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WILL BIO-JET AND E-KEROSENE REALLY DECARBONIZE AVIATION?

Decarbonizing transport is one of the key objectives for achieving net-zero emissions by 2050. In this context, in 2023 the European Union adopted the ReFuelEU Aviation regulation, which promotes the use of Sustainable Aviation Fuels (SAF) with the goal of replacing up to 70% of fossil kerosene - commonly known as jet fuel - by 2050. The article describes the main SAF production technologies, focusing in particular on processes for producing e-kerosene from renewable electricity and CO_2, and compares their potential and limitations.

According to the International Energy Agency (IEA), 38.1 Gt of CO_2 were emitted worldwide from energy-related activities in 2024, approximately 22% of which originated from the transport sector. The IEA has projected a substantial reduction in the contribution of fossil fuels in this sector as part of the pathway toward the ambitious Net-Zero Emissions (NZE) target by 2050. This transition is expected to rely on the widespread deployment of electricity, hydrogen, and renewable fuels. The latter include both advanced biofuels derived from waste biomass and several RFNBOs (Renewable Fuels of Non-Biological Origin), such as e-NH_3, e-CH_4, e-CH_3OH, e-gasoline, e-kerosene, and e-diesel, all produced using low carbon electricity **[1]**.

Among the transport sectors, maritime and aviation are experiencing the fastest growth in fuel demand, yet both are classified as hard-to-abate because replacing conventional fossil fuels with hydrogen or electricity is extremely challenging with current technologies. In maritime transport, these energy carriers may be viable for short-distance shipping, whereas long-distance ocean transport is increasingly considering LNG, CH_3OH, and NH_3, with the first two already used in specific applications.

The situation in aviation - responsible for the annual consumption of around 300 Mt of jet fuel and the emission of 950 Mt of CO_2, accounting for 2.5% of global energy-related emissions according to the IEA - is even more complex. Electricity and hydrogen are not viable options for anything beyond small aircraft with very limited range. As a result, bio-jet fuels and e-kerosene represent the most realistic pathways for aviation decarbonization. These fuels - recently grouped under the term Sustainable Aviation Fuels (SAFs) - are essential to reducing emissions from this sector. However, not all SAFs offer the same sustainability benefits. e-kerosene provides the greatest long-term potential: when produced from renewable electricity and captured CO_2, it is highly scalable, avoids land-use impacts and feedstock constraints associated with other SAFs, and can deliver lower lifecycle emissions than all bio-jet alternatives.

The ReFuelEU Aviation regulation, adopted by the European Union in 2023, mandates minimum shares of SAF in all jet fuel supplied at EU airports. The SAF share will rise to 6% of total aviation fuel consumption by 2030 and is set to reach 70% by 2050. Crucially, the regulation also requires that this 2050 target be met through an equal contribution of bio-based SAF and synthetic e-kerosene, each accounting for 50% of the mandated share **[2]**.

Even more ambitious is the U.S. Aviation Climate Action Plan, which commits the entire U.S. aviation sector to achieving climate neutrality by 2050 **[3]**. This goal is supported by the SAF Grand Challenge Roadmap, which calls for the production of 3 billion gallons of SAF by 2030 and 35 billion gallions by 2050, an amount that would be sufficient to cover 100% of projected domestic demand [4].

Why Electricity and Hydrogen Cannot Scale in Aviation?

The main factor limiting the use of electricity and hydrogen in aviation is their insufficient energy density: for batteries the constraint is gravimetric, while for hydrogen it is primarily volumetric. A *National Geographic* article published in September 2021 by Sam Howe Verhovek captured the issue vividly: "…no battery yet invented can power, say, a Boeing 747 from New York to London. My favorite expert calculation comes from David Alexander, director of aerospace standards at SAE International. He estimates it would take the juice of 4.4 million laptop batteries just to get airborne. Except that the jumbo jet could never leave the ground; the batteries would weigh seven times as much as the plane. Pound for pound, liquid fuel contains vastly more energy than even the most sophisticated battery in use today" [5]. This explains why electric propulsion may emerge for short-range routes with small aircraft, but no realistic pathway exists for battery-powered commercial aviation.

Hydrogen, while promising as a clean energy carrier, faces similar limitations. Although hydrogen delivers three times the energy per unit mass of jet fuel, its volumetric energy density is dramatically lower. Replacing 1 L of jet fuel requires approximately 4 L of liquid hydrogen or 7 L of hydrogen compressed at 700 bar. In today's aircraft, jet fuel occupies about 8% of the total volume of an Airbus; substituting it with liquid hydrogen would increase this to roughly 32%, with profound implications for aircraft design, payload, and safety.

For these reasons, the decarbonization of the aviation sector requires liquid SAF with an energy density comparable to fossil kerosene.

SAF Production Routes

SAF can be produced through different routes, depending on whether the feedstock is of biological origin (bio-jet) or derived from the reduction of CO_2 with green H_2 (e-kerosene).

Bio-jet production technologies include:

- Hydroprocessed Esters and Fatty Acids (HEFA);
- Alcohol to Jet (AtJ), which involves dehydration of bio alcohols to olefins, followed by oligomerization, hydrogenation, and fractionation;
- Biomass gasification to syngas (CO/H_2), which can then be converted through:
  - Fischer-Tropsch (FT) synthesis to produce hydrocarbon mixtures subsequently isomerized and fractionated,
  - Methanol synthesis, with methanol further upgraded to jet fuel via Methanol-to-Olefins (MtO), oligomerization, hydrogenation, and fractionation.

These pathways differ mainly in the type of biomass employed. HEFA are typically produced from vegetable oils - preferably from non food oilseeds or crops grown on marginal land - as well as from waste and residual lipids such as used cooking oil and animal fats. AtJ routes rely on bio alcohols (*e.g.*, ethanol, butanols) obtained via fermentation, while syngas based routes use gasified waste streams, including municipal solid waste (MSW) and biomass residues.

e-kerosene, part of the RFNBO family of fuels, is produced through Power to Liquid (PtL) processes using CO_2 and green H_2 generated by water electrolysis powered by renewable electricity.

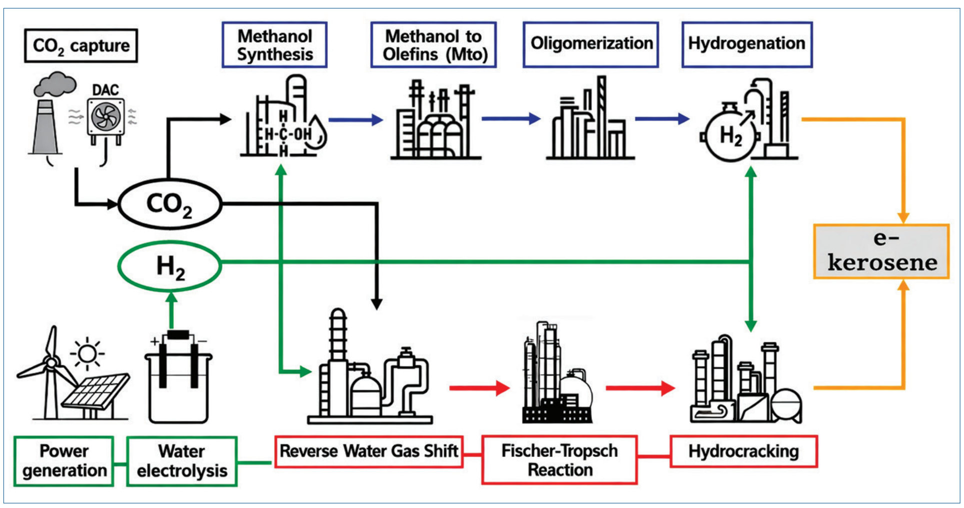

Fig. 1 - Most advanced PtL routes to e-kerosene

The two main PtL routes (Fig. 1) mirror those used for bio-jet - FT and methanol - but differ in the initial step:
- in the FT pathway, syngas is produced via the reverse water-gas shift (RWGS) reaction;
- in the methanol pathway, the alcohol is obtained by the direct catalytic reduction of CO_2 with H_2.

Among these routes, HEFA is currently the most mature technology, with several industrial-scale plants already in operation. Alcohol-to-Jet (AtJ) and gasification/FT routes follow in terms of technological readiness, although they are still at an earlier stage of deployment. Power-to-Liquid (PtL) e-kerosene, despite its clear sustainability advantages, has not yet reached large scale commercial implementation **[6]**.

Power-to-Liquid (PtL) Routes to e-kerosene

Following the adoption of the ReFuelEU Aviation regulation, the global market for e-kerosene is expanding rapidly. The regulation mandates jet-fuel suppliers to deliver increasing shares of SAFs to EU airports, including a binding sub-target specifically for e-kerosene. As a result, a wave of new projects has been announced across Europe. According to Transport & Environment (T&E) **[7]**, there are currently 41 large-scale projects under development. In addition, 14 smaller commercial-scale plants and 12 ongoing research initiatives bring the total number of projects to 67. Among these, 19 aim to be operational by 2030, with a combined projected output of 1.3 Mt per year of e-kerosene.
As with other C-containing e-fuels, e-kerosene derives from green H_2 and CO_2. Behind this seemingly simple statement lie factors that can significantly impact the actual possibility of generating mass production of e-kerosene. These are mainly related to the raw materials, particularly the technologies and energy required to sustain their production/supply, and the relative costs, which finally determine the cost of e-kerosene.
Hydrogen production via water electrolysis relies on established technologies such as alkaline electrolysis, alongside more efficient technologies currently under development, including proton-exchange membrane (PEM) systems and solid-oxide electrolysis cells (SOECs). To date, however, the share of conventionally produced hydrogen (using non-renewable electricity) obtained through these routes remains negligible compared with the far more widespread and cost effective steam-methane reforming. Moreover, the production of RFNBOs requires very large amounts of renewable electricity, and meeting future demand will necessitate substantial investments in photovoltaic and wind power capacity.
Regarding CO_2, ReFuelEU Aviation imposes stringent constraints. CO_2 captured from fossil fuel power-generation plants may be used only until 2036, while CO_2 from hard-to-abate industrial sectors (*e.g.*, cement, steel, refining, basic chemicals) remains eligible until 2040. From 2041 onwards, only CO_2 captured directly from the air (Direct Air Capture, DAC) or biogenic CO_2 may be used, enabling a virtually CO_2-neutral synthetic-fuel cycle. DAC, however, is a technically demanding process due to the extremely low concentration of CO_2 in ambient air (429.60 ppm was the global average for February 2026, according to NOAA's Global Monitoring Laboratory at Mauna Loa).
Despite the growing number of startups in the field, the largest operational plant to date - Mammoth, in Iceland, with a capacity of 36 kt CO_2/year - is run by the Swiss company Climeworks, not without significant technical and operational challenges. Current specific energy requirements for DAC remain very high and, although expected to decrease as the technology matures, they will still be more than double those of conventional post-combustion capture from flue gases and industrial processes. The energy needed to operate DAC facilities must also be entirely renewable.

Life-Cycle Emission Reduction and Energy Efficiency

European Commission studies confirm that e-kerosene produced from renewable hydrogen and direct air capture achieves lifecycle emissions of 8-15 gCO_2eq/MJ, compared with 89 gCO_2eq/MJ for conventional jet fuel, corresponding to an 83-91% reduction **[8]**.
A comprehensive comparison of Well-to-Wing GHG emissions for the various SAF technologies and feedstock types is reported in **[9]** and reproduced in Fig. 2. e-kerosene provides a substantial contribution to reducing GHG emissions in the

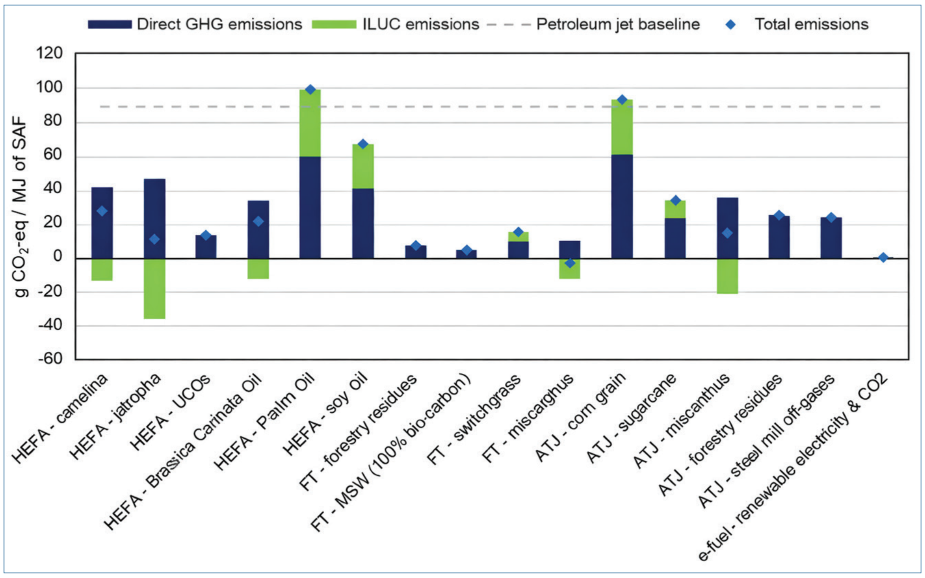

Fig. 2 - Well-to-Wing GHG emissions of the SAF from various routes and feedstocks. Dotted line fossil Jet Fuel. Reproduced from [9]

aviation sector. However, several bio-jet pathways also deliver significant reductions relative to the fossil-kerosene baseline. Among these, gasification of municipal solid waste and biomass residues shows particularly favorable results.

Beyond GHG emissions, the energy efficiency of SAF pathways is a crucial parameter for assessing their overall sustainability. Conversion processes differ markedly in terms of energy inputs, fuel yields, and by-product streams. Among them, the PtL pathways exhibit the lowest overall efficiency, both when considering e-kerosene alone and when accounting for all co-products [10]. In other words, e-kerosene production is associated with the largest energy losses among the SAF technologies currently available.

SAF Production Cost

As previously discussed, the most fundamental constraint for e-kerosene is its thermodynamic efficiency. The full conversion chain from electricity to usable aviation fuel achieves only about 20-30% overall efficiency, meaning that three to five units of renewable electricity are required to obtain one unit of fuel energy. This inevitably drives up production costs: current estimates place e-kerosene at roughly 4-10 times the price of conventional jet fuel [8]. Green-hydrogen production represents the largest single cost component, ranging from \$2.4 to \$5.6 per kilogram of fuel.

However, multiple studies project that green-hydrogen costs could fall below \$1/kg by 2050, driven by economies of scale in electrolyzer manufacturing and declining renewable-electricity prices.

CO_2 capture also has a major impact on e-kerosene costs, with DAC being significantly more expensive than point-source CO_2 capture (*e.g.*, from coal- and natural-gas power plants, steam-methane-reforming units, or conventional refineries). Current DAC costs range from \$400 to \$1,000/tCO_2 - figures that are certainly inflated by the small size of today's mostly pilot-scale plants - with projections indicating a decline to \$230-540/tCO_2 by 2050 [8]. For these reasons, e-kerosene is expected to become cost-competitive with other SAF pathways by 2050, although it will likely remain more expensive than fossil kerosene (Fig. 3, [11]).

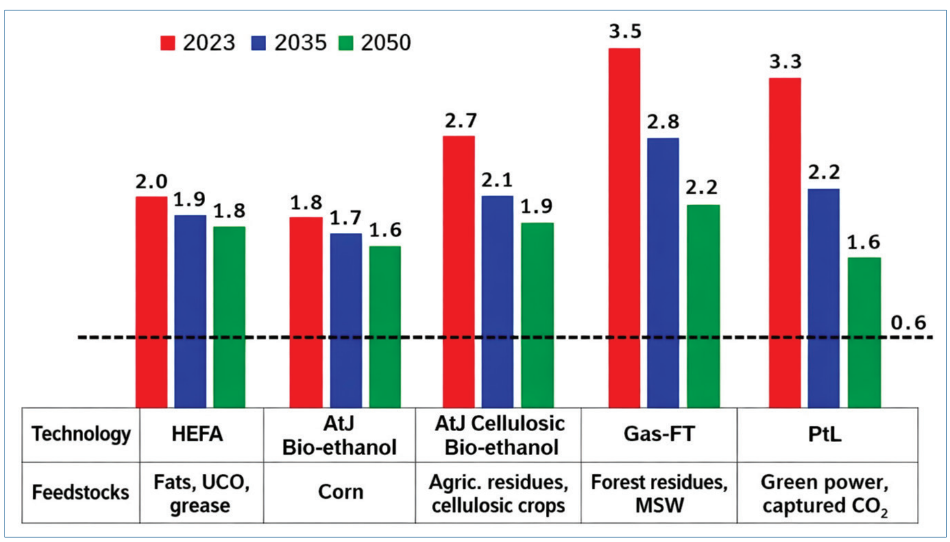

Fig. 3 - Levelized cost of SAF (k\$/t). Dotted line: Jet Fuel historical prize. Data from [11]

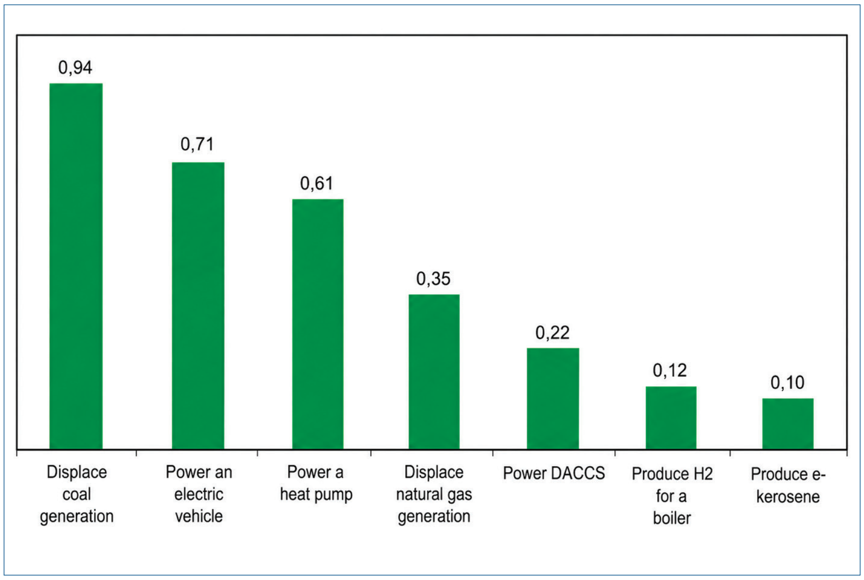

Fig. 4 - Emissions (tCO_2eq) saved using 1 MWh of green electricity for different applications. Data from [12]

Conclusions

The SAF landscape encompasses multiple production routes, each with distinct advantages, limitations, and scaling potential. Unlike biomass-based routes, which are inherently constrained by land availability, photosynthetic efficiency, and competing uses, e-kerosene production scales with the expansion of renewable energy. For this reason, in the near term, SAF supply will predominantly come from HEFA, AtJ, and gasification-FT pathways, owing to their lower costs and higher technological maturity. However, achieving net zero targets by 2050 will require e-kerosene to supply 50-70% of total aviation-fuel demand [8]. Yet concerns regarding the low energy efficiency of e-kerosene remain. Renewable electricity is a valuable resource: is converting it into e-fuels really the best way to use it? Fig. 4 illustrates several alternative uses of 1 MWh of green electricity - compared with e-kerosene production - based on the analysis of the UK Committee on Climate Change [12]. All the other options deliver higher CO_2 savings. The reason is the very low energy efficiency of e-kerosene production, with 70-80% of the input energy lost along the conversion chain. The same applies to other e-fuels such as e-gasoline and e-diesel. This raises a fundamental question: can we afford to waste such a large share of scarce renewable energy? Decarbonizing transport - and aviation in particular - requires a broader and more integrated strategy. According to the IEA [1], aviation-energy demand in 2050 will reach 16 EJ under the NZE scenario (equivalent to roughly 370 Mt of jet fuel, assuming a jet-fuel LHV of 43 MJ/kg). To comply with ReFuelEU Aviation - which is less demanding than the U.S. Aviation Climate Action Plan - 70% of jet fuel would need to be SAF, corresponding to 11.2 EJ (about 260 Mt of SAF). In the same scenario, total liquid-biofuel production in 2050 amounts to 9 EJ, largely allocated to heavy-duty trucking, long-haul aviation, and international shipping. Among the various SAF pathways, e-kerosene offers the significant advantage of not being constrained by feedstock availability and of relying on technologies that are already established and technically mature. At the same time, however, it suffers from a major drawback: its production is heavily dependent on large amounts of renewable electricity, most of which is lost due to the low efficiency of the different conversion steps.

Among bio-based SAFs, HEFAs are already commercially available and used in blends with fossil jet fuel. Their production is well established, but they face a fundamental constraint: the limited availability of sustainable lipid feedstocks, which will likely prevent very high production volumes. Other bio-jet-fuel technologies are not subject to the same feedstock limitations. In fact, the availability of biomass wastes and residues offers significant potential; an IEA report [13] estimates that total biomass resources - including MSW, agricultural residues, and forestry residues - could reach 130-240 EJ of energy equivalent by 2060. However, these pathways are not yet sufficiently mature to enable rapid deployment, and they remain the focus of extensive R&D efforts.

Another key aspect that could strongly influence SAF deployment - beyond regulatory mandates - is cost. By 2050, SAF prices are expected to remain 3-4 times higher than those of fossil jet fuel. This would translate into significantly higher operating costs for airlines, which are already projected to face economic pressures under current market conditions, potentially slowing the sector's expected growth. One possible approach, already adopted for example in the United States, is to introduce incentives or to penalize fossil fuels through taxation (*e.g.*, a carbon tax), but such measures depend on the financial capacity and political will of individual governments.

Therefore, in the short to medium term, biofuels are expected to supply a large share of the SAF requirement, also rebalancing the fractions currently allocated to other transport sectors where electric traction or hydrogen are easier to implement. e-fuels could become a viable alternative in the longer term, provided that electrolyzer efficiency improves significantly. In particular, emerging approaches such as CO_2 electrolysis using solid oxide electrolysis cells (SOECs) can produce syngas directly from CO_2 and H_2O, thereby eliminating the need for the RWGS step in the FT route to e-fuels [14] and improving the overall energy efficiency of the chain. Hydrogen and hydrogen-based fuels, including e-fuels, are expected to play an increasingly important role in the long term, especially as low-carbon electricity becomes available in large quantities and at low cost - for example, through future technologies such as nuclear fusion.

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Il bio-jet fuel e l'e-kerosene decarbonizzeranno davvero il settore dei trasporti aerei?

La decarbonizzazione dei trasporti è uno degli obiettivi centrali per raggiungere le emissioni nette zero entro il 2050. In questa prospettiva, nel 2023 l'Unione Europea ha adottato il regolamento *ReFuelEU Aviation*, che promuove l'impiego di carburanti sostenibili per l'aviazione (Sustainable Aviation Fuels, SAF) fino a sostituire il 70% del kerosene fossile - comunemente noto come jet fuel - entro il 2050. L'articolo descrive le principali tecnologie di produzione dei SAF, soffermandosi, in particolare, sui processi per ottenere e-kerosene a partire da elettricità rinnovabile e CO_2, e confrontandone potenzialità e limiti.