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ReFuelEU Aviation's Targets: A Feasibility Assessment

Future Cleantech Architects

Executive Summary

The EU benefits from a highly active aviation sector that, on average, consumes anually 10-15% of all the global jet fuel produced. The sector contributes significantly to EU annual emissions and makes up 14% of its transport emissions, second only to road transport. Emissions from aviation have been steadily rising in the EU, increasing by 30% from 2013-2019 and accounting for 5% of the EU's total emissions in 2019. Following the impacts of COVID-19, flight demand is on the rise once again and is almost back at 2019 levels. Thus, there is significant pressure on the sector to reduce its emissions and align with the EU's overarching 2050 climate goals.

As acknowledged by the EU, solutions such as all-electric and hydrogen planes are still in their testing phase and will play a limited role in decarbonization efforts over the next two decades. The EU has also identified the untapped potential of sustainable aviation fuels (SAFs) as drop-in fuels to reduce emissions from the sector by 2050. In 2023, the EU introduced the ReFuelEU Aviation regulation, a SAFs uptake mandate with progressively increasing minimum SAF targets – including subtargets for synthetic jet fuels – until 2050. Demand is expected to continue outstripping efficiency improvements in the EU, with fuel consumption rising by 50% by 2050 (relative to 2019). This will be accompanied by an exponential growth in the share of SAFs, both bio and synthetic, from current levels until 2050.

If the regulation's minimum targets are met, SAFs will be the largest contributor to the final fuel mix in 2050, at 70%. Today, the maximum production capacity for SAFs in the EU remains minimal at 0.24 Mtoe/year, or <1% of consumption. This analysis addresses key questions regarding the feasibility of meeting ReFuelEU Aviation's targets. Considerations include the availability of feedstocks for biofuels, whether the EU is equipped to produce the necessary quantities of bio- and synthetic jet fuels, and the amount of clean electricity needed to produce the requisite amount of synthetic jet fuels by 2050.

Findings

Biojet fuel

Focusing on electrification in road transport in the EU opens the potential for shifting liquid biofuel production to biojet fuel to help achieve the ReFuelEU Aviation targets. Shifting 35% of today's biodiesel capacity alone can help achieve the 2030 target. There is a high likelihood that the demand for biojet fuel past 2030 will have to be covered by diverting current liquid biofuel production to biojet fuel, installing additional capacity, and imports, with a heavier reliance on imports in the longer term. Converting 100% of today's EU liquid biofuel production to biojet fuels could help achieve 45% and 30% of the 2040 and 2050 targets, respectively. Challenges will arise from the strengthened feedstock restrictions of the Revised Renewable Energy Directive (RED III), due to the limited supply of eligible feedstocks such as forest residue, municipal solid waste (MSW), and waste oil. EU production of biojet fuels will face competition from sectors other than road transport looking to liquid biofuels as a decarbonization option, such as shipping. Importing biojet fuel in its final form and feedstocks for its production will also face competition from other regions over these scarce resources. This competition creates uncertainty around the amount of biojet fuel the EU can secure as 2050 approaches to meet ReFuelEU Aviation's targets.

Synthetic jet fuel

Synthetic jet fuel produced from green hydrogen and CO_2 from direct air capture (DAC) using clean electricity is the most expensive and energy-intensive pathway but is also the pathway with one of the lowest lifecycle Greenhouse Gas (GHG) emissions. Less than 5% of total projected EU electricity production would be needed to produce the requisite synthetic jet fuels to meet ReFuelEU Aviation's subtargets by 2030 and 2040. However, past 2040 there will be an exponential growth in the synthetic jet fuel contribution to the final fuel mix. By 2050, synthetic jet fuels must make up at minimum 35% of the final fuel mix, requiring 872 TWh of additional renewable electricity, with 80% of this electricity needed to operate the electrolyzers for green hydrogen production. Aviation currently requires minimal electricity; however, if synthetic jet fuels are to be fully produced on EU territory to meet ReFuelEU Aviation's targets, an extra 31% of current electricity production levels – and 16.5% of total projected electricity production in 2050 –must be dedicated to producing these fuels. This electricity must be additional and from renewable sources, and cannot be diverted from other decarbonization efforts, especially electrification of road transport. Any shortfall in supply will have to be overcome with imports. Additionally, despite synthetic jet fuel subtargets starting in 2030, investment and production ramp-up must begin today for the EU to be ready to meet these targets.

While it seems feasible that the EU will be able to meet its 2030 targets, mostly through biojet fuels, consideration must be given to meeting its later targets until 2050. Shortfalls in the supply of biojet fuels and shortages in resources, such as renewable electricity and green hydrogen, to produce synthetic jet fuels on EU territory, become more apparent past 2030.

Technical recommendations:

1. Implement a facts-based allocation of scarce resources across the EU:

- A full analysis of EU bioenergy needs and feasible production on EU territory by 2050 must be conducted. Liquid biofuels must then be prioritized for those sectors of the economy with limited decarbonization options, with a portion allocated for biojet fuels until 2050. This will help identify how much biojet fuel the EU can produce on its territory.

- A complete breakdown of electricity needs across the EU in line with decarbonization efforts is necessary, including feasible growth in generation capacity in the EU by 2050, especially for renewable electricity. This breakdown must account for the renewable electricity needed for synthetic jet fuel production and allocate a given quantity to produce these fuels starting from today, if the 2030 targets are to be met, until 2050. This will help identify how much synthetic jet fuel the EU can produce on its territory.

- A comprehensive feasibility analysis of green hydrogen production in the EU until 2050 is needed. The available green hydrogen must first be prioritized to decarbonize existing hydrogen needs in refining and fertilizer production and for use in emerging technologies in steel manufacturing. The amount of green hydrogen that can then be dedicated to aviation for use partly as the final fuel, but mainly as a feedstock for synthetic jet fuel production, must be identified.

2. Close the supply deficit with imports:

Once these resources are properly allocated to the aviation sector, it will become clear how much biojet and synthetic jet fuel can be produced on EU territory. Any discrepancy in supply must then be made up to meet ReFuelEU Aviation's targets. One option is eligible imports from third countries that meet the minimum sustainability criteria outlined in ReFuelEU Aviation and the RED III.

3. Look to flexibility mechanisms to widen the SAF tradability market:

A Book and Claim scheme can help ease market accessibility to SAFs and reduce reliance on physical SAF imports by trading with trusted third-country partners. This scheme can also help reduce SAF lifecycle emissions by minimizing transport emissions. As jet fuel consumption is not uniform across the Union, Book and Claim can help ease these supply pressures by trading SAFs across the Union, as well. SAFs are then claimed by the airlines who pay the premium for them, while the physical SAFs are supplied to the airports that are geographically closest to the SAF production sites.

Policy recommendations:

1. Promote alternative modes of travel:

Beyond operational improvements, alternative modes of travel must be promoted and incentivized following the 'polluter pays principle' on short-haul routes. This will help reduce overall jet fuel demand, helping to ease the SAF supply strain and easing the feasibility of achieving ReFuelEU Aviation's 2050 targets.

2. Accelerate SAF permitting and certification:

Facilitating permitting for the construction of new SAF plants and accelerating the approval of SAF production pathways by the American Society for Testing and Materials (ASTM) can reduce project lead times and facilitate the large-scale deployment of SAFs, especially for synthetic jet fuels. Additionally, a uniform certification process is crucial to streamlining SAF eligibility toward the ReFuelEU Aviation targets, especially those that are imported. These procedures can help maximize SAF production potential within the EU to meet the regulation's targets.

3. Incentivize the shift to biojet fuel:

Current liquid biofuel capacity in the EU is enough to help achieve ReFuelEU Aviation's 2030 target. However, the shift in production from biodiesel and biogasoline to biojet fuel incurs both CAPEX and OPEX costs. Regulation can help reduce cross-sectoral competition for biofuels, especially from road transport. Prioritized funding and subsidies for plants willing to convert production to biojet fuel can help incentivize the shift and accelerate production within the EU.

4. Implement the 'polluter pays principle':

To date, the EU still exempts jet fuel from fuel taxation. Taxing conventional jet fuel while exempting SAFs with lower lifecycle GHG emissions is a powerful tool that can help close the cost gap between the two. Internationally recognized and legally binding SAF uptake mandates at ICAO level can help minimize market distortions and maintain a level playing field. Tax revenue can then be reinvested into accelerating sustainable solutions in the sector.

5. Close the technological and commercialization gaps:

Revenue from carbon pricing is best used when reinvested into the sector to promote sustainable solutions. Bespoke policies, such as a frequent flyer levy, can also be used to cover higher SAF costs without affecting lower-income passengers who fly less. However, since aviation is a highly commercial sector, private support is crucial for accelerating SAF uptake through initiatives such as the First Movers Coalition.

6. Budget scarce resources:

While ReFuelEU Aviation has set clear progressive targets and eligibility criteria for SAFs, the quantity of clean electricity and sustainable feedstocks needed has not been highlighted. Budgeting these resources across various sectors of the EU economy must begin today. Incorporating this allocation within legislation will be crucial to the success of sector-specific regulations such as ReFuelEU Aviation.

7. Introduce flexibility mechanisms:

A SAF Book and Claim scheme can help widen the SAF market and reduce the dependence on physical SAF imports. However, effective implementation of a Book and Claim scheme requires clear guiderails on SAF eligibility and provisions against double counting. Incorporating Book and Claim for SAF tradability in the next revision of ReFuelEU Aviation, with clear guiderails for its implementation and a cap on eligible SAF quantities through this scheme, will help to ease supply constraints and strengthen the regulation's targets without creating an overdependence on virtual SAF claims.

If implemented correctly, these technical and policy recommendations can help achieve ReFuelEU Aviation's targets while minimizing its adverse effects on the sector.

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Glossary

ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-jet
CCU	Carbon capture and utilization
CO_2	Carbon dioxide
DAC	Direct air capture
DRI	Direct reduced iron
EU the Union the bloc	The European Union
EU ETS	EU Emissions Trading System
GHG	Greenhouse gases
FT	Fischer-Tropsch
H_2	Hydrogen
HEFA-SPK	Hydroprocessed esters and fatty acids to synthetic paraffinic kerosene
HHV	Higher heating value
ICAO	International Civil Aviation Organization
LTFT	Low-temperature Fischer-Tropsch
MSW	Municipal solid waste
NZE	Net Zero Emissions
PtL	Power-to-liquid
RED	Renewable Energy Directive
RFNBO	Renewable fuels of non-biological origin
rWGS	Reverse water gas shift
SAFs	Sustainable aviation fuels
SMR	Steam methane reforming

Introduction

To curb the effects of climate change, the EU aims to become the first carbon-neutral bloc by 2050 under the aegis of the European Green Deal[1], which was brought into law in 2021 through the European Climate Law[2]. The first milestone of this deal is commonly referred to as the 'Fit for 55' package of legislation, aiming to reduce carbon emissions by 55% by 2030 relative to 2019 levels. To achieve this 55% reduction, followed by net-zero emissions by 2050, all sectors of the economy must decarbonize. Since 1990, there has been a steady decline in CO_2 emissions across most sectors of the EU economy, such as in electricity and heat (the largest contributor to annual emissions in the EU), buildings, industry, and more. The only sector whose emissions continue to rise in the EU is the transport sector, the second largest emitter after electricity and heat, and currently responsible for ~30% of the EU's annual CO_2 emissions[3].

Air travel is currently the fastest means of global transit. Aside from enabling touristic travel, aviation facilitates trade and generates economic growth and employment opportunities. However, the sector's environmental impact is substantial, representing 2.5% of global CO_2 emissions[4]. In the EU, aviation makes up 14% of transport emissions, the second largest emitter after road transport[3, 5]. Emissions from aviation have been steadily rising in the EU, increasing by 30% between 2013-2019, and accounting for 5% of the EU's total emissions in 2019[3, 6]. To help achieve its 2030 targets, the European Commission presented the 'Fit for 55' package, which includes legislation specific to each sector of the economy, with the ReFuelEU Aviation regulation focusing specifically on the aviation sector. This regulation is a sustainable aviation fuels (SAFs) mandate with a progressively increasing share of SAFs in the final fuel mix until 2050.

SAFs will play a major role in getting the aviation sector on a more sustainable path and helping it align with the EU's climate goals. ReFuelEU Aviation is a first-of-its-kind SAF mandate that aims to increase the demand for SAFs and provide the necessary signals to increase the supply of SAFs on the market[7]. To date, SAFs remain a scarce commodity due to their reliance on limited feedstocks and the availability of clean energy. Therefore, some concrete questions need to be answered concerning the feasibility of achieving the targets outlined by this mandate. This report will analyze the feasibility of meeting ReFuelEU Aviation's targets by first outlining the important role of SAFs in decarbonizing aviation, then introducing the ReFuelEU Aviation regulation, and concluding with the results and recommendations based on this analysis.

The role of SAFs in decarbonizing aviation

Global jet fuel consumption increased by almost 50% over the period from 2005 to 2019, due to the steady rise in demand that has continuously outstripped efficiency improvement efforts[8]. While aviation was one of the sectors most affected by the COVID-19 pandemic, it is now on track for a complete recovery, with demand expected to reach pre-pandemic levels again by 2025 at the latest. In 2023, jet fuel consumption amounted to ~280 Mt globally[9], 99% of which is still conventionally produced from fossil fuels, with SAFs still playing a minor role in today's final fuel mix. While the supply of SAFs in 2023 doubled from 2022 levels, it only made up ~0.16%, or 0.5 Mt, of total fuel consumption for that year[10]. In the EU, jet fuel consumption increased by ~30% in 2019 relative to 2005[11].

On average, the EU is responsible for 10-15% of global jet fuel consumption, despite housing less than 6% of the world's population[9, 12, 13], requiring 44 Mt[1] in 2023. However, the maximum production capacity for SAFs in the EU remains minimal at 0.24 Mtoe/year, or <1% of consumption[5]. As demand rises once again in the bloc, reaching 92% of 2019 levels in 2023[15], there will be more pressure on the sector to reduce its emissions and align with the EU's overarching 2050 climate goals.

Jet fuel's unique characteristics make it an ideal energy source for flying that is difficult to replace. Its high energy density enables long-distance travel, and its low freezing point is compatible with high-altitude operations. Additionally, jet fuel is easy to handle and can be stored in the wings, providing stability and freeing up the fuselage to maximize passenger capacity. Finally, conventional jet fuel is still the most affordable option today, with alternatives costing up to seven times more in comparison[16]. Several other barriers delay the introduction of new technologies into the aviation sector, as outlined in Table 1.

[1] Based on actual fuel demand data for 2023 from Eurostat[14].

Table 1: Key sectoral and technological challenges in aviation that delay the entry of novel solutions to tackle emissions.

Safety	Safety is a primary concern in aviation, and any new technology must undergo rigorous testing and certification procedures before being cleared for commercial operation. For instance, the Airbus A380, the largest passenger airliner, took almost 20 years from concept to certification, and the A380 was still of a traditional tube-and-wing aircraft configuration. New designs such as the blended-wing aircraft are even more complex compared to conventional configurations.
Range	The wide range of flight distances makes a one-size-fits-all alternative solution to reduce the sector's warming impact extremely difficult. Additionally, not all flights emit equal amounts of emissions. While 55% of all flights are below 1000 km, they only make up 20% of emissions[6, 17]. In contrast, long-haul flights, over 4000 km, make up only 5% of all flights but are responsible for 40% of emissions and are the most difficult to decarbonize[6, 17].
Battery limitations	All-electric aircraft are best suited for flights below 500 km with limited passenger capacity. This is due to the low specific energy of batteries, which is <2% of jet fuel's energy content[2][18]. Further advancements in battery technology are needed for the wider applicability of electric planes in aviation, limiting their contribution to decarbonization efforts by 2050.
Hydrogen limitations	Hydrogen (H_2) could theoretically service long-haul flights, but that would require an airframe redesign optimized for hydrogen use, which would not be feasible before 2050. This limits hydrogen's contribution to flights up to a maximum of 4000 km in range with retrofits to current aircraft designs. However, hydrogen comes with additional challenges, including sourcing (especially in the case of green hydrogen), transporting, and storing the hydrogen.
Lifespan	Planes are built to last, with an average lifetime of 25 years[19]. Planes manufactured and sold today will most likely remain in operation in 2050 and are still predominantly conventional planes optimized for jet fuel use. The slow rate of fleet renewal until 2050 will further limit the contributions from hydrogen and all-electric aircraft in the short to medium term.

Therefore, one of the most talked about solutions to help the sector reduce its environmental impact by 2050 is SAFs. SAFs are considered a 'drop-in' solution, meaning that they can be used in aircraft engines today without needing to modify the engines nor the fuel's infrastructure, storage, and supply chain. These fuels are made up of hydrocarbons, like conventional jet fuel, but are not produced from fossil fuels. However, challenges across the value chain are associated with SAFs, which hinder large-scale ramp-up in production of these fuels. Challenges include feedstock and clean electricity availability as outlined in the coming sections.

Types of SAFs and their production pathways

SAFs is an umbrella term that includes two main types of fuels: biojet fuels and synthetic jet fuels[3]. SAFs can be produced using different pathways dependent on the type of feedstock in the case of biojet fuel, and the method of capturing CO_2 and producing hydrogen in the case of synthetic jet fuels. The manufacturing process is directly related to the lifecycle greenhouse gas (GHG) emissions savings and costs of the final SAF produced, as will be discussed next.

Biojet fuels

Aviation biofuels or biojet fuels can be considered 1st, 2nd, or 3rd generation based on the feedstocks used to produce them, as shown in Fig. 1. For example, 1st generation biofuels that are made from food crops such as sugar, starch, or oil, should be avoided as they directly compete with food sources. 2nd generation biofuels can be produced from a variety of sources such as waste oil, as well as lignocellulosic biomass such as forest residue, inedible energy crops, agricultural residue and waste, and municipal solid waste (MSW). 3rd generation biofuels are made from algae.

2nd and 3rd generation biofuels must be monitored and evaluated on a lifecycle GHG emissions basis to ensure maximum emissions savings potential. For example, 2nd generation biofuels can provide more than 70% lifecycle GHG emissions savings compared to conventional jet fuel[16], but that is subject to high uncertainty from upstream processing operations. While measuring the overall sustainability of biojet fuels, additional considerations must be given to the feedstocks' origins in the case of imports as well as the indirect impact on land use change. Only the pathways with the highest emissions savings potential and adherence to additional sustainability criteria, including indirect effects, should be eligible to produce biojet fuels as defined in Article 3 of ReFuelEU Aviation in line with Directive (EU) 2018/2001, known as the Revised Renewable Energy Directive or RED II, which came into effect in 2018[20].

[2] Based on the current industry standard Li-ion batteries with a specific energy content of 250 Wh/kg.

[3] ReFuelEU Aviation also classifies recycled carbon aviation fuels, produced from industrial waste streams, as a source of SAFs. However, this analysis focuses on biojet fuels and synthetic jet fuels, as most of the SAF produced will come from these two sources.

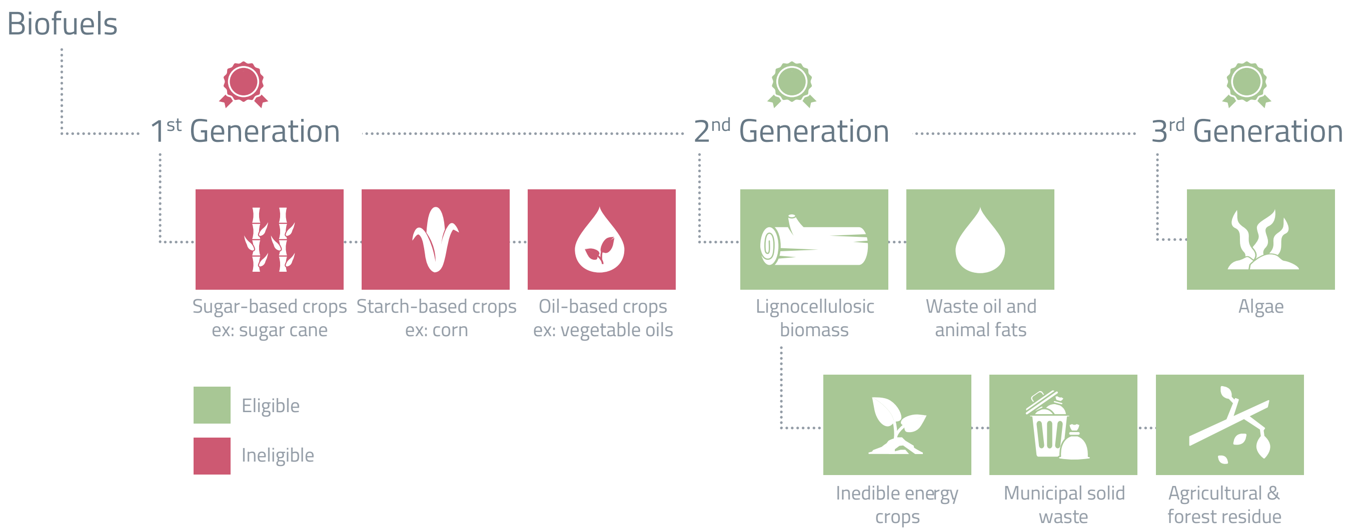

Figure 1: Breakdown of 1st, 2nd, and 3rd generation biofuels.

There are many pathways to produce biojet fuels, and pathway selection is dictated by the feedstock used. The pathways fall under three main categories as outlined in Table 2[17]:

Table 2: The three main categories for liquid biojet fuel production[17].

Bio-chemical	Used with feedstocks such as sugars and starches which necessitate fermentation in the presence of microbes followed by hydroprocessing. The most common pathway is the alcohol-to-jet (ATJ) pathway.
Oleo-chemical	Used with lipid feedstocks such as fats and oils which require hydrodeoxygenation followed by hydroprocessing[4], which are processes dependent on hydrogen. The most common conversion pathway is the hydroprocessed esters and fatty acids to synthetic paraffinic kerosene (HEFA-SPK).
Thermo-chemical	Used with lignocellulosic biomass feedstocks such as MSW or forest residue. In one of the most common pathways, the biomass is first gasified to produce syngas (CO and H_2) that is then converted to jet fuel via Fischer-Tropsch (FT) synthesis in the presence of a catalyst followed by hydroprocessing.

All three categories require hydrogen to produce the final desirable hydrocarbon product. To minimize the lifecycle GHG emissions of the final biojet fuel produced, green hydrogen must be used in their processing. Currently, seven technology pathways fall under the three main categories described in Table 2[21]. Pathways are approved by the international standards organization, the American Society for Testing and Materials (ASTM), with many more pathways still under review. ASTM is the global reference for SAF certification to produce 'drop-in' SAFs under standard ASTM D7566.

To date, biojet fuels remain more expensive than conventional jet fuel with costs ranging from two to four times higher, depending on the feedstock and pathway used[16].

While the demand for liquid biofuels has been steadily increasing in recent years, reaching ~130 Mtoe globally in 2022, most of the production is for bioethanol, biodiesel, and renewable diesel, which are primarily used in road transport[22]. As mentioned previously, global production of SAFs, all of which is currently from biofuels, was 0.5 Mtoe in 2023, up from 0.25 Mtoe in 2022[10]. Adapting biorefineries to produce biojet fuels is no easy feat, but it could theoretically be done if changes are implemented to current bioethanol, biodiesel, and renewable diesel production pathways. Changes include replacing process units, adding hydrocracking and hydrotreating units, switching out feedstocks and catalysts, and altering operating conditions to maximize biojet fuel yields. Therefore, though not technically impossible, these biorefineries would need to implement changes and incur additional CAPEX and OPEX costs to adapt their processes to biojet fuel.

Synthetic jet fuels of non-biological origin

Synthetic jet fuels, or power-to-liquid (PtL) fuels, of non-biological origin, or what is referred to as renewable fuels of non-biological origin (RFNBO), are produced by combining hydrogen and carbon dioxide (CO_2) to form the more complex hydrocarbons that make up jet fuel. This process contrasts with biojet fuel production, where complex hydrocarbons are already available, but in undesirable forms that require conversion and upgrading. Producing synthetic jet fuel by combining hydrogen and CO_2 requires energy, typically in the form of electricity, which is when these fuels are referred to as electro- or e-fuels. The inputs needed to produce these fuels are outlined in Table 3, with the more sustainable options highlighted.

[4] These steps refer to the catalytic reactions the feedstocks undergo with hydrogen at elevated temperatures and pressures to achieve the desirable product. Hydrodeoxygenation refers to oxygen removal from the compounds through a reaction with hydrogen. Hydroprocessing includes processes such as hydrocracking and hydrotreating, where larger hydrocarbon molecules are broken down into smaller, more desirable products in the presence of hydrogen.

Table 3: The inputs needed to produce synthetic jet fuels and the pathways to producing these inputs.

Hydrogen (H_2)	‣ Produced from steam methane reforming (SMR) with carbon capture and strict methane leakage controls (blue hydrogen). ‣ Produced via electrolysis using clean electricity (green hydrogen), this hydrogen production pathway has the lowest lifecycle GHG emissions.
Carbon Dioxide (CO_2)	‣ Captured through point source carbon capture and utilization (CCU) from biogenic or industrial sources, such as off gases from cement manufacturing. In the industrial case, the CO_2 emissions are shared across two sectors, and carbon accounting must be rigorous to avoid double counting. ‣ Captured through direct air capture (DAC), which is the method with the lowest lifecycle GHG emissions. In this process CO_2 is first extracted from the air, then used to make synthetic jet fuel, and finally released back into the atmosphere when the fuel is burnt, making the process carbon neutral.
Electricity	Electricity is needed to produce hydrogen and capture CO_2, which can be provided by: ‣ Direct electricity from the grid. ‣ Behind the meter clean electricity from nuclear or renewable energy sources (including biomass), which is the source with the lowest lifecycle GHG emissions.

The most common way to convert CO_2 and hydrogen to jet fuel is via the following three-step process:

- First, the reverse water gas shift (rWGS) reaction to produce syngas and optimize the CO:H_2 ratio.
- Following the rWGS, FT synthesis converts the syngas to a range of hydrocarbons[5].
- These hydrocarbons are then processed in a hydrocracker to produce jet fuel.

These steps require medium to high temperatures that should typically be supplied via clean energy sources in the form of electricity or direct heat.

Synthetic jet fuel production depends on scarce resources including green hydrogen, captured carbon dioxide, and clean electricity.

As a result, synthetic jet fuels are currently the most expensive alternative solution for the aviation sector, costing up to seven times more than conventional jet fuel[16], with the highest costs associated with the DAC route.

However, producing synthetic jet fuels from green hydrogen, CO_2 from DAC, and clean electricity represents the pathway with one of the highest lifecycle GHG emissions savings potential and will be the route that this analysis focuses on[16].

For both SAF categories, large-scale SAF development and deployment is contingent on the availability of resources that remain scarce today, are costly to produce or source, and are subject to high competition from other sectors. Legislation such as ReFuelEU Aviation will play a key role in stimulating demand and providing a market signal to increase the supply of these fuels.

The ReFuelEU Aviation regulation

Aviation plays a significant role in the EU economy, fostering connectivity among Member States, facilitating international travel, generating employment, and promoting trade and tourism. However, addressing emissions from air travel is crucial for the EU to achieve its goal of reducing GHG emissions by 55% by 2030 and reaching climate neutrality by 2050. The EU recognized that solutions such as all-electric and hydrogen planes are still in the pre-commercialization stage, limiting their emissions reduction contribution to short-haul flights over the next two decades. However, the EU also recognized the untapped potential of SAFs as drop-in fuels to reduce emissions across all flight ranges in the near and long term.

The International Civil Aviation Organization (ICAO) has set an aspirational target of net-zero emissions from international aviation by 2050. To meet these goals, ICAO has introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a global market-based carbon offset measure to reduce emissions. CORSIA incentivizes the uptake of CORSIA-eligible SAFs by reducing operators' offsetting requirements. However, participation in CORSIA remains voluntary until 2027, and the SAF requirements are not binding. At the end of 2023, the EU introduced Regulation 2023/2405, referred to as ReFuelEU Aviation, a first-of-its-kind, legally binding mandate that focuses on the uptake of SAFs[7].

The ReFuelEU Aviation regulation is a SAFs uptake mandate with progressively increasing minimum SAF targets, including subtargets for synthetic jet fuels of non-biological origin[6], until 2050, as detailed in Table 4. This mandate serves as a market signal, increasing certainty in the future demand for SAFs to de-risk and stimulate investment, ultimately increasing supply. Some of the key conditions of this regulation aimed at ensuring compliance, maintaining a level playing field, and minimizing market distortions are summarized in Appendix I.

[5] This second step can be accomplished by first converting the syngas to methanol via methanol synthesis and then to jet fuel.

[6] For all accepted fuels under ReFuelEU Aviation, please refer to Articles 3 and 4[7].

Table 4: ReFuelEU Aviation's SAF targets until 2050, including subtargets for synthetic jet fuels[7].

Target year	SAF target	Synthetic jet fuel subtargets
2025	2%	0%
2030	6%	1.2%
2035	20%	5%
2040	34%	10%
2045	42%	15%
2050	70%	35%

ReFuelEU Aviation is a comprehensive SAFs mandate that is legally binding and includes effective penalties to ensure compliance. For this policy to effectively minimize the environmental footprint of EU aviation, it is essential to evaluate its technical feasibility in the European context. Key questions include the state of EU aviation today, the availability of feedstocks for biojet fuels, whether the EU can produce the necessary quantities of bio- and synthetic jet fuels, and the amount of clean electricity required to produce the requisite amount of synthetic jet fuels by 2050. The following analysis will aim to address these critical considerations.

Aviation on a Member State level

While the EU benefits from a highly dynamic aviation sector that helps maintain connectivity between its Member States as well as the rest of the world, flight traffic is not uniform across the Union. The top 4 EU countries in terms of daily average flight traffic (Spain, Germany, France, and Italy) are responsible for 57% of the total traffic within the EU, with the top 10 EU countries being responsible for 80%, as can be seen from Fig. 2[7][15].

The seven busiest airports in the EU include Amsterdam Schiphol, Paris CDG, Frankfurt, Munich, Madrid Barajas, Rome Fiumicino, and Barcelona[15]. These airports make up less than ~1% of all EU airports but are responsible for 25% of average air traffic across the whole of the EU and 40% of traffic across Spain, Germany, France, Italy, and the Netherlands[15]. These five countries combined consume, on average, 61% of monthly EU jet fuel as can be seen in Fig. 3 for 2023[14]. The discrepancy in air traffic rates and demand for jet fuel across Member States means that SAF requirements will not be uniform across the Union as ReFuelEU Aviation's targets are approached. Member States will be responsible for enforcing ReFuelEU Aviation's targets; therefore, it is key to understand their requirements.

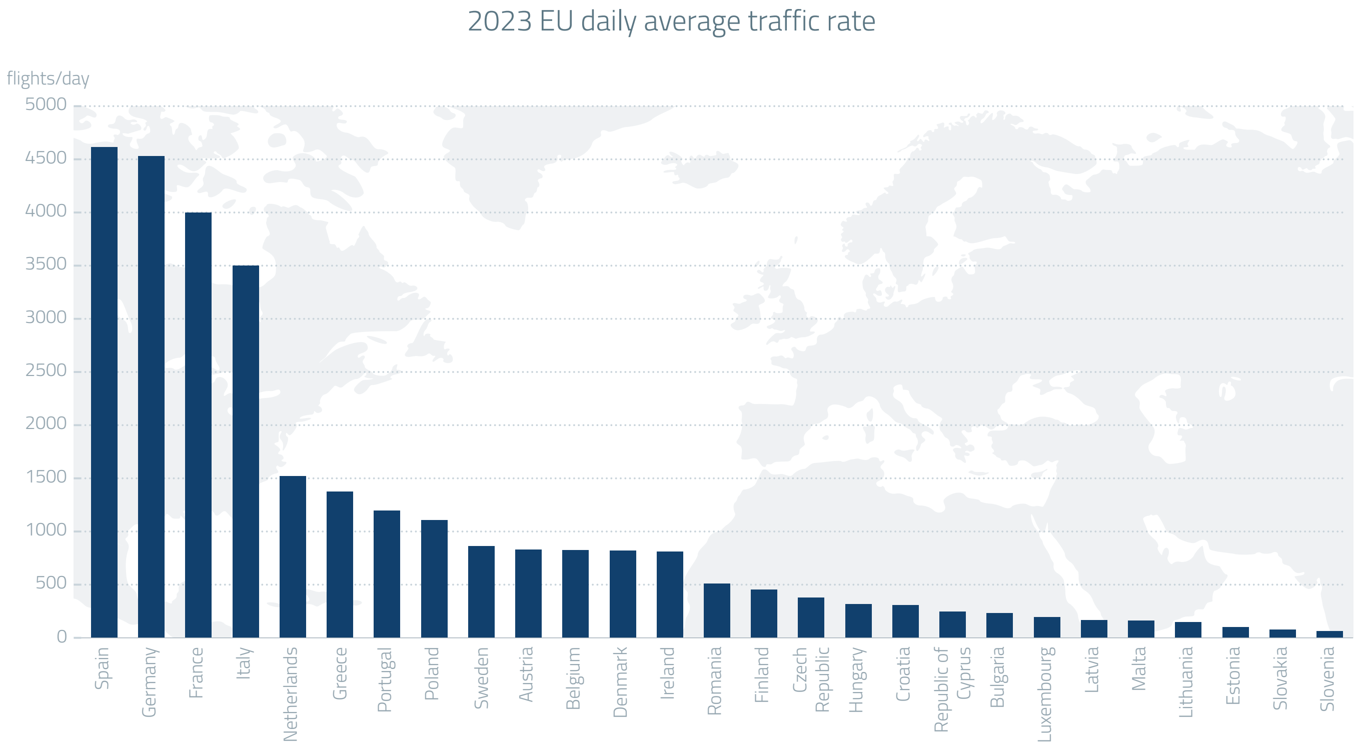

Figure 2: 2023 daily average traffic rate in the EU per Member State from EUROCONTROL[15].

[7] This data was retrieved from EUROCONTROL for 2023[15].

2023 EU monthly average jet fuel consumption

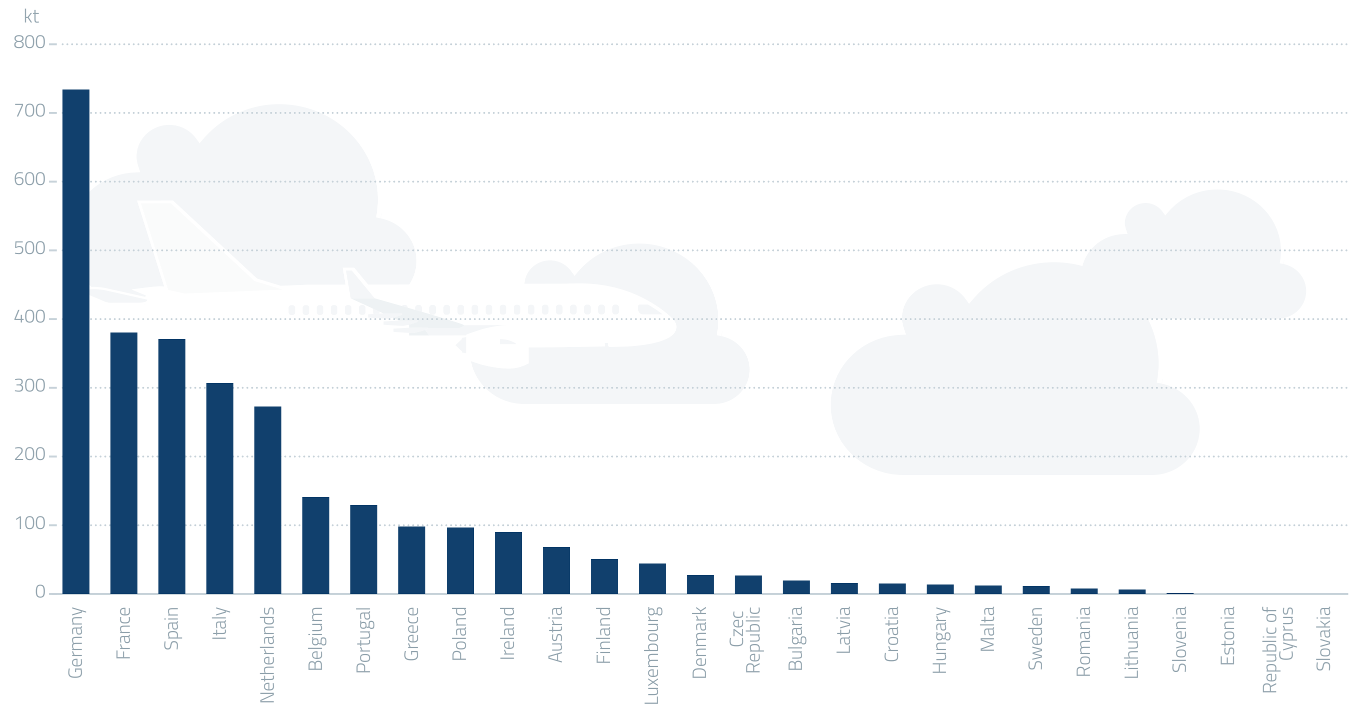

Figure 3: 2023 monthly average jet fuel consumption in the EU per Member State from Eurostat[14].

While assessing the possibility of producing biojet fuels and synthetic jet fuels in the Union at the quantities set out by ReFuelEU Aviation, it is essential to keep in mind the heterogeneous demand for jet fuel across the EU and how that might affect the fulfillment of this regulation.

ReFuelEU Aviation analysis

This section discusses the feasibility of meeting ReFuelEU Aviation's targets. First, the required ramp-up in biojet and synthetic jet fuel production in the EU until 2050 is analyzed. Then, the associated increase in clean electricity needed to produce synthetic jet fuels for EU aviation is considered.

Projected jet fuel demand in the EU

The changes in jet fuel demand in the EU until 2050 are shown in Fig. 4, based on current policy ambitions in line with ITF's 2023 Transport Outlook[23] (see Appendix II for calculations). Demand is expected to more than double in Europe by 2050, once again outstripping efficiency improvements, leading to a 50% increase (72.5 Mt) in fuel consumption relative to 2019 (47.5 Mt)[12, 23]. Figure 4 also shows the amount of SAFs, from both biojet fuels and synthetic jet fuels, needed if the minimum share of SAFs outlined in ReFuelEU Aviation is met at each target year. The total jet fuel required within the EU in 2050 will be 50% higher than in 2019. An exponential growth in the share of SAFs from biojet fuels is required past 2030, and past 2040 in the case of synthetic jet fuels, in line with ReFuelEU Aviation. SAFs will make up the largest portion of the fuel mix in 2050 at 70% with an equal share between bio- and synthetic jet fuels.

Final EU aviation fuel mix until 2050

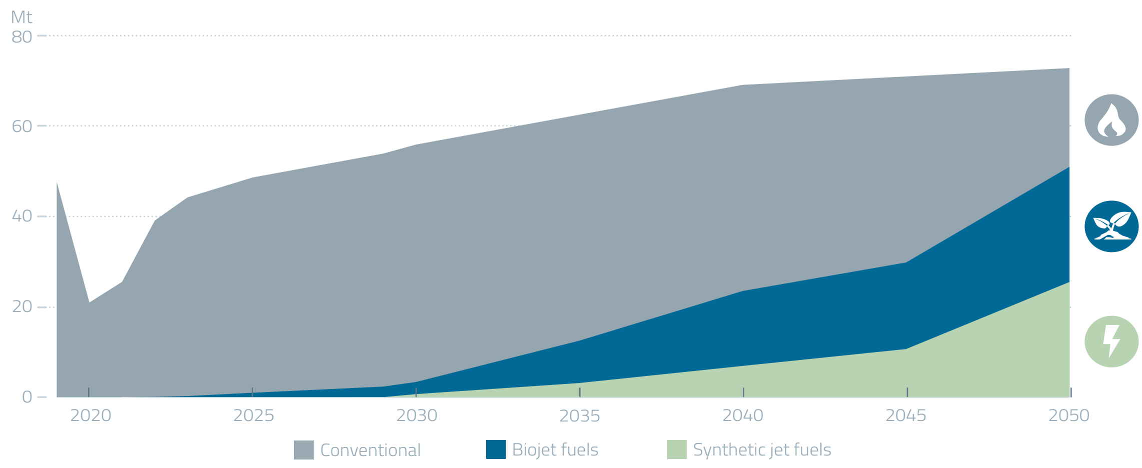

Figure 4: Historical and projected share of conventional jet fuel and SAFs, both bio- and synthetic, in the final EU aviation fuel mix until 2050.

Biojet fuels

Biojet fuels are expected to provide ta large portion of the SAFs required in the final fuel mix per the targets of the ReFuelEU Aviation regulation, reaching 16.5 Mtoe and 25.4 Mtoe by 2040 and 2050 respectively (see Appendix II for details on the methodology for biojet fuel calculations). However, what is the current state of biofuels in the EU and how feasible is it to supply 25.4 Mtoe of biojet fuels for EU aviation by 2050?

In 2022, the EU consumed 144 Mtoe of bioenergy, 70% of which were solid biofuels used for heat and electricity production[24, 25], as shown in Fig. 5. Figure 5 also reveals the breakdown in liquid biofuel consumption, which amounted to 18 Mtoe, or 13% of all the bioenergy consumed[24] Of the 18 Mtoe of liquid biofuels, more than 90% was in the form of biodiesel (77%) and biogasoline (18%), used mostly in road transport. Biojet fuel on the other hand represents a miniscule amount of the total liquid biofuels and total bioenergy consumed by the EU in 2022 at 0.3% and <0.1% respectively. Production of biojet fuels reached 0.170 Mtoe in 2022, up from 7 ktoe in 2018 when production first began[24]. All biojet fuels produced in the EU were exported up until 2022 when 0.054 Mtoe were consumed in the EU with the remaining 68% exported. As of 2022, the maximum production capacity of biojet fuels in the EU is 0.24 Mtoe/year[5].

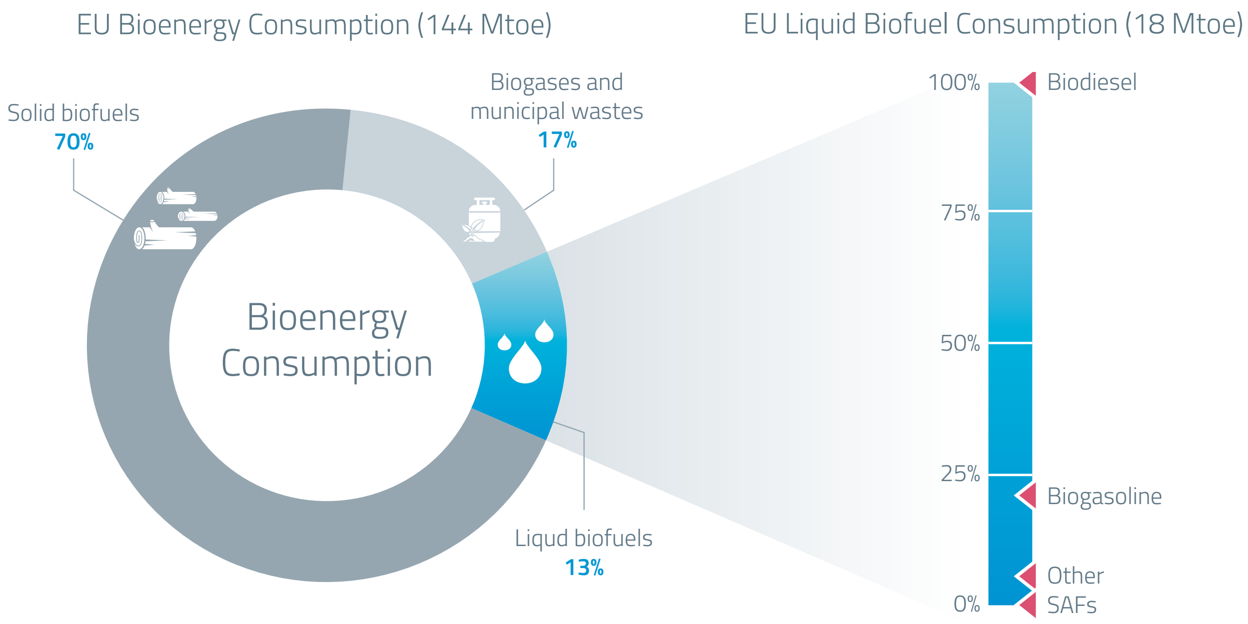

Figure 5: EU total bioenergy consumption in 2022 (left) and breakdown of liquid biofuel consumption by fuel (right) from Eurostat[24].

Figure 6 shows that the EU witnessed its fastest growth in liquid biofuel consumption in the early 2000s, with a year-on-year growth rate between 25%-50% up until 2009. This growth can be attributed to multiple factors such as increased awareness of climate change in the late 1990s and the start of efforts to curb emissions in the EU with the 1997 Kyoto Protocol[26]. Additionally, the 2003 Biofuels Directive 2003/30/EC came into force and aimed to promote the use of biofuels in the transport sector[27]. Oil prices increased in the first decade of the 21st century, peaking in 2008 before the start of the financial crisis[28]. These high oil prices incentivized diversification from fossil fuels in the EU and reduced dependence on imports through domestically produced biofuels. All these factors helped accelerate biofuel growth in the EU in the early 2000s.

Consumption has continued to grow in the last 15 years but at a slower rate below 15%. Figure 6 depicts that the 10-year average growth in consumption in 2010-2019 was 1/3 that of the previous 10-year period from 2000-2009. This can be attributed to the introduction of the Renewable Energy Directive (RED) in 2009[29], the end of the validity period of the Biofuels Directive in 2011, and sustainability concerns, especially from the use of food crops that placed limitations on eligible feedstocks. This would lead to a shift in focus to alternative renewable energy technologies, especially electric vehicles for road transport, in the second decade of the 21st century and a slowdown in growth in biofuel consumption. In the coming years, demand for biofuels in road transport is expected to slow down further due to the increased adoption of electric vehicles, feedstock constraints outlined in the RED II which came into force in 2018, and the amendments introduced in 2023 in the RED III[20, 30], as well as the higher associated costs of biofuels[22]. Therefore, annual growth in demand for all liquid biofuels was projected for 2020-2030, consistent with IEA projections[8][22], at half the average growth rate over the 10 years prior from 2010-2019, as displayed in Fig. 6.

[8] Consistent with the halving in liquid biofuels demand growth rate in Europe over the period 2023-2028 relative to 2017-2022 outlined by the IEA's Renewables 2023 Analysis and forecast to 2028 report[22].

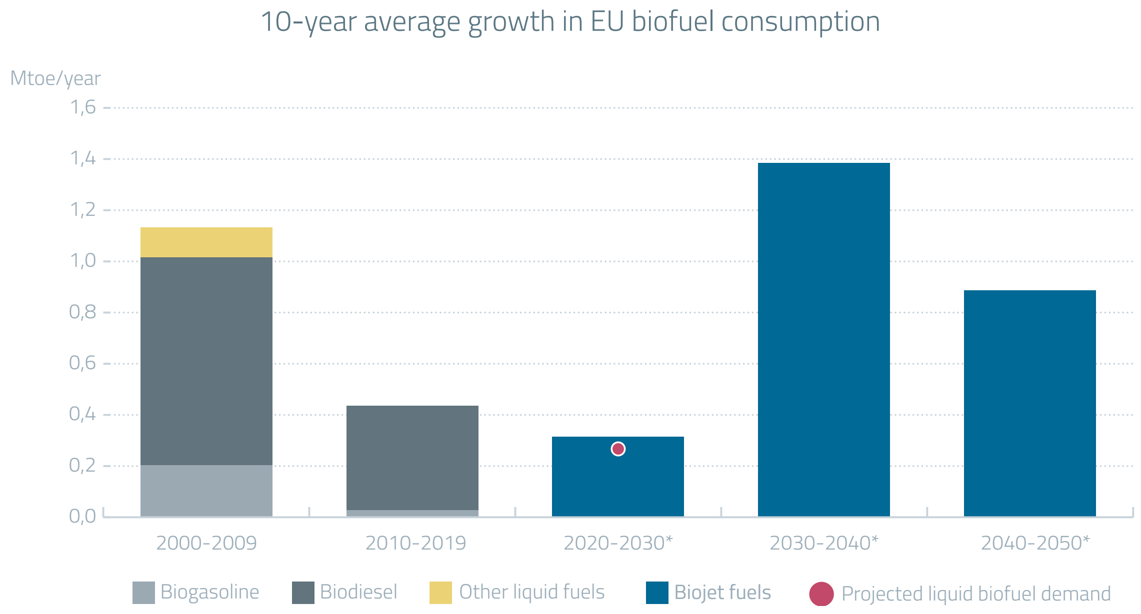

Figure 6: 10-year average growth in consumption of the two main types of liquid biofuels, biodiesel and biogasoline, as well as other liquid biofuels based on Eurostat data[24]. Projected 10-year average growth in biojet fuel consumption to meet the minimum targets of ReFuelEU Aviation as well as the projected growth in total biofuel consumption in Europe for the period 2020 – 2030 consistent with IEA projections[22]. *Projected periods are divided into increments based on the target years of ReFuelEU Aviation.

Historically, in the EU, liquid biofuel consumption consistently outpaced production, with consumption 18% higher than production in 2022[24]. Imports have always supplemented this surplus in demand in the Union. Additionally, of the biodiesels, which constitute ~77% of all the liquid biofuels consumed in the EU, 89% are produced within the Union[24]. However, 57% of the feedstocks necessary to produce these biodiesels are imported from countries such as Indonesia, Malaysia, and China, mostly in the form of palm oil and soybean oil[25]. Globally, most new biofuel demand is expected to remain first-generation, made from conventional crops such as sugarcane and vegetable oils[22]. However, second-generation biofuel demand is expected to grow in the EU due to strengthened feedstock restrictions and sustainability criteria from the RED III. This will add a strain on the indigenous supply of feedstocks as well as on the import of feedstocks to the EU, which will further slowdown the growth of biofuels in the EU. The limited supply of biofuels originating from feedstocks such as forest residue, MSW, and waste oil will potentially increase the bloc's dependence on imports for these scarce resources, in the form of feedstock and final product.

Globally, demand for liquid biofuels is expected to continue growing, especially in emerging economies such as Brazil and India, where some of the most used feedstocks for biofuels are sugars, maize, soybean oil, and rapeseed oil, all of which are first-generation biofuels[22]. ReFuelEU Aviation has strict criteria regarding eligible feedstocks for biojet fuel production, as outlined in Article 4, that can then be counted towards this regulation's SAFs targets. These criteria adhere to the guidelines set by the RED III[20, 29, 30]. These strict limitations on feedstocks that exclude food and feed crops, are necessary to ensure sustainability criteria are met, such as maximum lifecycle GHG savings and minimized indirect impacts such as land use change and competition with food. However, they add pressure on the EU to ensure the availability of these feedstocks and the biojet fuel produced from them. Additionally, it is crucial to ensure that imported feedstocks and fuels comply with the standards set out in ReFuelEU Aviation.

To date, Liquid biofuels have been mainly used in road transport in the EU. While the demand for biofuels, such as biodiesel and biogasoline, will not diminish completely in the coming years, growth is expected to be modest as renewable electricity for electric vehicles is now accepted as the primary solution for decarbonizing this transport segment. This is further supported by the RED III's prioritization of renewable electricity as the primary option for road decarbonization, by multiplying renewable electricity's energy content by a factor of four when used in electric vehicles compared to a factor of two for advanced biofuels, when calculating the minimum shares of renewable energy in the transport sector[30]. In 2023, every one in five new car registrations was electric in Europe, having increased by 20% relative to 2022[31]This reaffirms the primary role of renewable electricity over biofuels in decarbonizing road transport in the EU.

Biojet fuel 10-year growth projections are also shown in Fig. 6, with the growth rate until 2050 applied based on the minimum shares dictated by ReFuelEU Aviation. Figure 6 reveals that in 2020-2030, growth in biojet fuel demand alone will be greater than the projected demand for all liquid biofuels, if the minimum targets of ReFuelEU Aviation are to be met. While the growth rate is slightly higher in 2020-2030 for biojet fuels relative to the projected growth of all liquid biofuels over the same period, it is still lower than the average growth in liquid biofuel consumption between 2000-2019. Growth in biojet fuel demand from 2030-2040 outstrips that of 2000-2009 when liquid biofuel demand was growing at its fastest rate in the EU. As for the 2040-2050 period, growth declines relative to the previous 10-year period. Given the changing landscape of road transport, it is expected that biojet fuels will be a primary contributor to the growth in liquid biofuel demand in the EU in the coming decades.

Although challenging, meeting ReFuelEU Aviation's 2030 targets of 2.67 Mtoe from SAFs, mainly from biojet fuels, could be possible through a combination of ramping up production capacity, currently able to supply 9% of the 2.67 Mtoe, and converting current biofuel production from liquid products such as biodiesel to biojet fuel. If no additional biojet fuel production capacity is added by 2030, converting 35% of current biodiesel production to biojet fuel could supply the remaining SAF needs to meet the 2030 target[9]. It is not simple to convert biodiesel production to biojet fuel, but it is not impossible. This would require process modifications, including the installation of new units, and changing operating

[9] Based on an average 50% conversion of oil feedstock to biojet fuel via the HEFA pathway[32].

conditions and feedstocks to achieve the desired biojet fuel quality[10]. However, if current producers ramp up production to meet their targets in the coming years, ReFuelEU Aviation's 2030 targets would be met through additional SAF supply without diverting biodiesel production to biojet fuels. For example, Neste is aiming to produce 2 Mt of biojet fuel by 2026[33], which alone could meet 75% of the EU's SAF needs by 2030.

As of 2040, demand for biojet fuels will outpace historical demand for biodiesel and be larger than the total liquid biofuel production capacity in the EU in 2022.

If all of the EU's current liquid biofuel capacity, excluding imports, was progressively switched to producing biojet fuels for aviation instead, then ~45% and ~30% of the minimum required biojet fuel targets for 2040 and 2050 respectively would be met. Should all biojet fuel production be additional by 2040[11], then this exponential growth would be comparable to the total growth in all liquid biofuel production from 1990 until 2022, a feat that took 32 years to achieve.

It is most likely that demand for biojet fuel past 2030 will have to be covered by diverting current liquid biofuel production to biojet fuel, installing additional capacity, and imports, with a heavier reliance on imports in the longer term. While it is unlikely that demand for biodiesel and biogasoline in the EU road transport will be eliminated, their role will be highly diminished due to the increased role of electrification in this transport segment. Therefore, more capacity could be progressively converted to produce biojet fuels as the share of electric vehicles surges approaching 2050. However, liquid biofuel demand could increase in other hard-to-abate sectors where electrification is not a viable solution, such as in shipping and high-temperature heat applications, which creates uncertainty around the quantity the EU can dedicate to biojet fuels. Additionally, biodiesel and biogasoline will continue to play a major role in decarbonizing road transport in other regions, especially in emerging markets. As demand for liquid biofuels continues to rise globally, and with a surge in global demand for biojet fuels, especially in the EU and the USA where policies are incentivizing the uptake of SAFs, competition for the same scarce resources to produce the various liquid biofuels will increase as well. This will also create uncertainty around the quantity of biojet fuel the EU will be able to import to help meet its needs.

As demand for liquid biofuels in sectors other than road transport increases, including a surge in biojet fuel demand in the coming 20 years to comply with ReFuelEU Aviation's targets, the EU will have to contend with an added strain on its liquid biofuel production capacity and a widening gap between supply and demand. Demand for limited feedstocks will increase as well, adding strain on the liquid biofuel production capacity within the EU and increasing dependence on imports in the form of feedstocks and final products. Increased demand, strain on supply, and dependence on imports will only add to the costs of these products, which, as indicated previously, are already more expensive than conventional jet fuel. In the case of biojet fuels, which are in limited supply, they are currently two to four times more expensive than conventional jet fuel, with higher costs associated with second-generation biofuels due to higher feedstock constraints[16].

Biojet fuels key takeaways

- The changing policy landscape in the EU since the early 2000s has led to a shift in focus from liquid biofuels for road transport to alternative renewable solutions, mainly electrification. This has led to a declining growth in liquid biofuel consumption over the last 15 years.
- The focus on electrification in road transport and the rising demand for biojet fuel, with limited biomass supply, opens the potential for shifting liquid biofuel production to biojet fuel to help achieve ReFuelEU Aviation's targets. Shifting 35% of today's biodiesel capacity alone is enough to meet the 2030 target. However, switching 100% of today's liquid biofuel production to biojet fuels would only serve 45% and 30% of the 2040 and 2050 targets, respectively.
- It is most likely that demand for biojet fuel past 2030 will have to be covered by diverting current liquid biofuel production to biojet fuel, installing additional capacity, and imports, with a heavier reliance on imports in the longer term. Cross-sectoral competition within the EU and global competition for liquid biofuels creates uncertainty regarding the amount of biojet fuels the EU will be able to produce and import to help meet its needs until 2050.
- Challenges will also arise from the strengthened feedstock restrictions of the RED III. These restrictions place an additional strain on biofuel production in the EU because of the limited supply of feedstocks such as forest residue, MSW, and waste oil. Imports will also face competition from other regions over these scarce resources.

[10] Biojet fuels can be produced from an array of feedstocks, some more technically suitable for the process than others, providing higher biojet fuel yields. However, there are sustainability criteria that must be met for them to be eligible feedstocks under the RED III.

[11] From 2018, when the Union began producing slight amounts of biojet fuels.

Synthetic jet fuels of non-biological origin

Past 2030, synthetic jet fuels must provide a portion of the SAFs required in the final fuel mix per the subtargets of the ReFuelEU Aviation regulation, reaching 6.88 and 25.375 Mtoe by 2040 and 2050 respectively (see Appendix II for the methodology on synthetic jet fuel calculations). Past 2040, an exponential growth in synthetic jet fuel production is needed to meet the regulation's targets, as depicted in Fig. 4. What is the current state of synthetic jet fuel production in the EU, what are the barriers to its production, and how feasible is it to supply 25.375 Mtoe of synthetic jet fuels for EU aviation by 2050?

Unlike biofuels, where the feedstock is already made up of a chain of complex hydrocarbons that need to be either cracked or processed to produce biojet fuel, synthetic fuel needs to be manufactured from the basic building blocks that are hydrogen and carbon dioxide, an energy-intensive process. The amount of hydrogen and CO_2 needed to produce the requisite synthetic jet fuel to meet the subtargets of ReFuelEU Aviation are displayed in Fig. 7 and were estimated based on a process optimized to maximize jet fuel yield[34]. This process utilizes the rWGS reaction followed by low-temperature Fischer-Tropsch (LTFT) synthesis. For every tonne of synthetic jet fuel produced in this optimized process, 0.52 tonens of hydrogen and 3.4 tonnes of CO_2 are needed[12]. As mentioned earlier, the maximum SAF production capacity in the EU is 0.24 Mtoe/year, but all are biojet fuels, with minimal contributions from synthetic jet fuels to date. Therefore, investment in synthetic jet fuel production must begin today if the 2030 subtargets of ReFuelEU Aviation are to be met on time.

However, to put things into perspective, in 2050 ~13.2 Mt of hydrogen will be needed to produce the requisite synthetic jet fuels, which is 50% larger than the EU's current total annual hydrogen demand, 99% of which is still made via fossil fuels[35].

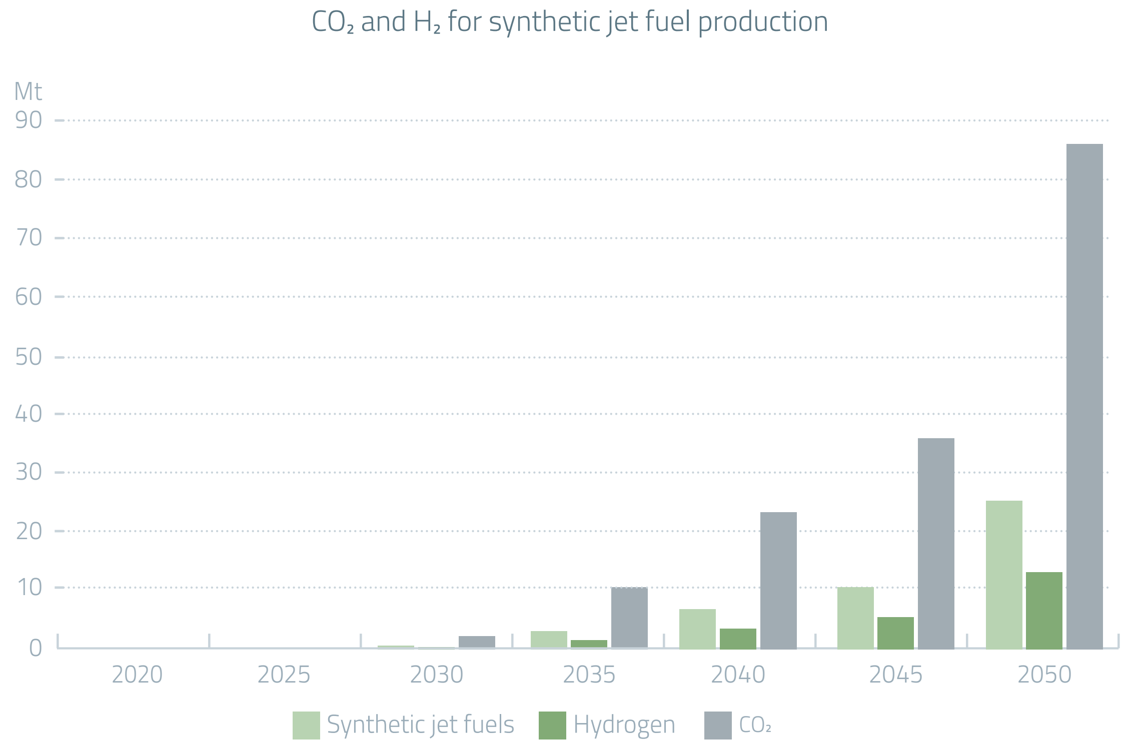

Figure 7: The amount of CO_2 and hydrogen needed to produce the requisite minimum amount of synthetic jet fuels until 2050 per the subtargets of ReFuelEU Aviation.

Hydrogen production is highly dependent on fossil fuels, with more than 98% of the hydrogen in use today produced from natural gas and coal[36]. However, to minimize the lifecycle GHG emissions of the synthetic jet fuel produced, hydrogen must be produced sustainably, via electrolysis using clean sources of electricity (from renewables or nuclear[13]). Additionally, CO_2 must be sourced sustainably, ideally through DAC. The feedstock production pathway significantly affects the emissions savings potential and final cost of synthetic jet fuel. Global average green hydrogen production costs at 6.4$/kg in 2023 are still three times more expensive than fossil-based hydrogen[38]. In the EU, hydrogen costs remain higher at 12€/kg-14€/kg, up to seven times more expensive than fossil-based hydrogen[39]. The way CO_2 is sourced widely affects the price as well, with CO_2 from DAC costing ~1000$/tonne[14][40], approximately 10 times more expensive compared to point source CO_2 capture from industrial processes[41]. These processes have an accompanying energy cost as well, as can be seen in Fig. 8. While approximately six times more CO_2 by weight is needed to manufacture synthetic jet fuel, 80-90%[15] of the electricity required is for hydrogen production due to electrolyzer losses and the high energy needed to break the strong chemical bonds of a water molecule to produce hydrogen. Additionally, double the energy is needed if DAC is opted for over point source CO_2[16]. DAC requires CO_2 removal from the

[12] In less selective processes with lower jet fuel yields, such as those in operation today, more hydrogen and CO_2 is needed per tonne of jet fuel produced, exasperating the need for more of these feedstocks, sourced sustainably. The amount of hydrogen and CO_2 needed varies with other processes as well, such as via the methanol to jet fuel pathway.

[13] Nuclear is expected to play a minor, complementary role to renewable electricity, as the EU is planning for renewable electricity to be the main driver of the energy transition[37]. Therefore, this report assumes all electricity to produce synthetic jet fuels comes from renewable sources.

[14] Based on costs from the largest DAC plant currently in operation, the Orca plant in Iceland.

[15] Depending on whether the CO_2 is sourced via DAC or point source.

[16] It is assumed that the electricity requirements are those of an Orca unit operating with a heat pump[42]. The amount of electricity needed also varies based on the DAC technology used.

air, where the concentration is minimal, necessitating higher energy expenditure for CO_2 extraction compared to point sources where flue gases have higher CO_2 concentrations. While opting for green hydrogen in combination with DAC is the most expensive and energy-intensive pathway, this is the option with the lowest lifecycle GHG emissions, if renewable electricity is used, leading to near-zero emissions on a lifecycle basis, if strict upstream hydrogen leak controls are also implemented.

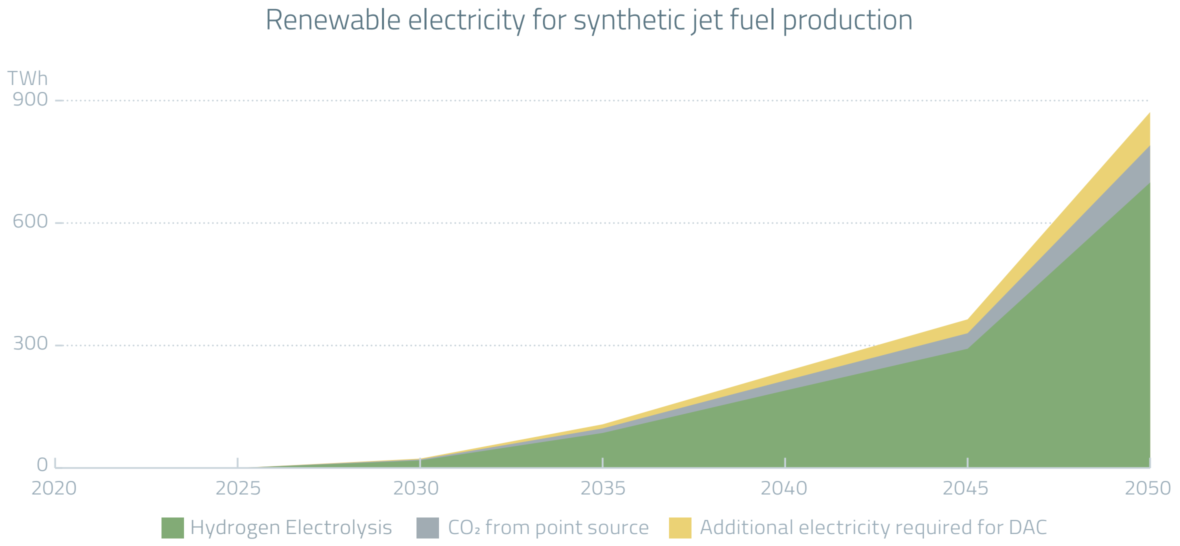

Figure 8: The renewable electricity required to produce hydrogen via electrolysis, CO_2 from point source CCU, and the additional electricity needed if CO_2 from DAC were opted for over point source CCU.

To meet ReFuelEU Aviation's targets, an exponential rise in renewable electricity is required from 2040 to 2050, as shown in Fig. 8. By 2030, an additional 23 TWh of renewable electricity is needed for synthetic jet fuels, rising to 872 TWh annually by 2050. BOX 1 expands on the additional renewable electricity generation capacity needed in the EU to meet ReFuelEU Aviation's 2050 subtarget.

This makes the synthetic jet fuel feasibility discussion one that centers around the availability of renewable electricity.

Where will this additional renewable electricity come from, and will the EU be able to cope with this additional demand?

Additional renewable electricity generation capacity

Box 1

To produce the 872 TWh of renewable electricity needed to produce the requisite amount of synthetic jet fuel, via electrolysis and DAC, 99.5 GW of additional clean firm electricity generation needs to be installed, assuming continuous renewable electricity production. However, a key defining characteristic of many renewable electricity sources, such as wind and solar, is intermittency, which necessitates a capacity overbuild to meet demand.

For illustrative purposes, assuming an average 40% capacity factor from wind[43], i.e. how often this resource is available during the day to generate renewable electricity, then the installed generation capacity needed increases by at minimum a factor of 2.5 to 250 GW. **80% of this installed capacity is needed to run the electrolyzers for hydrogen production.** In reality, it would be far from easy for these facilities to run on intermittent renewables alone, as continuous operation is needed. Additionally, intermittent operation would lead to higher levelized costs of hydrogen (LCOH). Therefore, these facilities would need to implement electricity flexibility tools if electricity is sourced from intermittent renewables alone.

The EU has identified offshore renewable energy as one of the sources with the highest potential for scaleup. In the EU's strategy to harness offshore renewable energy, it has set targets for 300 GW of offshore wind installed capacity by 2050, a 25-fold increase from today's 12 GW of installed capacity[44]. **To further illustrate the renewable energy required to produce synthetic jet fuel at the quantities needed to meet ReFuelEU Aviation's 2050 subtargets, the equivalent of more than 80% of the EU's target for offshore wind installed capacity in 2050 would need to be dedicated to the production of these fuels.**

Synthetic jet fuels key takeaways

- Synthetic jet fuel produced from green hydrogen, CO_2 from DAC, and using clean electricity is the most expensive and energy-intensive pathway. However, this pathway has the lowest lifecycle emissions, when strict hydrogen leak controls are implemented.
- Synthetic jet fuel will consume 13.2 Mt green hydrogen in 2050, which is ~50% larger than today's entire EU hydrogen demand of ~9 Mt/year.
- 80-90% of the clean electricity required to produce synthetic jet fuels is needed to run the electrolyzers for hydrogen production.
- Current SAF production capacity in the EU remains predominantly from biofuels. Investment in and production ramp-up of synthetic jet fuels must begin today if ReFuelEU Aviation's synthetic jet fuel subtargets are to be met from 2030 onwards.
- An additional 872 TWh of renewable electricity will be needed to meet ReFuelEU Aviation's minimum 2050 synthetic jet fuel subtarget. This makes the feasibility of producing synthetic jet fuels at the required quantities in the coming decades a question of renewable electricity availability.

Electricity: fundamental for synthetic jet fuel production

European electricity production has been roughly constant over the past two decades, peaking in 2008 at 2994 TWh, as shown in Fig. 9. In 2020, electricity production dropped to its lowest levels in two decades, before recovering to 2019 levels again in 2021. However, electricity production today remains ~5% below peak 2008 levels[17][45]. Renewable electricity production[18] on the other hand, has been steadily increasing over the past two decades, more than doubling in 2022 compared to 2000[19], and becoming the single largest contributor to the EU's total electricity mix in recent years, producing 39% of EU electricity in 2022[20][46]. If the EU follows its trends from the past 20 years, as illustrated in Fig. 9, total electricity production will increase slightly, by 2.5% compared to 2008, to 3071 TWh in 2050. However, as the EU pursues further decarbonization efforts in line with the Fit for 55 package, RePowerEU, and the overarching goal of the Green Deal aiming to achieve carbon neutrality by 2050[1, 47], various sectors of the economy will become more dependent on electricity, surpassing historical trends.

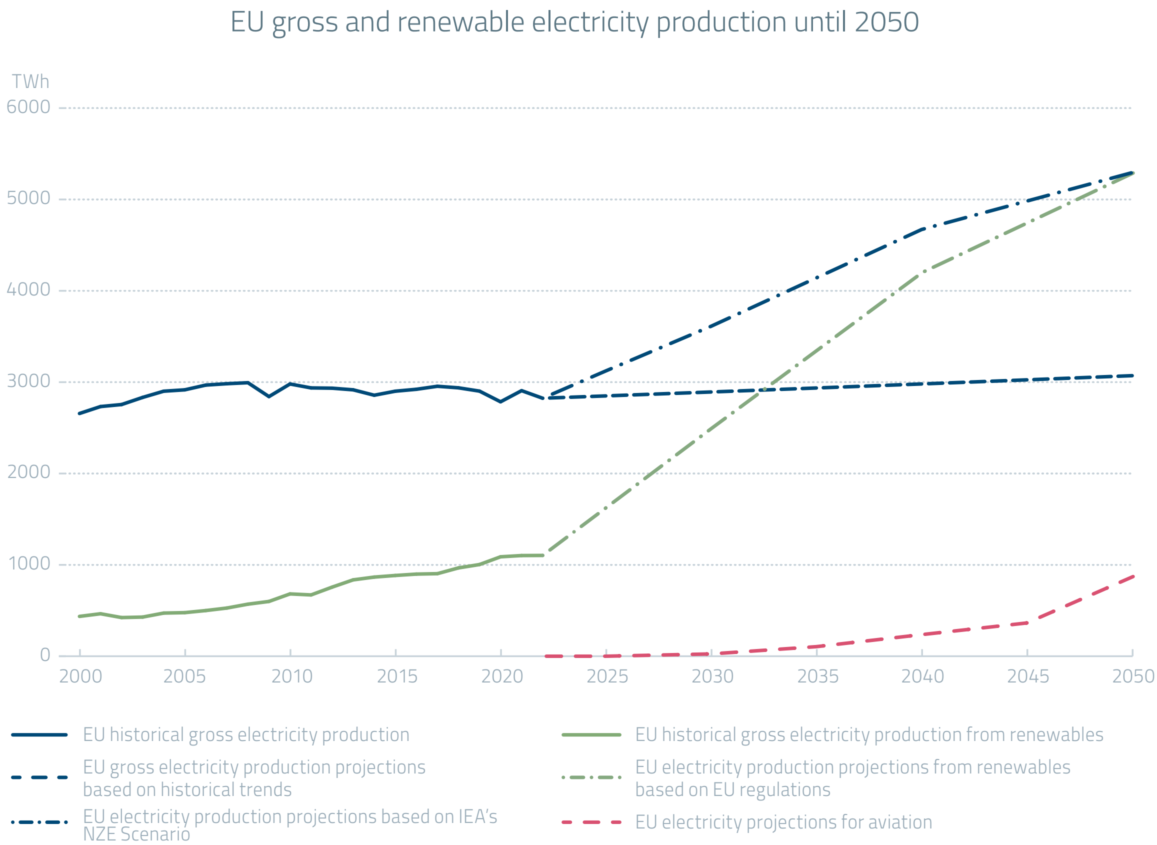

Figure 9: EU historical gross and renewable electricity production from Eurostat[45] and EU gross electricity production projections until 2050, based on historical data, are included. Additionally, EU electricity production projections until 2050 based on the IEA NZE scenario and the share of renewables based on EU regulations are shown. Finally, EU electricity demand projections for the aviation sector until 2050 are also included, based on ReFuelEU Aviation's synthetic jet fuel minimum subtargets.

Sectors such as industry (including manufacturing and construction), buildings, and transport account for ~41.5% of annual emissions and are the three largest contributors to the EU's total annual emissions after the electricity and heat sector[48]. These sectors will require more electricity as they decarbonize and increase their demand for heat pumps, electric vehicles, etc. Thus, electricity production in the EU must outpace historical trends and is expected to double by 2050, in line with regulations such as RePowerEU[49]. Figure 9 displays projections for electricity production in the EU based on the IEA's Net Zero Emissions (NZE) scenario for advanced economies[21], where electricity nearly doubles by 2050 relative to current levels[50].

Figure 9 also depicts estimated percentages of renewables as part of the final electricity mix based on implemented regulations within the EU. According to the RePowerEU plan, 69% of the electricity mix must come from renewables by 2030, increasing to 90% by 2040[22][37, 51], based on the EU's 2040 targets, finally reaching 100% renewables by 2050. This will also require increased growth in renewables, surpassing historical trends, and growing by a factor of five relative to 2022. Aviation today requires minimal electricity, but to meet the 2030 and 2040 subtargets of ReFuelEU Aviation, 23 TWh and 236 TWh of additional electricity production will need to be dedicated to synthetic jet fuel

[17] Based on Eurostat data for the year 2022[45].

[18] Renewable electricity production includes electricity from biomass sources.

[19] The growth rate for new renewable technologies is even higher over this period when the constant baseload contribution from hydropower is considered.

[20] 2022 was taken as the reference year as it is the most recent year with a breakdown in electricity production by source in Eurostat[46].

[21] The NZE scenario projects electricity demand until 2050 for advanced economies. Based on historical data for the EU, production and consumption follow one another, and thus the projections for demand were assumed identical to production in this analysis.

[22] Supplemented slightly by nuclear.

production. This could be feasible, as it is equivalent to 0.6% and 5% of additional electricity based on the current total projected electricity production in the EU in 2030 and 2040 respectively. However, growth past 2040 is exponential and 872 TWh of additional electricity will be needed in 2050. This 872 TWh is 30% larger than the entire renewable electricity production added by the EU over the 17 years from 2005-2022. Additionally, it is equivalent to 31% of current production capacity and 16.5% of the EU's total projected production in 2050, up from 0% today, as is shown in Fig. 9. The electricity needed to produce these fuels must be additional and from renewable sources. While ReFuelEU Aviation is the main regulation driving the sector's transition until 2050 and includes minimum subtargets for synthetic jet fuels, it does not yet include provisions for renewable electricity to produce these fuels. Therefore, when accounting for future synthetic jet fuel needs in the final EU fuel mix, the corresponding renewable electricity needed must be accounted for as well, if these fuels are to be produced on EU territory. Thus, the additional renewable electricity capacity needed to produce these fuels must be factored into the EU's overall renewable energy and decarbonization strategies. Additionally, if the ReFuelEU Aviation subtargets from 2030 onwards are to be met, then growth in synthetic jet fuel production capacity must begin today. It is important to note that these electricity estimates are solely to produce synthetic jet fuel. However, renewable electricity needed for green hydrogen production for use in refineries to produce biojet fuel is not negligible and must be accounted for as well[23].

To further contextualize the additional needs of the aviation sector, electricity demand in the EU transport sector is displayed in Fig. 10. This demand has been steady over the past 10 years, but grew ~10% in 2022, relative to 2021, mainly due to increased demand for electricity in road transport with the rise in electric vehicle shares[24][45]. If electricity production for and consumption in transport follow historical trends, they will be unable to cover the added demand for electricity to produce synthetic fuels for aviation. However, as the transport sector decarbonizes, its electricity consumption is expected to outpace historical trends. Therefore, electricity projections based on the Fit for 55 and RePowerEU inspired scenarios made by Eurelectric are also shown in Fig. 10[52]. Projections for renewable electricity needs in line with these regulations are aimed at road transport, rightfully so as it is the largest emitter in the transport sector, responsible for ~75% of the sector's emissions in the EU[3]. Therefore, of the projected 989 TWh and 1024 TWh based on the Fit for 55 package and RePowerEU plan respectively, 80% is dedicated to decarbonizing road transport, which includes motorcycles, passenger vehicles, and light- and heavy-duty vehicles. Most of the remaining electricity is then allocated to decarbonizing rail. To put things into context further, ~800 TWh is needed to help electrify most road transport, while 872 TWh would be required to produce synthetic jet fuels alone, which will only make up 35% of the total fuel supply in 2050. Any electricity needed to produce synthetic jet fuels will have to be additional to what is required to decarbonize the road sector, as electricity must not be diverted from road decarbonization efforts to aviation. In these scenarios, SAFs are highlighted as the main drivers for decarbonizing the aviation sector but synthetic jet fuels are dependent on renewable electricity. One could argue that the electricity needed goes into producing the final energy carrier, which is synthetic jet fuel and is not the final energy carrier itself. However, future electricity needs for industry still focus on decarbonizing existing processes, through electric boilers and industrial heat pumps, with less focus on novel processes such as the additional electricity needed to produce synthetic jet fuels. Thus, for synthetic jet fuels to be produced in the EU, their renewable electricity needs must be accounted for as well.

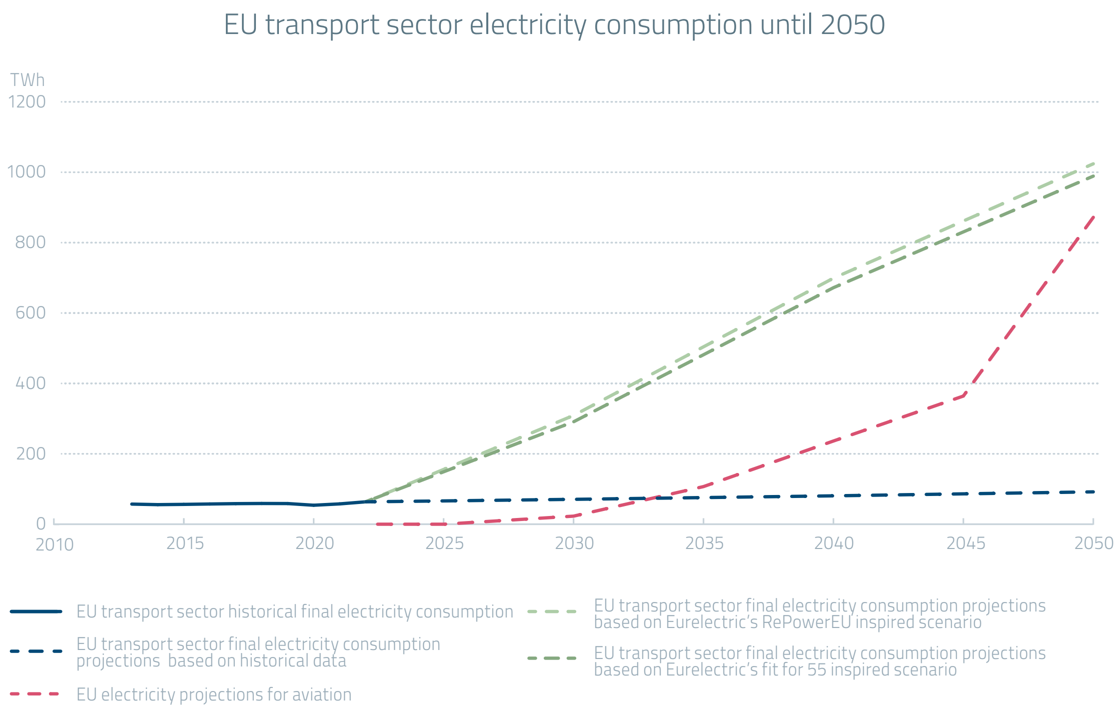

Figure 10: : EU historical final electricity consumption in the transport sector from Eurostat[45] and projections until 2050 based on historical data and the Fit for 55 and RePowerEU inspired scenarios from Eurelectric are included[52]. EU electricity demand projections for the aviation sector alone until 2050 are also included, based on ReFuelEU Aviation's synthetic jet fuel minimum subtargets.

[23] Green hydrogen needs in refineries for biojet fuel production are significant, but not as high as for synthetic jet fuel production. FCA will release a comprehensive analysis on green hydrogen, including needs for biojet fuel production, in the first quarter of 2025.

[24] 2022 was taken as the reference year as it is the most recent year with a breakdown in electricity consumption by sector in Eurostat[45].

Finally, as per ReFuelEU Aviation's targets, by 2050 SAFs must make up at least 70% of the total fuel supplied at EU airports. Additionally, at minimum 35% of the final fuel mix in 2050 must come from synthetic jet fuels. To achieve this percentage, an additional 872 TWh of electricity will be needed in 2050, if the synthetic jet fuels are to be fully produced within the EU.

Thus, an extra ~16.5% of electricity requirements must be factored in relative to current estimates for total EU electricity production and consumption in 2050, as these do not yet account for the electricity required for synthetic jet fuel production.

Relative to the transport sector, an additional ~85% of electricity from today's 2050 projections must be made available for aviation to produce synthetic jet fuels, as today's projections still focus mainly on road transport's electricity needs. This additional electricity must come from renewable sources to maximize GHG emissions reductions from synthetic jet fuels, which amounts to an extra 250 GJ of generation capacity as outlined in BOX 1. However, a thorough feasibility analysis of renewable electricity generation capacity in the EU by 2050 must be conducted, with a clear allocation of resources for the aviation sector starting today. Cross-sectoral competition for electricity as a feedstock to produce synthetic fuels, such as synthetic jet fuels for aviation and e-methanol and e-ammonia for shipping, will only grow as 2050 approaches. This will create an added strain on the electricity that can be dedicated to synthetic jet fuel production, especially past 2040 when synthetic jet fuel needs rise exponentially. Any shortfall in EU synthetic jet fuel production will then have to be made up for by imports, with clear guiderails on the sustainability and lifecycle emissions of said imported fuels. However, global competition for synthetic fuels across hard-to-abate sectors will only rise as 2050 approaches creating uncertainty over the quantity of synthetic jet fuels the EU will be able to import to help meet its needs.

Electricity key takeaways

- Electricity production in the EU is expected to outpace historical trends and double by 2050, with renewable electricity growing by a factor of five relative to current levels. Currently, aviation requires minimal amounts of electricity.

- Based on the current total projected EU electricity production by 2030 and 2040, less than 5% of additional electricity must be factored into current projections to produce the requisite synthetic jet fuels. Considerations for this additional renewable electricity must begin today, if ReFuelEU Aviation's subtargets for synthetic jet fuels are to be met from 2030 onwards.

- In 2050, synthetic jet fuels must make up at minimum 35% of the final fuel mix, requiring 872 TWh for their production, an exponential growth from 2040. This 872 TWh is equivalent to 31% of current production capacity and 16.5% of the EU's total projected production in 2050, up from 0% today. Additional electricity will also be needed to produce the green hydrogen required in refineries for biojet fuel production. This electricity must comply with the additionality requirements of the RED III and must not be diverted from other decarbonization efforts, particularly those dedicated to decarbonizing road transport.

- At a minimum, an extra 16.5% of electricity production, if feasible, must be factored into estimates of total EU electricity needs by 2050, as current projections do not yet focus on the electricity requirements for synthetic jet fuel production on EU territory. In the coming years, competition for electricity as a feedstock will arise across sectors looking to synthetic fuels as a decarbonization option. This will only add a strain on the amount of electricity that can be allocated to synthetic jet fuel production. Any shortfalls in renewable electricity for synthetic jet fuel production on EU territory will need to be overcome through imports.

ReFuelEU Aviation analysis: technical recommendations

While it seems feasible that the EU will be able to meet its 2030 aviation targets (mostly through biofuels), attention must be directed towards meeting its later targets until 2050. Shortfalls in the supply of biofuels and shortages in resources, such as renewable electricity and green hydrogen, to produce synthetic jet fuels become more apparent past 2030. The Union must start planning and developing a clear strategy from now on how to overcome these later-stage shortfalls and meet ReFuelEU Aviation's targets. Consideration must be given to the aviation sector's needs across the whole value chain, accounting for cross-sectoral competition for scarce resources.

1. Implement a facts-based allocation of scarce resources across the EU:

- Competition for bioenergy across the EU will increase, especially in hard-to-abate sectors where direct electrification is not feasible, such as aviation and shipping. A full analysis of EU bioenergy needs until 2050, including planned projects on EU territory, must be conducted. From there, understanding EU growth in liquid biofuel demand beyond road transport, production capacity, and accessibility to eligible biomass feedstocks is necessary. It is crucial to prioritize liquid biofuels for those sectors of the EU economy with limited decarbonization solutions. Based on this technical analysis, a set quantity of liquid biofuels can then be allocated to the various sectors of the economy based on need. Allocating a portion of the resources for biojet fuel production until 2050 will provide visibility over how much the EU can produce on its territory.

- Direct electrification will play a major role in EU decarbonization efforts. Additionally, competition for electricity as a feedstock will arise across sectors looking to utilize synthetic fuels, such as synthetic jet fuels for aviation and e-ammonia and e-methanol for shipping. Therefore, a complete breakdown of electricity needs across the various sectors of the EU economy that are decarbonizing, in line with RePowerEU and the European Green Deal is necessary. This breakdown should include a technical feasibility study of the potential growth in renewable electricity generation capacity within the EU by 2050 and whether this growth will be enough to achieve the overarching climate goals of the bloc. This breakdown must account for the renewable electricity needed for synthetic jet fuel production starting today. As competition for renewable electricity will be high, this resource must be quantitatively allocated to the various sectors of the EU economy based on availability and need. How much renewable electricity can feasibly be allocated to producing synthetic fuels for aviation must be identified. This will indicate how much synthetic jet fuel the EU can produce on its territory.

- Green hydrogen is still a scarce resource today, with hydrogen production still highly dependent on fossil fuels in unabated processes. A comprehensive feasibility analysis of green hydrogen production in the EU until 2050, including planned projects on EU territory with clear guiderails for downstream deployment, must be conducted. Hydrogen is energy-intensive to produce, and it must be strategically deployed based on its emissions reduction potential and industrial and societal relevance. The available green hydrogen must first be prioritized to decarbonize existing hydrogen needs, such as that used in refineries and manufacturing ammonia for fertilizer production. Hydrogen must also be prioritized for emerging technologies such as the direct reduced iron (DRI) process in steel manufacturing. Competition for novel green hydrogen applications will arise across sectors looking to use it directly or as a feedstock to produce hydrogen-derived fuels. This will add uncertainty around how much green hydrogen can be dedicated to synthetic jet fuel production. A clear downstream hydrogen prioritization strategy is necessary to avoid its use in sectors where direct electrification is more efficient. Therefore, based on production capacity and need, the amount of green hydrogen that can then be dedicated to aviation for use partly as a final energy carrier, but mainly as a feedstock for synthetic jet fuel production, can be identified.

2. Close the supply deficit with imports:

Once these scarce resources are properly allocated to the aviation sector, it will become clear how much biojet and synthetic jet fuel can be produced on EU territory. Any discrepancy in supply must then be made up to meet ReFuelEU Aviation's targets. One option is eligible imports from third countries that meet the minimum sustainability criteria outlined in ReFuelEU Aviation and the RED III. However, while utilizing SAFs helps the EU diversify its energy supply and reduce its dependence on fossil fuels, relying primarily on imports reduces the Union's energy security and autonomy and will keep it dependent on external players.

3. Look to flexibility mechanisms to widen the SAF tradability market:

Aside from physical SAF imports from third countries, flexibility mechanisms must be considered in conjunction with ReFuelEU Aviation's targets to ease market accessibility to SAFs. One such mechanism is Book and Claim, a SAF tradability scheme that removes geographical barriers, decouples supply from demand, and widens the SAF market to include SAF suppliers potentially located outside of the Union[53]. Additionally, since minimizing the lifecycle GHG emissions of SAFs is key, implementing a Book and Claim scheme would help keep SAF transport emissions low.

The Book and Claim scheme has the added benefit of easing SAF supplies across the EU if incorporated into ReFuelEU Aviation, as SAF producers and consumers may not always be within proximity. As was seen in Fig. 3, jet fuel consumption is concentrated in a handful of Member Countries. These countries may be unable to physically supply the amount of SAFs needed annually at their airports. Book and Claim can help ease these supply pressures by allowing the trading of SAFs across the Union. SAFs are then claimed by the airlines that pay the premium for them, while the physical SAFs are supplied to the airports that are geographically closest to the SAF production sites. However, to maximize the impact of such a flexibility tool, strict guiderails must be adopted to regulate its implementation, minimize double counting and greenwashing, and maximize its efficacy. To reduce overreliance on Book and Claim and avoid hindering SAF development in the EU, a cap on the percentage of SAFs that can be claimed towards ReFuelEU Aviation's targets through a Book and Claim scheme can be employed. In this manner, Book and Claim can be a last resort to overcome shortfalls in supply rather than relied upon over physical SAF usage.

Following these guiderails could help get the EU aviation sector on track to meeting ReFuelEU Aviation's targets by 2050.

ReFuelEU Aviation analysis: policy recommendations

ReFuelEU Aviation is a first-of-its-kind regulation aiming to stimulate demand for SAFs through progressively increasing targets. This will, in turn, send a market signal to fuel suppliers that SAFs are expected to play a long-term role in decarbonizing the sector and are fuels to be invested in, thereby increasing supply. While this regulation is a great first step, it is not enough to close the commercialization gap and create a viable business case for SAFs. Several synergetic policy measures must be implemented to help make ReFuelEU Aviation's targets achievable by 2050.

1. Promote alternative modes of travel:

Demand for aviation within the EU is expected to continue rising as 2050 approaches, with jet fuel consumption expected to increase by 50% relative to 2019. Implementing ambitious efficiency improvements will increase the fleet's overall fuel efficiency and reduce fuel consumption by 2050. However, as demand continues to outstrip these efficiency improvements, this operational improvement on its own won't be able to limit growth in jet fuel consumption relative to today. More sustainable alternative modes of travel must be promoted as well and incentivized following the 'polluter pays principle' on short-haul routes (under 1500 km in range), which are responsible for 25% of annual EU aviation emissions[54], especially on high-traffic air routes that can be serviced by rail. Shifting demand away from aviation in the short-haul flight segments where alternatives are readily available will help reduce the overall demand for jet fuel in the coming decades, thereby reducing the SAF supply strain and easing the feasibility of achieving ReFuelEU Aviation's targets by 2050.

2. Accelerate SAF permitting and certification:

In a highly streamlined and safety-oriented sector such as the aviation sector, introducing new technology is usually cumbersome and time-consuming. Even SAFs, which are drop-in fuels and do not require engine modifications to be utilized, still only made up <1% of total jet fuel consumed in 2023. Facilitating permitting for the construction of new SAF plants can reduce project lead times significantly and increase the success rate of SAF start-ups and scale-ups entering the market, especially in the case of synthetic jet fuel. Accelerating the approval of SAF production pathways by ASTM can further facilitate the large-scale deployment of these fuels. Additionally, a uniform certification process based on feedstock origins, lifecycle GHG emissions, and indirect effects is crucial to streamlining the eligibility of SAFs towards the ReFuelEU Aviation targets, especially those imported from third countries. These procedures can help maximize the SAF production potential within the EU to help meet ReFuelEU Aviation's targets, particularly for synthetic jet fuels whose production must be stimulated today if the EU is to be ready to meet the subtargets of ReFuelEU Aviation as of 2030.

3. Incentivize the shift to biojet fuel:

Current liquid biofuel production in the EU focuses on road transport applications. However, as the share of electric vehicles in the EU increases, demand for biofuels in this transport segment will decrease. Current liquid biofuel capacity in the EU is enough to help achieve ReFuelEU Aviation's 2030 target and 45% of its 2040 target. However, the shift in production from biodiesel and biogasoline to biojet fuel incurs both CAPEX and OPEX costs. Incentives must be put in place to stimulate this shift in production. Introducing regulations to reduce competition for liquid biofuels by other transport segments, mainly road transport, and providing funding and subsidies for plants that aim to convert to biojet fuel production could help accelerate biojet fuel production in the EU.

4. Implement the 'polluter pays principle':

The cost of alternative solutions, including SAFs, remains higher than conventional jet fuel. While aviation will no longer be exempt from the EU Emissions Trading System (EU ETS) as of 2026, jet fuel is still exempt from fuel taxation. Taxing conventional jet fuel while exempting SAFs with lower lifecycle GHG emissions would be a powerful tool that could help close the cost gap with sustainable aviation fuels. Additionally, internationally recognized SAF uptake mandates at ICAO level that are legally binding can help minimize market distortions and maintain an international level playing field. SAFs become more economically viable when conventional fuels with higher carbon intensities are taxed accordingly. Aviation fuel taxation is an untapped revenue stream that can be reinvested into accelerating sustainable solutions in the sector, for example, through funding new SAF production plants.

5. Close the technological and commercialization gaps:

Creating funds dedicated to investing and derisking projects that help decarbonize the sector is crucial. Revenue from carbon pricing is best used when reinvested into the sector to promote sustainable solutions. SAF uptake in compliance with ReFuelEU Aviation can be claimed in the EU ETS to help close the cost gap with conventional fuel. Revenue from the EU ETS could then be reinvested into aviation decarbonization projects such as SAF production plants, via a dedicated basket in the Innovation Fund, to reduce the commercialization gap further. Additionally, prioritizing funding for synthetic jet fuel plants can help derisk and incentivize these projects, aiding in synthetic jet fuel production ramp-up in the Union. Bespoke policies – such as a frequent flyer levy, which progressively increases flight taxes based on the number of flights flown per year – can be an additional revenue stream used by airlines to cover higher SAF costs without affecting lower-income passengers who fly less frequently. Since aviation is a highly commercial sector, it cannot be as dependent on public funds as other sectors, such as construction. While support for novel SAF projects from programs such as the EU Innovation Fund is necessary, private support is crucial for accelerating SAF uptake. Initiatives such as the First Movers Coalition can stimulate demand by bringing in the collective purchasing power of participating companies that commit to the uptake of SAFs.

6. Budget scarce resources:

While higher costs are a roadblock to higher SAF uptake rates, having access to green hydrogen, sustainable CO_2, sustainable biomass feedstocks, and clean electricity is a major limiting factor to meeting the targets of ReFuelEU Aviation. While ReFuelEU Aviation has set clear progressive targets and eligibility criteria for SAFs, the quantity of clean electricity and sustainable feedstocks needed was not highlighted. Cross-sectoral competition for these scarce resources will dictate how much electricity and biomass is allocated to the aviation sector. If future targets are to be met, budgeting these resources across the various sectors of the EU economy, based on a technical feasibility analysis, must begin today. Including the availability of these scarce resources within legislation will highlight how much the EU can produce on its territory and will be crucial to the success of regulations such as ReFuelEU Aviation as well as the overarching goal of the Green Deal and carbon neutrality by 2050 in the Union.

7. Introduce flexibility mechanisms:

Any shortfall in SAF production on EU territory will need to be made up for with imports. Depending on imports, while not always conducive to energy security, will still help the EU to divest from fossil fuels. Opting for a SAF Book and Claim scheme can widen the SAF market beyond the EU's borders and reduce the dependence on physical SAF imports. This will allow fuel suppliers and airlines within the EU to pay the SAF premium and book eligible SAFs with third countries, which will help ease supply constraints within the EU, and thus claim the SAF usage without needing physical access to these fuels. A Book and Claim scheme can also be utilized across Union territory to ease supply constraints when consumers cannot easily access physical SAFs due to geographical limitations. However, effective implementation of a Book and Claim scheme requires clear guiderails on SAF eligibility and provisions against double counting. Independent auditors are necessary to ensure no greenwashing or double-counting practices take place. Incorporating Book and Claim for SAF tradability, with a cap on eligible quantities through this scheme, between EU countries as well as with third countries in the next revision of ReFuelEU Aviation could help to ease supply constraints and strengthen the regulation's targets.

These policy recommendations work together to help reduce jet fuel demand, increase SAF supply and accessibility, and make SAFs more economically viable, thereby helping to achieve the targets of ReFuelEU Aviation while minimizing this regulation's adverse effects on the sector. Therefore, ReFuelEU Aviation cannot be a standalone initiative but must be part of a basket of measures that reinforce each other, help keep the sector competitive, and contribute to making the targets of this regulation feasible[55]. Measures must also go beyond this key regulation to fully mitigate aviation's environmental impact. Finally, due to the global nature of aviation, international consensus over, and adherence to, standardized decarbonization efforts is crucial to minimizing market distortions and maintaining a global level playing field to ensure a successful net-zero transition.

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Appendix I

The following are some of the key conditions outlined in ReFuelEU Aviation[7]:

- This regulation applies to commercial flights and excludes military, humanitarian, rescue operations, etc.
- This regulation excludes remote airports and smaller airports below a threshold passenger and freight traffic[25] while still encompassing most of the traffic departing from EU airports. It is possible, under Member State evaluation or the specific airport's request, to include such exempted airports within the purview of this regulation.
- Fuel suppliers must supply all eligible airports with an equal minimum share of SAFs in the fuel mix, as outlined in Table 1, but airports are also free to acquire SAFs in larger quantities.
- Under this regulation, SAFs refers to biofuels, recycled carbon fuels, and synthetic fuels. Only the SAFs that meet the threshold lifecycle emissions savings criteria set out in Directive (EU) 2018/2001 are eligible under this regulation.
- The SAF targets are also deemed met if low-carbon hydrogen, or low-carbon synthetic fuels with lifecycle emissions reduction potential greater than 70%, or renewable hydrogen that meets the threshold outlined in the previous point, are used.
- For biofuels to be deemed eligible, they must meet additional criteria outlined in Article 4(4) and (5). For example, feedstocks from food and feed crops, amongst others, are considered ineligible.
- This regulation circumvents tankering practices by mandating aircraft operators to uplift 90% of their annual fuel needs for flights departing from eligible EU airports, including foreign operators. Exemptions apply upon request in exceptional circumstances evaluated on a case-by-case basis.
- As of 2025, aircraft operators must report on their fuel requirements in compliance with this regulation. This report includes information on the amount of fuel uplifted at eligible airports; the amount of SAFs purchased from fuel suppliers; the name of the fuel supplier, and SAF characteristics, which includes sustainability information on the feedstock, conversion process, and lifecycle emissions; amongst other information.
- As of 2025, fuel suppliers must report information that includes the amount of fuel they supply every eligible EU airport with, including for each type of SAF. For the SAFs, this includes details of the conversion process, feedstock, and lifecycle emissions.
- The uptake of SAFs in compliance with this mandate will allow aircraft operators to claim allowances against this SAF through the EU ETS to help minimize cost disadvantages with competing carriers not flying through the Union.
- Aircraft operators uplifting SAFs should be able to claim allowances through the EU ETS or CORSIA, when possible, to minimize the cost differential, while avoiding double counting the same batch of SAFs by declaring the scheme they participate in.
- Competent authorities, designated by each Member State, are assigned to oversee implementation by airports and fuel suppliers and to enforce fines in the case of non-compliance.
- To ensure this regulation is adhered to, effective penalties are introduced in the case of non-compliance on behalf of the airport, aircraft operator, or fuel supplier:
    - A failure in obligations to provide SAFs at Union airports will lead to a fine.
    - Any aircraft operator failing to adhere to the non-tankering conditions will be liable to a fine equivalent to twice the annual cost of aviation fuel multiplied by the total amount of fuel not uplifted at the departing EU airport.
    - A shortfall in the supply of SAFs or misleading information on the SAFs' characteristics, including synthetic fuels, by the fuel supplier will lead to a fine.
    - The effective penalty in the case of non-compliance by fuel suppliers will be, at minimum, twice the difference in annual cost between conventional fuel and SAF (including synthetic fuels and their subtargets), applied to every tonne of fuel not complying with the regulation (being through a shortfall or misleading characteristics).
    - Any shortfall by fuel suppliers must be recouped in the next reporting period, but that does not exempt them from the fine for the shortfall.
    - Revenue from these fines shall be reinvested into research and innovation in SAFs to help close the cost gap with conventional fuels.
- Every four years, starting from January 2027, the Commission will draft a report on this regulation's progress for the European Parliament and the Council. This report will evaluate the impact of the regulation on the EU aviation sector and identify any need to revise this regulation. Such revisions could include widening the scope of fuels to non-drop-in fuels and incorporating flexibility mechanisms mentioned in Article 15.

[25] The threshold in Article3(1) of ReFuelEU Aviation is set at 800,000 passengers and 100,000 tonnes of freight from the previous reporting period.

Appendix II

To analyze the feasibility of achieving ReFuelEU Aviation's targets, first, the EU's total jet fuel needs until 2050 were calculated. This was based on demand projections for Europe in line with the ITF's Transport Outlook 2023 following current policy ambitions[23]. Annual efficiency improvements followed the assumptions in MPP[56], which are in line with the ICAO aspirations of 2%/year efficiency improvement until 2050[57]. A 1.5%/year – 2%/year linear increase in fuel efficiency improvements from 2023 – 2030, followed by a constant 2%/year improvement until 2050, was applied.

Table II.1: European demand projections, compound efficiency improvements, and their effect on final fuel demand until 2050, taking 2023 as the base year.

	2023**	2025	2030	2040	2050
Demand projections (DP)	--	1.15	1.45	2.2	2.84
Compound efficiency improvements (CEI)	--	0.95	0.87	0.71	0.58
Final fuel demand (Mt)*	44	48.4	55.7	68.8	72.5

* Final fuel demand = Demand projections*compound efficiency improvements * final fuel demand (2023).
** Based on actual fuel demand data for 2023 from Eurostat[14].

Once fuel consumption was calculated, the minimum share of SAFs, including synthetic jet fuels, until 2050 was calculated based on this fuel consumption and the ReFuelEU Aviation targets. Projected SAF quantities until 2050 can be found in Table II.2.

Table II.2: Projected share of SAFs until 2050, with a breakdown of those from biojet fuels and synthetic jet fuels until 2050.

	2023**	2025	2030	2040	2050
Final fuel demand (Mt)*	44	48.4	55.7	68.8	72.5
Share of SAFs (%)	0%	2%	6%	34%	70%
Total SAFs (Mt)	0.24**	0.97	3.34	23.4	50.75
of which Biojet fuels (Mt)	0.24**	0.97	2.67	16.5	25.375
of which synthetic jet fuels (Mt)	0	0	0.67	6.9	25.375

* Based on actual fuel demand data for 2023 from Eurostat[14]. **Current maximum EU capacity.

Based on these initial calculations. a feasibility analysis was performed as follows:

Biojet fuels: targets were compared to current and future EU liquid biofuels potential. The EU currently consumes ~18 Mtoe of liquid biofuels, mainly in the form of biodiesel (~77%), where over 50% of the feedstock to produce this biodiesel in the EU is imported[24, 25].

Historical EU biofuel production and consumption data were retrieved from Eurostat[24], and a ten-year average growth in consumption for the two decades spanning 2000-2020 was calculated. Then, from the biojet fuel targets set out by ReFuelEU Aviation for 2030, 2040, and 2050, a 10-year average growth for the coming three decades was projected. The feasibility of achieving this growth was compared against historical trends in EU biofuel consumption and production as well as the IEA's projections for biofuel demand in Europe for the period 2023-2028[22].

Synthetic jet fuels: producing synthetic jet fuel depends on three feedstocks: green hydrogen, sustainable CO_2, and clean electricity. The amount of green hydrogen and sustainable carbon dioxide needed to produce the requisite amount of SAFs for each target year was calculated. This was based on a rWGS, followed by low-temperature FT synthesis in a plant optimized for a 90% jet fuel yield[34]. Details of the plant's main inputs and products are outlined in Table II.3.

Table II.3: Main input and product flowrates for a plant optimized for jet fuel production[34].

Main flow rates	
CO_2 requirements	340 kg/hr
H_2 requirements	52 kg/hr
Liquid products	110 kg/hr
of which jet fuel	90.7 kg/hr
Jet fuel yield	90.7%

From the amount of hydrogen and carbon dioxide needed, the following was calculated:

▪ The amount of clean electricity needed to produce the green hydrogen, based on a 75% electrolyzer efficiency and the higher heating value (HHV) of hydrogen at 142 MJ/kg.

▪ The amount of clean electricity needed to capture carbon dioxide from (1) DAC and (2) point sources. Point source requirements were based on a standard CO_2 separation unit with typical duties in the range of 3.6-4 GJ/tCO_2[58]. DAC electricity needs were based on Climework's Orca plant in Iceland, which would require 2 kWh/kgCO_2 of electricity if heat pumps provided the plant's low-temperature heat[42].

EU electricity: To understand the feasibility of producing the requisite amount of clean electricity, historical EU electricity production and consumption data, both for total and renewable electricity, were retrieved from Eurostat[45]. From there, based on this 20-year historical average growth, projections of future electricity demand until 2050 were estimated. Historical electricity needs for the transport sector were also retrieved from Eurostat[45], and projections until 2050 were made based on a 10-year historic average growth.

About Future Cleantech Architects:
We are a climate innovation think tank. We exist to close the remaining innovation gaps to reach net-zero emissions by 2050. To reach this objective, we accelerate innovation in critical industries where sustainable solutions are still in very early stages.

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