NATIONAL ACADEMY OF TECHNOLOGIES OF FRANCE
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POSITION PAPER
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ROADMAP TOWARDS THE PRODUCTION OF E-FUELS

1) Introduction

The production of sustainable fuels is a critical part of the path towards decarbonising the aviation and maritime sectors, which together account for 28% of greenhouse gas (GHG) emissions from the overall transport sector in the European Union. The European Parliament and Council recently endorsed the decarbonisation trajectory for maritime[1] and air transport[2]:

European objectives approved by the Parliament and the Council	AVIATION Incorporation rate of low-carbon fuels	MARITIME Carbone intensity reduction
2025	2%	2%
2030	6%	6%
2035	20%	14,5%
2040	34%	31%
2045	42%	62%
2050	70%	80%

Table 1: Decarbonisation trajectories for the aviation and maritime sectors, as adopted by the European Parliament and Council in 2023.

1 Sustainable maritime fuels, 'Fit for 55' package: The FuelEU Maritime proposal, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698808/EPRS_BRI(2021)698808_EN.pdf

2 Sustainable aviation fuels (ReFuelEU Aviation Initiative), https://www.europarl.europa.eu/doceo/document/TA-9-2023-0319_EN.pdf

The mass production of sustainable energy molecules[3] is at the heart of this trajectory: hydrogen, ammonia, advanced biofuels (methanol, ethanol, naphtha, kerosene, diesel, etc.) derived from lignocellulosic biomass, e-fuels or synthetic fuels (e-kerosene, e-fuel, e-methanol or even e-LNG for liquefied natural gas), etc.

Biofuels and e-fuels are complementary solutions that will ultimately have to be deployed in parallel to satisfy all transport needs. The production of e-fuels must therefore be prepared, which requires the implementation of a proactive energy and industrial policy to overcome three challenges: *i)* the harnessing of large quantities of decarbonised electricity, *ii)* the maturing of certain technological building blocks, and *iii)* large-scale industrial deployment.

These are major challenges, which need to be seen in the context of a more general ambition: the decarbonisation of our European societies, which still consume more than 75% of their energy in the form of fossil fuels. No simple or effortless trajectory will achieve significant decarbonisation.

Section 2 presents the possible technological pathways. *Sections 3* and *4* explain the rationales and analyse the alternatives, all of which require heavy investment to synthesise energy molecules in large enough quantities. *Section 5* proposes a technological roadmap in line with *sections 3* and *4*.

The report of the National Academy of Technologies of France on decarbonising the aviation sector[4] refers to and justifies most of the quantitative assessments below. This report sets out the technological, energy, and economic conditions for a sustainable fuel production trajectory on the required scale and with the right momentum. Given the limited availability of biomass, a significant proportion of needs will have to be met by the production of synthetic fuels as early as the next decade. With its low-carbon electricity mix, France is one of the few countries that can envisage the rapid deployment of an industrial sector for the production of synthetic fuels on its territory. This will require significant technological and industrial investment to achieve yields of around 50%, to ensure the economic and energy viability of synthetic fuels.

2) The technological paths considered

Fossil hydrocarbons can be replaced by sustainable energy molecules using a wide range of input/technology combinations.

Some molecules avoid CO_2 emissions during propulsion (hydrogen, ammonia), reducing the carbon footprint to that of their production; other molecules guarantee a net carbon footprint close to zero by taking carbon from the environment before releasing it during the process of propulsion. These two approaches are equivalent in terms of CO_2 emissions.

A major advantage of sustainable hydrocarbons, particularly for air and sea transport, is that they can be used without modifying existing infrastructures, enabling a manageable transition on a worldwide scale thanks to their ability to be blended with fossil fuels.

[3] In what follows, sustainable energy molecules, including sustainable fuels, refer to energy carriers with a carbon footprint close to zero.

[4] Report by the National Academy of Technology of France on decarbonising aviation with sustainable fuels, February 2023, https://www.academie-technologies.fr/wp-content/uploads/2023/03/Rapport-decarbonation-secteur-aerien-production-carburants-durables-AT-Mars-2023.pdf

The production of sustainable energy molecules requires biomass and/or low-carbon electricity resources. For the sake of simplicity, only two families will be considered here:

- The first family concerns biofuels produced from biomass, such as bio-jet fuel or bio-LNG for the maritime sector. Here, biomass provides both the carbon and the hydrogen needed for energy molecules.

- The second family concerns synthetic fuels or e-fuels. For aviation, this involves synthetic jet fuel. For the maritime sector, several types of energy molecules are envisaged: e-fuel, ammonia, e-LNG, e-methanol, and hydrogen. At first order, all these molecules will require the same amount of low-carbon electricity per unit of service provided. Electrolysis on a GW scale, and CO_2 capture for most of the energy carriers considered, are the central challenges here.

There is an intermediate route between biofuels and e-fuels: e-biofuels produced from biomass with added hydrogen.[5] This pathway has strong technological synergies with the synthetic hydrocarbon pathway. For the sake of simplicity, this intermediate route will be referred to below as synthetic fuels or e-fuels.

3) Challenges and Incentives for mass production of e-fuels

There are three key issues in scaling up this production.

Following the decarbonisation trajectory

The first issue concerns the timetable and mass of sustainable fuels imposed on maritime and air transport by the European 'Maritime FuelEU'[1] and 'ReFuelEU'[2] regulations.

France	2035	2050	2035	2050
Airport fuel requirements	9.0 MT	9.0 MT	110 TWh	110 TWh
Of which sustainable fuels	1.8 MT	6.3 MT	22 TWh	77 TWh
Port fuel requirements	2.8 MT	3.8 MT	31 TWh	43 TWh
Of which sustainable fuels	0.3 MT	3.0 MT	3 TWh	34 TWh
Sustainable fuel - Total	**2.1 Mt**	**9.3 Mt**	**25 TWh**	**111 TWh**

Table 2: Estimated quantities of sustainable fuels (biofuels and e-fuels) needed for aviation and shipping (in Mt and TWh).

These estimates are based on the rules adopted at the European level (*Table 1*) and on assumptions about traffic growth and progress in energy efficiency. The orders of magnitude in *Table 2*, and in particular the requested acceleration, are robust. Of course, the precise values could change, for example downwards by around ten percent or more, depending on efforts to reduce fuel consumption or if the global economy stagnates.

In addition to regulatory obligations, there is a strategic incentive for French ports and airports, whose attractiveness and economic development will depend on their ability to make large quantities of sustainable fuels available.

5. This increases the hydrogen to carbon ratio from 3:2 in biomass to 2:1 in hydrocarbons. Producing one million tonnes of e-biofuel requires 2.2 Mt of dry biomass and 6 TWh of low-carbon electricity.

Mastering the technological building blocks

The second challenge is to master the technological building blocks required for large-scale, economically viable industrial deployment of these technologies.

The motivation behind this challenge lies at the heart of the French reindustrialisation policy.

If France is to re-industrialise, it will need to take up positions in new markets rather than repatriating markets that have already been offshored and where leadership is already firmly entrenched elsewhere. The production of e-fuels, and more generally hydrogen and energy molecule technologies, represent a major new technological wave for which France's low-carbon electricity is a key asset.

The aim here is to develop an industrial sector that can internalise the e-fuel value chain, contribute to exports of technology and know-how, deploy production sites in France and abroad, and ultimately increase France's industrial added value. To achieve this, and in view of the targets set out in *Table 1*, it is necessary to invest now in order to develop and fully master the necessary technological building blocks.

Beyond these macroeconomic factors, it is worth highlighting the strong motivation of the major air and maritime industries (transport companies, aircraft-, ship- and engine manufacturers) to invest in exploring the technologies needed to produce sustainable fuels. In the short term, their contribution to technological exploration will enable them to anticipate and secure their strategic choices in terms of fuel supply and motorization.

Mastering the deployment of large-scale production of sustainable fuels

The third challenge is to master the large-scale deployment of sustainable fuel production.

This raises the question of importing sustainable fuels from an international market that currently exists at a very low level: for aviation, for example, 0.3 Mt of low-carbon jet fuel will be available worldwide in 2022, representing around 0.1% of global needs, estimated at 400 Mt.

Some countries will invest in third countries, in Africa and South America, which have natural resources, in biomass or renewable electricity, favourable to the production of sustainable fuels. Other countries, such as the United States or Asian countries will have low-cost production capacity because they do not impose on themselves rules such as the European ones on the exclusion of resources with food potential, such as corn or palm oil.

Sustainable fuel production on the international market will remain below demand for a long period of time. Securing access to this international supply will require customers to participate at a very early stage in the investment required for this production.

The driving force behind this third issue is security of supply, which requires French investment to develop production sites in France and abroad.

Given its biomass and low-carbon electricity potential, France has the opportunity to implement a first stage of industrial deployment over the next decade. This stage is a strategic cornerstone, both for ensuring the credibility of the necessary technological building blocks (including with a view to export) and for establishing an industrial sector for mass production on domestic or foreign production sites.

Finally, investment in domestic production is also spurred by its socio-economic impact. For a primary energy consumption of 230 Mtoe in 2019, France imported 120 Mtoe of fossil fuels[6], giving a fossil dependency rate of 51.5%. A significant proportion of the need for sustainable fuels produced in France will lead to a significant injection of investment in France, an increase of a few percent in the added value created by French industry[7], with the creation of value-added jobs that cannot be relocated, and a reduction of a few percent in oil imports, with a commensurate impact on the bill and the rate of fossil fuel dependency.

4) The issues underlying e-fuel production strategies

The production of sustainable fuels is not a matter of growth in an already established market. As a result, this activity involves a number of technological uncertainties and market risks that raise the following questions.

When will access to e-fuels become inevitable?

Alternatives to e-fuels will not enable us to meet our decarbonisation commitments beyond 2035-40:

- For the maritime sector, switching from heavy fuel oil to LNG is currently an attractive option, with a 25% reduction in emissions. LNG therefore offers a good transitional solution. The number of LNG-powered ships is currently small but growing. With a lifespan in the region of 25 to 30 years, these ships could account for a significant proportion of freight transport by 2050, by which time they will have to consume bio-LNG[8] and e-LNG[9]. Indeed, the "Maritime ReFuel" regulation adopted by the European Parliament and Council on 23/3/2023 requires a reduction in carbon intensity of 14.5% in 2035, 31% in 2040, and 80% in 2050. LNG propulsion will not make it possible to follow the decarbonisation trajectory beyond 2035-40.

- Aviation currently uses biofuels derived from the recycling of used cooking oils and animal fats, accounting for 0.1% of its total consumption. The growth prospects for this technology are limited to a few percent of requirements, i.e. 0.3 Mt for France[4]. Lignocellulosic biomass will have to take up the growth relay in Europe. Analysis[4] of the French situation shows that the bioenergy available in France will remain at around 60 Mt of dry biomass, giving an energy potential of 27 Mtoe. Competition for this resource is fierce and will require delicate political arbitration to provide the market with an ethical, socially, and economically acceptable framework. Assuming that 10% of this resource can be converted (excluding the addition of hydrogen) into sustainable aviation fuels, it will be possible to produce 1.3 Mt of bio-jet fuel. The bio-jet fuel routes alone will therefore not be sufficient to ensure the decarbonisation of air transport beyond 2035, by which time a significant and growing proportion of consumption will have to be based on e-bio-jet fuel[10] and e-jet fuel, which will account for most of the fuel used in 2040.

The climate commitments, reflected in the decarbonisation trajectory shown in *Table 1*, call for significant production of e-fuels (including e-biofuels) over the next decade, which will become dominant by 2040. This timetable means that a roadmap for the production of biofuels and e-fuels

[6] BP statistical review, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

[7] In 2018, the value added of French industry was €280 billion, compared with €766 billion for Germany.

[8] CGM-CMA and ENGIE have signed a partnership agreement to produce 0.2 Mt of bioNGL by 2030 (Salamandre project in Le Havre); https://newsroom.engie.com/assets/salamandre-cc-engie-fr-30-06-2022-pdf-6e0b-ff316.html?lang=fr

[9] The Jupiter-1000 project at Fos-sur-Mer, piloted by GRT-gaz, has demonstrated the production of synthetic methane from renewable energy and the capture of carbon from industrial emissions; https://www.jupiter1000.eu

[10] The decision on 16 June 2023 to build the BioTJet project in the Lacq basin, an investment of €1 billion, is a good example of the initiatives involved in this roadmap; https://www.ifpenergiesnouvelles.fr/sites/ifpen.fr/files/inline-images/202306 %20CP %20ElyseEnergy %20implantation %20 biotjet %20- %20 %2016 %20Juin %202023.pdf

needs to be put in place now.

Is France's low-carbon electricity mix an asset?

The production of sustainable energy molecules for the decarbonisation of transport, but also for agriculture and industry, is electricity intensive. Moreover, the synthesis of these energy molecules requires very low-carbon electricity, otherwise the net carbon footprint associated with these energy molecules will be worse than the footprint resulting from the direct use of fossil fuels.

From the point of view of physical CO_2 emissions, countries with high carbon-intensity electricity must first decarbonise their electricity mix before producing energy molecules.[11]

Thanks to its decarbonised electricity, it makes sense for France to invest rapidly in an industrial sector for the mass production of sustainable fuels, whereas other countries should be prioritising the decarbonisation of their energy mix for electricity generation.

But this physical and factual reality is hampered by the current European regulatory framework, which makes a commitment to renewable energies rather than a commitment to decarbonisation.[12] Despite recent progress in taking account of nuclear power in European regulations, the European reference framework as a whole is largely detrimental to France and to Europe's decarbonisation performance.

In the future, France's nuclear and renewable energy mix could be appealing to national and international investors attracted by its effective carbon performance and availability, but this presupposes that this performance takes precedence over the current regulatory context in Europe. The proposed roadmap builds on the evidence that France has a major advantage in terms of decarbonisation: its low-carbon mix. This implies three fundamental commitments: *i)* rapidly restore the availability levels of France's existing nuclear fleet to the levels achieved in the past; *ii)* actively invest in a robust nuclear and renewable energy mix; and *iii)* strive to put Europe back on the path towards a pragmatic and effective energy policy.

Domestic production or imports?

Today, Europe is a major energy importer[6], with 883 Mtoe of imported fossil fuels for a primary energy consumption of 1,450 Mtoe, making it 61% dependent on imported fossil fuels.

The domestic production of sustainable fuels from nuclear and renewable energy sources will reduce Europe's and France's dependence on fossil fuels. But the scale of this dependence (51.5% for France and 61% for Europe) shows that in a low-carbon world, it will be necessary to import energy in the form of sustainable energy molecules (hydrogen, hydrocarbons, ammonia, etc.).

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[11] Consider a country whose electricity mix has a carbon footprint of 0.3 $kgCO_2/kWh$ (European average). The production of 1 Mt of e-fuel, using wind power at 0.01 $kgCO_2/kWh$, for example, will require 22 TWh, enabling this country to avoid burning 1 Mt of fossil fuel, thereby reducing its emissions by just under 4 Mt of CO_2. But if this country injects the same 22 TWh into its electricity mix to decarbonise it, it will reduce its emissions by 22*(0.3-0.01) = 6.4 Mt CO_2. For the average European country, reducing the carbon footprint is 1.5 times more effective when electricity from renewable sources is fed directly into the grid than when e-fuel is produced.

[12] National Academy of Technologies of France; " Pour une nouvelle politique européenne de l'énergie "; May 2023; https://www.academie-technologies.fr/wp-content/uploads/2022/11/Academie-des-technologies-Politique-europeenne-energie.pdf

It is important to distinguish between two approaches to imports. The first is to buy on an open market some of the production provided by third-party investors, whether private or public. The second approach, which is strategic and consistent with the challenges of security of supply, involves encouraging national private investment in international partnerships that guarantee rights to draw on projects deployed in areas that are favourable to the production of sustainable fuels (i.e. with high biomass and/or renewable energy content). This strategic approach therefore requires a policy of targeting partnerships and high-potential geographical areas, and this inevitably in a context of geostrategic competition for these areas. In this strategic approach, the need for investment to meet France's commitments no longer depends primarily on the ratio between domestic production and imports (although it should be noted that domestic investment leads to a strengthening of the national mix, which is not the case for investment abroad).

The approach can then be identical for hydrogen and sustainable fuels. The European strategy for 2030 targets both domestic production of as well as imports of 10 Mt of hydrogen respectively.[13] At this stage, it seems reasonable to think that at the European level, domestic production and imports of sustainable fuels could eventually make contributions of the same order.

The ratio between domestic production and imports will have to be modulated over time according to the creation and development of an international market for sustainable fuels, economic competition between countries, and prevailing geopolitical conditions. The debate on the ratio between domestic production and imports in 2050 is premature because it will depend on a context that cannot be anticipated.

However, to ensure that this ratio can be steered according to France's vital interests, it is necessary to:

- Significantly bolster France's low-carbon electricity mix, because not only does it permit domestic production levels to be maintained, but it is also highly attractive to foreign investors looking for low-carbon energy resources. In addition, there is no risk of over-investment, as neighbouring countries will be long-term importers of low-carbon electricity.

- Master the first stage of domestic industrialisation for the production of sustainable fuels. The investments associated with this first stage must be identified and put into practice; the purpose of this "2035 roadmap" is to point out the elements on the critical path of this first industrial stage.

[13] Communication on the Commission's REPowerEU plan Brussels, May 2022
https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0003.02/DOC_1&format=PDF

5) Proposal for a "2035 roadmap" for the development of e-fuels

Target and scope of the proposed roadmap

Paragraph 3 estimates the French demand for sustainable fuels at 2.1 million tonnes in 2035 and 9.3 million tonnes in 2050. There are many reasons that can lead to a delay or a reduction in the quantities actually required, but this yardstick has the advantage of properly addressing the problem and allowing for an evaluation of the efforts to be made.

The objective of the proposed roadmap is to achieve technological mastery by 2035 in order to *i)* secure the technological choices expected in a few years' time for deployment in the industry and *ii)* have the know-how and exploitation rights for a coherent technology portfolio for domestic use and for export. This objective is critical for e-fuel production by 2035 and for securing growth beyond 2035, the terms of which are not explored here.

The biofuel route, for example for oleochemicals for aviation or biomethane for shipping, is not discussed here because these fuels benefit from an established but limited market in relation to needs. Notwithstanding, this route will be an essential component of the regulatory trajectory (*Table 1*) at least until 2030. The e-biofuel route (from lignocellulosic biomass with added hydrogen), initiated for example with the BioTJet[10] project, can ensure the transition until synthetic fuel production is effective.

The 2035 technology roadmap

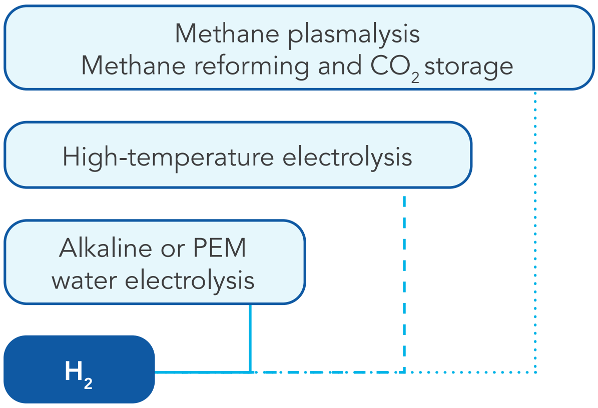
France already has a portfolio of proven technologies for CO_2 capture on concentrated emitters, for CO_2 reduction and for the synthesis of second-generation fuels. We will distinguish three levels in order to prioritise the technologies needed to produce e-fuels:

- **"Conventional technologies"** benefit from a high level of maturity, well-established industrial players in the field, and a chain of manufacturers with a wealth of experience.

- **"Key technologies"** are technologies with established know-how but no industrial experience. Although as such they do not give rise to major uncertainties, key technologies present significant risks when it comes to ramping them up to industrial scale and/or integrating them into the complete production process. To reduce these risks, the development of technical and economic demonstrations at scale is an essential element in the roadmap.

- **"Critical technologies"** exist and have been validated on a pre-industrial scale. They carry the greatest technologically related risk. Before major investments are made, these technologies will have to undergo a careful selection process and performance assessment, as well as a quantification of their market potential.

Hydrogen production for the process



to produce e-fuels is used to produce hydrogen.

Today, hydrogen is mainly produced from fossil methane using a steam reforming process that produces significant CO_2 emissions. This process could be considered in the future, provided it is combined with CO_2 capture and storage. The development of large-scale CO_2 storage capacity[14] will be the determining factor here, putting this solution in the medium to long term.

Alternatively, the reforming process can be operated using biogas instead of fossil methane, guaranteeing low-carbon hydrogen. The technology does not pose a problem, but the use of large quantities of biogas to produce hydrogen does not seem possible in the short term.

Hydrogen can be produced from water by electrolysis, which requires a large amount of electricity, and its carbon footprint depends on the carbon footprint of the electricity used. For e-fuel to have a net carbon footprint 10 times lower than fossil fuel, electricity with a carbon footprint as low as 20 gCO_2/kWh is needed, a performance that is within reach for the French electricity mix.

Conventional alkaline and proton exchange membrane (PEM) electrolysis technologies are now mature; the short-term challenge is essentially linked to the rapid growth in electrolyser production (just under 3 GW of PEM electrolysers are required to produce 1 Mt of e-fuel per year) and to competition from China (in a similar pattern to that seen for solar panels).

In the medium term, high-temperature electrolysis (HTE), currently being industrialised by Genvia and other European companies, will reduce electricity consumption by 20%. This saving is significant: for a production of one Mt of e-fuel per year, the saving on electricity consumption is of the order of 5 TWh, that is an annual saving of €250 million if the cost of electricity is €50/MWh. This technology is important for the economic performance of e-fuels.

Emerging hydrogen production technologies exist. Plasmalysis uses natural gas and electricity. Its advantage is that it cuts the amount of electricity needed by a factor of five compared with electrolysis while using four tonnes of methane per tonne of hydrogen produced. What's more, the carbon released by this process is solid and makes no contribution to the greenhouse effect. Another emerging technology concerns the extraction of "natural hydrogen", produced underground. A growing number of sites of interest have been identified, but it is not yet possible to assess the scale of the deposits. This technology could take a share of the market within ten years if large, exploitable deposits are found.

[14] 2023 consultation file for the carbon capture, storage, and utilisation (CCUS) strategy

The above overview shows that the massive production of hydrogen needed for e-fuels can be achieved through an evolutionary strategy, with several generations of technologies whose market penetration can take place in a continuous fashion as they mature technically and economically:

- **Measure 1a:** This measure is in line with the hydrogen deployment acceleration plan.[15] The aim is to produce 6.5 GW of electrolysers by 2030. The production of 2.1 Mt of sustainable fuels (e-biofuels and e-fuels) by 2035 will require around 2 GW of electrolysers.

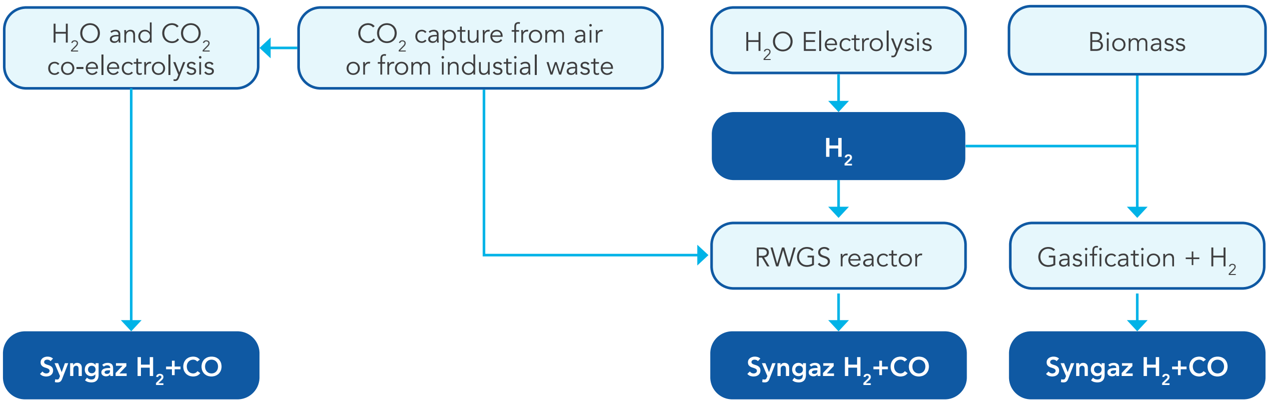
- **Measure 1b:** This measure involves supporting the industrialisation of high-temperature electrolysis, which can reduce electricity bills by 20% and improve the production efficiency of e-fuels by 10%.

- **Measure 1c:** The aim of this measure is to support innovation and development efforts in emerging technologies, such as plasmalysis and the exploration of existing and potential natural hydrogen production sites, in order to maintain a state-of-the-art technological portfolio in the strategic area of low-carbon hydrogen production.

These three complementary measures will ensure the effective availability of electrolysis on a large scale in the short term, while at the same time enabling technological advances to be assimilated.

Syngas production

Syngas is the H_2+CO mixture that feeds the synthesis reactor producing e-fuel.



One possibility is to use biomass, which can produce syngas directly by gasification. Hydrogen is added to obtain the right proportion of hydrogen in the syngas.

The alternative is to capture the CO_2 in industrial fumes or directly in the air, before reducing it to carbon monoxide:

- Capturing CO_2 from industrial fumes is a well-established technology. But it only halves overall emissions, by dividing the gain between the industrial emitter and the transporter using the fuel produced. This solution is transitional in nature and may offer interesting opportunities for initial projects to kick-start the market.

[15] Press file "Accélérer le déploiement de l'hydrogène, clé de voûte de la décarbonation de l'industrie", Février 2023" (Accelerating the deployment of hydrogen, the key to decarbonising industry", February 2023), https://www.gouvernement.fr/sites/default/files/contenu/piece-jointe/2023/02/230202_dp_hydrogene_decarbonation_industrie.pdf

- Capturing CO_2 from the air is an existing technology, but mastering it and deploying it on a large scale requires short-term development efforts. Given the decarbonisation trajectories in *Table 1* and the limitations of biomass, the production of synthetic fuel produced from CO_2 captured from the air should start around 2035 and be in the majority from 2045. Investment in these technologies must therefore be made quickly. CO_2 capture is currently being proposed by a number of industrial companies.[16] The first large-scale plant - 0.5 MtCO_2/year - has been under construction in Texas since 2022, using Siemens compressors and an investment of €1 billion. This critical technology is still in its infancy, and there is still considerable potential for innovation. A development strategy is therefore needed to select the right technology or technologies, while improving their industrial performance.

CO_2 capture, a technology at the heart of decarbonisation trajectories from 2035 onwards, must be the subject of rapid development investment:

- **Measure 2:** IFPEN has the expertise and know-how to secure control of air capture technologies. The measure consists of funding public research bodies to develop a research and development platform that will make it possible at the same time to *i)* qualify the technologies available on the market, *ii)* develop proprietary technologies, and *iii)* optimise a high-performance first-generation technology for rapid industrialisation. This measure will enable a technology to be selected and de-risked in the short term for initial industrial deployment in 2035, while acquiring control of a portfolio of technologies that will support the state of the art in the field over the long term. This measure is critical because CO_2 capture technologies are both essential to the decarbonisation trajectory and suffer from a negative perception due to a lack of knowledge about them. Failure to make rapid progress on this technology in France would prevent the development of an industrial sector capable of ensuring the decarbonisation trajectory and would leave the sector in the hands of the only countries investing in these technologies today (notably the United States).

When CO_2 is available, it must be converted into syngas. The reduction of carbon dioxide to carbon monoxide can be achieved by the so-called "reverse water gas shift" or RWGS reaction, which consumes large quantities of hydrogen. An alternative is to co-electrolyse water and carbon dioxide at the same time to produce H_2 and CO directly. At the limit of perfect efficiency, these two methods consume exactly the same amount of electricity. However, they do not have the same level of technological maturity. The RWGS process is part of a well-established body of technology, but it has not yet been industrially developed. The co-electrolysis route exists[17] but is in its infancy. Syngas production therefore calls for investment in this area:

- **Measure 3a:** RWGS syngas production is a key technology, and its industrialisation must be supported in existing and future projects. This technology forms the basis for the first stage of industrialisation in 2035.

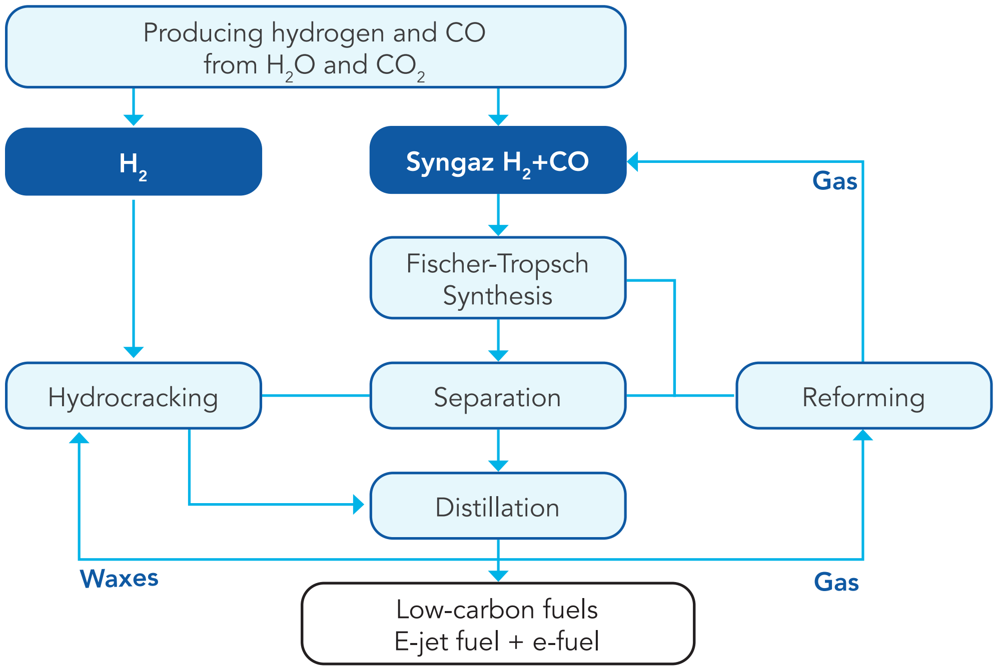
- **Measure 3b**: The co-electrolysis route is a promising one, using high-temperature electrolysis (HTE) technologies. This route will benefit from Genvia's efforts to industrialise HTE. *Measures 3b* and *1b* should therefore be managed together and could lead to the scaling up of HTE to produce both hydrogen and syngas. As soon as the HTE co-electrolysis route is industrially available, it could become the majority solution, to the detriment of the RWGS route.

[16] Canadian company Carbon Engineering and Swiss company Climeworks, which operates a small-capacity plant in Iceland.

[17] The German company Sunfire GmbH operates an industrial module that produces syngas directly;
https://www.sunfire.de/files/sunfire/images/content/Sunfire.de %20 %28neu %29/Sunfire-Factsheet-SynLink-SOEC-20210303.pdf

System Integration

There are several possible processes for producing e-fuels. Below is an example of a thermochemical process, which highlights the critical technological building blocks that are common to all processes.



Downstream of the process are the classic petrochemical technologies, which are perfectly under control. The central part, in this case a thermochemical reactor known as "Fischer-Tropsch Synthesis", is a key technology. It has benefited from several years of development and a demonstrator (BioTfuel) that has enabled the launch of a project to produce 0.11 Mt/year of sustainable fuel (BioTJet[10]). The level of risk associated with this key technology is considered low.

Other types of synthesis reactors can also be envisaged. One example is the Futurol[18] alternative technology for producing advanced ethanol from lignocellulosic biomass, providing a basis for developing a wide range of chemical applications.

Thermochemical synthesis technology (Fischer Tropsch) is ready to move on to an advanced industrialisation stage, as illustrated by the implementation of the BioTJet[10] project. Given the importance and diversity of applications, alternative routes must continue to be explored and benefit from development and demonstration projects.

System integration in itself should be seen as a critical technology. The economic performance of an e-fuel depends first on the overall efficiency of its production, defined as the ratio between the energy content of the fuel produced and the electrical energy required to produce it. A properly integrated process can achieve an efficiency of up to 55%. But this requires optimum recirculation of the heat released by exothermic reactions downstream of the process (in particular the Fischer Tropsch reaction, which emits 20% of the incoming energy as heat). This waste heat could be sufficient to power the high-temperature electrolysis and CO_2 capture processes at zero cost. This optimisation involves accumulating experience on projects integrating all the technological building blocks. Optimisation is therefore at the heart of the road to the first stage of industrialisation:

[18] https://www.ifpenergiesnouvelles.fr/article/biocarburants-2e-generation-premiere-industrielle-technologie-francaise-futuroltm

- **Measure 4a:** Optimising the system and integrating the various technological building blocks is in itself a critical issue. This measure involves promoting and supporting the emergence of projects integrating the various functions required for e-fuel production on a large scale. Achieving the first industrial milestone by 2035 is the core objective of this measure. Of course, it includes support for technological integration efforts, but more generally, it involves multi-sector coordination efforts to guarantee access to inputs (biomass, CO_2, low carbon electricity) and stabilise market rules. The aim of this measure is therefore to establish the economic viability of the available solutions, with the compelling prospect of being able to extrapolate these solutions to the quantities required in 2050.

- **Measure 4b:** The aim of this measure is to implement generic *measure 4a*. It involves inviting the major industrial players concerned with energy, aeronautics, and maritime sectors to discuss joint projects on the scale of the 2035 requirement. The unit projects could produce 0.1 to 0.3 Mt of e-fuel from a mix of CO_2 capture from industrial waste but also from the air. To ensure feasibility, hydrogen would initially be produced by PEM electrolysers and syngas by RWGS. The performance of these projects would, of course, be lower than at technological maturity4 (for the production of 0.1 Mt/year of e-fuel: capex €0.5 billion, 0.3 $MtCO_2$ to be captured, 0.22 GW of electrolysers, 2.2 TWh of annual consumption, conversion efficiency 55%). In line with the requirements to which France has subscribed (*Table 1*), these initial projects should benefit from decisions in principle between 2025 and 2027, with the aim of seeing the light of day in 2035.

Biomass and carbon-free electricity requirements

Securing inputs (biomass and electricity) is part of the 2035 roadmap, as it is a prerequisite for investment decisions.

Biomass refers to a complex set of activities and issues that are subject to tension. Prioritising these activities is delicate but necessary. The public authorities will have to arbitrate in order to guide the market according to these priorities. For example, directing lignocellulosic biomass towards the production of sustainable fuels would appear to be a priority compared to its use as wood energy, for which there are low-carbon alternatives.

The quantity of eligible biomass in France that is compatible with the European benchmark for bioenergy production is around 60 Mt. The proportion of this biomass that will be devoted to aviation and shipping could amount to 6 Mt by 2035 and 9 Mt by 2050 of dry biomass. In turn, this assumption means that around 20 TWh of electricity will be needed to meet the 2035 target of around 2 Mt of sustainable fuels.

- **Measure 5:** The technological investments proposed in this roadmap are aimed at an initial industrial stage enabling the production of just over 2 Mt of sustainable fuels by 2035. To achieve this, it will be necessary to harness a significant proportion (10% in 2035) of the biomass eligible for energy production and to produce around 20 TWh of electricity.

6) Summary of the road map

Technologies needed to produce e-fuels		
Conventional technologies	Key technologies	Critical technologies
Petrochemicals (hydrocracking, separation, distillation, reforming)	Fischer Tropsch synthesis	Capturing CO_2 from the air
Hydrogen production using PEM or alkaline technologies, with a GW production target	Capturing CO_2 from industrial flue gases RWGS chemical reactor	High-temperature electrolysis
	Biomass gasification	Co-electrolysis of water and CO_2
	Addition of H_2 to syngas from biomass	System Integration

Roadmap towards the production of e-fuels
List of measures

- **Measure 1a:** This measure is in line with the hydrogen deployment acceleration plan.[15] The aim is to produce 6.5 GW of electrolysers by 2030. The production of 2.1 Mt of sustainable fuels (e-biofuels and e-fuels) by 2035 will require around 2 GW of electrolysers

- **Measure 1b:** This measure involves supporting the industrialisation of high-temperature electrolysis, which can reduce electricity bills by 20% and improve the production efficiency of e-fuels by 10%.

- **Measure 1c:** The aim of this measure is to support innovation and development efforts in emerging technologies, such as plasmalysis and the exploration of existing and potential natural hydrogen production sites, in order to maintain a state-of-the-art technological portfolio in the strategic area of low-carbon hydrogen production.

- **Measure 2:** IFPEN has the expertise and know-how to secure control of air capture technologies. The measure consists of funding public research bodies to develop a research and development platform that will make it possible at the same time to *i)* qualify the technologies available on the market, *ii)* develop proprietary technologies, and *iii)* optimise a high-performance first-generation technology for rapid industrialisation. This measure will enable a technology to be selected and de-risked in the short term for initial industrial deployment in 2035, while acquiring control of a portfolio of technologies that will support the state of the art in the field over the long term. This measure is critical because CO_2 capture technologies are both essential to the decarbonisation trajectory and suffer from a negative perception due to a lack of knowledge about them. Failure to make rapid progress on this technology in France would prevent the development of an industrial sector capable of ensuring the decarbonisation trajectory and would leave the sector in the hands of the only countries investing in these technologies today (notably the United States).

- **Measure 3a:** RWGS syngas production is a key technology, and its industrialisation must be supported in existing and future projects. This avenue forms the basis for the first stage of industrialisation in 2035.

- **Measure 3b:** The co-electrolysis route is a promising one, using high-temperature electrolysis (HTE) technologies. This route will benefit from Genvia's efforts to industrialise HTE. *Measures 3b* and *1b* should therefore be managed together and could lead to the scaling up of HTE to produce both hydrogen and syngas. As soon as the HTE co-electrolysis route is industrially available, it could become the majority solution, to the detriment of the RWGS route.

- **Measure 4a:** Optimising the system and integrating the various technological building blocks is in itself a critical issue. This measure involves promoting and supporting the emergence of projects integrating the various functions required for e-fuel production on a large scale. Achieving the first industrial milestone by 2035 is the core objective of this measure. Of course, it includes support for technological integration efforts, but more generally, it involves multi-sector coordination efforts to guarantee access to inputs (biomass, CO_2, low carbon electricity) and stabilise market rules. The aim of this measure is therefore to establish the economic viability of the available solutions, with the compelling prospect of being able to extrapolate these solutions to the quantities required in 2050.

- **Measure 4b:** The aim of this measure is to implement generic *measure 4a*. It involves inviting the major industrial players concerned with energy, aeronautics, and maritime sectors to discuss joint projects on the scale of the 2035 requirement. The unit projects could produce 0.1 to 0.3 Mt of e-fuel from a mix of CO_2 capture from industrial waste but also from the air. To ensure feasibility, hydrogen would initially be produced by PEM electrolysers and syngas by RWGS. The performance of these projects would, of course, be lower than at technological maturity[4] (for the production of 0.1 Mt/year of e-fuel: capex €0.5 billion, 0.3 $MtCO_2$ to be captured, 0.22 GW of electrolysers, 2.2 TWh of annual consumption, conversion efficiency 55%). In line with the requirements to which France has subscribed (*Table 1*), these initial projects should benefit from decisions in principle between 2025 and 2027, with the aim of seeing the light of day in 2035.

- **Measure 5:** The technological investments proposed in this roadmap are aimed at an initial industrial stage enabling the production of just over 2 Mt of sustainable fuels by 2035. To achieve this, it will be necessary to harness a significant proportion (10% in 2035) of the biomass eligible for energy production and to produce around 20 TWh of electricity.