Ambitions and resources for alternative fuels

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Ambitions and resources for alternative fuels

Introduction

Decarbonizing a society implies a structural transformation of all sectors, from the production to the distribution of energy and the equipment that uses it.

Today, transportation is still the sector that emits the most CO_2, after energy generation. More specifically, road transport is by far the biggest emitter of greenhouse gases (GHGs), accounting for 73 percent of the transportation sector's CO_2 emissions and nearly 12 percent of total global GHG emissions. Maritime and air transport are each responsible for 1 percent of total emissions with relatively similar emission levels up until 2014. Since then, the increase in emissions from aviation has intensified by almost 2 percent per year[1] – accounting for around 13 percent of CO_2 emissions from global transport. Emissions from aviation are now increasing faster than CO_2 emissions from maritime transport, which are growing at around +0.85 percent per year[2].

While the health crisis triggered by the Covid-19 pandemic caused global carbon emissions from the transportation sector to drop by around 15 percent, they are now gradually returning to pre-Covid levels. This is mainly due to the fact that means of transport are highly dependent – at 91 percent – on hydrocarbons. Additionally, the steady rise in the use of means of transport worldwide is alone driving 5 percent annual growth in commercial air traffic.

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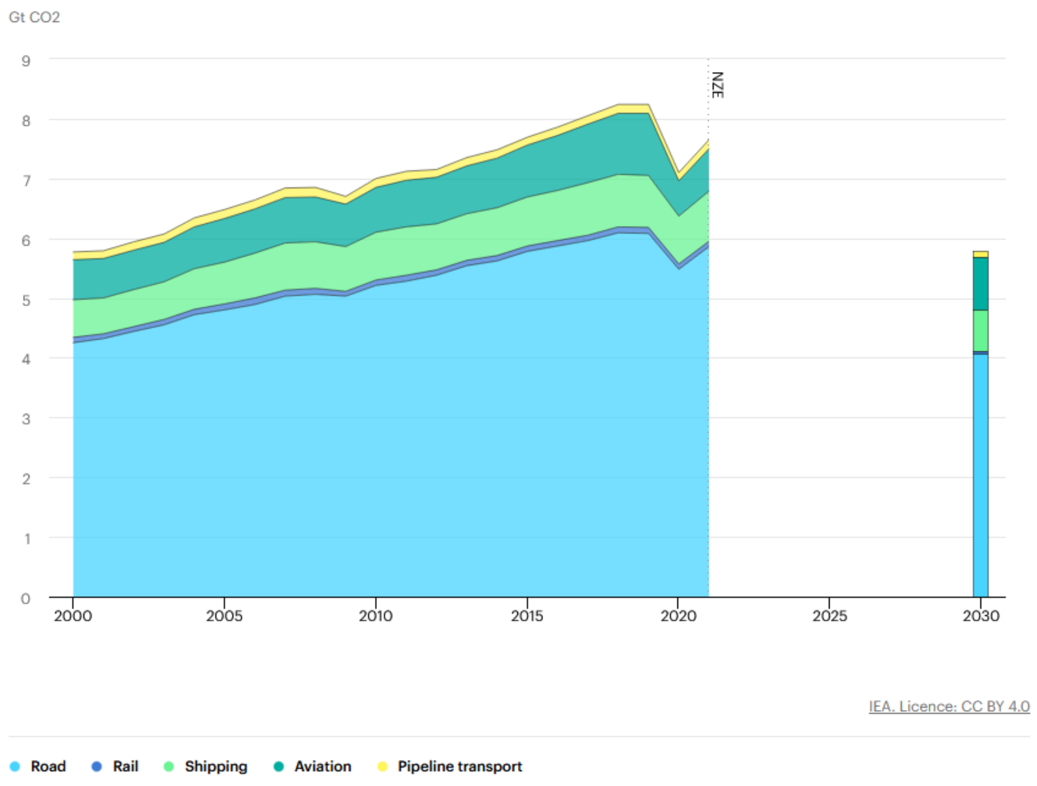
[1] Fact Sheet – Climate Change, United Nations Global Sustainable Transport Conference, October 15, 2021, Beijing.

[2] These measurements do not apply to other pollutants present in fuels, such as aromatics (nitric oxides, NOx) or sulfur (sulfur dioxide SO2). Final Report: *Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)*, European Aviation Safety Agency (EASA), September 2020.

Figure No. 1: Global CO_2 Emissions from Transport by Sub-Sector in the Net Zero Scenario (NZE), 2000-2030



Source: International Energy Agency (IEA), September 22, 2022

Energy policies are currently focusing on the electrification of small means of transport, *i.e.* land vehicles. Other branches of transport (trucks, aviation, shipping) are more difficult to electrify, mainly because of technical issues with today's batteries[3]. Other avenues are therefore being explored for these means of transport, starting with the use of alternative fuels – not entirely derived from hydrocarbons – but derived from organic matter (biofuels) or produced from electricity and hydrogen (synthetic fuels or e-fuels).

In the case of both electrification and alternative fuels, the entire supply chain needs to be adapted, from the methods of producing and distributing these fuels to the vehicles that run on them. Electric vehicle infrastructure (charging stations, for example) is beginning to develop, but facilities for alternative fuels (production, charging stations, etc.) are yet to emerge, partly due to a lack of technological maturity.

[3] For example, they do not have the required energy intensity, nor the run time needed for long-haul flights. Other factors, such as weight and reliability, can also be problematic.

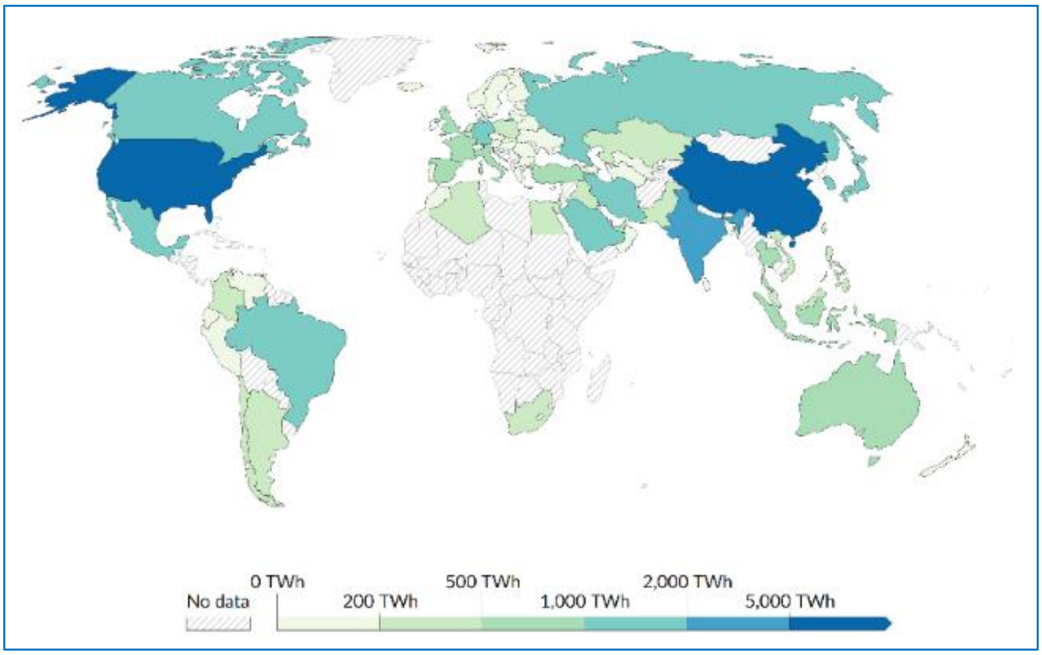
1. Markets and technologies: an overview

1.1. Complex developments in the global energy market

At present, 80 percent of the world's energy needs are still met by fossil fuels. Global energy demand is heavily influenced by China, which has accounted for around 55 percent of the growth in global energy demand since 2012, and 85 percent of the rise in CO_2 emissions over the same period[4]. However, demand for energy is tending to stagnate somewhat in advanced economies, while emerging economies are seeing their energy needs increase (or even soar) due to economic and demographic growth, and the development of their industrial fabric, which is generating greater use of carbon-based means of transport[5].

Regarding energy supply, trends in hydrocarbon production are returning to pre-Covid levels, but the share of investment in hydrocarbon projects and technologies is tending to decline, suggesting a peak in hydrocarbon production in 2030, according to the International Energy Agency[6]. This is due to a growing concentration of investments in low-carbon technologies, driven by public policies aimed at supporting this dynamic (such as the Inflation Reduction Act in the United States, the Green Deal and the NetZero Industry Act in the European Union, and all the measures taken to promote low-carbon energies in China). With decarbonization efforts focusing on the electrification of societies, the divide between investments in fossil fuel projects and those in low-carbon technologies based on electricity (including hydrogen) is becoming more visible.

Figure No. 2: GLOBAL OIL CONSUMPTION IN 2022 (TWH)



Graph: Our World in Data – Source: *Energy Institute Statistical Review of World Energy*, 2023.

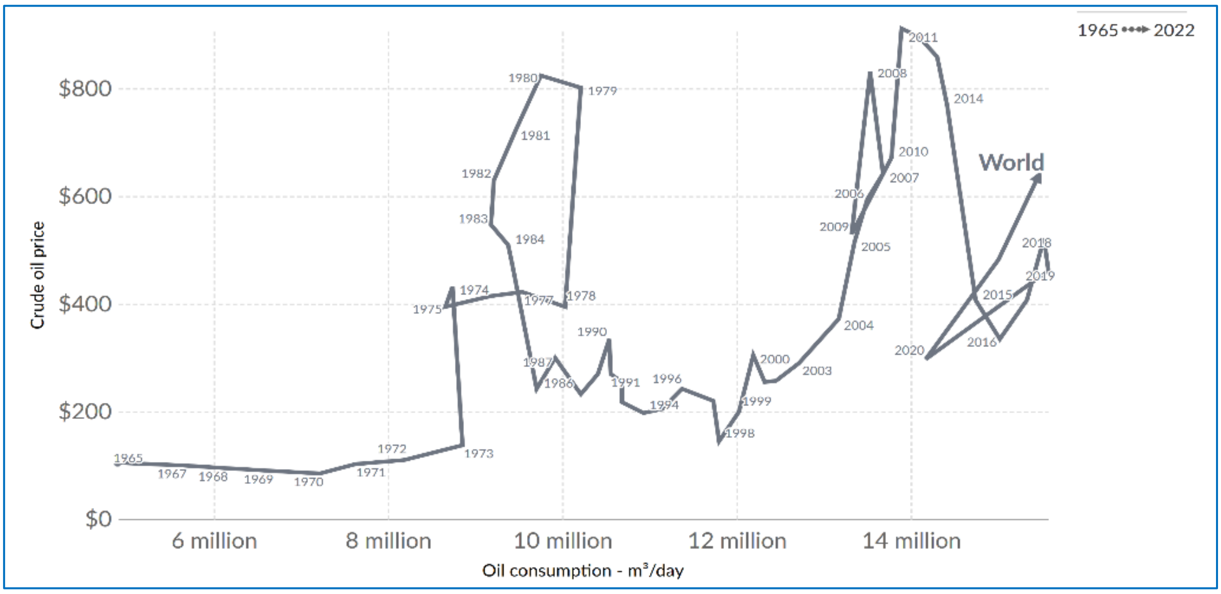
[4] *Energy Outlook 2023*, International Energy Agency, October 2023, pp. 31-36.

[5] *Ibid*., pp. 93-95.

[6] *Ibid*., pp. 26-30; pp. 80-86.

Current trends in global demand for and supply of energy underscore the renewed geopolitical dimension of energy, with recent events leading to structural upheavals in energy flows. The embargo on imports of Russian energy products and policy discussions within OPEC+ explain the volatility of fossil fuel prices[7]. A second structural effect of the European REPowerEU embargo concerns the route of energy supplies (gas, oil, and coal). As the pipelines from Russia to Western European are greatly reduced, energy products are now transiting by sea, which corresponds to other commercial logics, particularly for gas[8]. This tension on the global oil and gas market initially confirmed – and even reinforced – the momentum of political and financial investment in low-carbon energies[9].

Figure No. 3: PRICE OF CRUDE OIL *VS.* OIL CONSUMPTION (USD/M3 VS. M3/DAY)



Graph: Our World in Data – **Source:** *Energy Institute Statistical Review of World Energy* based on *S&P Global Platts*, 2023

The energy crisis triggered by the war in Ukraine has reminded EU member states that, if they wish to pursue their investment plans, the resilience and competitiveness of their industrial fabric will increasingly depend on their energy consumption costs and the predictability of energy prices over the medium term[10]. This is reflected by the reform of the European electricity market, which provides for the price of electricity to be decoupled from the price of gas (or any other last source of power needed on the market[11]). The introduction of

[7] *Oil Market Report*, International Energy Agency (IEA), October 13, 2022, pp. 14-19. Also see Yousef F. Nazer, Andrea Pescatori, *OPEC and the Oil Market*, International Monetary Fund, WP/22/183, September 2022.

[8] Nicolas Mazzucchi, "La France et l'Europe face à la décontinentalisation des flux énergétiques", *Revue Défense nationale*, n° 853, October 2022, pp. 19-24. To replace natural gas from Russia, European countries are now importing liquefied natural gas (LNG) – which involves converting natural gas into a liquefied state for transport by LNG tanker before regasifying it at onshore conversion stations or temporary floating stations (FSRUs - Floating Storage and Regasification Units). Due to the conversion steps, the price of LNG is higher than that of natural gas.

[9] *World Energy Outlook 2023*, IEA, October 2023, pp. 80-86. Also see Emmanuel Hache, "La guerre en Ukraine rebat les cartes de la géopolitique de l'énergie", *L'Année stratégique 2023*, Armand Colin, 2022.

[10] Annabelle Livet, "Crise énergétique : quels enjeux pour l'Allemagne ?", *Défense & Industries*, n° 17, June 2023.

[11] Electricity prices in Europe are based on the mechanisms of supply and demand, with the order of response depending on the level of carbon produced. In other words, renewable and low-carbon energies come first, followed by gas and coal-fired power plants. It is the price of the last power plant needed that determines the wholesale electricity price.

Contracts for differences (*CfD*) defines a price range for electricity between the electricity generator and the public entity in which the generator must redistribute to end customers the excess revenues received when the price of electricity exceeds the defined price range. Conversely, the power generator receives a refund for the difference from the public entity when prices are below the agreed range[12]. This reform mitigates the highly liberalized development of the European energy market, which initially aimed to guarantee competitive prices for consumers, but with no cap, thus leading to very high price volatility in the event of a supply crisis, as was the case in 2022. A reform of this kind is crucial for EU member states, both for industry and for the development of low-carbon energies, since it will bring relative stability and predictability to electricity prices and will support the electrification process launched by the EU.

In the same vein, price trends and the availability of raw materials (energy products, ores and other) are important variables that must be taken into account to determine the direction and pace of European countries' energy choices, including the use of alternative fuels.

1.2. Specificities of alternative fuel technologies

Compared with "conventional" fuels derived from hydrocarbons, alternative fuels meet the primary criteria of replacing petroleum products (gasoline, diesel, kerosene, etc.) and decarbonization, which means that the way they are produced, right down to the emissions discharged by the combustion process, must at least drastically reduce CO_2 emissions compared with their fossil equivalent. Basically, another difference lies in the fact that hydrocarbons follow an extraction and refining process, whereas alternative fuels are produced chemically. The idea of finding a substitute for fossil fuels has been around for a long time, in both the military and civil sectors, in response to the oil crises, but did not include the environmental dimension[13]. For example, tests were conducted with vegetable oils for diesel engines or synthetic fuels produced by a coal liquefaction process during World War II[14]. The latter process is still used in South Africa and accounts for almost 30 percent of national fuel consumption; coal liquefaction activities are responsible for nearly 10 percent of the country's emissions[15].

Today, the aim is to retain the advantages (performance and ease of use) of conventional fuels as much as possible, while limiting the environmental impacts. This freedom from petroleum products means that alternative fuels can provide an opportunity to reduce the critical level of dependency on hydrocarbon imports. There are two families of alternative fuels: biofuels,

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[12] See the dedicated page: "Electricity Market Reform", Council of the European Union, October 23, 2023.

[13] Except in the case of the United States, whose 1977 Clean Air Act promoted alternative fuels with lower atmospheric emissions for ground transportation (see *Alternative Fuels and US automobile manufacturers*, US Environmental Protection Agency, 2017).

[14] On the United States, see "Early Days of Coal Research", Department of Energy (DOE) [accessed November 22, November 2023]. On Germany, see Anthony Stanges, "Germany's synthetic fuel industry, 1927-1945", *in* John E. Lesch (ed.), *The German Chemical Industry in the Twentieth Century*, January 2000, pp. 147-216.

[15] Aditya Pant, Mostafa, Richard Bridle, *Understanding the Role of Subsidies in South Africa's Coal-Based Liquid Fuel Sector*, International Institute for Sustainable Development (IISD), October 2020.

and synthetic fuels, which respectively represented 4 percent and less than 1 percent of the transport sector's global consumption in 2019[16].

1.2.1. Biofuels

Biofuels are refined products obtained from organic materials (such as rapeseed, sugar, wood extracts, biomass or algae) by various processes (*e.g.*, hydrolysis, pyrolysis, gasification, extraction, fermentation, catalyzed synthesis, etc.). In this case, carbon neutrality is justified by the upstream capture of CO_2 by the dedicated crops or the reuse of a material (in the case of cooking fats, for instance), while the combustion of the biofuel discharges the same CO_2 as is, in theory, absorbed.

Today, the most widespread biofuels (also known as first-generation biofuels[17]) are derived from sugar crops and dedicated oils, in particular rapeseed and palm oil, and are mostly produced on the American continent (USA and Brazil)[18]. Biofuels derived from agricultural and domestic residues belong to the second generation and are generally obtained through a process of thermochemical conversion of residues (crops, biomass, fats) to be subsequently used as fuel[19]. Lastly, algae (microalgae and seaweed) form the third generation of biofuels and involve a different approach since they do not require as much space as the other generations. They also offer interesting energy properties[20]. These generations of biofuels, which can be described as oil-based for the first generation, residue-based for the second and algae-based for the third, involve different actors within the agricultural and chemical industries.

The European Union categorizes biofuels according to the raw materials used rather than using the generation categorization. It distinguishes between "simple" biofuels produced from crops intended for human and animal consumption, and "advanced" biofuels derived from marine crops, waste, residues, and co-products (*e.g.*, algae, biomass from urban waste, straw, non-food cellulosic materials and lignocellulosic materials). A third category is constituted by biofuels derived from used cooking oils and animal fats that cannot be consumed by human nor animal[21].

The performance/cost ratio also differs between the generations of biofuel, with a clear advantage for the first generation. Third-generation biofuels suffer from a lack of technological maturity, making their deployment relatively uncertain and costly. In the case of second-generation biofuels, biomass from food waste offers relatively good properties for the

[16] In 2013, biofuels accounted for 2 percent of total fuel, and just over 3 percent of fuel for land-based transportation (see report *Quel avenir pour les biocarburants aéronautiques ?*, Académie des Technologies (ADT) et Académie de l'Air et de l'Espace (AAE), June 26, 2014).

[17] The categorization of alternative fuels is still relatively unsettled and might depend on the actors, regions and institutions.

[18] Both of these countries have a widely developed ethanol sector, whereas in Europe, biodiesel was favored in the 1990s.

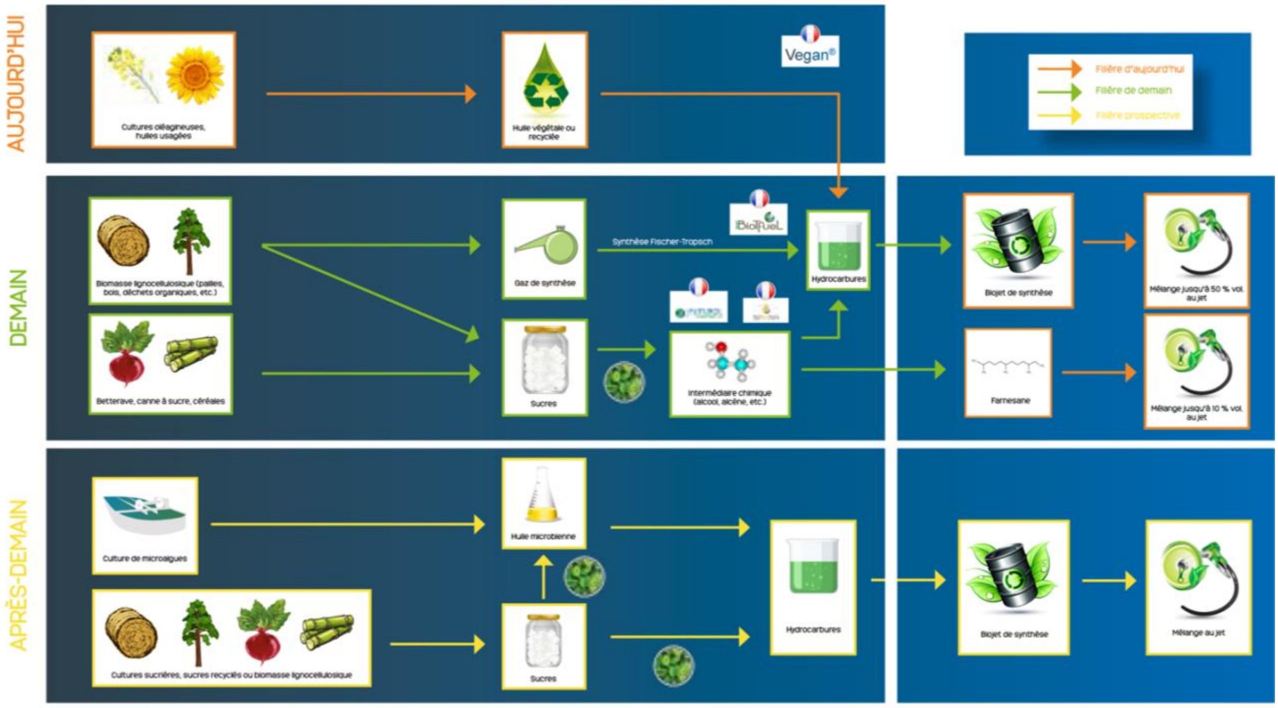
[19] Two processes can be distinguished here: one corresponds to the direct conversion of the biological substance (the hydrogenation of fatty acids from vegetable or animal oils, sugar, biomass) into fuel; the other involves a strict alcoholic fermentation stage, in the form of butanol for example, which is then processed into fuel. The latter process is particularly used by the firm Swedish Biofuels, which has partnered with alcohol producers.

[20] Taroffeq D. Moshood *et al.*, "Microalgae biofuels production: A systematic review on socioeconomic prospects of microalgae biofuels and policy implications", *Environmental Challenges,* 5, 100207, 2021.

[21] European Court of Auditors, Special report 29/2023: *The EU's support for sustainable biofuels in transport – an unclear route ahead*, December 2023.

production of biofuels. However, biofuels – particularly the first and second generations – are favored in road transport more than in aviation for which their properties are deemed too "limited"[22].

Figure No. 4: MAIN FRENCH BIOFUEL PRODUCTION METHODS



Source: IFPEN (accessed November 22, 2023)

1.2.2. Synthetic Fuels

For the EU, synthetic fuels belong to the advanced alternative fuels, so are the "advanced" biofuels defined above. The principle of synthetic fuels (or *e-fuels*) is based on the chemical combination of a gaseous source (such as hydrogen (H_2)) with carbon monoxide (CO) to create a liquid solution using different production methods such as the Fischer-Tropsch (FT) thermochemical process[23]. A second production method involves the synthesis of alcohol (methanol, ethanol or isobutanol). The technology of both methods is relatively mature. In addition to the method, the major difference between synthetic fuels and biofuels is the main source, which is not biological but chemical, with materials that can be captured (carbon) and others that can be "produced" (hydrogen). Although the FT method has been known since the

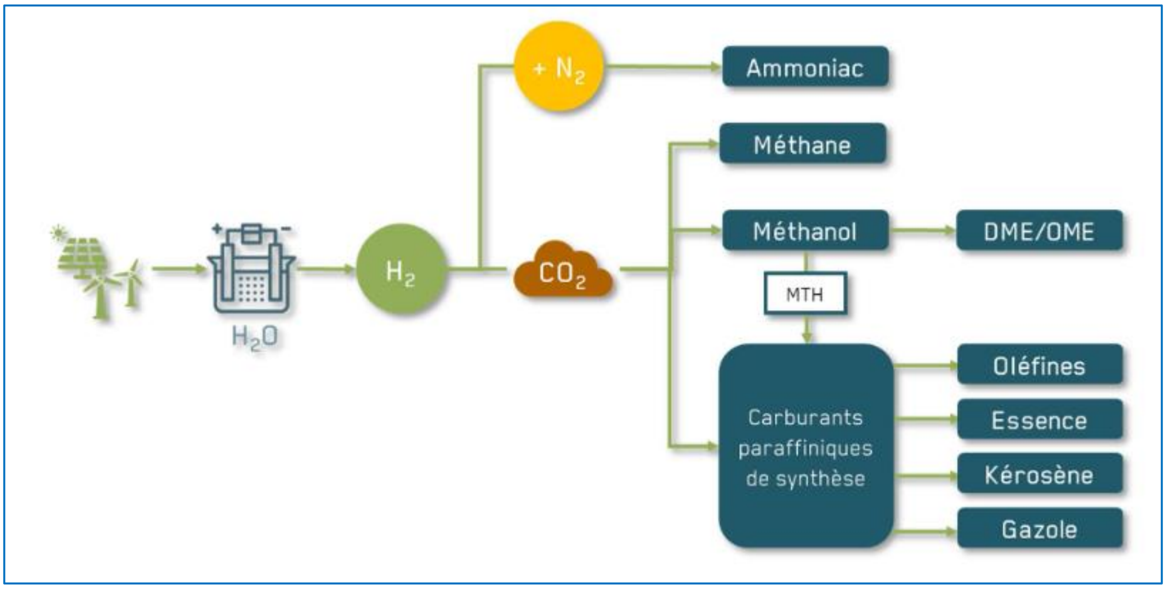
[22] For example, ethanol has a Lower Heating Value (LHV) of 28.9 MJ/kg and a flash point below 13°C, whereas the aviation industry requires an LHV above 42.8 MJ/kg and a flash point above 38°C. The LHV indicates the level of yield (or performance) of a fuel by measuring the actual amount of heat produced during the combustion process. Here, the higher the value, the better the yield. The flash point corresponds to the degree of flammability, *i.e.* the minimum temperature at which a product can momentarily ignite on contact with a source of ignition. In other words, a fuel must not ignite too "quickly", or at too low a temperature, so that it can be stored and transported in vehicles.

[23] A process for producing a liquid hydrocarbon from synthesis gas. A polymerization reaction is provoked (*i.e.* a "combination" of light molecules), in this case of hydrogen and carbon monoxide. FT process needs synthetic gas, which can be produced differently (example: from natural gas, coal, biomass hydrogen or power and biomass). Using hydrogen for a FT process in the production of e-fuel corresponds the so-called *PtL* (Power-to-Liquid) method.

1920s[24], its deployment is limited by the costs of the various production processes, namely gasification, synthesis, and conversion, and by the amounts of electricity and water needed to implement them. For example, producing one metric ton of synthetic kerosene requires almost seven metric tons of water, five metric tons of CO_2 and 37 MWh of electricity[25].

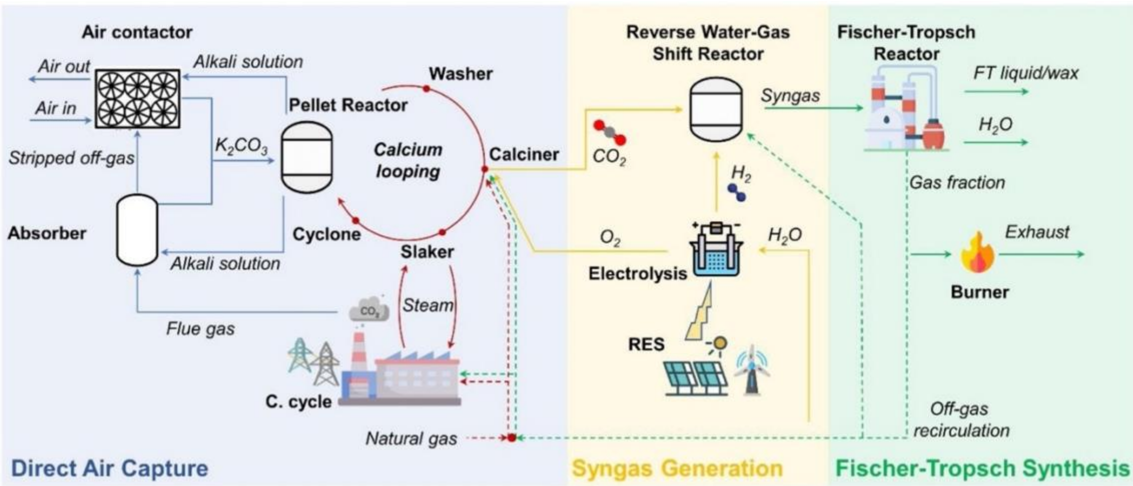
Synthetic paraffinic fuels are very similar to fossil fuels in their properties, unlike other e-fuels (ammonia, methane, methanol). As such, they can be blended directly with conventional fuels and used in existing infrastructure and means of transport, making them "drop-in" fuels.

Figure No. 5: MAIN E-FUEL SYNTHETIC PATHWAYS



Source: Evolen, *Note de synthèse sur les électro-carburants*, February 2023

Figure No. 6: DETAILS OF A FISCHER-TROPSCH SYNTHETIC FUEL PRODUCTION SYSTEM AND USE OF DIRECT AIR CAPTURE (DAC)



Source: Marco Marchese *et al.*, "CO_2 from direct air capture as carbon feedstock for Fischer-Tropsch chemicals and fuels: Energy and economic analysis", *Journal of CO2 Utilization*, vol. 46, April 2021

[24] "The return of a classic to fuel production", *Max-Planck Gesellschaft*, December 14, 2005.

[25] *Note de synthèse sur les électro-carburants*, EVOLEN, February 2023.

However, the development of synthetic fuels is attracting interest since it avoids the need to cultivate land as with biofuels, and it fosters co-production. Hydrogen production (along with CO_2) is also used in other by-products, such as ammonia gas, fertilizer, and aluminum. Beyond the question of cost, and depending on their hydrogen content, synthetic fuels (except the paraffinic e-fuels) may require more or less extensive technical adaptations to the equipment that uses them, for reasons of both metal corrosion and safety (risks of explosion, skin aggression, and irritation of the respiratory tract)[26].

Synthetic fuels meet the sustainability (or decarbonization) criterion when the hydrogen produced is itself decarbonized. This concerns the production of hydrogen, in which the atoms of the water molecule (hydrogen (H_2) and oxygen (O)) have been split by an electric current (also known as electrolysis of water). This process thus releases only oxygen (*cf.* Figure 6). The electrolyzer's thermochemical reaction is powered by electricity which, in the case of decarbonized hydrogen, must come from low-carbon primary energy sources (wind, solar, nuclear, etc.). The carbon neutrality of the hydrogen production process is recognized when it is based on a production method that captures CO_2, thereby offsetting the CO_2 emitted during the combustion stage (valid for blue and turquoise – methan pyrolysis – hydrogen). In all these cases, a significant supply of electricity is necessary to produce hydrogen and, hence, synthetic fuels.

1.3. Policies promoting alternative fuels

In the current context, there is no international market for sustainable fuels involving large flows of exports and imports from one region/country to another. In the case of aviation, 0.3 Mt of low-carbon kerosene were traded in 2022, *i.e.* less than 0.1 percent of the 400 Mt required in theory[27]. For the time being, the dynamics of alternative fuels market development are mainly at regional or even national level.

Interest in alternative fuels varies with the continent and region. Generally speaking, biofuels are favored where there are agricultural sectors able to supply the primary components needed for their production (particularly for first- and second-generation biofuels). This explains the significant pioneering interest of the United States, Brazil, India and Indonesia in the deployment of biofuels[28].

Other countries, such as Germany and the Netherlands, but also South Korea and Japan, have all heavily invested in the industrial development of hydrogen, which partially explains their keen interest in synthetic fuels[29]. In this respect, the correlation between this interest in hydrogen and the existence of a dense chemical industrial fabric can be underlined in the countries mentioned above.

26 *Ibid.*, p. 15.

27 "Feuille de route vers la production de e-carburants", Académie des Technologies (ADT), September 13, 2023, p. 4.

28 "Biofuel Policy in Brazil, India and the United States: Insights for the Global Biofuel Alliance", IEA, July 24, 2023.

29 In France, the methanization and biomass sector is relatively large and seems to be leading to a policy that is less extensively focused on synthetic fuels.

Figure No. 7: Breakdown of Biofuel Production by Country (percent) in 2020

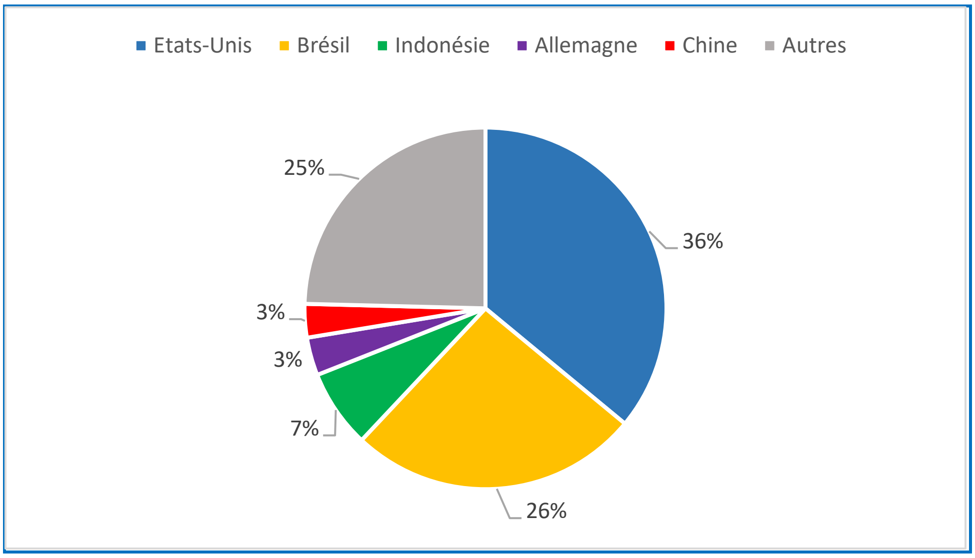
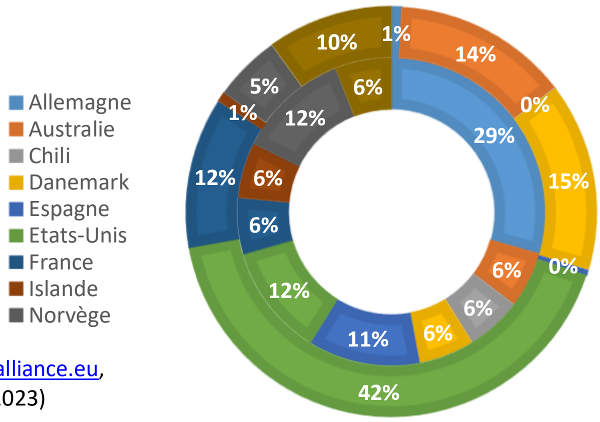


Figure No. 8: Breakdown of the Number of PtL Projects by Country (inner circle) and Announcements of Synthetic Fuel Production (metric ton) between 2024 and 2026 (outer circle)



Source: data from efuels-alliance.eu, (accessed November 25, 2023)

The European Union made its first commitments concerning the air transport sector in 2002 as part of the ACARE 2020 program (Advisory Council for Research and Innovation in Europe). This program provided for an improvement in the energy efficiency of aircraft, leading to a 50 percent reduction in CO_2 emissions by 2020 and a 75 percent reduction by 2050 compared to 2000 levels. However, energy efficiency alone, achieved through technological progress, already seemed insufficient at the time, as these efforts must, at the very least, be coupled with the integration of alternative fuels into the blends used.

A number of European initiatives have targeted the use of biofuels in the aviation sector. Regarding biofuel production, the European Advanced Biofuels Flightpath initiative, defined in 2011, set an initial EU production target of 2 million metric tons of biojet fuel[30] to be used in commercial aviation by 2020. Along similar lines, the Fit for 55 plan adopted in 2019 as part of the Green Deal led to the creation of the ReFuelEU Aviation Initiative aimed at regulating sustainable aviation fuels (SAF) – and the FuelEU Maritime for the maritime sector –, which comes into force on January 1, 2024[31]. These European regulations cover the period from 2025 to 2050, and have two main focus areas:

- the blend ratio of fuel (between bio/e-fuels and conventional fuels); and
- the introduction of sustainability criteria (which components and production conditions are required for biofuels and synthetic fuels to be sustainable?).

These focus areas also oblige European fuel supplier and airports to guarantee the supply, storage and refueling of these fuels, which means they must have the appropriate infrastructure[32]. Moreover, the Fit for 55 legislative package aims to reduce the EU's GES by at least 55 percent by 2030.

TABLE NO. 1: ESTIMATED DECARBONIZATION GOALS FOR THE AIR TRANSPORT SECTOR BY INCORPORATION OF ALTERNATIVE FUEL IN THE EU IN 2023

Deadlines indicated by the European Parliament and Council	Percentage of incorporation of net low-carbon fuels (or alternative fuels)	Airport fuel requirements (France)	Of which sustainable fuels (France)
2025	2%		
2030	6%	0.5 Mt	1.2%
2035	20%	9.0 Mt = 110 TWh	1.8 Mt[33]= 22 TWh
2040	34%		
2045	42%		
2050	70%	9.0 Mt = 100 TWh	6.3 Mt = 77 TWh

Source: "Feuille de route vers la production de e-carburants", Académie des Technologies (ADT), 2023

For land transport, biofuels (E10 and E85) were included in European legislation in 2011. However, their development remains strictly regulated and limited due to the risk of rivalry between farm lands dedicated to biofuels and those devoted to food[34]. This argument is taken up in the broader *Renewable Energy Directive* (2018/2001, known as RED II), which provides the framework for promoting secondary energies derived from renewable energies. The European Commission requires fuel suppliers to attain at least 14 percent renewable energy

[30] Another word used for aviation biofuels.

[31] See the infographic "Fit for 55: increasing the uptake of greener fuels in the aviation and maritime sectors", European Council, October 2023.

[32] Council of the EU, Infographic – Fit for 55: *increasing the uptake of greener fuels in the aviation and maritime sectors*, 2023.

[33] Note that in 2014, the European target for the production of sustainable aviation fuel (biojet fuel) by 2020 was already 2 Mt, corresponding to 3.5 percent of expected fuel consumption. (Aca2014, p. 50).

[34] An argument again raised in Article 26 of the RED II. See *Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources*, EU Parliament and Council, December 11, 2018.

(including in the form of synthetic fuel) in final energy consumption in the transport sector by 2030[35].

More specifically, for synthetic fuels, the RED II now requires an increase in hydrogen production capacities dedicated to e-fuels and provides a methodology for assessing greenhouse gas emissions (other than CO_2)[36] while preparing a provision[37] on the origin of the CO_2. As far as biofuels are concerned, the European Commission seems to be focusing more on the second generation (and even third generation, despite the issues of technological maturity) in order to guarantee control over the land used for crops dedicated to biofuels (particularly first generation)[38]. Fears regarding biofuel-dedicated land are also found in dialogues with potential partner countries, given the highly non-European production of biofuels (see figure 7). For synthetic fuels, e-diesel and e-kerosene (FT-SPK and AtJ-SPK)[39] are already certified by ASTM[40].

Alongside the roadmaps and legal frameworks established for the production and use of alternative fuels, the deployment of dedicated infrastructure is governed by Directive 2014/94/EU, which creates a basis common to all member states[41]. In July 2021, the European Commission submitted a proposal (COM2021/0223) to convert this directive into a European regulation in order to foster more coordinated and faster development of dedicated infrastructure (charging stations for example)[42].

2. The main variables of an energy transition to alternative fuels

In addition to the specific technical features of each type of alternative fuel, there are a number of related issues that need to be taken into account for their deployment. These variables must be considered both for the development of production capacities and for the large-scale use of these fuels. In essence, alternative fuels must be compatible with current and future means of transport, while capitalizing on technological know-how that can be integrated into a broader normative framework. At the same time, the availability of energies needed for the production of these fuels is a key factor for the resilience and stability of the alternative fuels supply chain.

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[35] *Ibid.*, RED II, article 25.

[36] Final report: "Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)", European Union Aviation Safety Agency (EASA), September 2020.

[37] *Ibid.*, Art. 25(2) and 28(5), RED II.

[38] By avoiding imports that would encourage deforestation or upset the balance in terms of food security. EU legislation excludes biofuels derived from crops grown for human or animal consumption from the alternative fuels targets.

[39] Currently still 50 percent blended with conventional fuels.

[40] See the presentation by James Hileman, "Fuel Approval Process and Status", Federal Aviation Administration, ICAO, April 30, 2019.

[41] This does not apply to the paraffinic fuels.

[42] In European law, a Directive corresponds to imposing a European objective, but the trajectory and the policy implemented to achieve it are managed by the member states. A regulation is a binding legislative act whereby European law takes precedence over domestic law (*cf*. Press release, "European Green Deal: ambitious new law agreed to deploy sufficient alternative fuels infrastructure", European Commission, March 28, 2023).

2.1. Technology

2.1.1. Alternative fuel consumption and production

Except for paraffinic efuels, any change of fuel requires acceptance, to a greater or lesser extent, by the equipment that uses it (automobiles, aircraft, etc.). The propulsion performance indicator cannot be the only factor considered; attention must also be devoted, for example, to the seals resistance, as well as the stability of the fuel in liquid form (without decomposition) over a wide range of temperatures due[43]. In this context, the concept of drop-in fuel means finding alternative fuels that offer the same performances and mechanical acceptability as conventional fuels.

Today, the cost of producing e-fuel is high compared to fossil fuels and depends on the price of CO_2[44] and hydrogen. Given that the price of "green" hydrogen, *i.e.* hydrogen produced exclusively with renewable energy, is not completely determined[45], the e-fuel price variability band remains vague with a fairly high ceiling. As a result, research is focusing on e-fuels since their properties allow existing infrastructure to be retained. The least amount of infrastructure adaptation is therefore a lever for limiting costs, and this is particularly true of distribution and storage infrastructure. Yet, adaptations are required, to varying degrees: on production units and their connection to decarbonized power grids (*e.g.*, decentralized with renewable energies); then for storage methods (not for paraffinic efuels); and finally, due to the chemical specificities that render them more or less toxic or reactive to the external environment (in particular depending on the hydrogen or ammonia content). In addition to this "alternative fuel" infrastructure, all the infrastructure and supply chains for hydrogen and CO_2 need to be built (as they are still practically nonexistent today).

2.1.2. Mastering the technology

Technological expertise must also be considered given the European political quest for industrial sovereignty. The energy technologies sector is already deemed a critical industrial asset by the European Union[46]. Low-carbon energy technologies (wind, nuclear and others) and energy vectors (alternative fuels, hydrogen) are greatly defended by member states and face heightened global competition from Asian nations and the United States. The search for synergies between these different branches is helping to reinforce European industrial supply chains. As sustainable alternative fuels are end products, since they are derived from all the other energy components (electricity, conversion), their production requires command of the full spectrum of low-carbon energy technologies.

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[43] Air temperature at 11,000 m –cruising flight altitude– is -56.3°C. In the case of conventional aviation fuel "JetA1", the fuel must remain stable between -47°C and 280°C.

[44] This is mainly biogenic CO_2, *i.e.* CO_2 from plant matter recovered, for example, from biogas purification (methanization) or alcoholic fermentation. This type of CO_2 is not the same as air captured CO_2, which is still very much in the minority and expensive. The price of biogenic CO_2 greatly depends on the distance traveled by truck (in liquid form). For distances of less than 200 km, the supply chain is still considered "local" and competitive; distances of less than 5 km avoid the liquefaction stage and thus save on conversion costs (source: GRDF).

[45] The cost of green hydrogen is expected to fall in line with the drop in the price of electricity from renewable sources.

[46] This point is also reflected in the creation of the Strategic Technologies for Europe Platform (STEP) (see "Critical technologies: how the EU plans to support key industries", European Parliament, October 17, 2023).

As mentioned above, the system of alternative fuel (apart from paraffinic fuels) supply chains is different from that of fossil fuels. Whereas the latter correspond to a logic of extraction, refining, importing and consumption, the logic of alternative fuels is one of production, conversion, distribution, and consumption. Fuel suppliers and aircraft (or port) operators must therefore have the facilities needed to produce these alternative fuels. As the costs increase significantly when fuels are transported and distributed over long distances, production units should be located close to the places of consumption. Additionally, the production of alternative fuels itself requires a nearby connection with suppliers of hydrogen, CO_2, and biomass, etc. Consequently, the whole supply chain must be relocated on a more local or regional scale. And such a change of supply chain requires constant coordination between the various stakeholders to avoid interruptions. On the other hand, a consolidated and efficient supply chain guarantees continuity and resilience in terms of demand, as well as predictable available volumes and prices for consumers.

More indirectly, mastering the sustainable fuels of the future (notably the paraffinic efuels) would be an advantage in terms of mechanical engineering. Retaining internal combustion engines not only saves on the entry costs associated with investing in engines other than combustion engines (*e.g.*, electric engines), it also means that know-how and advances in combustion technologies can continue to be optimized.

Furthermore, a supply chain for alternative fuels needs dedicated and qualified labor. However, the necessary workforce would appear to be compatible with the human resources already available for internal combustion engines insofar as alternative fuels require the acquisition of knowledge but not a complete renewal, or a complete loss, of knowledge. These “minor” adjustments are also factors enabling the rapid deployment and use of alternative fuels, the idea already being to drastically reduce the use and carbon footprint of conventional fuels. In other words, alternative fuels are an opportunity to initiate the route to decarbonization in the short term, and to gradually shift to potential other technologies that have either matured or offer major competitive advantages for the decarbonization of transport.

2.2. Green energy availability

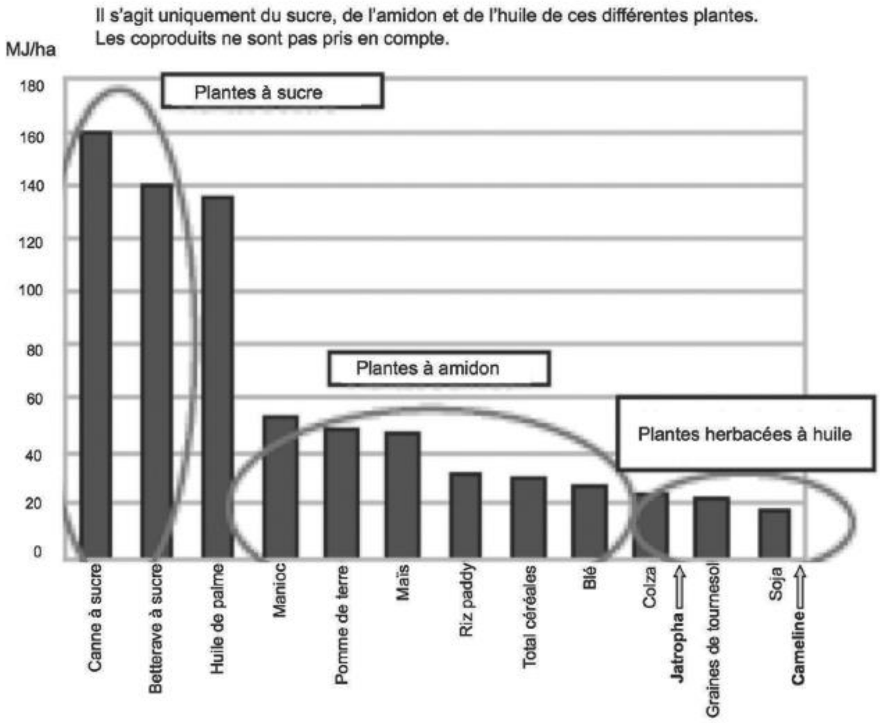
In addition to the technological challenges involved in producing and using alternative fuels, there is also the issue of having a constant supply. This variable depends not only on installed production capacities, but also on the availability of the raw materials needed to manufacture these fuels.

Given that France, like most European countries, imports the vast majority of the fossil fuels used in the transport sector (mainly refined products), the question of where to produce sustainable fuels becomes a key issue. The question of the location of sustainable fuel production sites revolves around that of allocating land to crops dedicated to biofuels, and the availability of a sufficient source of electricity – and CO_2 – reserved for the production of synthetic fuels.

2.2.1. Availability of land

In the case of first-generation biofuels, development remains limited both for legal reasons, defined by the EU, and for structural reasons, since substantial areas of land are required in addition to the crops already grown for food. Diversification of the biological materials used for biofuels (biomass) offers some scope for overcoming the problem of monoculture farming, especially as these crops vary with the geographical location. Biofuel is a more open option in France than in other countries because the plant-based oil industry is relatively well organized for biodiesel. The ethanol (or sugar) production sector had been identified as offering potential in France via beet. Production capacity combined with a relatively high energy yield seemed to be an interesting prospect[47].

Figure No. 9: ACADÉMIE DES TECHNOLOGIES 2014



Source: RM/STD/RMMB according to FAO Stats

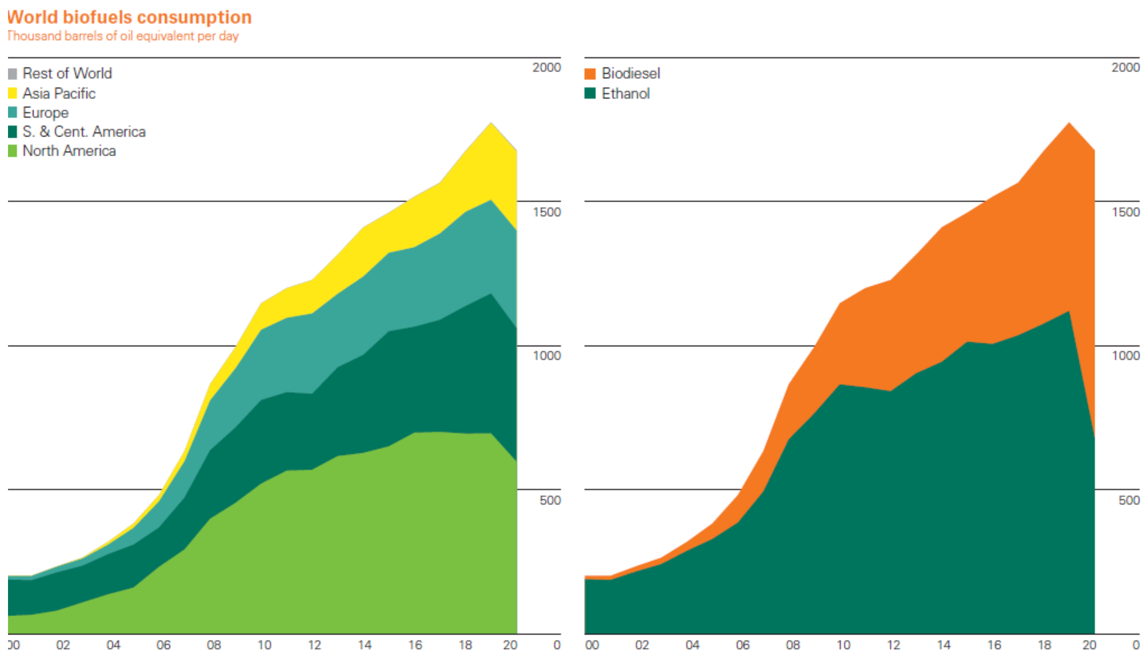
The competitiveness of biofuel prices depends on the price of raw materials, and hence on their availability. In other words, the security of biofuel supply and production depends on the yield and consistency of plant crops. This variable is beyond control, as it hinges largely on environmental factors such as levels of drought, climatic events, soil quality and the legal framework defined for the allocation of space. These variables could encourage more systematic recourse to imports, particularly from outside Europe. Brazil, Indonesia and even the United States are currently the countries with the capacity to export. In all cases, distortions in environmental standards need to be considered, with the risk of continued deforestation. Questions relating to adequacy between production and demand, international

[47] Sébastien Abis, *Géopolitique du sucre : la filière française face à ses futurs*, IRIS Editions, November 2023. Also see *Quel avenir pour les biocarburants aéronautiques ?*, *op. cit.*, p. 48.

consequences, security of supply and price competitiveness are already prevalent in some regions.

Resorting to imports must be considered having regard to the growing needs of other economies, particularly in Asia, such as China, which doubled its biofuel consumption between 2010 and 2019, and India and Indonesia. Such growth could attract investment in biofuels to these regions more than Europe and, above all, put a strain on the anticipated capacity to export to Europe. In this regard, the United States is a representative case. As the world's leading producer of starch-based biofuels (60 percent corn) for the ethanol sector, the crop split is 36 percent for animal feed and 40 percent for biofuels. Given that improvements in energy yields appear to be reaching their limits, the total conversion of corn crops to ethanol would cover 15 percent of U.S. fuel consumption. Greater dependence on biofuels in the United States would therefore put pressure on the balance between the food and biofuel markets and would restrict the country's capacity to export[48].

Figure No. 10: Structure of Global Biofuel Consumption in 2020



Source: *BP Statistical 2021*

2.2.2. Availability of resources

In the case of synthetic fuels, water and electricity resources must also be taken into account, since they are vital for the production of hydrogen (by electrolysis of water) and the conversion processes. The water variable, and in particular the frequency and degree of stress during periods of drought, is inevitably an increasingly important factor for the location of synthetic fuel production units. It is also already a key focus in studies on hydrogen, with many of the projects announced being located by the coast.

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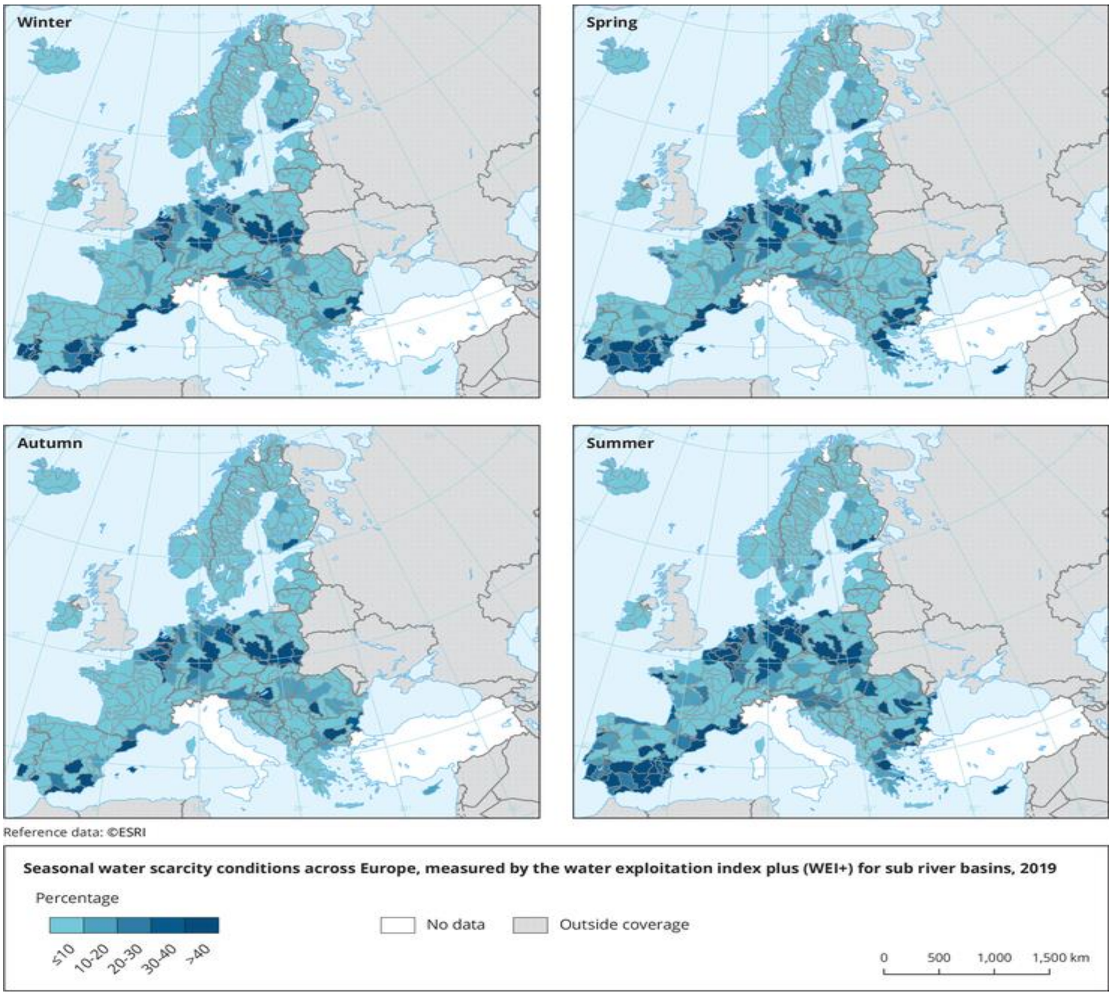
[48] Ahmed *et al.*, "Bio-jet fuel: An overview of various feedstock and production routes", *AIP Conference Proceedings*, July 2023, pp. 3-4.

Figure No. 11: SEASONAL WATER SCARCITY CONDITIONS IN EUROPE



Source: European Environment Agency, January 11, 2023

On the other hand, the electricity variable is more complex since it comes on top of various uses which are also transitioning (heating, light transport, etc.). For a country like Germany, electricity requirements are expected to triple as a result of these changes and the implementation of the hydrogen strategy for domestic industry. In France, current electricity consumption is around 500 TWh, while the needs anticipated by the Académie des Technologies (ADT) for the aviation sector (excluding the maritime and road transport sectors) already amount to 110 TWh[49]. In short, the power generation capacity would need to be expanded by one-fifth compared to the current level of total consumption. Given that e-fuels are expected to be deployed as of 2030-2035, the pace of their development needs to be coordinated with grid (electricity) infrastructure and production capacity.

As a result, the development of synthetic fuels depends on the existing electricity mix, and on the availability of electricity, initially for the production of hydrogen and then for the synthesis of these fuels. In this case, hydrogen production represents approximately 85 percent of electricity needs, the rest being used for synthesis[50]. According to the decarbonization

[49] "Feuille de route vers la production de e-carburants", Académie des Technologies (ADT), 2023.

[50] Presentation, Observatoire français des e-fuels, July 2023, p. 20.

criterion, only electrical power from renewable sources and nuclear energy is recognized. Electricity requirements for the production of synthetic fuels in France is currently defined at 14 TWh/year[51] (up to 110 TWh by 2050). As a theoretical example, 14 TWh/year corresponds to the continuous annual production of at least two 900 MW reactors[52], or 12 percent of Germany's annual wind power production[53]. Considering the figure of 110 TWh of electricity needed for the production of synthetic fuels in France by 2050, the requirement corresponds to the annual production of five nuclear reactors or to Germany's entire wind power production.

These figures must be seen in the context of the geographical reality, which is obviously more dynamic. Firstly, other energy-intensive sectors, often concentrated in the same regions, are in competition for this production of electrical power. This particularly concerns industrial and petrochemical regions and major transit hubs. In France, this is especially the case of the Auvergne-Rhône-Alpes, Nouvelle-Aquitaine, and Hauts-de-France regions[54]. In Germany, the western and south-western regions are mostly concerned, due to their robust industrial fabric (automotive, electronics, metalworking) and transport routes (land, airports, and inland waterways). In addition to competing uses, there is the competition in terms of footprint, *i.e.* the use of land dedicated to the production of synthetic fuels. In this latter case, these are surface areas dedicated to power generation units (solar, wind, hydraulic, nuclear, etc.), and those accommodating synthesis or storage facilities[55].

The question of importing hydrogen is also being addressed, with Germany in particular envisaging a rate of imports of between 50 percent and 70 percent[56]. Here again, import capacity will depend on the growth of electricity and hydrogen installations in other countries (both in and outside Europe). At this stage, this strategy seems very ambitious, and still involves a few hypothetical variables (actual investments, hydrogen transportation methods, actual production capacity, etc.). Given that hydrogen will also be used to decarbonize sectors that are difficult to electrify, such as the steel and cement industries, the required volumes of hydrogen represent a major challenge. At the same time, it will not be possible to produce synthetic fuels without an available supply of hydrogen, and the availability of hydrogen will itself depend on the development of production technologies and related infrastructure.

2.3. The question of standards

The highly international dimension of the air and maritime transport sectors necessarily requires extensive coordination between stakeholders (*e.g.*, international airports or ports, aircraft manufacturers, shipyards) for the supply of fuel. This is where the concept of drop-in fuel comes into play, *i.e.* a fuel that can be used as a total or partial substitute for jet fuel (aviation fuel), and which does not affect aircraft operation or the supply system at airports (infrastructure). Given that aircraft are designed to operate for decades, it must be possible

51 *Ibid.*

52 Based on EDF estimates that a 900 MW reactor produces an average of 500,000 MWh per month.

53 Based on 2022 and 2023 production (German Wind Energy Association – BWE).

54 Presentation, Observatoire français des e-fuels, *op. cit.*

55 *Ibid.*, p. 22.

56 Federal Ministry for Economic Affairs (BMWi), *The National Hydrogen Strategy*, June 2020.

to integrate alternative fuels into existing engineering systems, an issue that ties in with the question of certification, to guarantee the coherence of fuels for all aircraft flown.

From the perspective of standards, alternative fuels are subject to the international standard ASTM[57] D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthetized Hydrocarbon) for all safety-related issues. This standard is based on the one defined for conventional fuels (ASTM D1655 - Standard Specification for Aviation Turbine Fuels) and was extended to synthetic fuels (but not the *efuel*) in 2010 (ASTM D7566) and to biofuels in 2011. In both cases, certification can include a blend of up to 50 percent conventional fuel with synthetic fuels (e-kerosene[58]) or biofuels (HEFA – Hydroprocessed Esters and Fatty Acids). Discussions are currently focusing on an ASTM standard enabling the use of 100 percent SAF (aviation fuel of the future).

TABLE NO. 2: FUTURE PROSPECTS FOR AVIATION BIOFUELS

ASTM specifications (air)	Description
Energy content	LHV (Lower Heating Value), the fuel's heat of reaction with air, in MJ/kg. The standard is 42 MJ/kg, and alternative fuels must not be lower (*e.g.*, hydrogen = 120 MJ/kg).
Specific gravity of fuel	Corresponds to the question of loading energy and therefore the volume to be carried. The standard includes the density range between 0.775 and 0.840 (kg/L).
Heat stability	Guarantee of fuel in a unified, liquid state at temperatures ranging from -56°C to +300°C.
Viscosity	Thus allowing the fuel to be pumped from the tanks. Minimum value: 8 mm^2/s at -20°C.
Flash point	Temperature at which vapors ignite (combustion). The minimum flash point is +38°C (and +60°C for naval aviation).
Storage	Need to guarantee low toxicity, low sensitivity to natural oxidation and low sensitivity to bacterial and fungal contamination.
Not included in the standard	Self-ignition temperature Fuel vapor pressure Clogging effect Safety of ground-based refueling systems

Source: Académie des Technologies (ADT), Académie de l'Air et de l'Espace (AAE), June 26, 2014

The European Union is working on two types of index. The first is a labeling system for consumers on the environmental performance indices of aircraft using SAF. The second corresponds to the development of emission criteria, excluding CO_2, which would be based on data collection and reporting obligations (fuel suppliers and aircraft operators). At the same time, the EU intends to closely monitor how this regulation effects operator competitiveness

[57] The American Society for Testing and Materials is the main international standards organization for fuels.

[58] This is e-kerosene produced by the Fischer-Tropsch method (FT-SPK, Synthetic Paraffinic Kerosene), or the Alcohol-to-Jet method (AtJ-SPK), except for the method involving methanol.

(distortion of competition)[59], the aim being to initiate international discussions and to position alternative fuel sustainability standards and criteria within the International Civil Aviation Organization (ICAO)[60].

3. Exploration of three levers for the security of alternative fuels supply

In essence, energy security is the ability to ensure a continuous and sufficient supply of energy to points of consumption. In the energy chain for alternative fuels, fully controlling the production and supply of electricity, carbon monoxide/dioxide or organic materials is the first link. The number and capacity of production units for these fuels represents the second link, the end point of consumption being the last. These links are "connected up" by energy distribution and storage systems (electricity and fuels). This energy chain embodies the supply of energy and indicates the volume and degree of constancy.

When it comes to producing electricity (and then fuels), the availability of energy depends on production capacities and the density of the distribution network. Energy supply finds itself opposite the energy demand variable, which will match, exceed or fall short of supply. Energy demand is therefore the variable that determines whether or not the energy supply is sufficient to meet needs.

3.1. The need to rationalize demand

In conventional economic thinking, economic growth is linked to the availability of energy. In other words, being able to free up more energy, either through a bigger supply or through energy efficiency efforts for example, allows an increase in the number of activities (production, travel, etc.). However, the structure of energy demand in Europe is seeing a profound shift toward "all-electric":

- The energy transition is centered on the electrification of heating, transport and other needs;
- Hydrogen is the key to decarbonizing sectors that are difficult to electrify, but its production requires significant amounts of electricity.

These two points should be considered in light of announcements concerning the re-industrialization of Europe, which suggest that energy requirements are set to rise. For example, Germany's energy needs are projected to triple by 2050. Growth is also anticipated in France. Current electricity consumption in the country is around 500 TWh per year (without re-industrialization), while the electricity needs of the aviation sector, in line with the energy transition, are expected to rise to 77 TWh by 2050; in other words, electricity consumption in

59 *Cf.* Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation), October 18, 2023.

60 Since air fuel is not taxed at international level (Chicago Convention (7/12/1944) and creation of ICAO), the EU cannot resort to tax incentives, apart from those based on carbon trading.

the aviation sector alone would correspond to one-fifth of current national consumption. In this context, recourse to imports would seem vital. A number of EU member states are already considering importing energy to cover, in some cases, more than half of their energy needs[61]. Energy demand thus emerges as a fundamentally under-exploited lever. In contrast to energy efficiency, which focuses on optimizing energy availability, structural work should be undertaken to reduce demand. A structural reduction in demand requires efforts in terms of consumption and mobility systems, right down to the design of transport vehicles to make them less "energy-intensive". While this is therefore a societal project, its political leadership, as well the efforts made and results attained, can nevertheless be observed in the short term[62].

3.2. The potential to guarantee a dedicated production volume through planning

The challenge for the development and security of alternative fuels supply consists of ensuring sufficient quantities at several points of consumption to meet demand, which is itself growing, ideally at the same pace. Therefore, the aim is to optimize economic profitability and avoid having to deal with storage issues or shortages. Since the development of production capacities also depends on the adjustment, or development, of distribution and storage systems, widespread development of the sector cannot be achieved without driving and coordinating the three links in the alternative fuels product chain: production units (electricity and fuel), transport and distribution infrastructure, and points of consumption[63].

Technological expertise for the construction and deployment of fuel production units (electrolysis, CO_2 capture, production of third-generation biofuels, etc.) must also be factored into the reasoning to meet the challenges of industrial sovereignty. These challenges correspond, by extension, to the choices made by nations in defining their industrial fabric and to the resilience of their economies. These structuring choices will allow the necessary measures to be taken as regards the needs for imports (energy products, spare parts or whole equipment, etc.), the exports to be promoted, and above all, the identification of what must be produced domestically in order to guarantee a policy of strategic autonomy. The question of the ability to build alternative fuel production facilities thus embodies an industrial and strategic dimension for the resilience of the alternative fuels supply chain.

Ultimately, this vital inclusion of the energy chain means that roadmaps for the development of alternative fuels are no longer based solely on a price indicator, which actually corresponds to hypothetical production cost values[64]. On the other hand, the variable of production volume over a given time frame (*e.g.*, total production per year) can become a reliable indicator, providing guidance both for the extent of fuel supply capacity development and the

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[61] For example, Germany's hydrogen strategy currently includes between 50 percent and 70 percent of imports.

[62] The French government's energy frugality plan in place at the time of the winter 2022 energy crisis proved effective and should continue as part of an "Act 2" due to be implemented over the longer term.

[63] This does not really apply to the paraffinic efuels, since these can be directly integrated into the existing structures dedicated to conventional fuels.

[64] Here, reference is made to the costs of decarbonized hydrogen, CO_2 capture and other biofuel production methods, for which supply chains do not yet exist. All these variables are assigned price projections that are currently based on simulations, as there are currently too few tangible price references.

availability of fuel for consumers. Incitement is no longer based on prices, which are in any case hypothetical at this stage, but on the predictability and stability of the development of fuel production, which necessarily implies a strategy with different horizons (short, medium, and long term) and monitoring at each stage.

The impetus for the development of such a supply chain appears to lie primarily in the ability to coordinate and to organize geographic coherence. A close link with the relevant authorities and stakeholders is therefore necessary, as well as an adequate supply of qualified labor, to enable the creation of ecosystems that are destined to grow. In this regard, mobility hubs such as airports and ports have interesting characteristics for attracting means of transport (aircraft, boats, vehicles, trains), and possibly industry and labor. Coordination obviously requires the involvement of the various stakeholders (both public and private) and continuous dialogue, in a spirit of compromise in terms of planning and commercial efficiency, to guarantee relative cost control[65].

In 2014, airlines did not wish to become producers of alternative fuels, despite the clear benefits for their needs[66]. Instead, they chose to adopt a position as “facilitator” in talks between biofuel producers, “consumers” and national, European, and international regulatory bodies. Today, studies are being initiated on building a supply chain close to airports or ports, so that fuel can be consumed directly on site. This has the dual advantage of keeping transport and distribution costs to a minimum, and providing visibility of energy demand at airports, thereby enabling coordination when a fuel production capacity is planned. For example, studies into the creation of a sustainable aviation biofuels supply chain in France[67] would appear to open up some interesting prospects.

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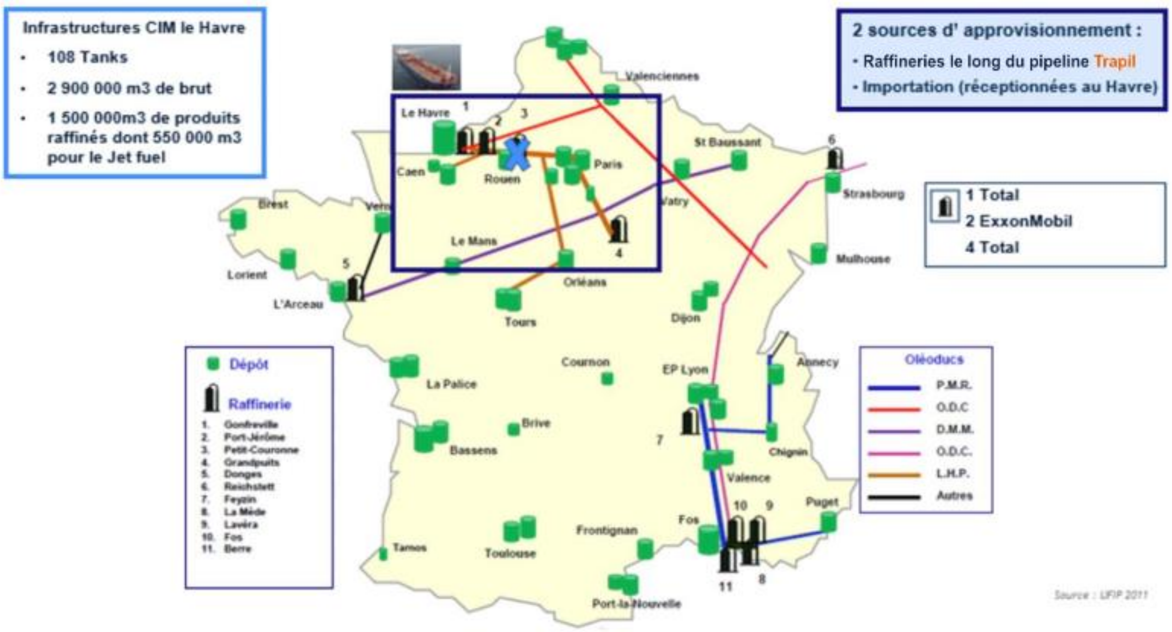
[65] See Marc-Antoine Eyl-Mazzega, “L’impératif de sécurité économique requiert mobilisation et planification”, *La Revue de l’Énergie,* n° 668, September-October 2023.

[66] “Quel avenir pour les biocarburants aéronautiques ?”, Académie des Technologies (ADT) and Académie de l’Air et de l’Espace (AAE), June 26, 2014.

[67] Report “Mise en place d’une filière de biocarburants aéronautiques durables en France”, Ministry of Ecological Transition, 2020.

Figure No. 12: General Scheme of Aviation Biofuel Supply to Paris – Charles de Gaulle Airport



Source: "Mise en place d'une filière de biocarburants aéronautiques durable en France", Ministry of Ecological Transition, 2020, p. 45

3.3. *Toward an XtL or poly-fuel era?*

Diversifying sources of supply is one strategy that guarantees a sufficient level of energy security. This principle consists of diversifying the supply routes through partnerships with different stakeholders in different locations. However, diversification is also possible by varying the types of raw materials, provided that they do not affect the performances or engineering safety of vehicles. In this way, the plurality of alternative fuels can be seen as a source of complementarity.

First, this plurality allows for a theoretically optimal development of supply chains, as long as it is based on geographical assets (availability of agricultural or forestry residues, availability of electrical power, proximity of major consumption points) and on the capacity for coordination or territorial coherence when the supply chain emerges. Secondly, it fosters the inclusion of a wider range of vehicles, including a part of existing land transport vehicles. Following the example of the air transport sector, which plans a hydrocarbon blend with an increasingly high SAF content (up to 70 percent), it seems likely that the land and maritime transport sectors (partially for the latter) will follow the same path.

The main difference as regards the land transport sector is the parallel trend towards the electrification of vehicles. The decision adopted by the European Parliament in June 2022 to ban the sale of new internal combustion-engine vehicles[68] by 2035, makes the future development of alternative fuels less clear, since alternative drop-in fuels could only be integrated into the existing land fleet. Yet this measure, which is considered highly ambitious,

[68] "L'Union européenne acte la fin des moteurs thermiques en 2035", *Le Monde*, October 27, 2022.

focuses solely on engine technology and not on energy consumption, in this case electricity. Whether the electricity generated directly charges an electric car or is used to produce fuel, the challenges in terms of energy capacity remain high. The difference, however, lies in the potential impact on expertise in maintenance in operational condition (MOC), with a likely halt in advances in internal combustion technology.

3.4. The civil-military connection

The energy transition of transport means – whether toward electric propulsion or through the integration of alternative fuels – raises the question of the logistics structure of armed forces and their energy supply methods, both on national territory and during external operations. At the end of the 1970s, the issue of interoperability between coalition armed forces, particularly within the framework of NATO, led to the introduction of a Single Fuel Policy which standardized the petroleum logistics in external operations. This policy is based on tactical and operational reasoning, to increase the security of energy supply in external operations, since all the fuels used must meet NATO criteria[69].

Following the development of biofuels in the United States between 2000 and 2010, experimental work on blending biofuels and conventional fuels was carried out with the US Air Force and then the US Navy, leading to the Great Green Fleet program in 2014[70]. Coordinated by the Department of Defense (DoD), technical efforts were made, and tests were carried out on platforms, until the arrival of the Trump administration, which put a brake on this dynamic.

Regarding land forces, the integration of biofuels into military logistics is primarily based on environmental considerations and does not seem to make a real contribution to the operational efficiency of land forces. The capacity to produce synthetic fuels locally is regarded as an alternative to transporting conventional fuels, especially in geographical areas where supply is difficult or where there is a risk of shortage (*e.g.*, insular or isolated environments). Guaranteeing the availability of fuel through local production would thus allow a certain degree of operational autonomy. However, this advantage needs to be qualified in view of the production costs, which require significant rationalization of uses.

The United Kingdom, via the Royal Air Force, is giving priority to the use of synthetic fuels for air transport[71], in addition to the country's SAF announced activism both in terms of technology and standards. Germany is also considering synthetic fuels for land vehicles[72], echoing the country's strong commitment in hydrogen. Other studies are concentrating on hybrid propulsion (electric and fuel, or all available types of alternative fuels, and conventional fuels), one idea being to integrate the plurality of fuels right from the design stage, to be able to mix available fuels without altering performances. The advantage of this hybrid option would seem to be based on its flexible use and its complementarity with the electrification of

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[69] List of criteria: "Fuels, Oils, Lubricants and Petroleum Handling Equipment", Chapter 15, *NATO Logistics Handbook*, October 1997.

[70] Colonel Mark F. Cancian, "Sink the Great Green Fleet", US Naval Institute, September 2017.

[71] "RAF and Zero Petroleum to research and develop synthetic fuel technology", *Airforce Technology*, July 2022.

[72] Björn Müller, "Nachhut an der Klimatfront", Bundeswehr Reservist Association, May 27, 2021.

light land fleets (particularly reconnaissance vehicles) by 2050[73], without needing a complete overhaul of the armed forces' energy logistics systems, given the skilled labor required for the new types of propulsion.

It should be noted that, like batteries, the development of alternative fuels for military use seems to depend greatly on advances in the civil sector, even in terms of standards. In other words, military logistics depend on technological and systemic directions taken in the production and distribution of alternative fuels. The point of divergence would appear to be the criterion of energy performance for military equipment, and the guarantee of operational efficiency. It is particularly in these areas that civil standards are being adapted to military applications. In any event, these will be key questions since they must, at the very least, be addressed by NATO and potentially imply a relative reform of the Single Fuel Policy.

By extension, the question of alternative fuels should be seen in perspective with the strategic storage and distribution infrastructure in NATO member countries, which currently only concerns hydrocarbons[74]. If alternative fuels are developed, studies will no doubt emerge on the supply of inter-Allied oil pipelines. Reflection on hydrogen networks dedicated to the European armed forces is a central component of the *RESHUB* project[75], led by Slovenia in coordination with the European Defence Agency. A connection can thus be drawn between the development of this type of network and synthetic fuel production capacities.

[73] Objective set by the United States, "Climate Strategy", US Army, February 2022.

[74] See web page "NATO Pipeline System", NATO, March 9, 2017.

[75] See the SiEnE "RESHUB Project" presentation page, March 17, 2021.

Conclusion: ambitious challenges… and opportunities

Alternative fuels represent a compromise: they are a less carbon-intensive alternative to conventional fuels, while avoiding a complete overhaul of logistics architectures and internal combustion engine engineering. Alternative fuels bring structural changes to the supply chain, which can be relocated close to the point of consumption, rather than being totally dependent on exports from countries with hydrocarbon-rich soils.

However, a realistic approach must be taken to the development of alternative fuels, since they imply high production costs that are fundamentally dependent on the maturity of technologies, the availability of land (for biofuels) and limited resources (organic residues, CO_2, hydrogen and electricity). Similarly, the issues of technological expertise and industrial development of alternative fuel production units will be key factors in achieving an effective level of strategic autonomy.

Electricity is the main variable, given the very high demand for this energy (conversion to digital technology, electrification of uses, hydrogen production, etc.). It is therefore necessary to think in terms of limited energy availability. In this context, rationalizing energy demand (electricity and alternative fuels) and the principle of plurality of fuels become levers. The combination of these two aspects would ensure the economic development of supply chains while guaranteeing their security.

To achieve this, local, regional, national, and European roadmaps are essential. However, given the numerous hypothetical values of production costs, the indicators serving to give impetus and direction to alternative fuel product chains should be based on production capacity volumes, and on the assurance that the volumes produced will be used. Reliable indicators would provide the predictability and continuity necessary for the development of such technological branches. An approach coordinated geographically by local stakeholders around major points of consumption such as airports or ports would appear to be both relevant and realistic, in order to match energy supply to demand, while minimizing transportation costs. However, this requires extensive coordination between all the stakeholders involved (both public and private).

The diversity of alternative fuels seems to bring greater flexibility and improved security of supply. Achieving this vision will largely depend on the ability of countries to integrate it and to coordinate at different levels (EU, NATO, and other international organizations). In other words, standards should be developed based on criteria of sustainability and technological acceptability of vehicles, rather than imposing a specific technological direction geared solely to national economic interests.