Advanced Sustainable BIOfuels for Aviation

Deliverable D5.5:

Market Scaling Strategy

Consortium:

Acronym	Legal entity	Role
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ENI	ENI S.p.A.	BEN
SKYNRG	SKYENERGY BV	BEN
CENER	FUNDACION CENER-CIEMAT	BEN
ETA	ETA – Energia, Trasporti, Agricoltura Srl	BEN
CCE	CAMELINA COMPANY ESPANA S.L.	BEN
JRC	JOINT RESEARCH CENTRE – EUROPEAN COMMISSION	BEN

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	
CON	Confidential, only for members of the Consortium	

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1 Abbreviations

ASTM – American Society for Testing and Materials
CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation
EC – European Commission
EU – European Union
EU28 – Member States of the European Union
FQD – Fuels Quality Directive
FT – Fischer-Tropsch
GHG – Greenhouse Gas
HBE – ‘Hernieuwbare Brandstofeenheid’, Renewable Energy Unit
HEFA – Hydro-processed Esters and Fatty Acids
HVO - Hydrogenated Vegetable Oil
IATA - International Air Transport Association
LCA – Life Cycle Assessment
OEM’s – Original Equipment Manufacturers
PoS – Proof of Sustainability
RED – Renewable Energy Directive
RSB – Roundtable of Sustainable Biomaterials
SAF – Sustainable Aviation Fuel
t – metric ton, equal to 1,000 kg
    kt – 1,000 t
    Mt – 1,000,000 t
UCO – Used Cooking Oil
UN–ICAO – United Nations International Civil Aviation Organization

2 Introduction

This report will summarize 4 years of development work in the Bio4A project, focusing on the market scaling potential and strategy of the HEFA pathway. Hydrotreating Esters and Fatty Acids (HEFA) is the most advanced and commercialized pathway to make SAF today. The HEFA pathway stood central in the Bio4A project. In this project we have shown and proven industrial production of SAF volumes. In this deliverable we will assess the potential scaling strategy for the HEFA pathway.

Aviation accounts for a significant (>2%) contribution to global manmade emissions. Even though the sector has been hit hard over the past two years by the COVID-19 pandemic, we have seen rapid recovery in the sector and prospects of growth as quick as 2023. This comes with significant pressure of increased emissions and challenges to decarbonize the aviation industry. SAF plays a very important and significant role in decarbonizing aviation and therefore a significant market will exist for HEFA production capacity[1]. Over the course of the projects, many SAF projects have been announced to be in development, as well as significant production capacity has come online[2].

In 2020 we have covered the policy framework in Deliverable 3.3 and 3.4 as part of the Bio4A work. At the time the work focused on the transposition of the RED I as well as outlook to RED II implementation (3.3) and in deliverable 3.4 we focused on the current status of policy implementation relevant to SAF uptake with a main focus on the newly suggested blending obligation as part of the Fit for 55 package, ReFuel EU. Since then, new policy updates have come to the market, especially further refining the targets and potential fuels allowed under the specific obligations.

This deliverable first reviews the status of the market since the start of the project until today. We will provide background to what has happened in both policy and feedstock development. As part of the Bio4A project, we have developed a market outlook which provided insights in which technologies are expected to fulfil the mandates, the market outlook from 2021 and 2022 as well as other industry reports are used to reflect on the development since. Furthermore, we will review the feedstock availability, taking into account deliverable 5.3 of the Bio4A project.

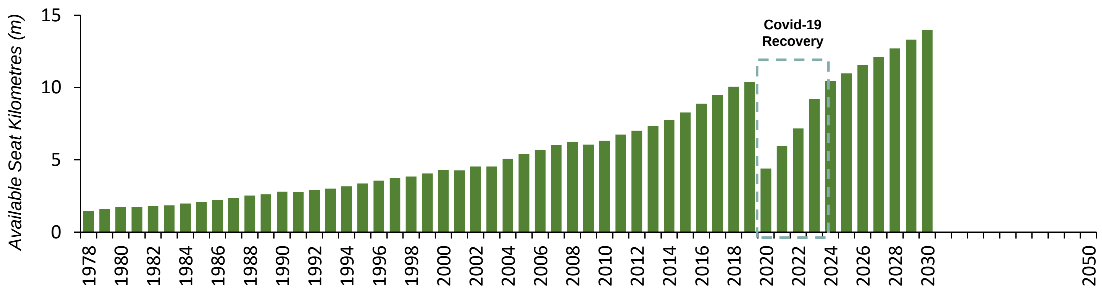
Based on these demand, policy, supply and feedstock reflections we reflect on the potential scaling strategy for the HEFA technology. This includes recommendations for industry and policy makers, focusing on the scalability beyond 2030 reaching the targets for 2050.

[1]https://www.iata.org/en/pressroom/2022-releases/2022-12-07-01/#:~:text=Geneva%20%E2%80%93%20The%20International%20Air%20Transport,could%20reach%20450%20million%20liters
[2] https://view.argusmedia.com/Global_SAF_Capacity_Map.html

3 SAF demand market trends

3.1 Aviation industry

When Bio4A started in 2018, the aviation market was in continuous growth for the past decades. In early 2020 the COVID pandemic hit the industry hard, throwing out all market forecasts and significantly disrupting the market, Figure 1 shows the impact in especially 2020 and 2021. Reducing the flight movements and therewith impacting the industry in general. Even though the initial forecasts were showing a recovery only from 2024 onwards, the recovery of this gap went more rapidly than expected during the depth of the COVID crises in 2020 and 2021, in 2022 we have seen rapid recovery and close to similar aviation movements and therewith emissions compared to 2019 levels. The Chinese market and therewith Southeast Asian market is still heavily impacted by lockdowns and therefore further away from pre-covid flights, while the rest of the world is rapidly approaching old levels. This increases the sustainability challenge for aviation where growth is expected again for the coming decades.



Source: Wall Street Research on Aerospace and Defence Data, IATA 2021.

Figure 1. Market development and disruption due to Covid

On a global scale, growth is likely to be significant due to the impact of upcoming markets. According to UN-ICAO[3], the fuel consumption of international aviation during 2010 accounted for 142 million t of Jet fuel per year. Jet fuel demand is estimated to grow to approximately 860 million t per year by 2050, if only air fleet renewal and air travel demand management are adopted as CO_2 mitigation measure. This fuel volume corresponds to 71% of the expected global (i.e. International and Domestic) demand: in 2019, global jet fuel demand accounted for 300 million t per year with approximately 200 million t per year of which is used in International Aviation. Even if very substantial consumption-reduction improvement measures are implemented, the jet fuel demand increase might be limited to 570 million t per year in 2050 for international aviation only. Still more than 4 times the demand observed in 2010.

Aviation's CO_2 emissions can for 99% be related to the consumption and use of jet fuel. As the consumption-reduction and improved efficiency measure are insufficient and radically new aircraft are not yet commercially available, it is clear that a sustainable fuel alternative needs to be developed. SAF could theoretically substitute 100% of Jet-A[4]. To produce 860 million t of SAF in 2050, we would require building approximately 60 new biorefineries (500,000 t each) every year from 2020 to 2050. With a construction size and pace not even close to these numbers, the magnitude of the challenge is clear. This however also shows the enormous market potential and forms the basis for the scaling strategy. Even a less ambitious scenario to replace 10% Jet-A1, or 86 million t per year, would still require major investments in the sector and huge market potential.

3 UN-ICAO. Trends and scenario on alternative fuels – Working Paper. Conference on Aviation and Alternative Fuels, Mexico City, 11-13 October 2017, Mexico. Available at https://www.icao.int/Meetings/CAAF2/Documents/CAAF.2.WP.006.4.en.pdf
4 Currently not possible due to ASTM regulation, in future with newly accepted pathways this could be a possibility.

3.2 Sustainability targets in aviation

In deliverable 5.2 market dynamics we have shown the IATA targets[5] to address the rising emissions and support the reduction of the industry's footprint. Leading to three clear targets (Figure 2).

- Improve fuel efficiency by 1.5% till 2020
- From 2020 onwards grow carbon neutrally
- By 2050, net carbon emissions should be halved compared to 2005 levels

Since then, the ambition for 2050 was further increased to net zero in 2050.

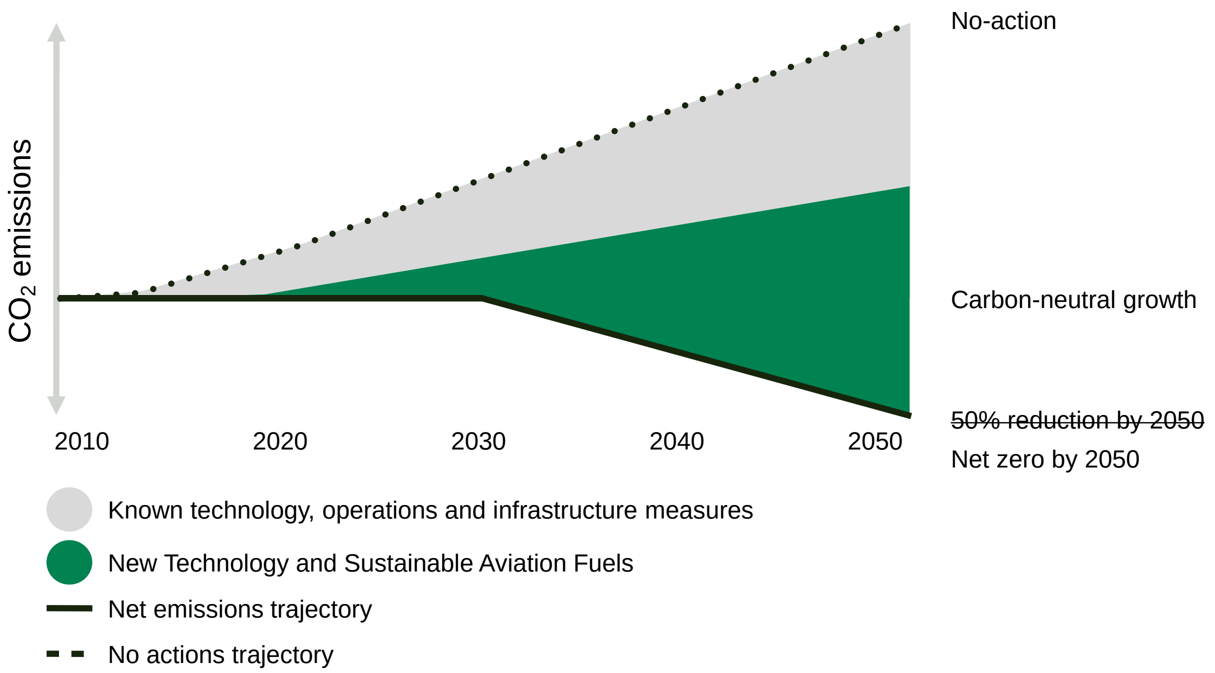


Figure 2. Aviation industry CO_2 emission reduction ambition (schematic)

The goal of net zero is built on a number of mitigation strategies, the first being the 1.5% efficiency improvement which has been consistently achieved in the past, with investments in new aircraft and improving operational efficiency. As can be seen in Figure 2 and discussed in the previous chapter, efficiency improvements will not be enough to cope with the increased demand nor is it a viable measure to reduce CO_2 emissions towards the 2050 target. This, combined with the fact that planes are not able to switch to alternative energy sources like hydrogen or electricity in the foreseeable future, sustainable aviation fuels (SAF) will play a key role in decarbonizing aviation.

Concluding, decarbonizing Aviation is a challenging but unavoidable action to fight climate change, heavily dependent on the introduction of cleaner aviation fuels (SAF), as also remarked in several occasions by the European Commission[6]. Shifting to SAF, such as advanced biofuels, recycled carbon fuels, and carbon-free e-fuels, is an urgent need, preferably combined with hybridization and other improvements in aircraft technologies.

[5] https://www.iata.org/policy/environment/Pages/climate-change.aspx

[6] European Commission. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE, THE COMMITTEE OF THE REGIONS AND THE EUROPEAN INVESTMENT BANK. A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy.

3.3 The European aviation industry

Having shown the SAF rationale it's important to quickly assess the conventional Jet fuel market, as this is the market that needs to be reduced and eventually replaced by SAF. The European jet fuel market has seen steady but slower growth than the world-wide market for aviation as it is already developed. Total volume in 2018 was approximately 63 million tonnes in the EU28 countries. For the sake of this deliverable, we assume the total jet fuel demand will remain constant, because of efficiency improvements and demand reduction, compensating for expected growth. This is a very conservative assumption and fuel volumes will likely be higher as predicted by IATA in various demand forecasts.[7]

As stated, the current uptake of SAF is limited to approximately 100,000 tonnes in 2022. It is not likely that from the currently limited uptake of <1%, a sudden jump towards the 50% technical limit, set by ASTM will or can take place. In deliverable 5.2 market dynamics we have shown a gradual increase of SAF uptake towards the 50% blend limit based on EU fuel demand. With progressed knowledge we can now better assess this demand by the voluntary targets from airlines and the policy driven target from the ReFuel EU initiative, we will further discuss the European demand numbers under the policy section.

3.4 Voluntary SAF demand

As shown in Deliverable 5.2 of the Bio4A project, SAF has developed from a nascent and new industry back in 2017 into a more mature market today. Even though COVID-19 has hit the full aviation industry significantly in 2020 and 2021, SAF demand has been consistently increasing. Especially with announced mandates in various European countries and increased pressure from the general public, airlines, corporates and cargo carriers have set increasingly ambitious voluntary targets.

Besides 'just' purchasing volumes of SAF, airlines have been getting more actively involved to enable new production capacity through long term guaranteed off-takes or direct investments. This is reflected by strong (voluntary) demand signals[8]:

- DHL Express: 30% of fuel uptake by 2030
- Delta Airlines: 10% of fuel uptake by 2030
- One World Group: 10% of fuel uptake by 2030
- AirFrance-KLM: 10% of fuel uptake by 2030

[7] IATA
[8] https://www.oneworld.com/news/2021-10-04-oneworld-aspires-to-reach-10percent-sustainable-aviation-fuel-target-by-2030 - https://nieuws.klm.com/science-based-targets-initiatief-sbti-keurt-2030-doelstellingen-van-klm-groep-voor-co-uitstootvermindering-goed/

4 Policy development and impact on the SAF industry

The development of global (corsia), European (Fit for 55 & RED) as well as regional policy has been at the core of recent SAF demand development. Policy has been crucial for the development of SAF until now and will be crucial to enable the uptake of SAF in the future. These policies are in constant development and at the time of finalizing this deliverable (November 2022) we are waiting on the final updates on Refuel EU trialogue negotiations between the EC, Parliament and Ministers. It's therefore hard to come up with final results and interpretations necessary for the SAF scaling strategy. We will refer to the deliverables in workpackage 3, related to policy developments and the latest known status of policy development which has been consistently changing over the course of Bio4A. In this chapter we will showcase the state of the main policy bodies relevant to the European context:

- Corsia
- RED I, II and III
- ReFuelEU Aviation and national mandates

Policy on allowed feedstocks relevant to the HEFA pathway will be discussed in later chapters of this scaling strategy.

4.1 Global – CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a global market-based measure to reduce aviation-related emissions, initiated in 2016. One of the initial goals through CORSIA was to reduce emissions by 50% in 2050. An update to the 2050 goal was recently taken and a large majority of countries voted in favor of having net-zero emissions by 2050 as the *Long-Term Aspirational Goal* (LTAG), agreed at the latest ICAO Assembly.

Participating countries would voluntarily reduce emissions to stay under a decreasing emissions ceiling. Targets can be reached by purchasing CORSIA eligible units (offsets) on the market, by blending SAF or making technological improvements and reducing fuel uptake. Due to Covid, the baseline year was changed to 2019, which effectively meant that countries didn't need to take any action to meet the reduction goals until the aviation sector had restored to 2019 levels. However, in the latest Assembly ICAO (International Civil Aviation Organization) members also voted in favor of adjusting the baseline to 85% of 2019 levels, meaning airlines would have to start offsetting emissions earlier.

In 2020 and 2021, CORSIA eligible units have transacted at significantly different prices ranging from less than USD 0.5/tCO_2eq to more than USD 45/tCO_2eq. Bullish price projections would see prices increase to an average of USD 32/tCO_2eq by 2026.[1] With SAF mitigation costs today exceeding 500 USD/tCO_2eq, credit prices are a long way from incentivizing SAF production on its own. However, ICAO does expect a large share of the emission reductions coming from SAF (65% in the realistic scenario).

The relevance of CORSIA for SAF lies mainly in the stacking of different incentives. When using SAF as an airline, or producing SAF as a fuel supplier, one may be able to generate incentives under policy schemes like RED II or the LCFS. If airlines use SAF, it can reduce compliance costs for CORSIA that will increase profitability. However, these credit revenues might not trickle down into the SAF price, depending on the costs airlines need to make for CORSIA compliance. When credit value goes into triple digits (e.g. 100 EUR/t CO_2), CORSIA may become an interesting additional driver: in a scenario where SAF reduces 3 tCO_2/t SAF, one could generate EUR 300/t SAF of credit revenue.

Table 1 shows what it cost to reduce 1 t of CO_2 by using SAF considering a range of SAF price premiums and CO_2 emission reductions. In deliverable 5.1 we have shown that the price premium for HEFA based SAF, excluding policy incentives, is roughly 1100 €/t, assuming 85% CO_2 emission reduction this results in CO_2 abatement cost of € 412. Due to increased feedstock prices we see significantly increased price premium values of up to 2.000 EUR/t premium in 2022[9]. If we compare this to the price of carbon offsets of 50 – 100 EUR/t it's clear that we are still an order of magnitude more expensive to reduce CO_2 using SAF. Since SAF will have to compete with carbon offsets in the CORSIA scheme we can conclude that this mechanism will not drive SAF demand on itself.

Table 1 Cost to reduce 1 t of CO_2 by using SAF considering a range of price premiums and CO_2 emission reductions

		SAF price premium (€/t)					
		€ 1,000	€ 1,100	€ 1,200	€ 1,300	€ 1,400	€ 1,500
CO_2 emission reduction	65%	€ 490	€ 539	€ 588	€ 637	€ 686	€ 735
	70%	€ 455	€ 500	€ 546	€ 591	€ 637	€ 682
	75%	€ 425	€ 467	€ 510	€ 552	€ 594	€ 637
	80%	€ 398	€ 438	€ 478	€ 518	€ 557	€ 597
	85%	€ 375	€ 412	€ 450	€ 487	€ 525	€ 562
	90%	€ 354	€ 389	€ 425	€ 460	€ 495	€ 531

4.2 European Union – Renewable Energy Directive II

4.2.1 Status update of Renewable Energy Directive

The Renewable Energy Directive II (RED II) establishes rules for the EU to achieve its renewable energy target by 2030 to continue the fight against climate change and help reach the climate goals of the Paris Agreement. It was preceded in 2009 by the first Renewable Energy Directive which worked towards a target of 20% renewables in Europe's total energy mix by 2020. At least 10% of this target has to be fulfilled through the use of transport fuels from renewable sources.

The RED II was 'recast' in 2018 to update the legislation in light of the EU's 2030 targets to achieve a share of 32% renewable energy in the final energy supply, see update below. Where there are individual targets set per member state, depending on its natural abilities to reduce its emissions. There is a sub-target in place of 14% for the transportation sector, with various sub-targets and caps related to specific fuel feedstocks. Because the policy is a 'Directive', it means that member states can develop national measures to ensure the targets are achieved.

The Directive also contains 'multipliers' for different types of fuels and fuel used in specific end-use sectors, like aviation/marine and renewable energy in rail/electric vehicles. These multipliers allow a country to count the final energy used multiple times against the target. These multipliers represent a higher compliance value and therefore in some policies can generate a higher premium, see Figure 3 below. In calculating the 14% target, only road and rail energy use is taken into account in the numerator. However, aviation and shipping can 'opt-in' and count in the numerator.

[9] Argus – summer 2022.

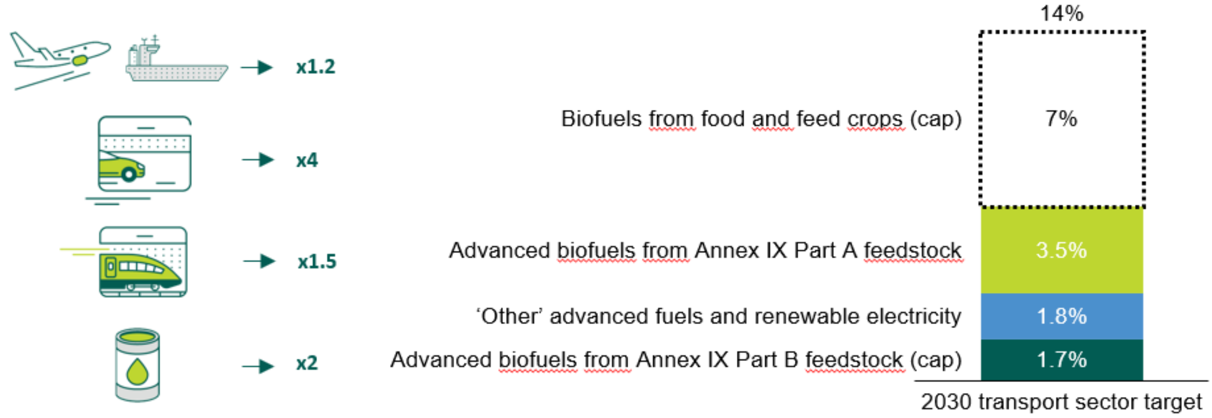


Figure 3. Overview of original multipliers depending on the transport modality

In the updated RED II, The overall target for renewable energy in the overall energy mix (power, transport, heating/cooling) will increase from 32% to 40% by 2030. For transport specifically, the renewable energy target has been changed from 14% (with various multipliers) to a GHG of -13% by 2030 compared to the conventional fuel baseline. This means that double counting for advanced fuels is removed and advanced fuels will be credited on the basis of their GHG intensity. The multiplier for maritime and aviation fuels remains 1.2x.

Sub-targets will be in place for:
- **Advanced biofuels**: 2.2% of final energy content.
- **RFNBOs** (i.e., hydrogen, e-fuels): 2.6% of final energy content.

This means that fuel suppliers need to ensure compliance with the overall GHG intensity target as well as the sub-targets. Even though the RED is still a directive, it's expected this will trickle down into national legislation. Aviation and maritime will be included into the scope of the RED. This means that the 5% blending mandate by 2030 under ReFuelEU (discussed in the next chapter) will contribute to the RED II targets. Furthermore, a requirement is introduced that 50% of the hydrogen use in industry should be green hydrogen by 2030, which is mostly impacting existing refinery complexes. The eligibility of fuels under the RED depends on the GHG emissions. There is a 70% GHG threshold for Recycled Carbon Fuels (RCFs) and RFNBOs, where general biobased fuels have a 65% threshold. The GHG methodology will be further specified in a forthcoming Delegated Act. RED II negotiations and thus clarity on all delegated acts is expected to be finalized by the end of Q2 2023, towards the end of the Swedish Presidency.

4.2.2 Aviation under the Renewable Energy Directive

The RED II does not include an obligation for the use of renewables in the aviation and maritime sector. However, Fuels used in these sectors can opt in to contribute to the 13% GHG reduction target in transport. This means that in calculating the share of renewables in transportation aviation and maritime are only counted for in the numerator but not in the denominator.

To account for the higher production cost for sustainable aviation and maritime fuels compared to fuels for road transport fuels, fuels used in these sectors will count for 1.2 times their energy content. Even though the updated RED has included this 'opt-in for aviation (and shipping)' in its formal text, it is not mandatory that each EU member state adopts this in legislation and the same holds for the multiplier for aviation and marine. Hence, the transposition of the RED II into national legislation is critical for the viability of SAF. This has been discussed in more detail in deliverables 3.4 on policy implementation. In the following we provide a summary of how the transposition has shaped up in the Netherlands taken from deliverable 3.4, as this is a relevant case study for the Bio4A project as well.

Bio4a RED transposition in the Netherlands – case study[10]

In the implementation of the RED, the Dutch Government chose to implement a flexible system allowing fuel suppliers to meet their obligation in the most cost-effective way. This meant that they can either supply renewable fuels or buy credits from others that have supplied a surplus of renewable fuels. These credits are called "HBE's", HBE's are generated when renewable fuel is supplied and represent 1GJ of renewable energy. At the end of the year, fuel suppliers must show compliance by handing over a number of HBE's equal to their obligation[11].

The road and rail sector are the only mandated sectors that must comply with the 10% renewable energy target of the RED. However, the Netherlands was the only Member State that chose to actively create an 'opt-in' for aviation. This means that when SAF is supplied to the Dutch market, the SAF (combined with a Proof of Sustainability (PoS)) can generate HBE's within this system. These HBE's can then be sold to obligated parties and thereby contribute to the targets of the mandated sectors under the RED.

Although the implementation of the RED II and now RED III is still ongoing, the HBE system with the opt-in for aviation will remain to exist. The RED II does require some changes to account for the new categorisation of fuels based on Annex IX. The Dutch authorities differentiate three different types of renewable fuels with corresponding HBE categories:

1. HBE Conventional for food/feed-based fuels
2. HBE Advanced for fuels produced from feedstocks listed in Annex IX part a
3. HBE Other for fuels produced from feedstocks listed in Annex IX part b

The HBE Other category stimulates fuels produced from feedstocks listed in the RED II Annex IX, Part B (these are animal fat and Used Cooking Oil type of feedstocks). Also types of feedstock which aren't included in the Annex IX or are excluded from the HBE Conventional category may be included in this category. In the case of Bio4A, a HEFA facility taking in waste oils and fats will fall under this category. In some cases, renewable electricity may also count towards the renewable energy target, in which case it is included in this category.[12]

The value of an HBE should in optimal market conditions equal the cost of a GJ of renewable fuel as suppliers have the choice to either produce or buy the physical product or the certificate. This price has increased over the past years, amongst other because the increasing blend mandates require for the incorporation of the (more costly) renewable diesel as the biodiesel (FAME) blend wall has been reached. But there are more factors that determine the value of the HBE (such as the feedstock cost) and thus the HBE price fluctuate. Looking at the historic developments we can conclude that the HBE price has increased from approximately € 5.00 in 2015 to € 10 per HBE on average in 2019 and as high as € 20 per HBE-O in 2022 (see Figure 4). Even though we see a reduction in price since its peak, we expect that the price per HBE will remain to be consistently high as policy incentives will get stricter and obligations will get higher.[13]

The value of the HBE will be necessary to bridge the price gap for SAF, discussed in more detailed in the pricing section of this report. One ton of SAF consists of 43.5 GJ[14], under the RED, 44 GJ is assumed for jet fuel, which can be counted 1.2 times due to the aviation multiplier plus double counting if produced from annex IX feedstock. Taking the 2019 HBE values this would result in 44*10*1.2*2= € 1056 resulting from the generation of HBEs per ton of SAF.

[10] This case study is taken from deliverable 3.4 on SAF policy development
[11] https://skynrg.com/wp-content/uploads/2019/03/Publications-The-voluntary-RED-opt-in-for-aviation-biofuels.pdf
[12] Wet Milieubeheer, article 9.7.4.6.
[13] The price developments of the HBE system, from 2015 onwards, can be found at: https://www.emissieautoriteit.nl/onderwerpen/rapportages-ev-2018/hbe-rapportages/publicatie-hbe-rapportage
[14] Vreuls, H.H.J. (2015). The Netherlands: list of fuels and standard CO2 emission factors. Ministry of VROM, page 5.

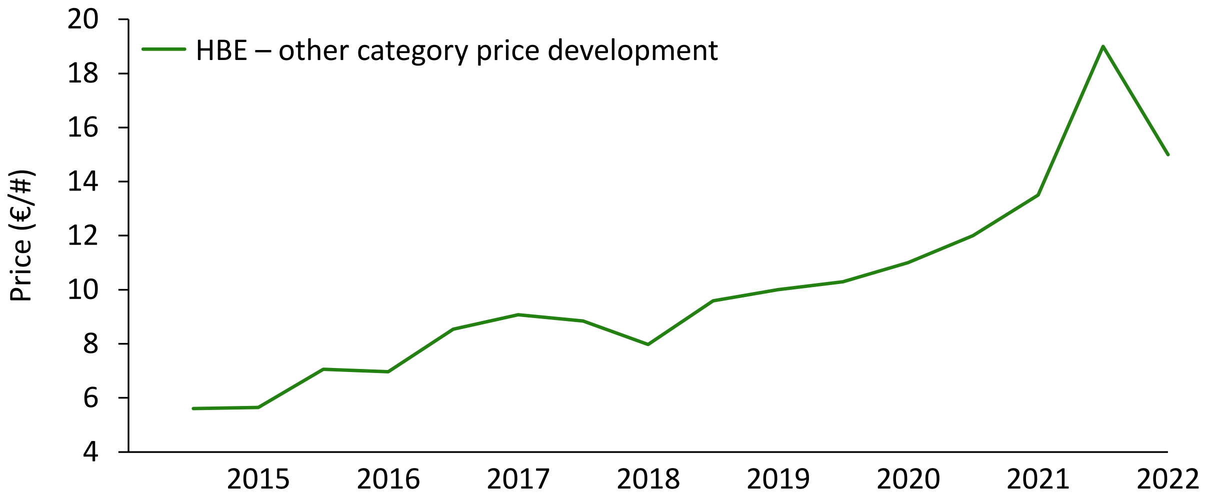


Figure 4. HBE-O historic price development

4.3 ReFuelEU Aviation and national mandates

Currently, the SAF market is a voluntary market stimulated through policy frameworks (RED, CORSIA, LCFS, etc.). The voluntary nature is however slowly changing. Especially within the European Union, member states are increasingly considering to implement a mandate for SAF uptake in their national legislation. These mandates often take a consumer-based approach, forcing the fuel supplier to substitute an X percentage of jet fuel supply by SAF.

An overview of the mandates in the EU and UK is shown in Figure 5. The member states take different approaches, from very near-term targets in Sweden and Norway to quickly kick-start the market, to more long term ambitions for 2030 by for example Finland and The Netherlands.

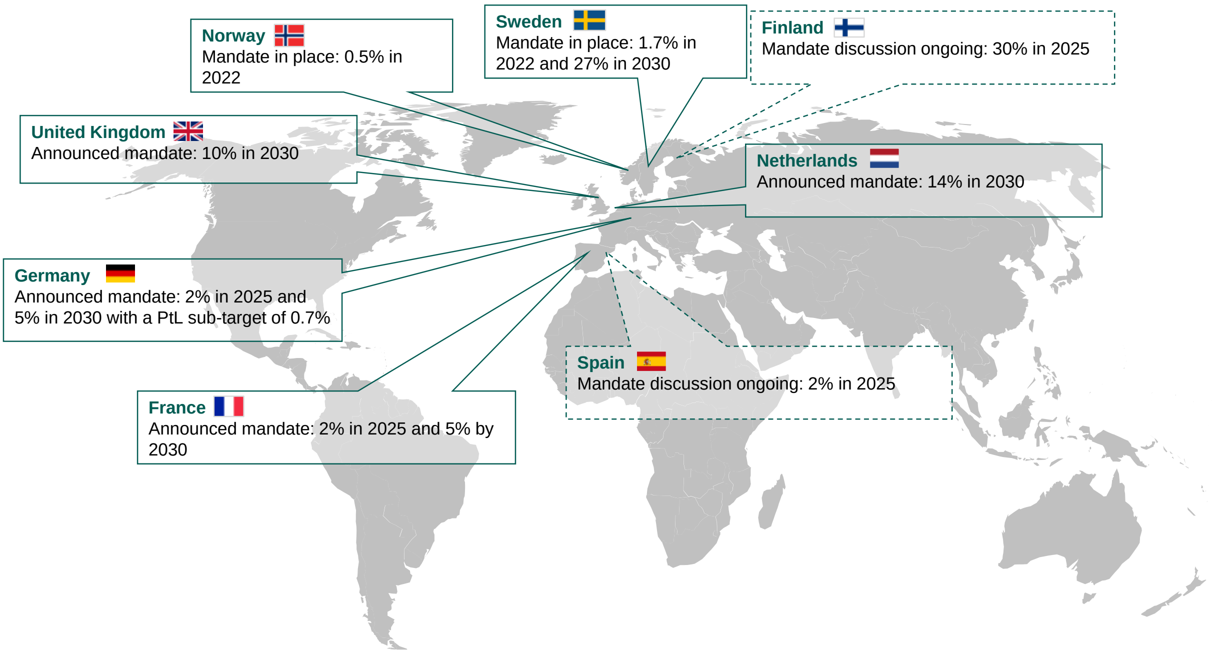


Figure 5. Status of SAF mandates in the EU (+UK)

Since the policy update in Deliverable 3.4 we have seen rapid development in the development of the Refuel EU Aviation policy. ReFuelEU is a proposed piece of legislation that would develop an EU wide blending mandate for Sustainable Aviation Fuels.

Starting in 2025, the European Commission (EC) proposes a SAF mandate, the mandate stimulates advanced biofuels and power to liquid (PtL) based SAF with separate targets, shown in Table 2.

Table 2. Overview of proposed SAF targets under ReFuel EU Aviation

SAF (%)	2025	2030	2035	2040	2045	2050
Bio-advanced	2%	4.3%	15%	24%	27%	35%
Synthetic aviation fuel	0%	0.7%	5%	8%	11%	28%

PtL based SAF or 'Synthetic Aviation Fuel' as shown above is defined as SAF produced from green hydrogen and CO_2, where advanced bio-SAF should come from feedstocks defined in Annex IX of the RED II. HEFA based SAF from the right feedstocks falls under the bio-advanced target, relevant for this Bio4A assessment. The mandate is pushed on the fuel suppliers, while aircraft operators will be subject to an uplifting obligation to ensure that every carrier really uses the percentages above.

Fuel suppliers have to physically supply all Union airports with the defined blend of SAF, although a transitional period applies until 2030 in which suppliers can take an average of all SAF supplied to EU airports. To mitigate competitive distortion, e.g. from fuel tankering, airlines are obliged to always uplift 90% of the fuel needed for their subsequent flight at an EU airport. Non-compliance penalties will apply to suppliers and airlines:

Mandate	Non-compliance penalty
Fuel suppliers	2x difference between SAF and conventional jet fuel
Aircraft operators	2x price of conventional jet fuel

Figure 6. Non-compliance penalties under ReFuel EU Aviation

As of May 2022, 'trialogue' discussions between the European Commission, the EU Parliament and the Counsel are in full force around the proposed legislative text. Several amendments are being proposed. Among the most debated topics is the height of the blending percentages and whether caps should be introduced for the blending of Annex IX Part B feedstocks to avoid the diversion of feedstock from the road sector to aviation. Most recent information shows that it's likely that the percentages, of especially the PtL side, of the mandate will be increased.

With these incentives in place, the aviation sector is forced to start delivering SAF volumes into the aviation industry. In this way, the implementation of mandates into national legislation will lead to the certainty of SAF demand and can therewith be an important reason for investors to invest in the sector. It's to be seen what role HEFA can take in this opportunity as this is relevant for this scaling strategy. In section 4.4 we will take a deeper dive on the market outlook of SAF created as part of Deliverable 5.2. The ongoing translation of the national and EU wide mandates into national legislation will determine whether feedstock requirements will indeed be a challenge and whether low-ILUC feedstocks could be allowed as an alternative for HEFA based facilities and therewith impacting the scaling potential of SAF.

4.4 The SAF market outlook

As presented in Deliverable 3.4 we have developed a SAF market outlook to assess the development of SAF in the European Union and UK. The basis for this assessment were the targets set by ReFuelEU. Translating the targets presented in section 4.3 and assuming consistent fuel demand (increase compensated by efficiency improvements).

This shows that the mandate results in a very steep SAF supply increase from 2.4 Mt in 2030 to 15.2 Mt in 2040 (in EU-27). The mandate for PtL SAF accelerates significantly after 2045 to 13.3 Mt in 2050. Total anticipated mandated volumes are 1 Mt in 2025, 3.5 Mt in 2030 and 30 Mt in 2050. The UK is currently considering installing a SAF mandate that would start at 10% in 2030,1 increasing to 75% by 2050 resulting in 9.3 Mt SAF demand. Division between advanced biobased or PtL-based fuels are still unclear within the UK proposal.

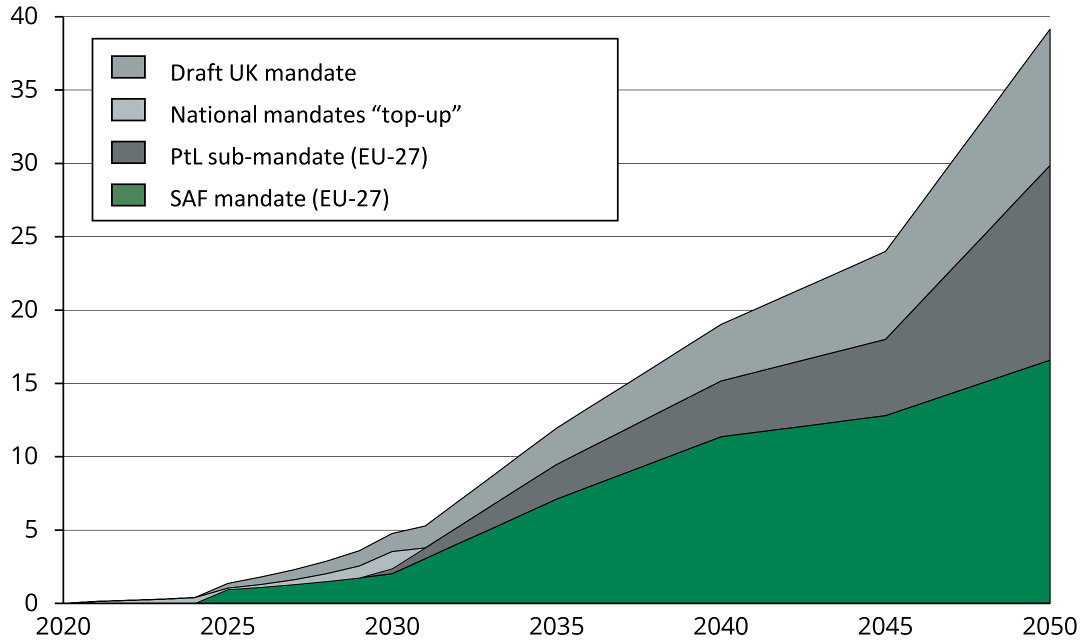


Figure 7. SAF Market Outlook (SkyNRG as part of D3.4) - showing SAF demand

Based on these initial targets, SkyNRG created a model to forecast fuel supply based on a combination of criteria:

- Scaling facilities is limited by global feedstock availability in case of HEFA, and EU feedstock availability for other pathways. (further discussed and challenged in the next section based on Deliverable 5.3).
- A maximum of 10 advanced biofuel plants are realized per year, and a maximum of 10 facilities is also considered for PtL – this is assumed based on limited resources at technology providers, project developers and financial institutes.
- Product slates of FT and HEFA technologies are not fully jet-optimized due to expected fuel demand from road sector.
- For this analysis the UK mandate is assumed to be fulfilled with the same PtL/Advanced Bio split as the EU mandate.

Based on these criteria and further methodology (available upon request) – we have developed a SAF supply scenario shown in Figure 8. Most important take aways from this analysis:

- About 400 SAF facilities will be required to fulfil the expected European mandates by 2050 (based on approximately 100 kt scale per facility).
- The HEFA pathway is essential to decarbonize aviation on the short term (till 2030), further scaling is restricted due to limited scalability of (waste) oil feedstocks. Further discussed in the next section.

- Pathways depending on cellulosic (waste & residue) feedstock will become essential to achieving mandated volumes for advanced bio-based pathways.
- Rapid deployment of new technologies (FT, AtJ, PtL) and feedstock mobilization is essential to supply mandated volumes post 2030.
- Imports are needed to achieve the mandated volumes, especially in the steep growth trajectory between 2030 and 2040.

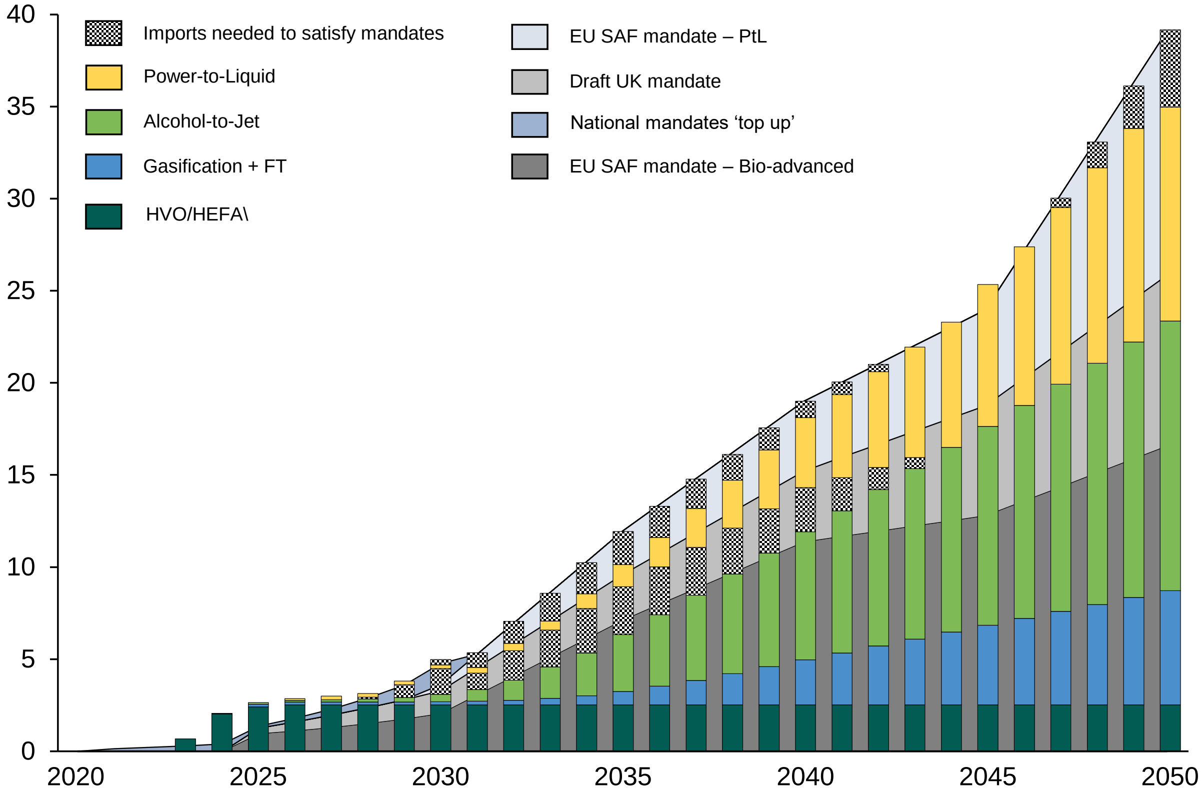


Figure 8. SAF Market Outlook - assumed SAF pathways fulfilling the demand

5 SAF supply developments

Although Bio4A focuses on the HEFA pathway, we have discussed the other potential production pathways in deliverable 5.3. In this section we will review the currently announced and operational production capacity. We will follow with an assessment of the feedstock potential for the HEFA pathway, as this is the biggest determinant in the scaling potential of this pathway. For this we will review the policy framework in the EU and finally assess the feedstock availability according to Deliverable 5.4.

5.1 Announced and operational SAF capacity projects

The HEFA technology is currently the only pathway commercially exploited towards SAF on a significant scale. Most of these HEFA facilities focus(ed) on the production of renewable diesel (also known as HVO) due to higher yields and market/policy circumstances. Due to new market circumstances and increased demand and interest in SAF, this is now rapidly changing.

Figure 9 shows the total installed SAF capacity of which most is HEFA capacity. This figure is from Argus media and shows a snapshot of time. It also shows total production capacity and therefore not per se SAF focused capacity. It's clear that there is a lot of development in the EU, from announced facilities up till 2030 we see that there is an increased production capacity adding to approximately 2.5 million tonnes of SAF capacity[15].

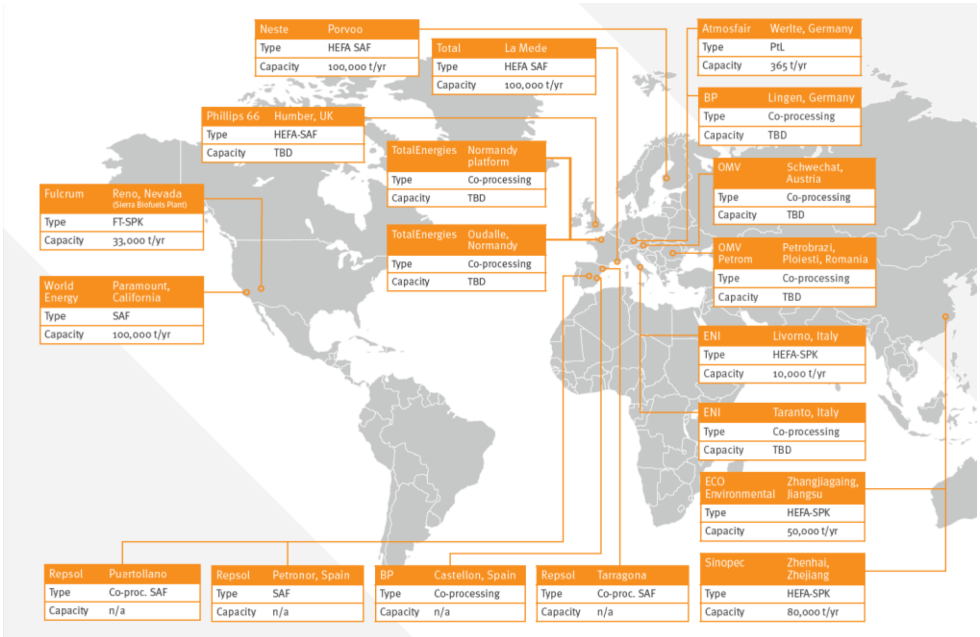


Figure 9. SAF operational production capacity[15]

5.2 Feedstock eligibility to produce SAF

It's clear that there is significant demand pull for SAF production and the initial capacity projects are developing and showcasing continues production and use of SAF (Bio4A project included). With this increased demand and policy frameworks come increased pressure and demand for (lipid based) feedstocks. This will be the main determinant for the scaling potential of the HEFA pathway. In this section we will review the main policy and certification frameworks to set the scene for feedstock potential in the next section.

[15] Argus Media - 2022

It's clear that along with other efficiencies in operations and aircraft design, SAF is intended to reduce the industry's growing share of greenhouse gas emissions and lower the overall climate impact of aviation. However, without proper compliance of the criteria verified under a robust sustainability certification scheme, some of these fuels risk having negative social and environmental impacts. Examples of such could be negligible greenhouse gas emissions reductions, reduced food security through the conversion of food-producing land to feedstock production, environmental degradation from deforestation, and unsustainable soil and water usage.

Though the term sustainability is commonly used to determine whether a fuel adheres to the criteria and avoids above sketched risks, there is currently no internationally agreed definition of what constitutes to SAF. There are several sustainability initiatives worldwide, with varying definitions. In the following section we will assess what policy frameworks state relevant for the HEFA pathway scalability.

EU history of sustainability criteria

The use of biomass and palm oil for energy purposes led to significant political debate in the European Union about the sustainability aspect of the policy driving demand for these resources. From this debate the Renewable Energy Directive (RED) started to include sustainability criteria in 2009 and later in the RED II in 2019. The RED II defines a series of sustainability and GHG emission criteria that bioliquids used in transport must comply with to be counted towards the overall 13% target of GHG reduction.

Some of these sustainable criteria are the same as in the original RED, while others are new or reformulated. In particular, the RED II introduces criteria related to sustainability for forestry feedstocks as well as GHG criteria for solid and gaseous biomass fuels. Feedstocks used to produce SAF are currently not restricted by the RED II as there is no specific SAF regulation in place to date, however for the ReFuelEU initiative the RED II criteria are used to determine eligibility of feedstocks. Another important criterion which was defined is Indirect Land Use Change (ILUC), see Figure 10 for a simplified explanation on the ILUC effect. In March 2019 the Commission adopted the Delegate Regulation (EU) 2019/807 defining which ILUC feedstocks can count towards this target, and it set a limitation to 2019 consumption levels in each EU Member State in period 2019-2023, phasing down to zero by 2030. Meaning (normal) vegetable oils cannot be used for fuel production in future, putting pressure on the waste oil market and potentially on Low-ILUC produced feedstocks on degraded lands or as intermediate crops.

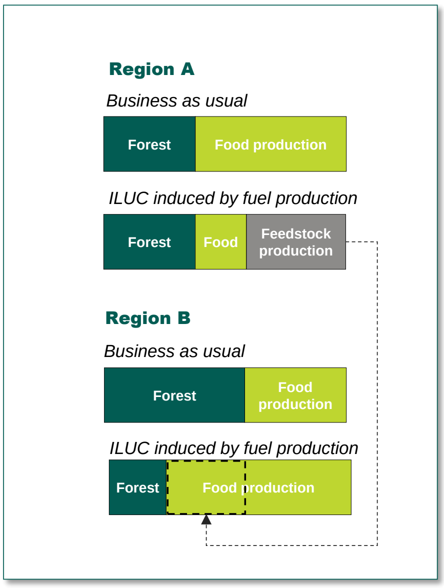


Figure 10. Indirect Land Use Change effect

Green House Gas impact off SAF

Feedstock-related emissions generally have the biggest impact on the overall Green House Gas (GHG) savings of SAF. These include emissions from:

- Direct effects: e.g., emission from fertilizer use and feedstock processing energy use.
- Indirect effects: e.g. ILUC. However, an indirect effect is also associated with the overall efficiency of the conversion process of feedstock to fuel. The lower the efficiency, the more feedstock is needed, thereby amplifying the direct effects mentioned above.

Another large determinant is the amount of GHG emissions released during the fuel production stage. Some conversion processes require more supply of external heat or power, potentially with associated emissions when fossil sources are used for this energy supply.

Logistics and blending operations, as well as fuel distribution and transport generally have a low impact on the GHG savings. Nevertheless, methods exist to minimize the carbon footprint by optimizing transport modes or making use of a Book & Claim approach for the uptake of SAF. Since the carbon emitted from the combustion of SAF is assumed to have been taken up by the feedstock within the same cycle, carbon emission from fuel combustion are often set to zero. However, when fossil feedstocks are co-processed or waste fossil feedstock is used, these emissions should be taken into account.

Sustainability certification of SAF

As part of deliverable 5.2 we have assessed the various sustainability schemes and compared the various schemes with each other. A way to avoid the negative impacts of SAF as described in the previous sections can be to adhere to the multi-stakeholder standards as set up by sustainability certification schemes. Certification under a scheme can happen on a voluntary basis to demonstrate sustainability but can also be required in order to claim emission reductions under specific policy schemes such as CORSIA or regulatory frameworks such as RED II.

The two main organizations relevant for SAF, are the International Sustainability and Carbon Certification (ISCC+) and Roundtable on Sustainable Biomaterials (RSB). RSB is commonly seen as the most ambitious standard for SAF, especially on the topic of feedstock, but also involves more administration and in-person auditing. Besides third-party certification it can also be very useful to engage with local non-governmental organizations (NGOs) to ensure sustainability and positive societal impact for local stakeholders and communities.

In order to have a global overview of the status of different sustainability schemes a review of the most common standard or regulations used in the biofuel sector was provided in D5.2. As stated previously, the European legislation does not yet have a binding target for SAF uptake, however due to the option of using SAF under the RED II and future implementation of the ReFuelEU legislation we did review SAF eligibility in various schemes, see Table 3 below.

Table 3. Comparison sustainable schemes-standards

Standard-Regulation		RED II	ISCC	RSB	RFS	CORSIA
Scope						
Geographical coverage of scheme		EU	EU	EU	USA	Global
Feedstock		Multiple agricultural feedstock, UCO, and agricultural residues	Multiple agricultural feedstock	Multiple agricultural feedstock	Multiple agricultural feedstock, MSW, UCO and agricultural/forestry residues	Multiple agricultural feedstock, MSW, UCO and agricultural/forestry residues
Sustainable criteria						
Environmental	GHG saving	✓	✓	✓	✓	✓
	Land criteria	✓	✓	✓	✓	✓
	Biodiversity protection (soil, water, ecosystems..)	✓	✓	✓	✓	✓
Social	Labour right and working conditions	X	✓	✓	X	X
	Land use right	X	✓	✓	X	X
	Food security	X	X	✓	X	X
Economic						
	Economic stability	X	X	X	X	X

Eligible fuels under the RED II
For SAF to be 'counted' towards the targets of the RED II and in future the ReFuelEU, a producer of must be able to document compliance to the RED criteria. This is discussed in more detail in the sustainability sections of Deliverable 5.2, we are summarizing the main results and updates since 2020 as it's important to understand the dynamics to interpret the scaling potential of the HEFA pathway.

First of all, the RED II specifies GHG reduction thresholds: 65% CO_2 emission reduction for existing biorefineries and 70% for new build biorefineries starting operations from 2026 onwards. Second, the EU differentiates fuels based on the feedstock used for production. Fuels produced from food (crops) and feed are capped at 7% and reduced to 0% in 2030. The use of wastes and residues is promoted by specifying a minimum level of incorporation for these fuels. Annex IX specifies which feedstocks can be used to produce these so-called advanced biofuels. The annex consists of two parts (see Table 4):

- Part A: waste and residue feedstocks which the EU wants to support
- Part B: specific used cooking oil and animal fats, these are limited in volume and are therefore capped

Table 4. Categorisation of feedstocks in Annex IX

Part A	Part B
Algae if cultivated on land in ponds or photobioreactors	Used Cooking Oil (UCO)
Biomass fraction of mixed municipal waste but not separated household waste subject to recycling targets	Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009
Bio-waste as defined in Article 3(4) of Directive 2008/98/EC from private households subject to separate collection	
Biomass fraction of industrial waste not fit for use in the food/feed chain, including material from retail/ wholesale and the agro-food and fish and aquaculture industry, excluding feedstocks listed in part B	
Straw	
Animal manure and sewage sludge	
Palm oil mill effluent and empty palm fruit bunches	
Tall oil pitch	
Crude glycerine	
Bagasse	
Grape marcs and wine lees	
Nut shells	
Husks	
Cobs cleaned of kernels of corn	
Biomass fraction of wastes and residues from forestry and forest-based industries, i.e. bark, branches, pre-commercial thinning's, leaves, needles, tree tops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil	
Other non-food cellulosic material	
Other ligno-cellulosic material (...) except saw logs and veneer logs	

Since the Bio4A project is focussed on the HEFA technology, the feedstocks listed in part B (UCO and tallow) and potentially also tall oil are the most relevant feedstocks to consider and are the focus area for the next chapter.

In 2022, the European Commission announced their ambition to add a range of other non-feed crops such as "non-food crops grown on severely degraded land, not suitable for food and feed crops" to Part A. Even though commercial volumes of feedstock from these sources are yet to materialise, it is a very interesting move as these are the potential feedstocks tested in the Bio4A project by Camelina Company Espana. The current change and inclusion is a proposal and not yet fully allowed legislation. It is also not entirely clear what would be permitted under Part A as the crops need to be grown on land that cannot be used for food, and excluding cover crops grown between harvests in places such as Argentina in 'sub-tropical' climates.[16]

5.3 HEFA feedstock scaling potential

Based on the currently known targets for ReFuelEU, shown in section 4.4, we have identified the estimated market for advanced bio-based SAF in the EU to be approximately 15 Million tonnes in 2050, with very conservative market assumptions. As part of the market outlook, we identified that a portion of this approximately 3 Mt could be produced from the HEFA technology. This is based on a model which takes into account competing use in other regions and for other products, such as Renewable Diesel, for the same waste oil feedstocks. This did not yet take into account the potential of using 'cover crops' or wider use of imported waste oils. In this section we will take a more feedstock focused (rather than market driven) approach to give an indication of (waste) lipid feedstock potential.

Waste oil market

The market size of waste oils can be split in Used Cooking Oil and Animal Fats as defined by the EC in the RED II. On a high level we see that approximately 40 Mt of waste oils are available worldwide[17]. Currently a majority of these waste are either not collected or used in other sectors to produce e.g. Renewable Diesel or Biodiesel. It was also shown as part of Deliverable 5.3, that the Food and Agriculture Organization of the United Nations (FAO) estimates an annual consumption of vegetable oil for food use of 23.5 kg per capita. After processing and consumption these edible oils will yield approximately 50 Mt of waste oils worldwide in 2025[18].

In the EU specifically we have seen an approximate 4 Mt of UCO theoretically available in the market, of this only a fraction is collected. We have seen numbers of approximately 650,000 t collected in the professional sector (e.g. restaurants), while only about 5% of UCO is collected in the household market. The ICCT report 'Wasted' showed a total use of waste oils of approximately 1.2 Mt, of which approximately 700 kt was from local markets and the remainder imported from overseas[19]. The above shows both the limited availability of waste oils as well as the already existing competing use in the biodiesel and other biofuel industries, limiting scalability potential for HEFA in especially Europe.

Cover and rotational crop potential

Looking beyond waste oils to the potential of cover crops such as Camelina. We have looked at the EU MED countries, where 8.5 Mha of marginal land is available[20]. This land could, if allowed and fully used, yield (assuming an approximate 750 L/Ha yield[21]) approximately 5 Mt of oils ready to be processed into SAF and other fuels. Even though this is still not significant enough to cover all advanced bio-based SAF volumes, there is a very interesting potential in these lands as sustainable agronomic practices can be improved in parallel and therewith enhancing the agricultural industry in a wider sense, including food production. On a worldwide basis the WEF

[16] https://www.argusmedia.com/en/news/2397968-eu-mulls-changed-biofuel-feedstocks-lists
[17] https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf
[18] Fu Zhang *et al.* A new process for the production of second-generation biodiesel from waste oils and fats. Biomass Conversion and Biorefinery (2022)
[19] https://theicct.org/wp-content/uploads/2021/06/WASTED-final.pdf
[20] https://www.sciencedirect.com/science/article/pii/S0961953419301485
[21] https://www.ofimagazine.com/content-images/news/Camelina_2020-11-12-165216.pdf

has estimated cover crops and crops on degraded land could yield another 130 Mt of oils, yielding approximately 65 Mt of SAF production.

Summarizing the total potential of waste oils would be 40 Mt in the world and 130 Mt of oils from cover crops and degraded land agriculture. Assuming an average 50% SAF share, taking into account yields and alternative fuel production like diesel, this could in total yield approximately 85 Mt of SAF worldwide from the HEFA pathway[22]. This is still a significant market opportunity for HEFA in the future. However, as cover crops are still in development and waste oils are either not yet collected or already widely used in alternative fuel production facilities practical scalability is limited and restricted to regions where feedstock might still be available.

[22] https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf

6 Market scaling strategy conclusions

In this report we have assessed the scalability potential of the HEFA pathway based on the various deliverables and all the work done in the Bio4A project. Since the start of the project in 2018 the market of Sustainable Aviation Fuel has significantly developed and HEFA is (still) the only commercially ready and widely available technology today. The goal of Bio4A was to *proof scale up of industrial production and demonstrate the market uptake of sustainable aviation fuel*. While this has been successfully achieved, the market has since then also developed into a more mature and consistent market. With all this in mind, the market scaling strategy for HEFA-based SAF can be assessed on the following aspects:

Market potential
The demand for SAF is significant, aviation is here to stay and decarbonization options are very limited. We expect, under conservative circumstances with the ReFuelEU targets in place a total European market size in 2050 of approximately 25 Mt of which 15 Mt should be 'advanced bio-based'. Including the UK market and more ambitious targets proposed by the European Parliament we can see the total European market potential for 2050 grow towards ~50 Mt. On a worldwide level there is more uncertainty due to the lack of policy development, however we see significant movement in the US and Asia as well, creating market potential of >250 million tonnes towards 2050.

Technology readiness
There are various pathways to convert renewable feedstock into SAF, both bio-based as well as Power-to-Liquid pathways are currently pushed by policy in the EU. Even though there are 7 different pathways technically certified by ASTM D7566, the HEFA pathway is currently the only availably technology on a commercial scale. This is currently the only pathway for which licenses can be obtained at a fully proven (TRL 9) level. Other pathways such as Alcohol-to-Jet and Fischer-Tropsch (PtL-based) are in rapid development and could see commercial facilities as early as 2025. For widespread scaling we expect HEFA to be the dominant technology pathway up to 2030.

Feedstock potential
Regarding the feedstock availability for HEFA scaling, current focus of the EU RED and other policy frameworks is on the use of waste lipids, due to the risk of food/crop-based oils. Waste volumes are scarce reflected by the increasing price (partly due to the COVID pandemic reduced restaurant activities). There is room for better collection of Used Cooking Oil across Europe and the rest of the world especially on a household level. Animal fats are more uncertain especially due to the potential use of these feedstocks for animal feed or alternative products in the healthcare industry, this competing use impacts the ability to scale HEFA on these feedstocks.

To successfully scale the HEFA pathway beyond 2030 and beyond existing waste material, it is therefore essential to diversify the feedstock base. Low-ILUC crops and cover crops on degraded lands are a promising path to further scale the availability of sustainable lipids. On a world-wide level the industry sees potential to scale towards 130 Mt of oils from degraded lands. It's to be noted that these feedstocks are not yet developed and need significant policy push, to educate, train and invest in farmers to diversify their portfolio towards these crops. Also, clear policy and certification schemes are needed to verify sustainability of these feedstocks to avoid any unwanted (land use change) effects.

Concluding, the HEFA pathway is essential for SAF scaling. Especially until 2030, the HEFA pathway is the most scalable and commercially ready technology for widespread uptake of SAF. The scaling beyond 2030 towards the ambitious 2050 targets remains limited due to the limited availability of lipid-based feedstocks. Within Europe most of these waste-based feedstocks are already used for SAF production and alternative use cases such as Bio- and Renewable Diesel.

Further scaling on these feedstocks is dependent on the ability to import additionally collected waste material. With an increasing SAF industry in other places in the world, relying on the ability to import is a significant scaling risk.

To further scale the HEFA pathway towards the ambitious 2050 targets, we therefore recommend development on the following two points:

1. Policy makers, industry and the sustainability and NGO community should keep discussing the best use of certain feedstocks, such as sustainable lipids. The available sustainable lipids could potentially be prioritized towards the aviation industry without compromising other industries. With further electrification of road transport, waste oils might become available for use in the aviation sector. It is essential to avoid any unwanted effects in displacing renewable fuels in the road transport with fossil-based alternatives.

- The agricultural industry can, with the initial proposed changes by the European Commission to allow for low-ILUC oils in aviation, focus on developing sustainable lipids from degraded (and low-ILUC) land. This will diversify the feedstock pool for HEFA SAF and create an ability to scale beyond waste materials currently available. With the recently suggested addition of these feedstocks in ReFuelEU and within the RED sustainability framework (pending approval), the ability to further scale HEFA is opened. This change could further contribute to a more sustainable use of land in Europe and worldwide.