consumption of a DAC plant is related to the need for heat. In the referenced process simulation[30], after supplying heat to the high-temperature electrolysis, the FT reaction still has enough surplus heat to cover 67% of the DAC plant's requirements. It can therefore be seen that an improvement of a factor of 2 in the heat required to extract CO2 from the air would be sufficient to make the SAF production plant self-sufficient in heat supply.

The supply of one tonne of exogenous hydrogen will cost 40 MWh and will thus save 83 MWh of biomass.

Even if the above result will be modulated by more realistic calculations, the importance and need for priority to be given to the addition of exogenous hydrogen in thermochemical processes for efficiently decarbonising air transport is demonstrated by the energy gain of a factor of 2 thanks to that hydrogen addition.

It is assumed here (see Annex 3) that the addition of a mass of hydrogen equal to 15% of the mass of fuel produced makes it possible to extract 0.45 toe per tonne of dry biomass. On this basis, with a little less than 40 MWh per tonne of H_2 and a jet fuel selectivity of 60%, the electrical cost of producing 1 tonne of e-bioSAF is therefore 10 MWh.

In summary, with an optimised installation for the production of e-bioSAF, we will quantitatively have an energy consumption of 40 MWh/tH_2 and with a jet fuel selectivity of 60%, the production of one tonne of e-bioSAF will require 0.25 tH_2 (i.e. around 10 MWh in electricity) and 3.6 tonnes of dry biomass (i.e. 1.6 toe of bioenergy).

INSTALLED CAPACITIES OF SEVERAL GW ELECTROLYSERS

About 80% of the electricity requirement is justified by electrolysis. Considering an efficiency range of 80% to 90% for high-temperature electrolysis and a load factor in the range of 70% to 80%, about 1.5 GW of electrolysers will be needed for every 10 TWh of electrolysis.

Thus, the installed capacity of high-temperature electrolysers will be just under 5 GW (with an efficiency of 90% and a load factor of 80%) for an industrial site producing 1 Mt of e-SAF and 0.67 Mt of e-diesel per year.

SUMMARY OF ELECTRICITY REQUIREMENTS FOR THE E-BIOSAF AND E-SAF CHANNELS

In a context where both biomass and low-carbon electricity dedicated to the production of SAF are limited resources that will drive the development of SAF, it will be necessary to optimise the proportion between e-SAF and e-bioSAF on the basis of:

- electricity consumption of 37 MWh per tonne of e-SAF,
- electricity consumption of 10 MWh and 3.6 tonnes of dry biomass (or 1.6 toe of bioenergy) per tonne of e-bioSAF.

For each tonne of e-SAF or e-bioSAF produced, 0.67 tonnes of diesel and naphtha will be co-produced. Choosing the best bioenergy/electricity combination for SAF production is equivalent to selecting a region of interest in the following figure:

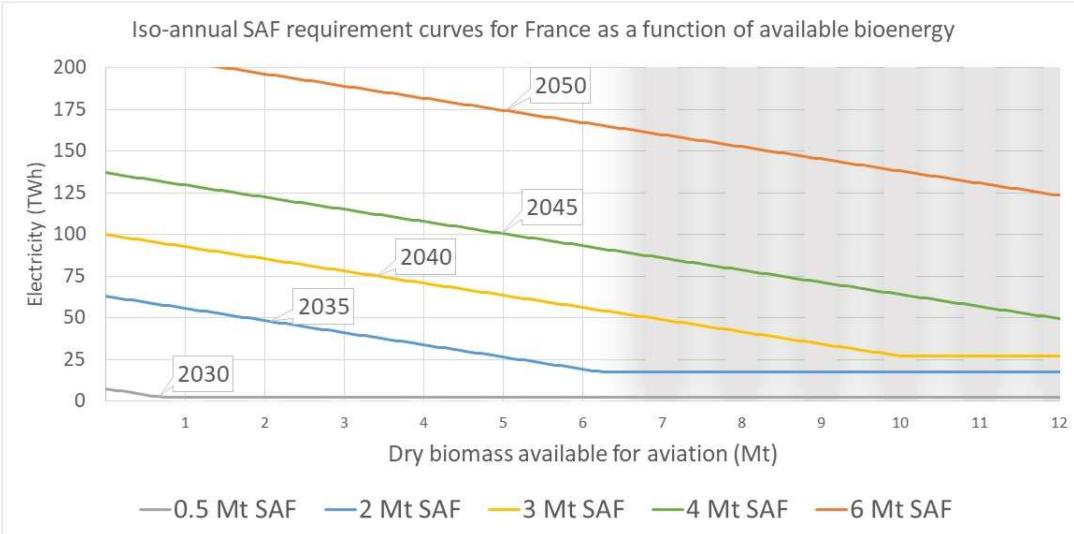


Figure 9 : Each curve reflects a quantitative SAF target. The points in the grey area imply an allocation of bioenergy to the aviation sector alone of more than 10% of the available bioenergy. Where bioenergy is sufficient, the SAF requirement (minus the oleochemical contribution) is met by e-bioSAF processes. Where bioenergy is insufficient, the remaining requirement is met by e-SAF processes.

Figure 9 expresses a system view necessary to establish a steering strategy between bioenergy consumption and electricity consumption:

- The availability of 50 TWh/year of electricity and 6.7 Mt of dry biomass would make it possible to meet the SAF requirement for 2040, i.e. 3 Mt of SAF (30% of the fuel consumption). The installed capacity of high-temperature electrolysers is of the order of 1.5 GW per 10 TWh.
- If only half of this biomass were available, 75 TWh/year of electricity would have to be used to produce SAF.
- In 2050, the electricity requirement, to cover 60% of fuel consumption, would be of the order of 170 TWh, to be set against a probable doubling of electricity production by that time (i.e. 1000 TWh).

The challenge is then to identify a low-carbon electricity resource of several tens of TWh in the next decade.

Chapter 5

THE AVAILABILITY OF LOW-CARBON ELECTRICITY IN FRANCE

With the 2019-2028 Multiannual Energy Plan (PPE[31]) and the RTE report "futurs énergétiques 2050" published at the end of 2021[7], French electricity production benefits from a short-term framework and long-term prospective scenarios. However, major decisions are still needed to set this trajectory in concrete terms. These decisions will profoundly modify the mix beyond 2040.

Before 2040, due to the inertia effect, the structure of the mix is known and is not dimensioned to accommodate a significant volume of new electro-intensive applications, in particular those related to hydrogen production. The effective launch of a SAF production industry, on the scale of the needs, must therefore be carried out on the basis of an electricity mix essentially dimensioned according to current consumption.

A decarbonised electricity mix, balanced between a controllable base and intermittent capacity, solar and wind, has the advantage of robustness in operation due to its controllable base and significant diversification in terms of generating technologies.

But such a mix, due to the increasing scale of its production, presents a new characteristic. The combination of sizing the mix according to peak demand and the intermittency of wind and solar power will generate excess production capacity with a large cumulative annual volume but with less than 100% availability.

To what extent can this "limited electricity availability" become a technically and economically viable product for the development of new industrial activities, including the production of SAF?

This chapter analyses the technical viability of a strategy to create the first significant level of SAF production from this "limited electricity availability". The next chapter will examine the economic viability of such a strategy.

SIZE AND CHARACTERISTICS OF THE ELECTRICITY REQUIREMENTS FOR SAF PRODUCTION

The orders of magnitude of the needs

The previous chapter has established the electricity requirements in France and over the next decade for SAF production. This demand depends on the level of biomass actually harnessed and of course on the trajectory imposed on this production.

The following table shows the electricity requirements for France in two situations. In the first, the biomass available for aviation reaches its high range of 6.7 Mt dry biomass and in the second it stagnates at a 40% lower value of 4 Mt dry biomass.

Electricity requirement		2030	2035	2040
Available biomass	6.7 Mtbs	2 TWh	17 TWh	51 TWh
Available biomass	4.0 Mtbs	2 TWh	34 TWh	71 TWh
for a SAF production of		0.5 Mtep	2 Mtep	3 Mtep

Table 6 : Orders of magnitude of the electricity consumption needed in the next decade according to the available biomass.

This table sets out the order of magnitude of the subject. In order to meet the need for SAF in the next decade, it will be necessary to unlock a rapidly growing electricity resource, up to 10% to 15% of current French production (538 TWh in 2019).

The level of electricity decarbonisation

The electricity used for the production of SAF must be deeply decarbonised. A consumption of about 37 MWh is needed to produce 1 tonne of e-SAF and 0.67 tonnes of sustainable diesel. The value of the operation is measured by comparing the emissions associated with the production of these 37 MWh with the combustion of 1.67 tonnes of fossil fuel, i.e. 6.9 tCO_2[O]. The carbon footprint of the electricity mix then determines the gain in carbon emissions associated with the production of e-SAF:

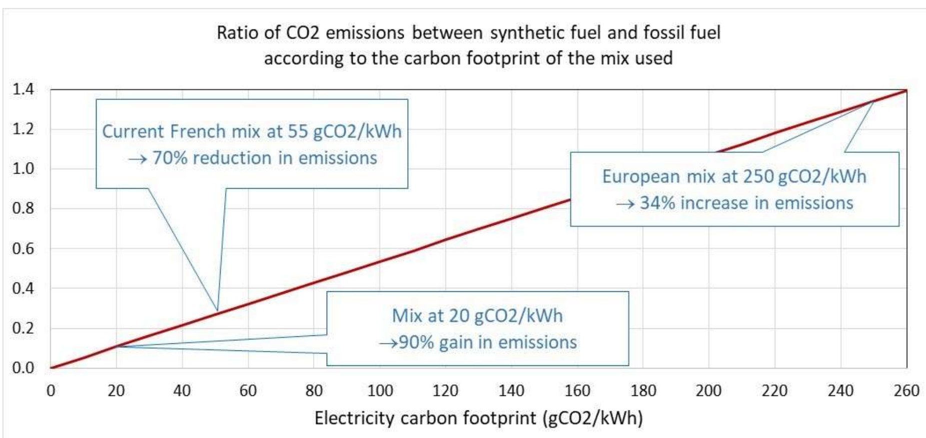


Figure 10 : The gain in carbon emissions associated with the production of synthetic fuel is highly dependent on the electricity mix used.

The considerable investments required by e-SAF production are only relevant if the carbon footprint of the electrical resource used is sufficiently low. Figure 10 shows that electricity at 20 gCO_2/kWh reduces kerosene emissions by a factor of 10.

The following assessments are based on the demand for a mix with a footprint of 20 gCO_2/kWh, thereby reducing the carbon footprint of fuels by a factor of 10, which is necessary to achieve a net neutrality target in 2050 together with sustainable abatement costs.

Competition between SAF production and decarbonisation of the mix

The production of e-SAF will therefore have to harness electricity resources that necessarily have a very low carbon footprint. The question then arises as to the best use of this electricity in terms of carbon efficiency. Indeed, this electrical resource can be used either for the production of e-SAF or to decarbonise the electricity mix:

[O] Fossil fuel combustion generates 44 GJ/t and 94 gCO2/MJ (ref.[9]).

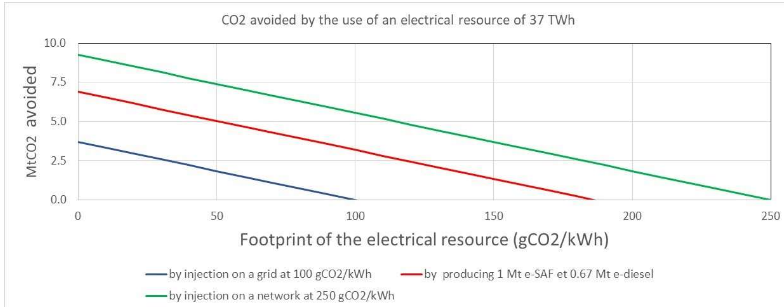


Figure 11 : The amount of carbon avoided for an electricity resource with a given carbon footprint depends on its use, i) the decarbonisation of a mix with a footprint of 100 or 250 gCO_2/kWh or ii) the production of 1 Mt e-SAF and 0.67 Mt e-diesel.

Figure 11 shows that the priority is to decarbonise the electricity mix rather than produce e-SAF in a mix with a footprint of 250 gCO_2/kWh, which is the average figure for emissions in the current European mix. More precisely, a synthetic fuel produced with electricity at 190 gCO_2/kWh will produce the same CO_2 emissions as fossil fuel.

With a mix of 55 gCO_2/kWh[P] (respectively 20 gCO_2/kWh), the production of each tonne of e-SAF (accompanied by 0.67 t of e-diesel) will avoid 4.9 tonnes of CO_2 (respectively 6.2 tonnes of CO_2). Thanks to its decarbonised electricity mix, France is already in a position to ensure the production of e-SAF with a positive impact on carbon emissions.

HYPOTHESIS ON THE EVOLUTION OF THE FRENCH ELECTRICITY MIX

The evolution scenario for the French electricity mix adopted here is based on i) life-extension of nuclear reactors to 60 years and ii) growth in installed wind and photovoltaic capacity consistent with the objectives of the PPE.

The conditions for achieving such a mix are not the subject of this report. They concern obtaining the necessary safety approvals, decisions on the renewal of the nuclear fleet, and a nominal capacity to deploy wind and solar generators.

The choice of this scenario is justified by the fact that only a robust mix will be able to release capacities allowing the production of SAF up to the level of need in the next decade. In order to be consistent, the following assessments are carried out on the basis of scenario N03, one of the scenarios developed by RTE in its study on the energy futures of 2050[32].

The RTE/N03 mix is designed to ensure a slightly increasing demand coming from the grid and the additional hydrogen production of 0.5 MtH2/year in the next decade (1 MtH2/year in 2050, i.e. 50 TWh). The hypothesis adopted here is that this hydrogen production will be oriented towards the decarbonisation of the current uses of hydrogen by industry (i.e. 0.9 MtH2/year and 9 MtCO2/year[33]). In its sizing, the RTE/N03 mix therefore does not include any capacity dedicated to the production of SAF.

In its "hydrogen+ scenario[34]", RTE envisages an increase in electricity production of 100 TWh by 2050 to meet the needs of a hydrogen economy (consuming 3 MtH2/year). Such an increase in demand will require a proportional increase in the installed capacity of nuclear (+16 GW) or solar (+89 GW) or wind power (+54 GW on land or 31 GW at sea) capacity, or any combination of these means. These scenarios will be important to consider for the decade 2040 and beyond.

[P] The production of the French mix emitted in 2021 36 gCO_2/kWh

The present analysis is focused on the next decade with the objective of a rapid and effective launch of the SAF industrial sector, at a scale of 1 to 3 Mt/year. This implies determining the electrical capacity that can be made available to this sector in the period 2030-2040 without requiring additional generators compared to the RTE N03 trajectory. Beyond 2030 and up to 2040, the deployment dynamics lead to marginal electricity needs (2 TWh); beyond 2040, an increase in electricity generation capacity will be necessary.

CAPACITY OF THE FRENCH ELECTRICITY MIX TO SUPPORT THE PRODUCTION OF SAF UNTIL 2040

The mix is dimensioned to meet the demand of the consumer grid as a priority. Due to its dimensioning on the peak of consumption and its important intermittent component, the mix presents periods of significant overcapacity compared to the need of the grid. The question is then to characterise this overproduction to determine if it offers opportunities for the launch of a SAF industrial sector in the next decade.

If one wants to capitalise on 100% of the overcapacity, it will be necessary to capture all the events, including the most intense and rarest ones (situations of high wind and solar overproduction associated with low demand); this will require a large installed capacity for the technological means of capturing the overcapacity, which will therefore have a low load factor. On the other hand, an average annual load factor can be imposed to ensure the economic viability of these capturing means, for example 80%, and the "quantity of electricity whose availability is greater than 80%" can be calculated and capitalised.

To evaluate this quantity, a simplified model is given, summarised in the double insert below, which deals precisely with solar and wind intermittency:

Characteristics of the electricity mix

Generating capacity is given by RTE's N03 scenario:

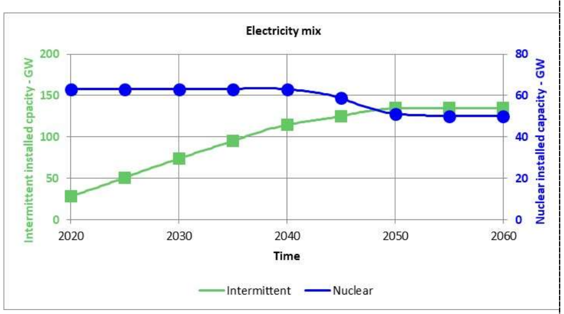


Figure 12: Evolution of installed capacity, nuclear and intermittent (i.e. wind plus photovoltaic) in the RTE/N03 electricity mix.

The hourly variability of demand, solar and wind generation is calibrated to the year 2019 (ENTSO-e data). The calibration on another year has no significant impact on this analysis.

When intermittent power is insufficient, the grid is fed by a compensation system consisting of gas-fired power plants and fuel cells that provide the necessary flexibility. The gas-fired power stations are domestic or foreign, thus simulating the power provided in practice by imports.

From 2030 onwards, the use of gas-fired power plants is limited by the carbon constraint of 20 gCO_2/kWh.

Effect of additional TWh demand

To test the robustness of the electricity mix, we add a demand E in TWh supposedly due to a new economic activity able to valorise over the next decade an electricity resource ensuring a load factor of 80 % to its production means.

The additional demand profile is as follows:

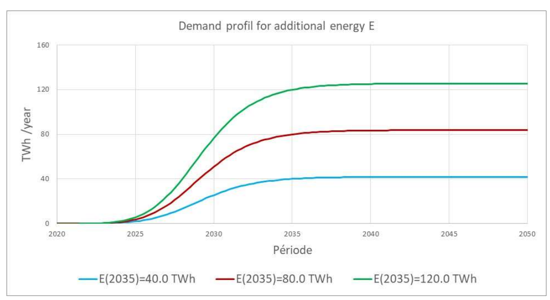


Figure 13: additional demand profile

The load factor of the energy harvesting means (e.g. electrolysers if the activity concerns hydrogen) then depends on the evolution of the mix and the additional demand of TWh:

Beyond this limit, the residual need for compensation is met by fuel cells powered by hydrogen produced by the electricity mix.

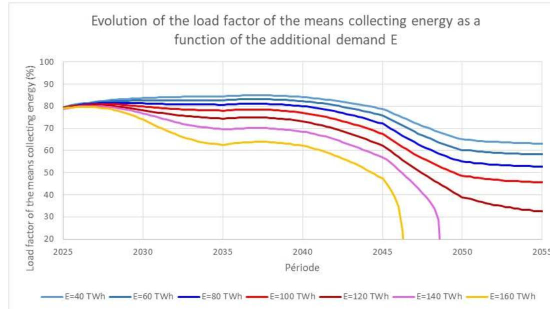


Figure 14: Capacity of the electricity mix to support additional demand.

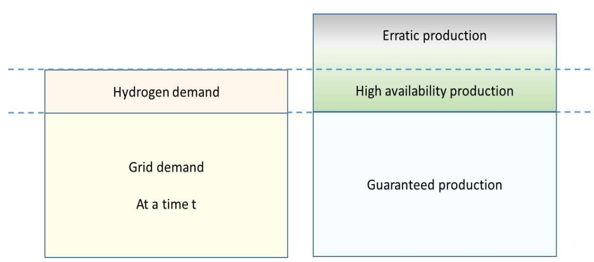
In the box above, the additional demand in TWh is fed by the episodes of overcapacity after the consumers' grid needs have been met. When this additional demand is too high, it is necessary to tap into the rarest overproduction events, which requires an increase in the installed capacity of the electricity-consuming facilities and a collapse of their load factor (Figure 14), until eventually, it becomes impossible to meet this additional demand.

The shape of the curves in Figure 14 follows from the evolution of the electricity mix given in Figure 12. It is clear that the robustness of the mix can only continue to be ensured if additional generating capacity comes onstream after 2045 to compensate for the nuclear units reaching the end of their life.

Figure 14 answers the question of how much electricity has an availability factor of 80%: until 2040, about 80 TWh of electricity can be collected by an economic activity that accepts a load factor of 80% for its means of production.

An availability factor of at least 70% until 2040 would allow 120 TWh to be harnessed for applications that accept such a 70% load factor for their generation assets. However, as shown in Figure 14, the system shows a bifurcation zone in its behaviour in the 120-140 TWh zone. This indicates a lower robustness to disturbances. In order to guarantee a certain robustness, a volume of 100 TWh can be envisaged with an availability of more than 70%.

This resource corresponds to the concept of "high availability generation". It complements the concept of "guaranteed generation" used to meet the demand of the grid. Beyond this volume of 80 TWh to 100 TWh with an availability of 70% to 80%, there is still significant generation that can be described as erratic, as its economic value gradually decreases with the decrease in the availability rate.



Such a result implies maintaining a robust and largely decarbonised electricity mix over the next decade, with a lifetime of 60 years for the nuclear fleet and a trajectory for wind and solar power that extends the commitments of the PPE. Numerous adverse realities may hinder this scenario. This raises the question of the robustness of the above results. If nuclear capacity were to be reduced by 5% (respectively -10%), at 80 TWh of additional demand, the load factor of collecting means would decrease by 4.7% (respectively -13%). For an additional demand of 100 TWh, for the same capacity reductions, the loss of load factor of the consuming facilities will be 6% and 16.5% respectively. This shows the beginning of non-linearity in the system response around 100 TWh.

The combination of an already largely decarbonised mix and an increase in intermittent installed capacity, while maintaining nuclear capacity at a constant level, provides France with a strategic opportunity to develop new industrial sectors (production of SAF, etc.) over the next decade, due to a resource of 80 TWh to 100 TWh with an availability rate of 70% to 80%.

High-temperature electrolysers can accept operation disturbed by some limited availability of electricity. This is made possible by keeping the electrolysers warm, by switching (on the scale of a few minutes) the operation of the electrolysers to an inert gas with a power consumption of the order of one percent of the nominal consumption.

COMPETITION FOR THE USE OF HIGH AVAILABILITY ELECTRICITY

This resource, with a high availability rate (80 TWh to 100 TWh for an availability of 70 % to 80 %), is obviously subject to competition for use. Only part of this resource will be allocated to SAF production.

If the electricity mix of the next decade has weaknesses, this resource with a high availability rate could be hampered by the need to maintain safety margins, thus preventing the development of industrial sectors, which require visibility and stability on this resource. Unsurprisingly, the production of SAF on the scale needed requires a robust electricity mix.

Exporting this resource is an alternative. In 2019, France exported 84 TWh and imported 28.3 TWh, giving a balance of 55.7 TWh. These flows are important in stabilising the European mix and the electricity exported by France has a positive impact on the decarbonisation of our neighbours' mix. There is thus a strategic trade-off between the export of this resource with a high availability rate and its domestic use for the benefit of reindustrialisation and the production of SAF. It should be noted that in all European countries that invest in hydrogen production, the question of the balance between direct export of electricity and domestic consumption in the production of hydrogen will arise and could have a major impact on the volumes of exchange between neighbouring countries.

Finally, this resource with a high availability rate will be called upon by several economic sectors, but on condition that the latter can be satisfied with electricity with an average annual availability of less than 100%. This condition limits competition.

Faced with these choices, it should be noted that the resource with a high rate of availability (80 TWh to 100 TWh) in the period 2030-2040 is a strategic capital whose impact may be decisive with regard to i) reindustrialisation objectives, ii) national commitments to decarbonisation, in particular for the aviation sector, and iii) sovereignty issues in the face of the economic and geopolitical challenges posed by energy.

Ensuring that some of this capital is allocated to the production of SAF is the best way to develop a capital-intensive industrial sector that produces SAF to meet the needs of the next decade.

CONCLUSION : FRENCH CAPACITIES FOR ELECTRICITY AND SAF PRODUCTION IN FRANCE IN THE PERIOD 2030-2040

The production of SAF is primarily driven by the availability of biomass and very low carbon electricity inputs. Chapter 4 showed that France could meet its SAF needs over the next decade (2 to 3 Mt of SAF) provided that 6 to 7 Mt of dry biomass and 50 TWh of electricity are available for this production.

A robust electricity mix of the RTE/N03 type allows for an electricity resource of 80 TWh to 100 TWh with an availability of 70% to 80% and a carbon footprint of 20 gCO_2/kWh in the period 2030-2040.

The arbitration on the use of this highly available electrical resource and biomass is a matter of public policy and, in coherence, of the implementation of instruments that will guide the market.

The low substitutability of liquid fuels in the aviation sector calls for a significant share of biomass and low-carbon electricity resources to be devoted to this sector. The table below illustrates the trade-offs that would be compatible with the decarbonisation objectives of the aviation sector:

	SAF Production in France	Electricity at 80% availability (e-bioSAF and e-SAF)			
	e-SAF + e-bioSAF + oleochimique SAF	25 TWh	50 TWh	80 TWh	100 TWh
Biomass for ebioSAF	2.0 Mtbs	1.4 Mt	2.0 Mt	2.9 Mt	3.4 Mt
	4.0 Mtbs	1.8 Mt	2.4 Mt	3.3 Mt	3.8 Mt
	6.7 Mtbs	2.3 Mt	3.0 Mt	3.8 Mt	4.3 Mt
	8.0 Mtbs	2.6 Mt	3.2 Mt	4.0 Mt	4.6 Mt

Reminder of the need for SAF	2030	2035	2040
France	0.5 Mt	2 Mt	3 Mt

Table 7: The comparison between the need and the quantities of SAF that can be produced (cumulatively from oleochemical SAF, e-bioSAF and e-SAF) determines the relative quantities of low carbon electricity and biomass that need to be reserved for SAF production.

The arbitrage of biomass and electricity resources, as illustrated by table 7, is the condition for reaching the SAF production objectives that are about to be set at the European level. It should be recalled that 6.7 Mt of dry biomass represents 10% of the bioenergy deemed available in France. Moreover, the additional electricity with 70% to 80% availability (in the order of 80 to 100 TWh) is a specific product, which is not called for by the conventional sectors that require a continuity of electricity supply, thus limiting competition between uses.

For every 10 TWh devoted to SAF production, the installed capacity of high-temperature electrolysers is 1.5 GW (cf. Chapter 4), confirming, as a central issue of an industrial policy associated with SAF production, the deployment in France and/or in Europe of a GW-scale industrial sector for high-temperature electrolysers

Beyond 2040, electricity generation capacity will need to increase significantly to support the growth in SAF production and the many other applications related to hydrogen production.

Chapter 6

SAF ECONOMICS

INTRODUCTION

The central issue in the economics of SAF is the cost differential between SAF and fossil jet fuel.

In the literature, an additional cost of a factor of 3 to 10 is most often mentioned. Such additional costs may become prohibitive for an airline industry where fuel represents 30% of operational costs.

A detailed examination of the assumptions that structure the evaluation of the additional costs associated with SAF is warranted. Important elements such as the cost of inputs or the maturity of technologies over time are rarely made explicit. This chapter analyses the cost of SAF from a medium to long-term perspective[Q]. The quantities of SAF actually required by the aviation sector are then significant, making the impact of SAF on the economic viability of the sector critical.

The analysis of the cost trends of fossil jet fuel in the coming decades provides the reference point (section "Fossil jet fuel, cost reference for SAF") to assess the economic relevance of the SAF option and to determine a carbon abatement cost.

The cost of SAF depends on the production technologies and the associated inputs. The previous chapters have shown that the technologies that will be driving most of the SAF scale-up will be based on the thermochemical pathway, with a start-up stage of the e-bioSAF type and a rapid transition to e-SAF. The feasibility of a complete decarbonisation of aviation rests, in the medium- and long-term, on the e-SAF pathway, which, moreover, is stated in all the references to be the most expensive one. Therefore this technology needs to be evaluated from an economic point of view in order to determine the feasibility of deploying SAF on the scale required. The following section specifies the production cost of e-SAF and its sensitivity to the components that make up this cost.

The sensitivity to the cost of electricity is important. The section "Cost of production of e-SAF" illustrates the economic gain associated with high availability electricity as identified in Chapter 5 for the French electricity mix in the 2030 - 2040 window.

Based on the above elements, the section "The carbon abatement cost of SAF" finalizes the evaluation of the abatement cost associated with the introduction of SAF, i.e. the additional production cost of that fuel in relation to the emissions avoided. These abatement costs are essential data for the development of an effective climate strategy, as they allow the prioritisation of decarbonisation actions and the identification of those likely to maximise the effective reduction of greenhouse gas emissions, at a given level of effort for the community[35].

[Q] The short term is dominated by the well-established market of the HEFA segment and low incorporation rates and used quantities. Although the period is important in terms of the emergence of standards and technologies, the economic stakes are less critical.

FOSSIL JET FUEL, COST REFERENCE FOR SAF

The rationale for SAF is the decarbonisation of air transport. The underlying logic is therefore to compare the incremental cost of the SAF pathway with the fossil one in a given period.

The issue of cost escalation between today's fossil jet fuel and tomorrow's SAF is an important issue for the economics of the airline industry, as it determines the evolution of the financial burden associated with the fuel. However, it is not the criterion for assessing the relevance of SAF. The price of SAF in 20 years' time must be compared with the price of fossil fuels in 20 years' time.

It is therefore necessary to establish a benchmark for the price of access to fossil jet fuel over the next two to three decades.

Oil price trends

Fossil fuels, led by oil, account for 84% of the 581 EJ consumed worldwide in 2019[36]. This figure shows the immense challenge associated with decarbonisation, whatever the vector is chosen: direct electrification where possible, conversion to low-carbon liquid or gaseous fuels for the rest.

The International Energy Agency (IEA) produces projections of oil production, consumption, and prices for the coming years. None of the forecasts have materialised, and often to a significant extent. Establishing a reference price for oil, the main resource underpinning our societies is indeed a delicate exercise given the high volatility of the subject.

Several factors explain the volatility of oil prices: capital intensity, production inertia in the face of changes in the context, inelastic demand due to the absence of substitute products, crises of various kinds, etc.

To simplify the subject, the aim here is to identify a reference oil price, defined as a trend quantity and accompanied by a wide range of uncertainty covering fluctuations in the real price over a dynamic range of a factor ½ to 2.

Figure 15 illustrates the evolution of the oil price over 150 years with 3 main stages, each characterised by a reference price:

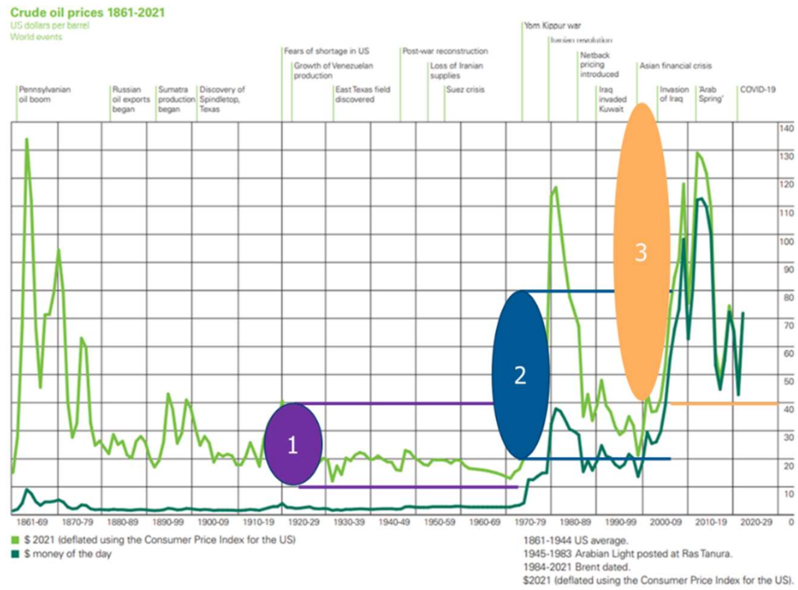


Figure 15 : Oil price developments since 1861[36]

After chaotic beginnings when oil was used as a lubricant, the beginning of the 20th century established the energy role of oil.

Tier 1, from 1928 to 1972, benefited from an administered oil price, essentially based on the domestic price in the US (the largest oil producer and consumer) around the $20/barrel reference price. Volatility was included in the ½ to 2 range, i.e. $10/barrel to $40/barrel.

Tier 2, from 1973 to 2007, is characterised by the US production peak in 1973 and the 1972 and 1979 shocks in the Middle East. For this stage, the reference oil price is set at $40/barrel with volatility in the range of $20 to $80 (except in 1979-80 when the fall in Iranian production wipes out 8% of world production).

Tier 3, from 2008 to 2020, sees the global peak in conventional oil production in 2008 and the Sub-prime crisis. This led to a continuous increase in the price of oil from 2002 ($36/barrel) to 2008 ($117/barrel, with a peak of $147/barrel). Since then, growth has been driven by other types of oil, which often have a worse CO_2 balance and are more expensive to extract. The reference oil price for this level is $80/barrel with volatility in the range of $40-160/barrel.

The peak of available oil resources, both conventional and unconventional, is predicted by a growing number of consulting firms before the end of the decade. As a result, it is likely that the stage that opens today will lead to a higher oil price than in tier 3.

Beyond the crises that have marked its history, the price of oil is structurally influenced by the evolution of its ease of extraction. This ease of extraction is measured by the *energy return on investment* (EROI), which is the ratio of usable energy to energy invested[37]. The historical EROI for on-shore wells in the Middle East was 30 to 100; for shale oil, it drops to 5 to 10. Historically high EROIs explain the prices in Tier 1. In Tier 2, the need to develop offshore fields is accompanied by a halving of the associated EROIs and justifies an increase in prices. In Tier 3, the rapid progress of unconventional oil (EROI<10) is driving up oil prices.

Provided that price volatility is encapsulated in a ½ to 2 range, the reference price for oil has risen in three historical steps from $20/barrel to $40/barrel to $80/barrel.

The benchmark oil price, excluding fluctuations, will continue to rise over the long-term due in part to the continued decline in EROIs.

The additional cost of SAF is often considered in reference to a price of 0.5 €/l for fossil jet fuel. This is consistent with Figure 16 for the period 2017 to 2021. But this cyclical reference cannot be used to measure the economic and social impacts associated with fossil fuel substitution. A conventional approach, but consistent with the above trend analysis, is to consider a jet fuel reference price over the period 2030-2050 at €1/litre (€1200/toe) with a volatility in the range of €0.5 to €2/litre.

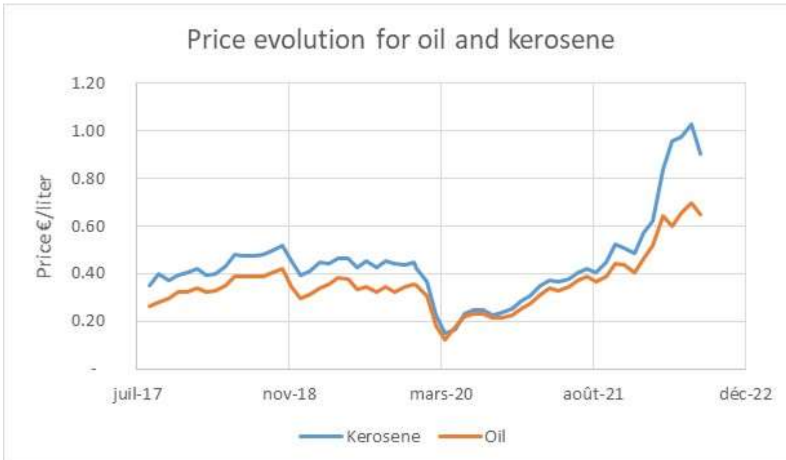


Figure 16 : Illustration of recent oil and jet fuel price developments.

The carbon penalty of fossil jet fuel

Air transport is exempt from the TICPE (Internal Consumption Tax on Energy Products, Article 265 bis of the French Customs Code); this concerns deliveries of petroleum products for the fuelling of commercial aircraft other than tourist aircraft.

The exemption from jet fuel taxes on international air routes dates back to the Chicago Convention (1944) which aimed to encourage air transport. The provision has been extended by bilateral agreements.

> Convention on International Civil Aviation[38]; Article 24, Customs duties
>
> (a) on a flight to, from or through the territory of another Contracting State, any aircraft shall be temporarily admitted free of duty, subject to the customs regulations of that State. Fuel, lubricating oils, spare parts, regular equipment and aircraft stores carried on an aircraft of a Contracting State on arrival in the territory of another Contracting State and still carried on the aircraft on departure from that territory shall be exempt from customs duties, inspection fees or other similar duties and charges imposed by the State or local authorities.

The tax exemption of aviation fuel is being debated in Europe. While it seems difficult to reverse the Chicago Convention, it is likely that intra-European flights will soon be taxed. The following box illustrates the direction taken by the European Commission.

> Revision of the Energy Taxation Directive (ETD): Questions and Answers 14/7/21[39]
>
> « Kerosene used as fuel in the aviation industry and heavy oil used in the maritime industry will no longer be fully exempt from energy taxation for intra-EU voyages in the EU. This is a crucial measure given the role of these sectors in energy consumption and pollution. Over a period of ten years, the minimum tax rates for these fuels will gradually increase while sustainable fuels for these sectors will benefit from a minimum rate of zero to foster their uptake. »
>
> « The tax for aviation fuel will be introduced gradually before reaching the final minimum rate after a transitional period of ten years. This means that ten years after the entry into force of the new rules, kerosene used in the aviation industry to power planes for intra-EU flights would be taxed at least €10.75/GJ EU-wide, as for petrol used in road transport. To encourage the use of cleaner energy in both the aviation and maritime sectors, sustainable and alternative fuels will enjoy a zero rate minimum tax rate for a transitional period of 10 years when used for air and waterborne navigation ».

The tax envisaged by the European Commission for intra-European flights is €10.75/GJ, i.e. a CO_2 tax of €114/tCO_2 (with 94 gCO_{2e}/MJ as defined in the RED II Directive). The additional cost for fuel would be 0.39 €/l.

The increasing efforts required to adapt society to the energy and climate challenges singularly reinforce the questions of social equity in the distribution of constraints and priorities. Whether or not a carbon tax is introduced for the air transport sector, the evaluation and comparison of decarbonisation strategies require a carbon penalty to be associated with fossil jet fuel. The strategic interest of developing SAF will thus be measured by a carbon abatement cost calculated from the above penalty trend excluding tax.

While it is impossible to predict the evolution of jet fuel costs between now and 2050, it is not relevant to use a jet fuel reference price of €0.5/l and a complete tax exemption of jet fuel as a benchmark to gauge the environmental, economic, and social value of SAF.

The peak of oil resources that can be put on the market before the end of the decade and the continuous decrease in the rates of return on oil investments justify taking as a conventional reference a fossil jet fuel price of €1 per litre for the next two decades.

It is against this conventional basis that the relevance of the deployment of SAF will be assessed by the associated abatement costs.

COST OF PRODUCTION OF E-SAF

For each component structuring the production cost of e-SAF, a central case is defined below around which it will be possible to analyse the sensitivity of the various assumptions.

Capex of e-SAF production facilities

The infrastructure necessary for the production of e-SAF is considered. The scope covers the electrolysers, Fischer-Tropsch reactor, hydrocracking and reforming facilities, but not the electricity generators. The facilities produce "diesel equivalent fuel" from which a diesel fraction and a jet fuel fraction are extracted.

Depending on the use, capex is expressed in €/(l/year), €/kW or €/(t/year). The transformation between these units is based on the density of the diesel equivalent produced (0.835 kg/l), its energy value (44 MJ/kg), and the annual load factor (8000 h/year). Furthermore, a clear distinction must be made between the capex values for the "diesel equivalent" fuel and for the SAF fuel, whose selectivity will be taken as equal to 60%.

The literature review[40] conducted by the industry association Concawe concludes that Capex costs could be reduced from €8 in 2015 to €3 in 2050 per annual litre of diesel equivalent, or from €9.6 billion to €3.6 billion per annual Mt.

With a selectivity of 60%, this corresponds for the production of a SAF unit to a decrease from 16 G€ to 6 G€ per annual Mt, or from 10 k€ to 4 k€ per kW or from 13 € to 5 € per annual litre.

In the Peters et al[30] reference already cited for its very detailed study, a capex of 3.2 € per annual litre of diesel equivalent can be envisaged in the short-term, a value consistent with the previous reference. At 760 €/kW, the weight of high-temperature electrolysers in the capex is of the order of 50%. The research agenda of the European Clean Hydrogen Partnership[29] anticipates a cost of 520 €/kW for 2030, i.e. a 32% reduction in the electrolysis capex and therefore a 16% reduction in the total capex. There is still room for improvement.

The capex cost for the production of synthetic fuel is assumed to be €3 per litre of diesel equivalent. If the electricity used by the installation has an availability factor λ, for example 80%, the capex cost increases by a factor of 1/λ.

The inputs for e-SAF

Input-related costs are the main component of operational costs.

For the central case, the cost of electricity is assumed to be 30 €/MWh. This point will be substantiated in a later paragraph. A range of 20 € to 50 € is retained around the central case.

The second input for the production of e-SAF is CO_2.

It can be obtained by extraction of industrial off-gases produced for example by cement plants. As shown in Annex 1, the energy cost of extracting CO_2 from such effluents is much lower[R] than that associated with direct air extraction (DAC).

The use of CO_2 from polluting industries is being debated in Europe. In addition to questions about who should receive the carbon credit, there are concerns that this approach will ultimately inhibit the decarbonisation efforts of these industries. The extraction of CO_2 from industrial waste may offer short-term opportunities, but regulatory uncertainty may discourage investors. As such, and still in the spirit of assessing the costs of massive SAF production in the medium- to long-term, the benchmark for making available CO_2 is DAC technology.

Today, this technology is being deployed in first industrial units by companies such as Carbon Engineering and ClimeWorks. The costs announced for these first units exceed €500/tCO_2 with a decrease announced towards €200/tCO_2. In its study of a large-scale installation[41], the company Carbon Engineering announces a cost of 94 to 232 $/t$CO_2$.

CO_2 extraction is mainly a heat-consuming process. The optimum is to use waste heat. In an integrated process, the Fischer Tropsch reactor is exothermic and can satisfy the heat requirements not only of the high-temperature electrolysis, but also of the CO_2 extraction. Specifically, according to Peters et al[30], after feeding the HT electrolysis, the residual thermal power in an integrated process is sufficient to cover 97% of the needs for CO_2 extraction from cement plant effluents and 67% of the needs of DAC systems. Annex 1 shows that current DAC processes consume 15 to 20 times more energy than the thermodynamic limit. Progress factors are therefore possible and it can be anticipated that the heat produced by the Fischer-Tropsch reactor will eventually be sufficient to cover the heat requirements of both HT electrolysis and DAC.

By optimising the thermal coupling of DACs and Fischer-Tropsch reactor, the cost retained in the central case for CO_2 is 150 €/tCO_2. An improvement of a factor of 2 in the extraction efficiency of DACs would allow the heat requirements to be covered by the exothermicity of the Fischer-Tropsch reactors and would further reduce the costs. A range of 100 € to 250 € is retained around the central case.

Production cost of e-SAF

The discounted cost of an e-SAF can then be assessed on the basis of the following assumptions:

[R] The reference Peters et al[30] considers an energy cost for the extraction of one tonne of CO2 equal to (0.2 MWh electrical, 1.03 MWh thermal) for cement effluents and (0.5 MWh electrical, 1.5 MWh thermal) for DAC.

	Cas central	Low range	High range
Capex	**3 € per litre/year** (= 3.6 G€ per Mt/year of e-fuel)	2.7 €/l (i.e. -10 %)	4.5 €/l (i.e. +50 %)
Discount rate	**5 %**	2 %	8 %
Amortisation	**20 ans**	15 ans	25 ans
Electrolysis efficiency	**90 %**	80 %	100 %
Expenses	**15 %**	10 %	20 %
CO_2	**150 €/tCO₂**	100 €/tCO₂	250 €/tCO₂
Electricity	**30 €/kWh**	20 €/kWh	50 €/kWh

Table 8: Three sets of cost assumptions to calculate the cost of producing e-SAF

The expenses correspond to maintenance, overheads, including taxes and insurance, and various production costs. The electricity requirement is determined by the efficiency of the process. This efficiency is equal to 55%, as derived from the analysis of the Peters et al study[30]. The effective capex cost equals that given in the table above divided by the availability of electricity taken here to be 80%.

The production of SAF is accompanied by the production of diesel, as well as other co-products such as waste CO_2 or oxygen. The economy of these co-products is neglected here. Furthermore, the SAF and diesel produced are assigned the same value, as otherwise the selectivity of jet fuel, taken here at 60%, could not have a viable value[S].

Based on the above information, the production cost of e-SAF can be presented in the form of a Tornado diagram:

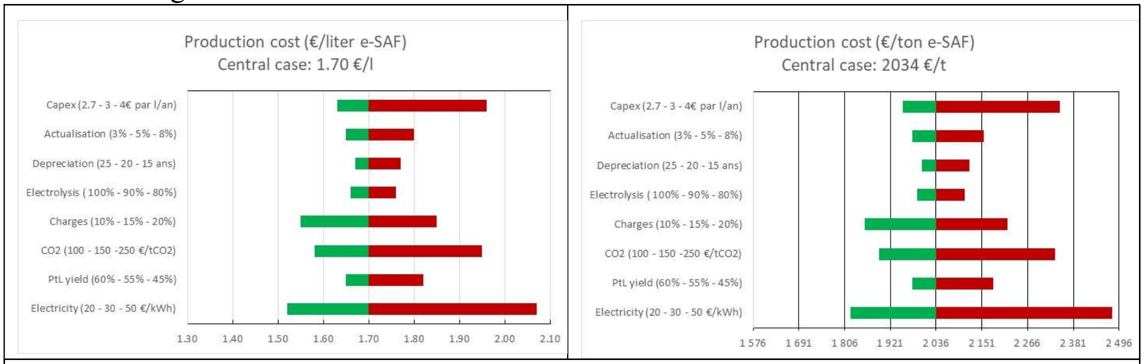


Figure 17 : The diagrams illustrate the sensitivity of the production cost of e-SAF to the different cost components, in € per litre on the left and in € per tonne on the right.

The production cost of e-SAF for the central case parameters is 1.7 €/l, or 2034 € per tonne. Figure 17 shows the sensitivity of the different parameters.

Unsurprisingly, the first challenge is to reduce the capex to 3 €/l (i.e. 3.6 G€ per annual Mt of e-fuel). This assumes, in particular, the industrial maturation of high-temperature electrolysers, which represents half of the investment.

The second critical parameter is the price of electricity. It is essential to identify approaches to minimise this price. Indeed, all other things being equal, each €10/MWh increase in electricity

[S] In the literature, diesel is sometimes valued at the current market price, which leads to an overpricing of SAF.

costs adds €0.2/l to the cost of e-fuels. Thus, a price of €80/kWh leads to e-fuel production costs of €2.64/l or €3160/toe.

A 10% reduction in capex to 2.7 €/(l/yr) and a reduction in CO_2 costs to 100 €/tCO_2 would reduce the cost of e-fuels to 1.5 €/l (1800 €/t). It is difficult to see the cost of synthetic fuels being significantly lower than 1.5 €/l.

Cost of electricity in the production of SAF

In the international arena

The share of electricity in the cost structure of e-SAF is a dominant term. The production of competitive e-SAF and e-bioSAF requires the identification of a strategy for low carbon and low-cost electricity. Indeed, since the production of one tonne of e-SAF requires at least 37 MWh, the sole contribution of electricity at €50/MWh to the cost of e-SAF would already be €1.54 per litre of e-SAF. To hope to produce e-SAF at less than €2/l, it is necessary to have electricity that costs significantly less than €50/MWh. This issue is not specific to SAF and is more generally part of the problem of low-cost hydrogen production.

Many projects under development are based on a strategy of producing electricity using dedicated wind and/or photovoltaic generators and deployed in host countries with favourable physical conditions for such production (Morocco, Chile, etc.). This approach decouples the production of SAF, and more generally of hydrogen, from the issues of the electricity mix supplying the domestic consumer grid. Project developers can then consider only the levelised cost of electricity (LCOE) without the significant system costs associated with the continuity of operation required for a national electricity mix. Orders of magnitude of 20 €/MWh can thus be reported in public communications. Nevertheless, it should be noted that each Mt of e-SAF requires at least 35 TWh, i.e. a quantity of energy commensurate with the national consumption of the host countries often cited. Import solutions, which are probably unavoidable, could raise sensitive geostrategic and ethical issues over time.

The alternative is to consider domestic production channels, an alternative that faces serious limitations in most countries.

This alternative is excluded for the vast majority of countries whose mix is carbon intensive. We have seen that for an e-SAF to bring a significant benefit to the decarbonisation of the aviation sector, its carbon footprint must not be much higher than 20 gCO_2/kWh.

In order to have both a low LCOE and a low carbon footprint, the concept of wind and/or solar generators dedicated to hydrogen production is being considered in Europe. However, it should be noted that, in an average European mix of 250 gCO_2/kWh, the same amount of low-carbon generators dedicated to decarbonising the electricity mix would have a much better carbon avoidance efficiency at a given cost.

In the US, the US/DOE is funding programmes to support the development of solutions that integrate nuclear power and high temperature hydrogen production[42]. The US/DOE envisages $30/MWh electricity supplied by nuclear power plants that can continue to produce when the grid is in low demand[43].

To evaluate the cost of hydrogen production, these studies are based on the cost of electricity production by specific power plants and not on the market price of electricity, taking into account local specificities and, in particular, the fact that these power plants are amortised[44]. This decoupling of the grid electricity market from the sustainable fuel production market is a structural point in the thinking.

In France

The specificity of the French situation, as introduced in Chapter 5, is based on a scenario involving stable nuclear production and continued growth of wind and photovoltaic energy. This scenario is by nature transitory and will last until 2040.

Such a scenario provides a volume of 80 TWh to 100 TWh/year for new applications with an availability guarantee of 70% to 80%.

The price of a $TWh_{80\%}$ (electricity with 80% availability) cannot be equal to the price of electricity with 100% guaranteed supply. The sale of a $TWh_{80\%}$ product is more generally included in grid services. The practical arrangements for managing and contracting a $TWh_{80\%}$ can be diverse, but when translated into long-term contracts, they result in a lower effective price for electricity with reduced availability.

The guaranteed availability factor $\lambda<100\%$ determines a product whose economic value is Π_λ expressed in €/TWh_λ. To create the same production unit, an industrialist will mobilise a capex production capacity $\mathcal{K}$ and an annual volume of electricity E if it is supplied with 100% guaranteed electricity. If the same industrialist uses electricity with availability λ, he will have to mobilise a larger production capacity of capex equal to $\mathcal{K}/\lambda$. For this industrialist, the optimal value of λ will then depend on the difference between the cost of the extra investment $\frac{\mathcal{K}}{\lambda} - \mathcal{K}$ and the gain on his electricity bill $E.(\Pi_{100} - \Pi_\lambda)$.

This illustrative reasoning is developed in Annex 4 and leads to the following results:

- The maximum price $\Pi_{N\lambda}$ that an industrialist is willing to pay for electricity with an availability rate λ is obtained by cancelling out the net present value of the extra investment project, which amounts to balancing the cash outlays related to the investment with the gains on the electricity price;
- This maximum price $\Pi_{N\lambda}$ depends on the value of the capex $\mathcal{K}$, the annual volume of electricity consumed, the discount rate and the availability factor λ;
- For an industrialist, the decision to make an initial extra investment against the promise of a guaranteed return through the long-term supply of electricity at price Π_λ implies a risk premium. The discount rate for the extra investment $\frac{\mathcal{K}}{\lambda} - \mathcal{K}$ is legitimately higher than that for the main investment $\mathcal{K}$;
- For example, based on long-term contracts allowing for 100% available electricity at a price of Π_{100} = 50 €/MWh_{100} (respectively 80 €/MWh) with a capex of 7.5 B€ and 35 TWh used for the production of 1 Mt of SAF, an industrialist will make use of electricity whose availability λ is guaranteed if its price Π_λ verifies :

discount rate r=12%	long term contract 50 €/MWh	long term contract 80 €/MWh
availability factor λ = 100 %	$\Pi_\lambda = \Pi_{N\lambda}$ = 50 €/MWh	$\Pi_\lambda = \Pi_{N\lambda}$ = 80 €/MWh
availability factor λ = 80 %	$\Pi_\lambda \ll \Pi_{N\lambda}$ = 41 €/MWh	$\Pi_\lambda \ll \Pi_{N\lambda}$ = 71 €/MWh
availability factor λ = 70 %	$\Pi_\lambda \ll \Pi_{N\lambda}$ = 34 €/MWh	$\Pi_\lambda \ll \Pi_{N\lambda}$ = 64 €/MWh

Table 3. Change in electricity price $\Pi_{N\lambda}$ at the neutrality point where the net value of the extra investment project is offset by the gains in electricity price.

During the transitional period up to 2040, the aim is to allow the development of applications such as SAF production and to delay the need for access to 100% guaranteed electricity, the sizing of which currently only meets the needs of the grid for normal consumers and not for new electro-intensive activities. To this end, the strategy is to ensure a price $\Pi_\lambda \ll \Pi_{N\lambda}$ that is sufficiently attractive to value the electricity guaranteed at only limited availability.

The opportunity related to electricity with availability λ<100% is a strategic one in the transitional period, both to help the development of new electro-intensive economic sectors and to give time for the reinforcement of the power infrastructure. With an electricity price in long-term contracts of €50/MWh (respectively €80/MWh), an electricity price close to €30/MWh (respectively €50/MWh) is conceivable with a guaranteed availability of 70% to 80%. This amounts to a 40% reduction in the price of electricity for a loss of availability of 20% to 30%.

The following table gives an illustration of the economic challenge involved:

Yearly production 0.3 Mt fuel	Electricity price	Electricity cost	Capex	e-fuel cost
Electricity availability 100 %	50 €/MWh	0.34 G€/an	1.10 G€	2.1 €/l
Electricity availability 80 %	30 €/MWh	0.20 G€/an	1.35 G€	1.7 €/l

Table 9 : Illustration of the balance between a gain on the electricity bill and an additional investment cost

Beyond 2040, it will be necessary to reshape the electricity mix to accommodate new applications of electricity, among others in connection with the decarbonisation of transport. In a balanced strategy between a controllable base, hydro and nuclear, and a significant intermittent share, the development of electricity with limited guaranteed availability will remain relevant. This will allow both to increase the value of electricity generators and to offer low-cost electricity to electro-intensive industries that can manage a load factor of some of their production means limited to 70% or 80%.

THE CARBON ABATEMENT COST OF SAF

The reference price of fossil jet fuel for the next two decades is €1/l, i.e. €1200/toe. With a carbon footprint of 20 gCO_2/kWh, the emissions associated with 1 litre of e-SAF are equal to 0.371 $kgCO_2$ compared to 3.45 $kgCO_2$ emitted by fossil jet fuel. The direct abatement cost[45] is the extra cost of the SAF option compared to the fossil reference divided by the volume of emissions avoided by the SAF option compared to the fossil reference:

$$CA(eSAF) = \frac{1.7\text{ €} - 1.0\text{ €}}{3.45\ kgCO_2 - 0.371\ kgCO_2} = 227\text{ €}/tCO_2$$

This direct abatement cost rises to 324 €/tCO_2 if the cost of electricity (50 €/MWh) justified a cost of e-SAF close to 2 €/l.

Reference fossil cost:	1.00 €/liter				
carbon abatement cost		Electricity carbon footprint			
	€/tCO2	10 gCO2/kWh	20 gCO2/kWh	50 gCO2/kWh	100 gCO2/kWh
e-SAF cost	1.55 €/liter	168	178	218	344
	1.70 €/liter	214	227	277	438
	2.00 €/liter	306	324	396	626
	2.50 €/liter	459	487	594	939

Table 10 : With a low-carbon mix and by investing part of the additional electricity in the production of SAF, France can produce SAF with a direct abatement cost of about 200 to 300 €/tCO_2.

The notion of 'carbon budget abatement cost' is introduced by France-Stratégie to evaluate long-term strategies from the point of view of the community. This carbon budget abatement cost is the ratio of the discounted SAF additional costs to the sum of the undiscounted CO_2 gains:

Discounting allows the determination of the relative efficiency of decarbonisation efforts in different areas, regardless of the date of carbon emissions. The abatement cost in the carbon budget associated with e-SAF is as follows:

With a socio-economic discount rate of r = 4.5 %: $CA_{BC} = \frac{\sum_1^N \frac{surcoût(t)}{(1+r)^t}}{\sum_1^N gain\ CO_2(t)}$.

Discounting allows the determination of the relative efficiency of decarbonisation efforts in different areas, whatever the date of the carbon emissions. The abatement cost in carbon budget associated with e-SAF is as follows:

Reference fossil cost	1.00 €/liter				
Abatement cost (€/tCO2) according Levelised carbone budget (4.5 %)		Electricity carbon footprint			
		10 gCO2/kWh	20 gCO2/kWh	50 gCO2/kWh	100 gCO2/kWh
e-SAF cost	1.55 €/liter	98	104	127	202
	1.70 €/liter	124	132	162	257
	2.00 €/liter	178	189	231	367
	2.50 €/liter	267	283	346	551

Table 11 : Abatement cost of e-SAF in carbon budget, discounted at a socio-economic rate of 4.5%.

The carbon budget abatement cost of e-SAF can therefore be less than 200 €/tCO_2. This result should be compared with the cost of transforming thermal cars into electric cars, estimated by the Criqui Commission[46] between €300/tCO2 and €400/tCO_2. This establishes the relevance of the e-SAF option for society.

Chapter 7

ELEMENTS FOR A PUBLIC POLICY

INPUT DATA FOR A PUBLIC POLICY ON SAF

In 2035 and 2040, SAF production should be around 2 Mt/year and 3 Mt/year in France. Figure 18 illustrates the resources needed per million tonnes of SAF:

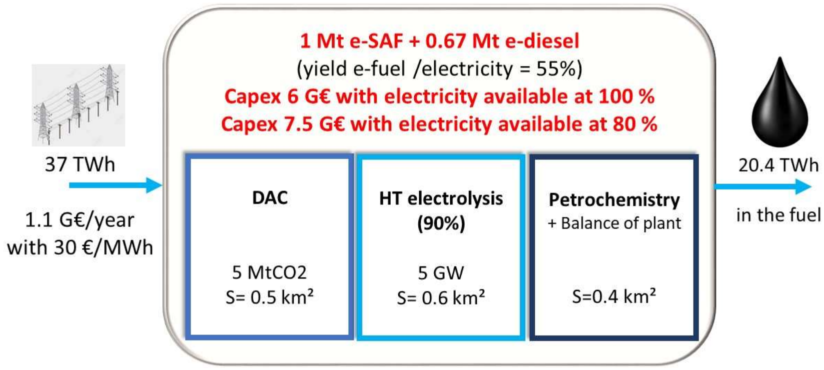


Figure 18: Illustration of the resources required to produce 1 million tonnes of e-SAF and 0.67 tonnes of e-diesel.

Many conditions must be met to allow such investments.

It involves building a capital-intensive industry, integrating innovative technologies, and leveraging resources that need to be secured on a large scale. The challenge is considerable and involves the establishment of an international SAF market that is financially, regulatory, and competitively viable. This must be done under the constraint of increasing competition for access to physical resources (biomass, low-carbon electricity). The increase in power requires a high level of integration, commitment, and coordination of public and private actors.

The production of the energy vectors necessary for decarbonisation will require a large volume of low-carbon resources (hydraulic, wind, solar, biomass, nuclear) as well as other inputs (soil, materials, water, etc.). It will be necessary to plan and control the use of these resources in an approach that is inevitably cross-sectoral, multi-criteria[T], and endowed with an integrative and long-term vision. It seems difficult to imagine that market forces alone can bring about the best allocation of these resources.

If only the market prevails, competition between different economic sectors would be regulated according to the "purchasing power" of these sectors. It can be assumed that the aviation sector will be able to adjust its "demand-price" curve (i.e. its tolerance of price increases) more easily than the domestic heating sector in order to pre-empt the biomass it needs. This then leads to an increase in biomass prices and a gradual exclusion from the market of less economically powerful sectors. More precisely, the equilibrium price of biomass is then induced by the abatement cost of alternative technology (e.g. synthetic fuels) available to the aviation sector. This equilibrium price then determines the ratio of access to biomass for each economic sector,

[T] These criteria concern inter alia environmental benefits, economic performance, social justice, substitutability of solutions, etc.

with the most economically powerful sector driving the process and depending on the cost of alternative technologies (synthetic fuels).

The natural behaviour of the market mentioned above is not without difficult social issues and political arbitrage. The allocation of both biomass and low-carbon electricity between different economic sectors is a central issue that will require inclusive approaches, not just based on marginal cost calculations. Access to biomass or low-carbon electricity determined by a free market is not necessarily optimal for society; it will be the role of regulation to frame market tensions and build the desired balance.

Given the heavy investments required, the guaranteed availability, over two or three decades, of critical inputs (biomass, low-carbon electricity) is a condition for the industrial ramp-up of SAF. Whatever the resource required for the production of SAF, it is either already used by one or more other economic sectors, or is in the process of being so:

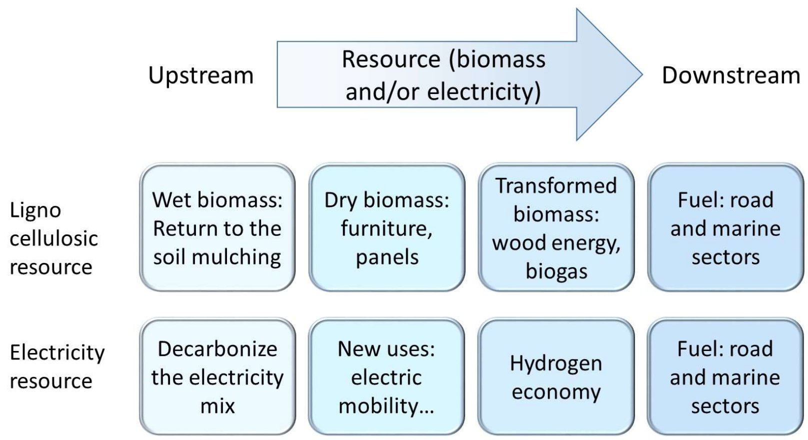


Figure 19: Illustration of competing uses with the aviation sector at different stages of biomass and low carbon electricity use.

Economic or geopolitical tensions can accelerate conflicts of use or modify their shape. For example, the conflict in Ukraine has significantly increased interest in the production of biogas from agricultural waste and could, in the long-term, complicate access to this primary resource on the European territory.

MAIN POINTS AND RECOMMENDATIONS

The above study illustrates the challenges and uncertainties posed by the decarbonisation of modern economies. The necessary convergence of public and private actors towards the same long-term objective justifies the early implementation of coherent and ambitious industrial and energy policies characterised by the following important points:

- The decarbonisation of the aviation sector, like that of other economic sectors, poses several challenges, the first of which is to identify and produce the low-carbon energy resources that are needed.
- The second challenge concerns the scaling up of a large-scale industry from 2030-2035. The dynamics of this industrial deployment are now on the critical path towards the 2050 targets.

- According to the objectives of the European ReFuelEU directive currently being finalised, the need for sustainable aviation fuel will be around 30 million tonnes for Europe and 6 million tonnes for France by 2050. One third of these needs will have to be met by 2035. The magnitude of these figures puts into perspective the uncertainties associated with, for example, the evolution of traffic, and the analysis below would not be different if the needs could be reduced by ten or twenty percent.
- Whatever technologies are considered, decarbonising the aviation sector and other economic sectors will require the production of a volume of low-carbon energy in 2050, comparable to current electricity production.
- Part of the low-carbon energy needed to decarbonise the aviation sector will come from the transformation of biomass. In Europe, the eligible biomasses are rigorously controlled to ensure their environmental relevance and their non-competition with food production. The oleochemical route, using used cooking oil for example, is in full development and could provide a few percent of the need. Lignocellulosic biomass will take over during the growth phase, but will probably not be able to produce more than 20% of aviation fuel consumption. There are uncertainties about this resource, both in terms of its physical availability and its collection, and because of complex trade-offs between economic sectors (residential and tertiary heating, biogas production, maritime and air transport, etc.). Structural uncertainties about the biomass available for aviation could discourage industrial investment and reduce the share of sustainable fuels produced in this way to below 20% of requirements. **Biomass can contribute about twenty percent to the production of "bio-jet fuel" for aviation, but this requires securing a rate of availability of biomass for the aviation sector within the framework of a public policy that rationalises the allocation of bio-energy to the different economic sectors in the long-term.**
- To significantly decarbonise aviation, it will be necessary to implement technologies that will require large quantities of low-carbon electricity. The first step is to make the best use of available biomass by doubling its conversion efficiency into biofuel by adding hydrogen. Thus, the production of 1 Mt of sustainable kerosene fuel (and concomitantly 0.7 Mt of sustainable diesel) will require 3.6 Mt of dry biomass and 10 TWh of electricity to produce the hydrogen. **However, the most of the need for sustainable aviation fuel will be met by the production of 'synthetic jet fuel' from hydrogen and CO_2 captured from the air.** In a transitory manner, CO_2 can also be captured in industrial waste at the cost of a decarbonisation performance that is half as good. The production of 1 Mt of synthetic jet fuel (and concomitantly 0.7 Mt of synthetic diesel) would then require 37 TWh of electricity, 85% of which would be used for electrolysis, 4 to 5 GW of high-temperature electrolysers, 5 Mt of CO_2, and a capital of 6 to 8 billion euros.
- The production of sustainable aviation fuel requires the deployment of large-scale, high-tech industrial infrastructures. Achieving the above performances requires the industrial maturation of high-temperature electrolysis and CO_2 air capture technologies and the optimised integration of these infrastructures. For these infrastructures and technologies to be ready by 2050, a first stage of industrialisation on a significant scale must be launched from 2030-2035: the challenge is, therefore, to take the decision quickly, and probably as early as 2025, to launch an industrial sector for the production of sustainable aviation fuel in the form of bio-jet fuel with the addition of hydrogen and synthetic jet fuel.

- The need for decarbonised electricity is considerable. By 2050, decarbonising the aviation sector, but also other sectors of the economy, will require a doubling of electricity production in advanced societies and a tripling on average worldwide. For the gain measured in cost per ton of CO_2 avoided to be viable and justify the significant investments required, this electricity must be highly decarbonised, down to 20 gCO_2/kWh, compared to the current 36 gCO_2/kWh for France and 275 gCO_2/kWh for Europe. Thanks to its low-carbon electricity mix, France has the opportunity to launch a domestic industrial sector for the production of sustainable fuel as early as 2030-35, whereas most countries will have to develop import strategies while waiting for the progressive decarbonisation of their electricity mix.
- By extending the lifetime of most of its nuclear reactors to 60 years and by maintaining a sustained growth in wind and photovoltaic energy, France can have a margin of a hundred TWh in the 2030-2040 decade sufficient to launch an industrial policy for the production of energy molecules such as hydrogen and more particularly the production of sustainable fuels for aviation. For the period 2040-2050, it will be necessary to aim for a doubling of the installed power generation capacity to decarbonise the various sectors of the economy, including the aviation sector, which, as of today, requires the relaunch of a nuclear reactor construction sector.
- Under these assumptions, it will then be necessary to clarify the trade-offs between the use of biomass and electricity (particularly regarding exports) as part of a coherent energy and industrial policy. The two pillars of these policies will be the establishment of a first industrial stage from 2030-35 for the production of energy molecules and robust and strongly growing low-carbon electricity production. For most countries, these policies will be based on import strategies raising complex geopolitical issues, whereas France will be able to develop an efficient domestic component thanks to its decarbonised electricity mix.
- Provided such policies are implemented and allow for both guaranteed inputs (biomass and electricity) and rapid industrial development at scale, the cost of sustainable fuel production could converge towards €2/litre, i.e. a direct carbon abatement cost close to €300 per tonne of CO_2. This abatement cost indicates that decarbonising aviation is a viable and desirable option, thus justifying efforts to implement it rapidly.
- A public policy supporting the rapid emergence of a sustainable fuels sector offers several strategic interests: effective decarbonisation of the aviation sector, virtuous use of periods of excess electricity production capacity (i.e. continuous use of nuclear reactors at nominal power), development of the hydrogen economy and other energy molecules, reinforcement of energy independence, important contribution to reindustrialisation, improvement of the trade balance, reinforcement of the economy of the territories.
- Such a policy could develop incentive and support mechanisms giving shared objectives to economic actors, a regulatory framework creating the conditions for an efficient market, and long-term planning for the production of biomass and low-carbon electricity both in terms of the quantities available and the frameworks for their use.

TECHNICAL ANNEXES

ANNEX 1: THE PROCESSES « DIRECT AIR CAPTURE »

Extracting CO_2 from a medium involves an entropic reduction whose thermodynamic cost depends on the concentration of CO_2 in the medium, as shown in the box below:

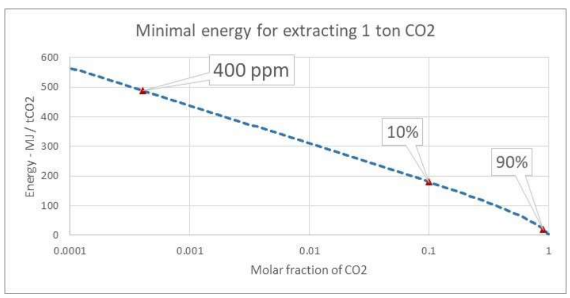
Minimum energy for CO_2 extraction from the air

The minimum energy required for the extraction of CO_2 from a carrier gas is obtained for an assumed perfect process by considering a carrier gas (x moles) and the CO_2 (y moles).

The concentration of atmospheric CO_2 has exceeded $\frac{y}{x+y}$ = 400 ppm in 2016 and grows by 2 ppm per year. It is worth noting $\frac{y}{x+y}$ = 10 % for flue gas from a fossil fuel power plant and $\frac{y}{x+y}$ = 90 % for biogas purified from methane.

At the limit of reversible processes, the extraction of CO_2 requires a heat input of Q to compensate for the entropy change:

$$Q = T\Delta S \text{ avec } \Delta S = -xRLog\left(\frac{x}{x+y}\right) - yRLog\left(\frac{y}{x+y}\right)$$



At T=20 °C, for concentrations equal to 400 ppm, 10 % et 90 %, the minimum energy to extract 1 tonne of CO_2 is respectively 490 MJ, 180 MJ et 20 MJ. :

To date, technological processes are 10 times less efficient than the theoretical thermodynamic efficiency: extracting one tonne of CO_2 from the atmosphere will use more than 5 GJ.

Carbone Engineering proposes a CO_2 capture plant (using a potassium/calcium cycle in the aqueous phase) that requires 8.8 GJ per tonne of CO_2 extracted. The company *Climeworks* proposes a process that would consume around 1750 thermal kWh and 200 kWh of electricity, i.e. a total of 7 GJ for 1 tCO_2 extracted.

Reference[47] evaluates the energy cost of different processes for extracting CO_2 from the air:

- ZSW process (absorption/electrodialysis): 430 kJ/molCO_2, or 9.8 GJ/tCO_2;
- PARC process (absorption/electrodialysis): 300 kJ/molCO_2, or 6.8 GJ/tCO_2 ;
- Carbon Engineering (absorption/calcination): 10 GJ/tCO_2;

- ClimeWorks (absorption/desorption, temperature swing adsorption): 7.1 GJ/tCO_2.

There is therefore a convergence on the energy requirement of DAC processes to date between 7 and 10 GJ/tCO_2. In existing industrial processes, the energy cost of CO_2 capture is mainly provided in the form of heat.

Estimates of energy consumption are currently in the order of 15 to 20 times the thermodynamic cost, suggesting a significant margin for progress. For example, in a more prospective manner, the so-called "Faradaic electro-swing reactive adsorption for CO_2 capture" process[48] allows us to expect an energy cost of capture equal to 3 GJ/tCO_2, i.e. an efficiency multiplied by 2 or 3. This process, with a low TRL (Technology Readiness Level), offers the decisive advantage of not being very dependent on CO_2 concentrations.

ANNEX 2: JET FUEL SELECTIVITY IN A FISCHER-TROPSCH PROCESS

The distribution of alkane chains of length C_n in a Fischer Tropsch reactor depends on a parameter α which designates a probability of propagation of carbon chains. The mass fraction of a C_n chain in the total production is then given as a first approximation[U] by the formula $n(1-\alpha)^2\alpha^n$. (Anderson-Schultz-Flory law):

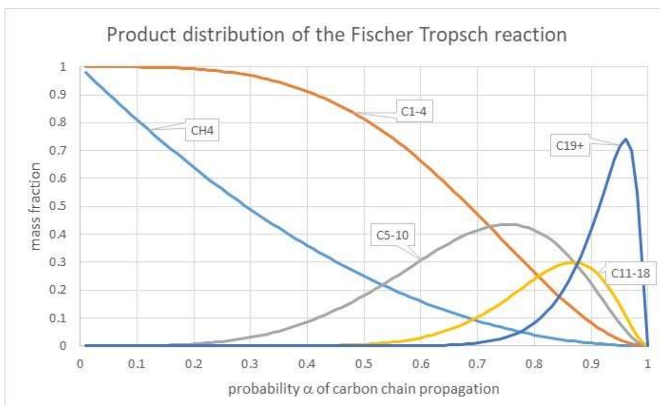
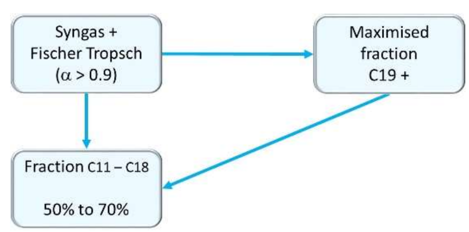


Figure 20: Through the choice of catalysts, it is possible to optimise the distribution of alkane chains produced in the Fischer-Tropsch reaction

The maximum direct production of the diesel-jet fuel fraction is around 30% (for α=0.87). At this value of α, 27% of long chains (C19+) are equally obtained, which can be cracked and thus increase the diesel-jet fuel fraction to 40%[49].

The figure above shows that the selectivity of the Fischer-Tropsch process can only approach 100% for very short and very long chains.



Exploiting this fact, Shell developed the two-stage SMDS[50] process in the early 1990s. Through the choice of catalysts in the Fischer Tropsch reactor, the first stage allows α to be close to 1 and thus maximises the production of long chains. The second step optimises the cracking mechanisms to target intermediate chain lengths. Since the early 1990s, the process has demonstrated its ability to achieve 75% to 85% selectivity in the production of diesel and jet fuel, with the possibility of maximising the share

[U] The mass fraction of a chain of length n is proportional to its length n multiplied by the probability of attaching n-1 carbons, i.e. $\alpha^{(n-1)}$ and by the probability of closing the chain with two hydrogens, i.e. $(1-\alpha)^2$.

of jet fuel in a 2:1 ratio, i.e. 50% to 57% jet fuel production. The process has been deployed in several GtL refineries[51].

In view of the results already obtained over a long period of time, it is appropriate to consider a jet fuel selectivity in the range of 50% to 70%. A selectivity of 60% will be used.

ANNEX 3: CONVERSION EFFICIENCY OF BIOMASS TO FUEL

The composition[52,53] of the biomass $C_xH_yO_zN_tS_u$ is well characterised in all its diversity:

N°	Biomasse	Analyse élémentaire (%)					Formule chimique				
		C	H	O	N	S	x	y	z	t	u
Bois et biomasse ligneuse											
1	Bois de hêtre	46,9	6,2	45,9	0,3	0,7	3,90	6,2	2,86	0,02	0,02
2	Bois de bouleau	48,4	5,6	45,8	0,2	-	4,03	5,6	2,86	0,01	-
3	Bois dur (moyenne)	48,6	6,2	41,1	0,4	-	4,05	6,2	2,56	0,02	-
4	Bois d'épicéa	48,3	6,3	44,6	0,4	0,4	4,02	6,3	2,78	0,02	0,01
5	Bois de Subabul (Leucaena leucocephala)	48,2	5,9	45,1	0,0	-	4,01	5,9	2,81	0	-
6	Bois tendre (moyenne)	52,1	6,1	41,0	0,2	-	3,25	6,1	2,56	0,01	-
Déchets agricoles											
7	Coquille de noisette	52,3	6,5	26,8	5,2	9,2	4,35	6,5	1,67	0,37	0,28
8	Bagasse	43,8	5,8	47,1	0,4	-	3,65	5,8	2,94	0,02	-
9	Tige de maïs	43,8	5,7	48,9	0,9	0,1	3,65	5,7	3,05	0,06	0,028
10	Bagasse de canne à sucre	45,1	6,0	42,7	0,3	-	3,75	6,0	2,66	0,02	-

La composition élémentaire de certaines biomasses est inférieure à 100, à cause de la non-quantification du soufre et des minéraux.

Table 12 : Elementary composition of some lignocellulosic biomasses, taken from the reference [53]

For an idealized model, the average formula $C_6H_9O_4$ can be used.

The ability to convert dry biomass into fuel depends directly on the mass ratio of carbon $R_{C/dry\ biomass}$ and hydrogen $R_{H/dry\ biomass}$. With a biomass model given by the formula $C_6H_9O_4$, these mass proportions are $R_{C/dry\ biomass} = 49.7\%$ and $R_{H/dry\ biomass} = 6.2\%$.

With a hydrogen-to-carbon ratio of 3:2, biomass has a hydrogen deficit compared to fuel (2:1 ratio). Hydrogen is the limiting factor that drives the production of fuel through the Fischer-Tropsch reaction, $(2n+1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$.

Definitions

The following quantities are used to characterise the performance of a biofuel production process:

Chemical energy of one tonne of fuel:	$\varepsilon = \frac{11.63\ MWh}{toe} = \frac{42\ GJ}{toe}$
Chemical energy of dry biomass (db):	$\varepsilon_{db} \equiv \frac{Biomass\ energy\ (toe)}{Mass\ of\ dry\ biomass\ (tdb)}$
Mass conversion efficiency:	$\rho \equiv \frac{Fuel\ mass}{Mass\ of\ dry\ biomass}$
Energy efficiency:	$r \equiv \frac{Fuel\ energy}{Dry\ biomass\ energy} = \frac{\varepsilon}{\varepsilon_{db}} . \rho$
Carbon efficiency:	$\sigma \equiv \frac{Mass\ C\ /\ fuel}{Mass\ C\ /\ biomass} = \frac{6}{7} \frac{\rho}{R_{C/db}}$
The supply of exogenous hydrogen:	$\mu \equiv \frac{Exogenous\ hydrogen\ mass}{Fuel\ mass}$

Maximum efficiency

If 100% of the carbon is transferred from biomass to fuel (σ=1), the maximum mass conversion efficiency is obtained: $\boldsymbol{\rho}_{\mathbf{max}} \equiv \frac{\textbf{Maximum fuel mass}}{\textbf{Mass of dry biomass}} \equiv \frac{7}{6}\mathbf{R}_{C/bs} = \mathbf{57,9}\ \%$.

For intermediate values of carbon efficiency $\sigma \equiv \frac{\text{Mass C/fuel}}{\text{Mass C/biomass}}$, by definition, the mass conversion efficiency is $\boldsymbol{\rho} \equiv \boldsymbol{\sigma}.\boldsymbol{\rho}_{\mathbf{max}}$.

The energy yield for a perfect transfer of carbon from biomass to fuel is then: r_{max}=100%. The maximum chemical energy of the biomass can be deduced from this:

$$\boldsymbol{\varepsilon}_{\mathbf{db}} = \boldsymbol{\varepsilon}.\ \boldsymbol{\rho}_{\mathbf{max}} = \mathbf{0{,}579}\ \mathbf{t_{oe}/t_{db}}.$$

In this idealized model, by the simple conservation of atomic masses, the energy yield is equal to the carbon yield:

$$r \equiv \frac{\text{Fuel energy}}{\text{Dry biomass energy}} = \frac{\varepsilon}{\varepsilon_{db}}.\rho \equiv \frac{\rho}{\rho_{max}} \equiv \sigma \equiv \frac{\text{Mass C/fuel}}{\text{Mass C/biomass}}$$

Efficiency without exogenous hydrogen supply

The biomass provides a mass of hydrogen equal to $R_{H/db}.\ M_{db}$. The mass ratios for the Fischer-Tropsch reaction are for hydrogen, carbon and fuel respectively: 1, 3, 7/2. The mass of carbon that can be converted to fuel in a Fischer-Tropsch reaction is therefore $3.R_{H/bs}.M_{db}$ and the fuel mass is then $\frac{7}{2}R_{H/bs}\ M_{bs}$.

The mass conversion efficiency without hydrogen input is therefore:

$$\boldsymbol{\rho}_{\mathbf{0}} \equiv \frac{\text{Fuel mass without } H2\ addition}{Masse\ of\ dry\ biomass} = \frac{7}{2}\boldsymbol{R}_{H/db} = \mathbf{21.7\ \%}$$

$$\text{and } \mathbf{r_0} \equiv \frac{Fuel\ energy\ witho\ \ \ H2\ addition}{\text{Dry } biomass\ energy} = \frac{\rho_0}{\rho_{max}} = \frac{\frac{7}{2}\boldsymbol{R}_{\frac{H}{bs}}}{\frac{7}{6}\mathbf{R}_{\frac{C}{bs}}} = \mathbf{37.5}\ \%\ ;\ \sigma_0 \equiv \frac{\text{Mass C/fuel}}{\text{Mass C/biomass}} = r_0$$

Each tonne of dry biomass provides 0.579 toe of energy and will supply 0.217 toe of fuel, resulting in an energy conversion efficiency of 37.5%.

Efficiency with exogenous hydrogen supply

To obtain an energy yield between r_0 and r_{max}, an exogenous hydrogen supply is required.

A mass M_{db} of dry biomass allows the production of a mass $\rho.M_{db}$ of fuel with an exogenous hydrogen input of $\mu.\rho.M_{db}$. The production of a mass $\rho.M_{db}$ of fuel requires a mass $\frac{2}{7}\ \rho M_{db}$ of hydrogen of which $\frac{2}{7}\ \rho_0 M_{db}$ is contributed by the biomass.

Thus, we have $\frac{2}{7}\ \rho M_{db} = \frac{2}{7}\ \rho_0 M_{db} + \mu.\rho.M_{db}$; i.e.:

$$\boldsymbol{\mu} \equiv \frac{\mathbf{M_{H2-exogenous}}}{\mathbf{M_{fuel}}} = \frac{2}{7}\left(\mathbf{1} - \frac{\boldsymbol{\rho}_{\mathbf{0}}}{\boldsymbol{\rho}}\right) \qquad \text{varying from 0 to } \boldsymbol{\mu}_{\boldsymbol{max}} \equiv \frac{2}{7}\left(\mathbf{1} - \frac{\boldsymbol{\rho}_{\mathbf{0}}}{\boldsymbol{\rho}_{\boldsymbol{max}}}\right) = \mathbf{17.9\%}$$

For each value of the additional mass μ of hydrogen, the yields are:

$$\boldsymbol{\rho} \equiv \frac{\boldsymbol{Fuel\ mass}}{\boldsymbol{Mass}\ \textbf{of dry}\ \boldsymbol{biomass}} = \frac{\boldsymbol{\rho_0}}{\mathbf{1}-\frac{7}{2}\boldsymbol{\mu}} \quad \textbf{et} \quad \mathbf{r} \equiv \frac{\textbf{Fuel energy}}{\textbf{Dry biomass energy}} = \frac{\boldsymbol{r_0}}{\mathbf{1}-\frac{7}{2}\boldsymbol{\mu}}$$

When μ = 0, we have again $\rho=\rho_0$ and $r=r_0$.

When $\mu = \mu_{max}$ = 17.9%, we have again $\rho=\rho_{max}$=57.9% et r=100%, since $1 - \frac{7}{2}.\mu = \frac{\rho_0}{\rho_{max}} = r_0$.

With a hydrogen input of 17.9% of the fuel mass, each tonne of dry biomass provides 0.579 toe of energy and will deliver 0.579 toe of fuel, i.e. an energy conversion efficiency of 100%.

To produce 1 tonne of fuel, 1/ρ tonnes of biomass and μ tonnes of hydrogen will be required. For a given fuel production, adding hydrogen saves biomass:

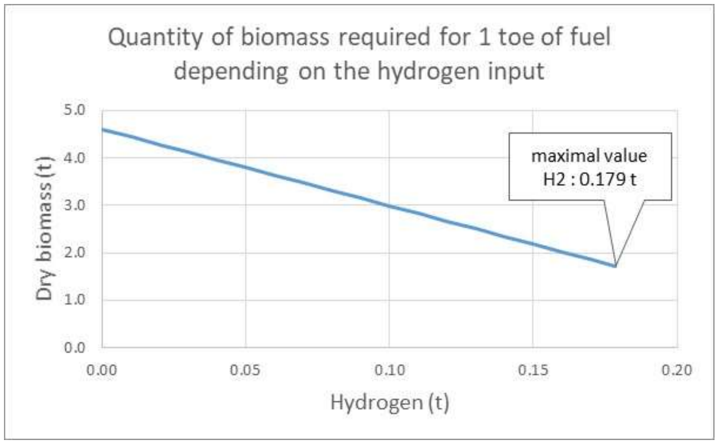


Figure 21 : The amount of dry biomass needed to produce one tonne of fuel is reduced from 4.6 tonnes to 2.2 tonnes by adding a mass of hydrogen equal to 15% of the fuel mass.

Comparison with physical data

In the idealized model, one tonne of dry biomass has an energy value of 0.579 toe which can be converted into fuel, without H_2 input, with a maximum efficiency of 37.7%, or 0.217 tonnes of fuel.

In practice, one tonne of dry biomass delivers an energy value of between 0.4 toe and 0.5 toe. We will use 0.45 toe. The conversion into fuel without H_2 input is often given with a maximum yield of 50%, i.e. 0.225 tonnes of fuel, which is comparable with the value of the idealised model.

Even if the orders of magnitude are satisfactory, there are significant differences between the complex reality of the biomass and the idealized model above.

In the idealized model, adding a mass of hydrogen equal to 15% of the mass of fuel leads to an energy conversion efficiency $r \equiv \frac{\text{Fuel energy}}{\text{Dry biomass energy}} = 79\ \%$. Applied to the energy value of biomass 0.579 toe/tdb, **0.45 tonnes of fuel per tonne of dry biomass are obtained by adding a mass of hydrogen equal to 15% of the mass of the fuel produced. This performance will be used to characterise the e-bioSAF processes.**

ANNEX 4: PRICE OF ELECTRICITY WITH GUARANTEED LIMITED AVAILABILITY

The price of electricity with guaranteed limited availability, for example at a value of λ = 70%, results from the tension between the interests of electricity suppliers and users. To illustrate this mechanics, a simplified model with two players is considered.

1. The Supplier is here the actor who aggregates the ecosystem of electricity producers, of regulation, and of private and public governance. The Supplier has the obligation to satisfy the needs of the Grid, defined as the whole of the consumers requiring

100% availability. The Supplier is responsible for the infrastructure necessary to meet this obligation.

2. The "User" represents a community of electro-intensive industrialists, developing a new sector of the economy. Initially, this User is not a consumer of the Grid: the initial mix does therefore not include this new economic activity in its dimensioning. The economic sector addressed by this User requires, in the long-term, a consumption of the order of a few tens of percent of the need associated with the Grid.

Here we examine the derivation of a price for electricity at availability λ as a result of the following tensions:

- the User may be interested in a volume of electricity with availability λ, but at the cost of an extra investment for his production capacity of the order of 1/λ . The trade-off between cheaper electricity per unit of volume and an extra capacity investment will determine his appetite for electricity with availability λ;
- if the price defined by the Supplier for electricity with availability λ is too high, the User will prefer to minimise its production capacity by buying its electricity from the Grid with two negative consequences for the Supplier: on the one hand, the by-product "electricity with availability λ< 100%" is not valorised, but above all, the level of demand from the Grid increases, obliging the Supplier to invest in heavy infrastructure.

Considering that the ARENH (French regulated access to historical nuclear energy) cost and the cost of long-term contracts for electro-intensive customers converge, we can consider that Π_{100}, the price[V] of guaranteed electricity at λ=100%, is of the order of Π_{100} = 50 €/MWh.

The User wishes to produce 1 Mt-SAF per year. Its annual electricity consumption is 37 MWh/ton-SAF, i.e. 37 TWh.

In order to benefit from an attractive tariff, the User shall enter into long-term contracts for the purchase of electricity with an availability rate λ characterised by a price Π_λ. This contract is deemed to ensure that the User has an average load factor for its generation infrastructure at least equal to λ. In practice, the specific commitments contained in such a contract result from the common interest of a given user and supplier to valorise together electricity with limited availability λ.

The capex $\mathcal{K}$ for such an industrialist is between 5 G€[54] and 10 G€[6] per Mt of SAF[W]. As an illustration, we can consider $\mathcal{K}$ = 7.5 G€/Mt-SAF.

What is then the best strategy for the User in terms of the value of λ?

There is a point of neutrality where the price of guaranteed limited availability electricity $\Pi_{N\lambda}$ is such that the User experiences the same economic performance either by minimising its capex at the price of 100% guaranteed expensive electricity, or by buying cheap electricity at the price $\Pi_{N\lambda}$ at the price of an extra capex cost.

To evaluate the influence of λ in concrete terms, we consider that the User builds his infrastructure in N_C years and makes it profitable over N_R years with a discount rate r. The capex for such a facility is $\mathcal{K}/\lambda$. For simplicity, we assume a constant annual expenditure stream

[V] In this annex, the notion of price covers only production costs. Transport costs, taxes and other elements of real price structuring are not mentioned here.

[W] The low range applies to mature costs, as assessed in prospective studies such as the study[54]. The high range applies to projects under development such as BioTJet[6].

during construction and during operation with a maintenance cost M and an annual electricity consumption E.

The User's production cost is then :

$$production\ cost = \frac{\sum_{n=1}^{N_C} \mathcal{K}/_{\lambda N_C}\frac{1}{(1+r)^n} + \sum_{n=N_C+1}^{N_R}\frac{M+E\Pi_\lambda}{(1+r)^n}}{\sum_{n=N_C+1}^{N_R}\frac{P}{(1+r)^n}} = \frac{\frac{\alpha\mathcal{K}}{\lambda}+M+E\Pi_{N\lambda}}{P}$$

The discount term α(r) incorporates the discount rate and the construction and amortisation periods:

$$\alpha(r) = \frac{1}{N_C}\,\frac{f(N_C)}{f(N_C+N_R)-f(N_C)}$$

$$with\ \ f(N) = \frac{1-{}^{1}/_{(1+r)^N}}{r}\ \ ;$$

$$\alpha(r=0) = 1/N_R$$

The neutrality point, for which the User can either minimise its capex with a high electricity cost or minimise its electricity cost with a higher capex is given by :

$$\frac{\alpha\mathcal{K}}{\lambda}+M+E\Pi_{N\lambda} = \alpha\mathcal{K}+M+E\Pi_{100}\quad i.e.:\quad \boldsymbol{\Pi_{N\lambda} = \Pi_{100} - \frac{\alpha\mathcal{K}}{E}\left(\frac{1}{\lambda}-1\right)}$$

If the industrialist accesses electricity of availability λ for a cost $\Pi_\lambda > \Pi_{N\lambda}$, it is better for him to minimise his capex (at the value $\mathcal{K}$) and buy guaranteed electricity for a cost Π_{100}.

If the industrialist accesses electricity of availability λ for a cost $\Pi_\lambda < \Pi_{N\lambda}$, it is better for him to buy electricity at the availability rate λ, and for this to assume a capex at the value $\mathcal{K}/\lambda$.

The price $\Pi_{N\lambda}$ at the neutrality point sets the scale for the value of electricity at availability rate λ. This price varies from one economic sector to another depending on the capex and the sector-specific electricity consumption.

The formula giving $\Pi_{N\lambda}$ shows that:

- if the availability λ is close to 100%, the price $\Pi_{N\lambda}$ converges well to Π_{100};
- if the availability λ decreases and becomes low, the price $\Pi_{N\lambda}$ decreases to zero. It will take a very low contract price Π_λ and below $\Pi_{N\lambda}$ for a User to agree to valorise this electricity. The slope of variation of $\Pi_{N\lambda}$ with λ depends on the capex and the electricity consumption;
- if the capex $\mathcal{K}$ increases or the need for electricity E decreases, the price at the neutrality point $\Pi_{N\lambda}$ decreases: the price that a User is willing to contract for electricity at availability λ decreases.

To illustrate the dependence on λ, the following case of application is considered:

- construction and amortisation periods: NC = 3 years and NR = 20 years;
- the discount rate is r = 8%;
- for an annual production of 1 Mt of SAF, the capex is $\mathcal{K}$=7.5 G€ and the electricity consumption is 35 TWh.

For the above application case, the dependence in λ of the price at the neutrality point $\Pi_{N\lambda}$ is given by the figure to the right for different capex.

For λ=70% and a capex of 7.5 G€, the price at the neutrality point is 40 €/MWh.

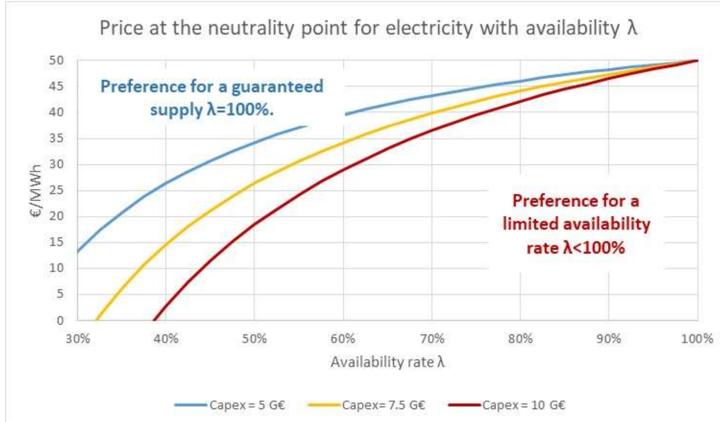


Figure 22: Price of electricity with limited availability, balancing the gains in electricity cost with the induced extra investment.

The strategic interest of the Supplier is to delay as much as possible the entry of the User among the consumers linked to the Grid, because this entry mechanically implies the increase of the infrastructures producing electricity. Such an increase of capacity requires a delay of a decade or more; it will be easier to justify if one or more electro-intensive industrialists have already succeeded in establishing their market.

Consequently, the Supplier must valorise its electricity production at λ availability, which implies a price Π_λ sufficiently attractive for the User.

In the above crude model, as soon as the price Π_λ is lower than $\Pi_{N\lambda}$, the User has a preference for electricity with availability λ. But this implies for the industrialist the decision of an initial extra investment against the promise of a guaranteed profitability by the long-term supply of electricity at price Π_λ.

Such a decision implies a risk premium which must be reflected in a price Π_λ significantly lower than $\Pi_{N\lambda}$.

In the illustration above, for a capex of €7.5bn, the price at the neutrality point is $\Pi_{N\lambda}$ = €40/MWh for λ=70%. For a given production (1 Mt-SAF), the extra investment cost of $\frac{7.5\ G€}{70\ \%} - 7.5\ G€ = 3.2\ G€$ is strictly compensated by the 10 €/MWh discount on the electricity price (i.e. the difference between Π_{100} = 50 €/MWh to $\Pi_{N70\%}$ = 40 €/MWh). The net present value of the extra investment is then 0 thanks to the discounted electricity price.

The extra investment of €3.2 billion can be considered as a project in its own right for which a positive net present value (NPV additivity) should be ensured. To reflect the additional risk of electricity supply at λ availability, the extra investment project will be valued with a higher discount rate than the main investment project:

	Capex	Discount rate	Electricity price
Strategy 1: Project powered by 100% guaranteed electricity	7.5 G€	r = 8 %	50 €/MWh
Strategy 2: Project powered by electricity with availability λ			
Main component	7.5 G€	r = 8 %	Π_λ(r=8 %)
Extra investment	3.2 G€	**r > 8 %**	Π_λ(r>8 %)

With a discount rate of r > 8% for the extra investment project, the maximum price $\Pi_{N\lambda}$ that the User can accept to pay is obtained by cancelling out the net present value of the extra investment project, which amounts to balancing the cash outlays related to the extra investment with the gains on the price of electricity:

$$\text{NPV (extra investment)} = 0 \quad \Rightarrow \quad \sum_{n=1}^{N_C} \frac{\left(\frac{1}{\lambda}-1\right).\mathcal{K}}{N_C(1+r)^n} = \sum_{n=N_C+1}^{N_R} \frac{E.(\Pi_{100} - \Pi_{N\lambda})}{(1+r)^n}$$

We find again the formula $\Pi_{N\lambda} = \Pi_{100} - \frac{\mathcal{K}}{E}\left(\frac{1}{\lambda} - 1\right)\alpha(r)$, but the discount rate to be considered is specific to the extra investment project and is higher than 8%, the value of the discount rate for the main component of the project.

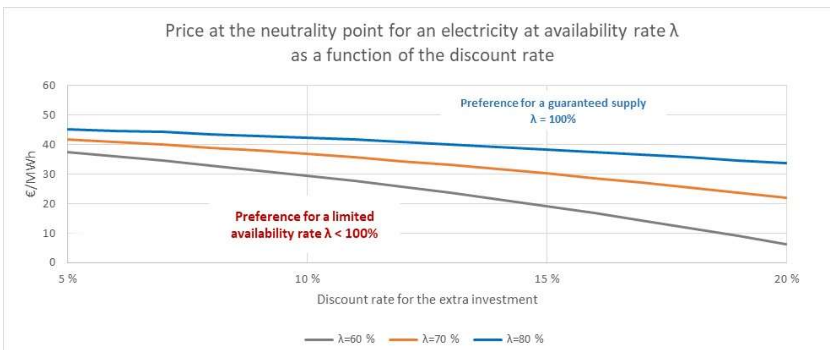


Figure 23: The equilibrium price between the gains on the cost of electricity and the induced extra investment decreases when the discount rate used for the extra investment project increases.

For an availability rate of 70%, if the anticipated risk for the extra investment project motivates a discount rate of 12% (respectively 15%), the maximum price that a User will accept to pay is in the order of 34 €/MWh (respectively 30 €/MWh).

The supply of electricity with availability λ<100% is limited in volume. When demand exceeds supply, the User has to join the consumers of the Grid, which makes it necessary to increase the generating infrastructure. For the share drawn from the mix feeding the Grid, the User will assume the standard price of long-term contracts Π_{100} = 50 €/kWh.

The opportunity related to electricity availability λ<100% is therefore strategic to manage the transition phase both to help the development of new electro-intensive economic sectors and to allow time for the reinforcement of the power infrastructure.

ANNEX 5: THE UNITS

The calculations considered in this document use the following units. Some data may vary from one reference to another, such as the conversion of biomass mass to bioenergy, but this does not affect the orders of magnitude handled in this document.

- Jet fuel and diesel
  - Density 0.82
  - 44 MJ/kg = 12.2 kWh/kg = 12.2 TWh/Mt
- Oil
  - 1 toe = 1 tonne oil equivalent = 7.33 barrels = 11.63 MWh
  - 1 barrel =159 litres
- General units
  - 1 Mt = 10^6 t = 10^9 kg
  - 1 EJ = 278 TWh= 10^{18} J
- Biomass — bioenergy
  - 1 tdb = 1 tonne of dry biomass
  - 1 Mtdb = 1 million tonnes of dry biomass
  - 1 tdb yields 0.45 toe of bioenergy

GLOSSARY

ASTM	American society for testing material
ATAG	Air Transport Action Group
ATJ	Alcohol to Jet
Capex	Capital expenditure
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
ECV	Engagements pour la croissance verte (French Green Growth Commitments)
EJ	Exajoule
EROI	Energy return on investment
FT	Fischer-Tropsch reaction
GHG	**Green-house Gas (GHG)**
HEFA	Hydrotreated Esters and Fatty Acids
HTE	High-Temperature Electrolysis
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
LCOE	Levelised cost of electricity
Mtdb	Million tonnes of dry biomass
PtL	Power to liquid
RED II	Renewable Energy Directive 2018/2001
ReFuelEU	European legislative proposal for sustainable aviation
RWGS	Reverse Water Gas Shift Reaction
SAF	Sustainable Aviation Fuel
bioSAF	SAF produced from biomass
e-bioSAF	SAF produced from biomass and electrolytic hydrogen
e-SAF	SAF produced by synthesis from hydrogen and CO_2
SNBC	Stratégie nationale bas-carbone (French National Low Carbon Strategy)
SOEL	Solid Oxide Electrolysis (SOEL)
TICPE	Taxe intérieure de consommation sur les produits énergétiques (French Internal consumption tax on energy products)

HEARINGS AND WORKING GROUP MEMBERS

Personalities interviewed

26-01-2022 :	Daphné Lorne and Jean-Philippe Héraud, IFPEN
22-02-2022 :	Kristell Guizouarn, Avril Group
23-03-2022 :	Paul Joel Derian, Avril Group, President Bionext/BioTfuel
23-03-2022 :	Sandra Leymonerie Combet, Air France
27-04-2022 :	Véronique Martin et Nora Susbielle, DGAC
12-05-2022 :	Jean Marc Durand, Total-Energies
23-05-2022 :	Sylvain Nizou, Frédéric Ducros, Julie Mougin, CEA Grenoble
20-07-2022 :	Thomas Veyrenc, Cédric Léonard, RTE
20-07-2022 :	Benoît Decourt, Elyse Energy, BioTJet project
04-10-2022 :	Florence Lambert, Patrice Trochon, Pierre Capelle, GENVIA

Members of the Working Group

Olivier Appert	**Member of the National Academy of technologies of France**
Jean-Pierre Chevalier	**Member of the National Academy of technologies of France**
Marc Florette	**Member of the National Academy of technologies of France**
Daniel Iracane	**Member of the National Academy of technologies of France**
Jean-Baptiste Jarin	**Safran and doctoral student at E2S — UPPA**
Bruno Jarry	**Member of the National Academy of technologies of France**
Michel Laroche	**Member of the National Academy of technologies of France**
Patrick Ledermann	**Member of the National Academy of technologies of France**
Frank Quatrehomme	**CEA**
Bernard Tardieu	**Member of the National Academy of technologies of France**
Dominique Vignon	**Member of the National Academy of technologies of France**

Editor : Daniel Iracane

Co-editor for chapters 6 & 7: Jean-Baptiste Jarin

BIBLIOGRAPHY

[1] https://www.assemblee-nationale.fr/dyn/15/rapports/cion-eco/l15b4892_rapport-information#

[2] https://www.notre-environnement.gouv.fr/donnees-et-ressources/ressources/graphiques/article/contribution-aux-emissions-de-gaz-a-effet-de-serre-du-transport-aerien-en-2016

[3] https://www.iata.org/contentassets/a686ff624550453e8bf0c9b3f7f0ab26/flynetzero_mediakit.pdf

[4] Proposal for a regulation of the european Parliament and of the Council on ensuring a level playing field for sustainable air transport, juillet 2021, https://ec.europa.eu/info/sites/default/files/refueleu_aviation_-_sustainable_aviation_fuels.pdf

[5] http://academie-technologies-prod.s3.amazonaws.com/2015/09/24/13/06/00/738/Biocarburants_internet.pdf

[6] https://www.ifpenergiesnouvelles.fr/article/decarbonation-laviation-elyse-energy-et-ses-partenaires-lancent-projet-biotjet

[7] https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques#Lesresultatsdeletude

[8] https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2021-rapport-les_couts_dabattement-_partie_2_transports-juin.pdf

[9] Directive UE 2018/2001 relative à la promotion de l'utilisation de l'énergie produite à partir de sources renouvelables, https://eur-lex.europa.eu/legal-content/FR/TXT/PDF/?uri=CELEX:32018L2001&from=EN

[10] ICAO environment ; approved Conversion Processes, https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx

[11] CORSIA Sustainability Criteria for CORSIA Eligible Fuels, https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2005%20-%20Sustainability%20Criteria%20-%20November%202021.pdf

[12] Corsia default life cycle emissions values for Corsia eligible fuels, https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf

[13] IATA déclaration,: https://www.iata.org/contentassets/dcd25da635cd4c3697b5d0d8ae32e159/iata-agm-resolution-on-net-zero-carbon-emissions.pdf

[14] ATAG déclaration, https://aviationbenefits.org/media/167501/atag-net-zero-2050-declaration.pdf

[15] Waypoint 2050, an air transport action group project, https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf, 2021, second edition

[16] https://www.iata.org/en/iata-repository/pressroom/presentations/environment-net-zero-carbon-at-iata-agm-2021/

[17] Feuille de route française pour le déploiement des biocarburants aéronautiques durables, https://www.ecologie.gouv.fr/sites/default/files/Feuille%20de%20route%20fran%C3%A7aise%20pour%20le%20d%C3%A9ploiement%20des%20biocarburants%20a%C3%A9ronautiques%20durables.pdf, janvier 2020

[18] Wolrd enegy outlook 2021, https://iea.blob.core.windows.net/assets/4ed140c1-c3f3-4fd9-acae-789a4e14a23c/WorldEnergyOutlook2021.pdf

[19] Material Economics (2021). EU Biomass Use In A Net-Zero Economy - A Course Correction for EU Biomass ; https://materialeconomics.com/material-economics-eu-biomass-use-in-a-net-zero-economy-online-version.pdf?cms_fileid=55bb9c799d736d81fdfb372fa5f59013 ; l'étude, cofinancée par la Commission, concerne la zone EU27+UK.

[20] « Sustainable biomass availability in the EU, 2050 », 2021 ; l'étude concerne la zone EU27+UK ; https://www.concawe.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf

[21] La biomasse agricole : quelles ressources pour quel potentiel énergétique ? https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-dt_-_biomasse_agricole_-_quelles_ressources_pour_quel_potentiel_energetique_-_29-07-21.pdf, juillet 2021

[22] https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf.

[23] https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf Clean Skies for Tomorrow, insight report Nov 2020, World economic forum & McKinsey

[24] Mise en place d'une filière de biocarburants aéronautiques durables en France, 2020, https://www.ecologie.gouv.fr/sites/default/files/ECV%20-%20Mise%20en%20place%20d%27une%20fili%C3%A8re%20de%20biocarburants%20a%C3%A9ronautiques%20en%20France.pdf

[25] The Alcohol-to-Jet Conversion Pathway for Drop-In Biofuels: Techno-Economic Evaluation https://chemistry-europe.onlinelibrary.wiley.com/doi/am-pdf/10.1002/cssc.201801690

[26] Baromètre énergies renouvelables dans les transports, https://www.eurobserv-er.org/barometre-energies-renouvelables-dans-les-transports-2021/

[27] Perspectives d'évolution des biocarburants : jeux des acteurs et enjeux fonciers, OSFME 2021, https://www.connaissancedesenergies.org/sites/default/files/pdf-pt-vue/OSFME-R7-Perspectives-d%C3%A9volution-des-biocarburants.pdf

[28] ADEME-FNB2019, https://cartofob.ign.fr/

[29] European Partnership for Hydrogen Technologies, Strategic Research and Innovation Agenda 2021 – 2027; 2022 ; https://www.clean-hydrogen.europa.eu/system/files/2022-02/Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf

[30] A Techno-Economic Assessment of Fischer–Tropsch Fuels Based on Syngas from Co-Electrolysis, Ralf Peters et al, 2022, https://www.mdpi.com/2227-9717/10/4/699

[31] Programmation pluriannuelle de l'énergie , 2019 - 2028 ; https://www.ecologie.gouv.fr/sites/default/files/20200422%20Synthe%CC%80se%20de%20la%20PPE.pdf

[32] https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques#Lesdocuments

[33] https://www.economie.gouv.fr/presentation-strategie-nationale-developpement-hydrogene-decarbone-france#

[34] https://assets.rte-france.com/prod/public/2021-10/BP2050_rapport-complet_chapitre9_hydrogene-couplages.pdf

[35] Les coûts d'abattement, rapport Criqui, France Stratégie janvier 2022, https://www.vie-publique.fr/sites/default/files/rapport/pdf/283466.pdf

[36] BP statistical Review of World Energy, juin 2021, 70th edition, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

[37] EROI of different fuels and the implications for society, Charles A.S. Hall n, Energy Policy 64 (2014), 141-152

[38] Convention on International Civil Aviation, Ninth edition 2006, https://www.icao.int/publications/Documents/7300_9ed.pdf

[39] https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3662

[40] A look into the role of e-fuels in the transport system in Europe (2030–2050) (literature review), 2019, https://www.concawe.eu/wp-content/uploads/E-fuels-article.pdf

[41] A Process for Capturing CO_2 from the Atmosphere, Keith et al., *Joule* 2, 1573–1594, 2018, https://www.cell.com/joule/pdfExtended/S2542-4351(18)30225-3

[42]https://www.energy.gov/eere/fuelcells/articles/doe-funding-opportunity-nuclear-coupled-hydrogen-production-and-use

[43] Techno-Economic Analysis of Synthetic Fuels Pathways Integrated with Light Water Reactors, Sept. 2020, https://www.osti.gov/servlets/purl/1777981

[44] Estimation of the Levelized Cost of Nuclear Hydrogen Production from Light Water Reactors in the United States https://www.mdpi.com/2227-9717/10/8/1620/pdf, 2022 ;

[45] https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2021-rapport-les_coûts_dabattement-partie_1_methologie-juin_0.pdf , 2021

[46] https://www.strategie.gouv.fr/sites/strategie.gouv.fr/files/atoms/files/fs-2021-rapport-les_coûts_dabattement-_partie_2_transports-juin.pdf

[47] “E-FUELS» STUDY, The potential of electricity-based fuels for low-emission transport in the EU. An expertise by LBST and DENA, 11/2017 ; https://en.lbst.de/wp-content/uploads/2021/03/dena_E-FUELS-STUDY_The_potential_of_electricity_based_fuels_for_low_emission_transport_in_the_EU.pdf

[48] Faradaic electro-swing reactive adsorption for CO2 capture, https://pubs.rsc.org/en/content/articlepdf/2019/ee/c9ee02412c

[49] Fischer–Tropsch Synthesis Catalysts as the Core of the Strategy for Obtaining Synthetic Liquid Fuels, 2011, https://link.springer.com/content/pdf/10.1134/S0023158412060067.pdf

[50] Shell Middle Distillate Synthesis Process (SMDS), 1990 https://link.springer.com/content/pdf/10.1007/BF00764507.pdf

[51] https://www.shell.com.qa/en_qa/about-us/projects-and-sites/pearl-gtl.html

[52] A comprehensive review on the pyrolysis of lignocellulosic biomass Vaibhav Dhyani a, Thallada Bhaskar ? Renewable energy 129, 2018 https://reader.elsevier.com/reader/sd/pii/S0960148117303427?token=8E12642529153765361D21686168FF24A3E076D7404F3E29B5F37EF778DB0CB0DC573431712C406981BE20011D448506&originRegion=eu-west-1&originCreation=20220820072014

[53] Modélisation chimique détaillée de la combustion de la biomasse dans les appareils de chauffage domestique en vue de réduire leurs émissions polluantes Amal Dhahak, Jan 2021, https://hal.univ-lorraine.fr/tel-02130719/document

[54] Techno-Economic Analysis of Synthetic Fuels Pathways Integrated with Light Water Reactors, septembre 2020, https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_26721.pdf

This report by the National Academy of Technologies of France addresses the major immediate challenge of modern societies: the profound decarbonisation of our economies and, consequently, of our fuels. Given the scope of the subject, and in order to provide concrete instructions, the report deals with a specific field: the aviation sector.

The proposed analysis identifies two major challenges: the availability of low-carbon energy resources and the need for rapid and large-scale industrialisation of new production sectors to meet the needs of 2050. The quantitative analyses developed in this report make it possible to set out in a concrete manner the terms that determine the dimensions of these two challenges.

The scope for responding to these challenges depends on local realities. The analysis of the solutions and the resulting recommendations are thus proposed at the European level and especially at the French level.

This paper shows that solutions to the profound decarbonisation of the aviation sector exist at the required scale.

They can be deployed effectively in France thanks to the availability of a decarbonised electricity mix. Of course, the path to decarbonise one of the key transport sectors requires technological, industrial and energy developments, as well as a financial effort, that are important and structuring in the medium and long term.

Académie des technologies
Le Ponant — Bâtiment A
19, rue Leblanc
75015 PARIS
+33(0)1 53 85 44 44
secretariat@academie-technologies.fr
www.academie-technologies.fr

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