ANALYSIS OF THE POTENTIAL FOR NORWEGIAN PRODUCTION

Sustainable Aviation Fuel from Non-Biological Feedstocks

Avinor AS

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This report provides a market study of sustainable aviation fuels (SAF) from non-biological pathways. It also includes a high-level assessment of the potential of producing SAF from non-biological feedstock in Mongstad.

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1 EXECUTIVE SUMMARY

Regulatory status for SAF

The aviation industry is working towards more sustainable practices, including the use of sustainable aviation fuels (SAF). SAF are drop-in fuels that can be produced through different pathways mimicking the natural formation of hydrocarbon chains, using either biological or non-biological input factors. The large SAF volumes needed to decarbonize aviation will challenge sustainable utilization of biological feedstocks, and establishing production of non-biological SAF will be important. The sustainability of fuels, and hence what fuels can be called SAF, depends on the origin of all input factors in the production value chain. Regulatory bodies are currently working towards defining common international sustainability criteria for SAF.

There are proposed and emerging regulations and certification schemes involved in the development and uptake of SAF, both in the EU, UK and US as is the focus of this report, but also other regions. The EU is leading the way in developing legislation for biological and non-biological SAF, with the European Green Deal and the Fit for 55 package as central policies. Within the Fit for 55 package, the main initiatives for the development of SAF in Europe are ReFuelEU Aviation and the updates to the Renewable Energy Directive (REDII). The trialogue negotiators reached a provisional agreement on the revised REDII (i.e. REDIII) in March 2023.

The EU regulatory framework is complex when it comes to definitions and criteria for non-biological SAF. REDII and associated Delegated Acts (DAs) (on Article 27 and 28) defines Renewable Fuels of Non-Biological Origin (RFNBOs) and Recycled Carbon Fuels (RCF), as well as methodology to calculate GHG emission savings and emissions criteria for these fuels. These DAs were in February adopted by the European Commission and are now being evaluated by the European Parliament and the European Council, with a four-month period to accept or object the proposals.

In short, the categorisation of a fuel is based on where the energy in the fuel comes from: The energy in an RFNBO comes from renewable electricity (these fuels are also known as e-fuels), and the energy in an RCF comes from non-renewable waste streams or waste processing gas. “Low-carbon fuels” is a third category of fuels based on blue hydrogen that previously has been discussed, but has not been included in REDII or the DAs.

Furthermore, the DAs specify that to qualify as a RFNBO or RCF, there is a GHG reduction requirement of 70% compared to the fossil comparator. For RFNBOs, which are made from renewable “green” hydrogen and CO_2, the origin of both the power used in the hydrogen production and CO_2 are important in the GHG calculation. Before 2041 (or 2036 if from electricity generation) fossil CO_2 can be considered as “avoided” if it comes from an activity in EU ETS or other effective carbon pricing scheme. From 2041 (or 2036 if from electricity generation), fossil CO_2 must be included in the emission calculation and only biogenic CO_2, or CO_2 from Direct Air Capture (DAC) can be considered as avoided.

April 25 2023 was an important milestone in the EU SAF sphere: After several rounds of trialogue negotiations under the ReFuelEU Aviation initiative an agreement was reached on EU’s first regulation mandating sustainable aviation fuel blending at European airports. The regulation includes binding volumetric SAF mandates and synthetic fuel sub mandates, as well as what types of fuels and feedstocks qualify towards these. The overall SAF mandate will start at 2% in 2025 and gradually increase to 70% in 2050, while the synthetic fuel sub-mandate will start at 1.2% in 2030 and gradually increase to 35% in 2050. Key clarifications to previous uncertainties are that the synthetic sub mandate includes all RFNBOs, the overall SAF mandate includes RCFs, while low-carbon fuels are not included. Figure 1-1 shows a simple illustration of the EU’s fuel categories and which are considered sustainable. These blending mandates will significantly increase the European SAF demand (both biogenic and non-biogenic) towards 2050, and this decision is essential to reduce uncertainty for fuel production projects. There is still uncertainty around how this will be implemented in the EU countries and how Norway will follow up and adopt own national blending mandates.

Contradictions between international regulations have made it difficult for airlines and producers to make investments and carbon reduction strategies. The International Civil Aviation Organization (ICAO) has provided high-level definitions and guiding values for climate effects through the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). In addition, several countries have introduced their own legislation to incentivize the production and use of SAF, such as the US Sustainable Skies Act and the Aviation Climate Action Plan, the US Inflation Reduction Act of 2022 (IRA), and the UK's Transport Decarbonisation Plan and proposed SAF mandate.

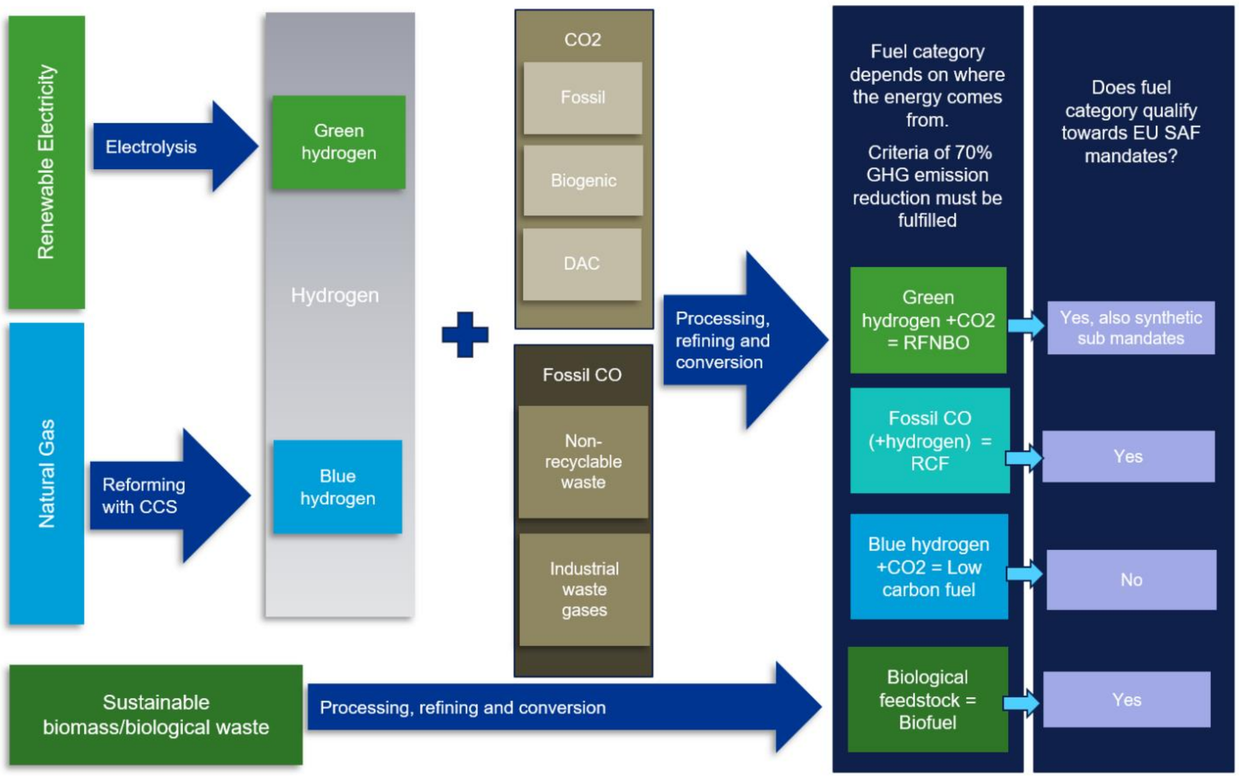

Figure 1-1: Feedstocks, fuel categories and EU SAF mandates

There are several barriers for the establishment of SAF production value chains in Norway, but also several drivers compared to other countries. As SAF-production from waste products is a relatively new concept, with immature technologies, processes and frameworks, there are several barriers to the establishment of this industry worldwide. Many of these barriers are common and not country-specific, e.g. the barriers related to certification and traceability, regulations, standards and technology costs and maturity. For Norway, the barriers are in general related to risk capital and investments with uncertainty on subsidies or investment support. However, with blending mandates the added costs may be sent to the end-user as increased flight ticket prices. Infrastructure constrains with access to the power grid, and competition for feedstock, such as sustainable CO_2 and renewable hydrogen are other barriers. The drivers, on the other hand for Norway are; a high renewables share in the electricity mix, “relatively low” power prices (in some regions due to bottle necks in the grid), and high-quality power supply. It is also planned further development of renewable power, Norway has leading CCS and CCU competence and the first value chains are being constructed. In addition, Norway has high standards for gas and fuel value chains, and Norwegian aviation has been an early mover in sustainable aviation fuel sourcing and supply as the first country with a blending mandate.

Mongstad as a location for SAF production

This analysis includes a pre-feasibility assessment of a production process for non-biological SAF on Mongstad. The process is based on Municipal Solid Waste (MSW) as feedstock and includes the combination of gasification, blue hydrogen and DAC to produce ethanol using proprietary technology from LanzaTech, followed by proprietary technology from LanzaJet to produce SAF. Further, a specific supplier of DAC technology at Kollsnes (Carbon Engineering), for CO_2 supply to the plant at Mongstad, is included in the production process. Synergies with ongoing blue hydrogen projects will be important to utilize the emerging value chains for CO_2 transport and storage.

Feedstock constraints are apparent for the Mongstad location. Non-biological feedstocks may be mainly plastic waste and MSW (excluding the biological fraction which may be counted as a biofuel from the same plant). A uniform feedstock is key for the next steps of the process, and a higher calorific value is strongly preferred. The logistics and variability of the feedstock supply and the related process control requirements are some of the key challenges facing any SAF production process based on waste products. However, based on DNV's assessment, local sourcing of MSW is deemed not to be enough to produce the targeted amount of SAF, 113 million litres per year (LanzaTech's "standard" plant size). It must either be imported, or a regional and local feedstock will have to be complemented using on-site blue hydrogen and CO_2 from DAC. There are also significant technology risks related to the proposed production process, as particularly the gasification of waste products and the DAC process are still not mature.

The potential for production of SAF has been assessed through the review of three different scenarios, based on the source and volume of MSW as a feedstock. The first scenario illustrates an ideal case where all feedstock can be sourced locally, looking at both using solely MSW and a combination of MSW, (blue) hydrogen and CO_2 from DAC. In the second scenario, all feedstock is assumed to be imported from Italy and the UK. In the third scenario, the MSW deemed available locally is combined with CO_2 from DAC and (blue) hydrogen. These scenarios give significant variation in energy consumption, CAPEX, OPEX and emissions. Also the categorisation of the fuel produced vary in the different scenarios depending on the share of biogenic and non-biogenic feedstock going into the process, and the inclusion of blue hydrogen and CO_2 from DAC.

The process and scenarios have GHG emissions of 21.2-27.9 gCO_2eq/MJ of SAF, which corresponds to a CO_2 reduction in the range of 70-77 % GHG emissions reduction. These estimates are high level and rough estimates, and not detailed Life Cycle Assessments (LCA), including all CO_2 equivalents. The margin for the threshold of >70% GHG reduction compared with the fossil comparator is likely reached.

The production process analysed in this report shows promising potential, with opportunities for relatively rapid scale-up with a co-location of Alcohol-to-Jet at Mongstad, but there are still significant barriers to overcome. Some barriers are project-specific, like the sourcing of feedstock and the optimization of conceptual and technical designs, but there are also commercial and regulatory barriers related specifically to the uncertainties in the regulatory landscape and the current competitiveness of non-biological SAF to biological SAF and regular jet fuel. The EU blending mandates and clarifications around including RCFs but excluding low-carbon fuels are important to understand for this project. To meet the climate target and the growing demand for SAF, incentives must be adopted, and industry actors and investors should have a regulatory landscape with a higher degree of predictability and stability than apparent today.

2 INTRODUCTION AND BASIS FOR WORK

In 2020, the Norwegian Airport Operator, Avinor, together with NHO Luftfart, LO, Widerøe, SAS and Norwegian, set the ambitious goal that Norwegian aviation should be fossil free by 2050. Sustainable aviation fuel (SAF) is expected to play an important part in reaching that goal. In 2021, the same actors published a program for increased production and uptake of SAF, with plans and recommendations to speed up the SAF development in Norwegian aviation.

Figure 2-1 shows DNV's Energy Transition Outlook's view on European energy demand from aviation towards 2050. It shows that energy demand from aviation is expected to increase significantly, and that SAF will play an important part. But this "most likely future" is far from what is required to reach emission reduction targets – to reach these the SAF share would have to increase significantly.

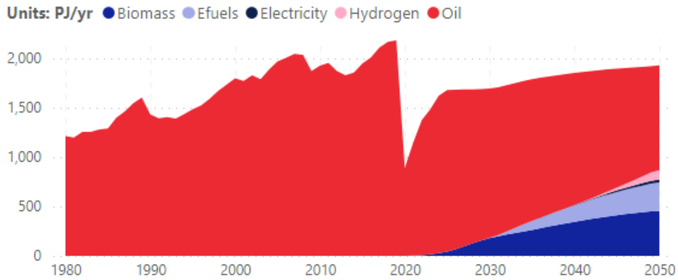

Figure 2-1 European aviation energy demand by carrier (DNV, 2022)

The small volumes of SAF produced and used today are mainly based on waste oils, and pilot production facilities for SAF from various biological feedstock are being established globally. There are seven approved value chains for biobased SAF, and others are under development[1]. However, the large SAF production capacity needed to reach the SAF targets will challenge sustainable utilization of renewable bio-based feedstocks - there are insufficient bio-based feedstocks with no direct or indirect negative impact on emissions or other environmental aspects. Establishing SAF production from other feedstocks is hence important for decarbonising the aviation sector.

European regulations are being shaped to accelerate the transition towards renewable energy and reduction in greenhouse gas emission. In March 2023 there was a provisional agreement on the revised Renewable Energy Directive, with a binding target of 1% RFNBOs of all fuels in the transport sector by 2030. In April 2023, ReFuelEU Aviation came to a provisional agreement on binding SAF blending mandates including synthetic fuel sub-targets. Figure 2-2 shows proposed EU and UK SAF mandates and production capacity outlook[2]. The agreed mandates (increasing from 2% in 2025 and 70% in 2050) are higher than the original proposal from Figure 2-2 (63% in 2050).

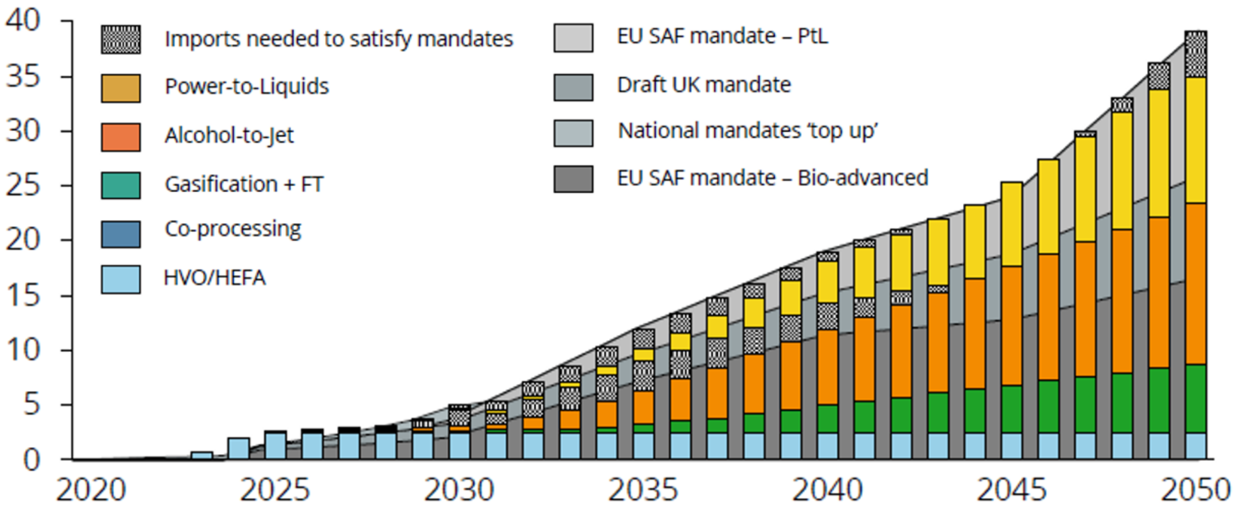

Figure 2-2: EU and UK SAF capacity outlook May 2022 (Mt) (SkyNRG, 2022)

[1] DNV's Technology roadmap for sustainable aviation fuels describes status for biobased SAF (DNV, 2021).

[2] SkyNRG, A Market Outlook on SAF (May 2022)

While a challenge for biological SAF production is feedstock availability, a challenge for RFNBO production can be access to (and prioritization of) large amounts of renewable electricity and sustainable/biogenic CO_2. Therefore, there is also an increased focus on SAF production based on recycled carbon sources, so called Recycled Carbon Fuels (RCF). In the European regulatory framework, the sources for carbon, hydrogen and energy in each production process are defining for the categorization of fuels.

Norway is well positioned for production of various types of SAF. The industrial possibilities of producing biofuels have been assessed earlier, but there is a need to develop knowledge and information regarding the possibilities related to Norwegian production of SAF from other feedstocks.

Based on this, Avinor sees a need for extended knowledge on the different production pathways for SAF produced from non-biological feedstocks, i.e. RFNBOs and RCFs. Relevant production pathways include gasified municipal solid waste (MSW) and plastics, as well as synthesis gas (syngas) produced through a combination of carbon capture and utilization (CCU) / direct air capture (DAC) and hydrogen. Avinor also seeks to understand the regulatory framework and the use of measures internationally for these production paths. With this background, DNV has analysed the potential for Norwegian SAF production from non-biological feedstocks and issued this report funded by Avinor and Innovation Norway.

Part one of the report, chapters 3 to 5, gives an overview of status for SAF with a focus on RFNBOs and RCFs. Chapter 3 describes current and proposed regulation, chapter 4 describes production pathways, including maturity, planned production projects, sustainability and costs, and chapter 5 lists drivers and barriers for establishing production in Norway.

Part two of the report is a case study with focus on Mongstad as a location for SAF production.

3 REGULATORY STATUS FOR SAF

In this chapter, DNV provides a high-level overview of regulatory status for SAF from non-biological feedstock, with special consideration to EU, UK and USA. Norwegian climate commitments are expected to be aligned with those of the EU. As policies and regulation on fuels and feedstocks are in development, this is a snapshot of the status as of March 2023.

Sustainable aviation fuels are subject to a variety of regulations, certifications, and criteria. Due to the high focus on safety in the aviation industry, testing and certification of physical and chemical properties for new SAF are an important aspect. The testing and certification of physical properties for aviation fuels are specified in the standards ASTM D7566 and DEF STAN 91-091. For SAF to be used in commercial flights, compliance with these standards is required.

Legislations in relation to SAF production and usage within the aviation industry is still developing within the different markets where at present the EU is leading the process by having initially legislative frameworks in place for biofuels and e-fuels. Not all of this is yet fully compliant with the needs and expectations of the aviation industry[3]. Other jurisdictions such as North America (MoU Stainable Aviation Fuel Grand Challenge, U.S. Sustainable Skies Act) and Asia are still in earlier stages of developing SAF programs.

Recent moves by the EU Commission to further restrict biomass of unsustainable origin or marginal GHG benefits have put more focus on waste materials and streams. This is evident in the EU Green Deal and Fit for 55. Other aspects that also need to be considered in the development of SAF legislation within the different jurisdictions is that while within EU much focus is towards e-fuels and waste-based biofuels, North America sees a higher focus on expanding its SAF production through its existing biomass production capacity (i.e. corn to biofuel) with considerable less focus on waste materials.

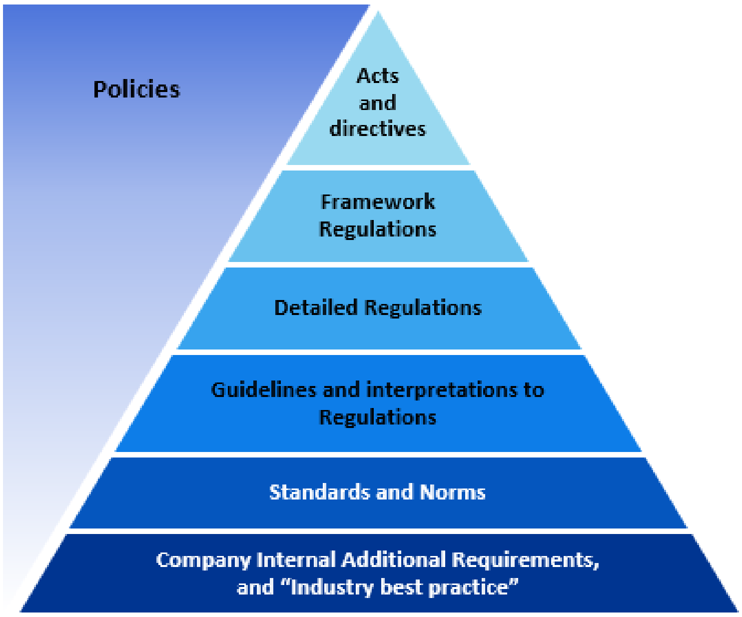

Figure 3-1: EU regulatory framework

Figure 3-1 shows the EU regulatory framework, in generic terms, illustrating how directives set the high-level ambitions with policies, and then must be implemented by the lower steps, both on EU level, and national level. The industry also works on bottom-up development to meet the policies and directives.

Currently there are no international definitions that cover all the aspects of sustainability. In the following sections, the key players in policy formulation and the related regulatory status across Europe, North America, and UK, is given. With the backdrop of existing and proposed EU regulation, section 3.3 presents definitions for the different fuel terms used in this report, and section 3.4 discuss how fuels from combinations of different hydrogen and carbon pathways fit with the SAF terminology and criteria. Section 3.5 describes regulation for testing and certification of aviation fuels.

3.1 EU regulation, definitions and classification of fuels

The overview provided by DNV in this report gives a "snapshot" of the current regulatory environment.

[3] i.e. fuel technical compliance standards, namely ASTM D7566 and DEF STAN 91-091

3.1.1 The EU's Environmental and emissions legislation

The EU's legislation for SAF is interlinked with the EU Green Deal and Fit for 55:

- The European Green Deal is the roadmap for making the EU's economy sustainable by turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all. The European Green Deal covers all sectors of the economy; transport, energy, agriculture, buildings and industry.
- Fit for 55 is a package that consists of a set of proposals to revise and update EU legislation and to put in place new initiatives with the aim of ensuring that EU policies are in line with the climate goals agreed by the EU's Council and the European Parliament. Fit for 55 refers to the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990. The proposed package aims to bring EU legislation in line with the 2030 goal.[4] In the Fit for 55 package, the ReFuelEU Aviation initiative is central for the development of SAF.
- Within the European Green Deal and Fit for 55, there are several EU Directives that are relevant for the production and usage of SAF. These include the Renewable Energy Directive (RED) and the Directive on deployment of alternative fuels infrastructure. The Delegated Acts (DAs) are subsets of the directives to provide more details to what a directive means or how the directives should be interpretated.[5]

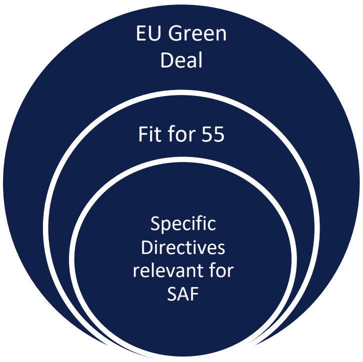

Figure 3-2: EU legislation relevant for SAF

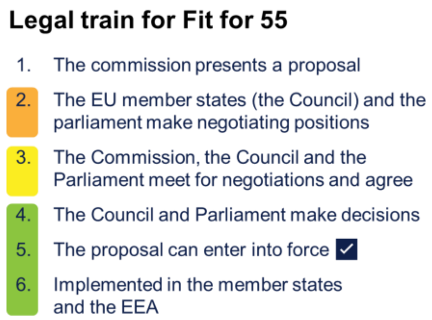

Figure 3-3 shows the current legal train status, where some affect aviation directly, and other indirectly for the feedstocks, as well as biobased SAF.

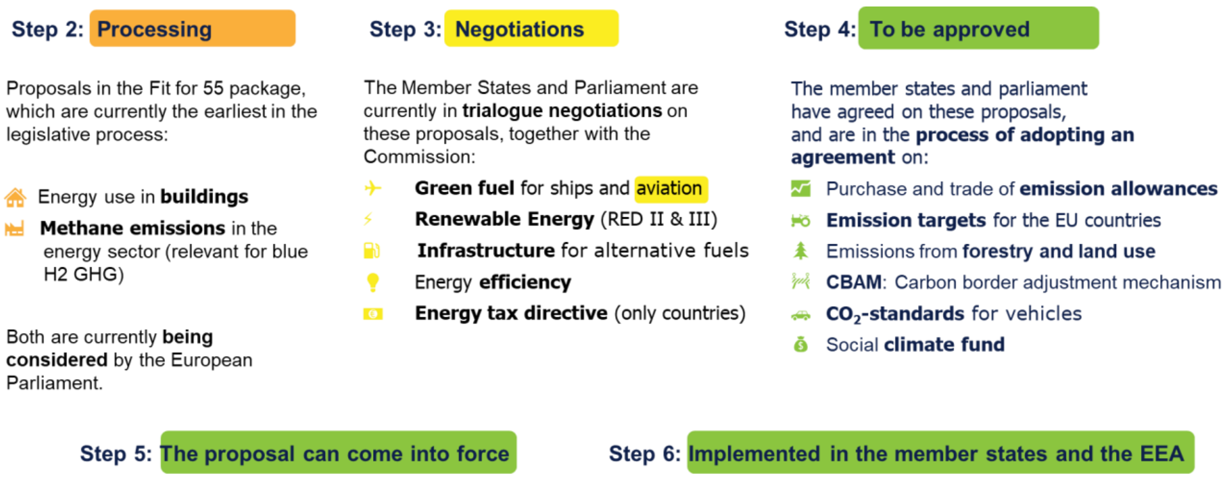

Figure 3-3: EU Legal train status relevant for fuels.

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4 https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

5 Implementing and delegated acts | European Commission (europa.eu)

3.1.1.1 ReFuelEU Aviation

ReFuelEU Aviation is the EU's first regulation mandating sustainable aviation fuel blending at European airports.[6] The first proposal from the European Commission (EC) was released in July 2021, and a year later the Council of the EU (CEU) and the European Parliament (EP) released suggested amendments. After several rounds of trialogue discussions they came to a provisional political agreement April 25 2023 on binding volumetric SAF mandates from 2025 with synthetic aviation fuel sub mandates from 2030[7]:

- The overall SAF mandate starts at 2% in 2025 and gradually increases to 70% in 2050.
- The synthetic fuel sub mandate starts at 1.2% in 2030 and gradually increase to 35% in 2050.

The agreed mandates are more ambitious than the original European Commission proposal, but less ambitious than the proposed amendments from the European Parliament. See Table 3-1 for the original proposal, the amendments and the agreed mandates.

Table 3-1: Volume share of SAF and synthetic aviation fuels in the European Commission ReFuelEU proposal, the European Parliament and the Council of the European Union amendments[6], and the agreed mandates

Year	Original European Commission proposal		European Parliament amendments		Council of the European Union amendments		Agreed mandates (April 2023)	
	Overall SAF mandate	Synthetic sub-mandate	Overall SAF mandate	Synthetic sub-mandate	Overall SAF mandate	Synthetic sub-mandate	Overall SAF mandate	Synthetic sub-mandate
2025	2%	-	2%	0.04%	2%	-	**2%**	**-**
2030	5%	0.7%	6%	2%	6%	0.7%	**6%**	**1.2%**
2032								**2%**
2035	20%	5%	20%	5%	20%	5%	**20%**	**5%**
2040	32%	8%	37%	13%	32%	8%	**34%**	**Unclear***
2045	38%	11%	54%	27%	38%	11%	**42%**	**Unclear***
2050	63%	28%	85%	50%	63%	28%	**70%**	**35%**

*The press release did not include synthetic mandate for 2040 and 2045 (to DNV's knowledge)

The trialogue discussions also included what types of fuel and feedstocks should be included in the overall SAF mandate and the synthetic sub mandate. Table 3-2**Error! Reference source not found.** shows the original proposal, suggested amendments and agreed definitions for the categories relevant in this report (definitions on what biofuels qualify as SAF have also been agreed). The Commission and the Council's position was that the synthetic sub-mandate only should include "drop-in electrofuels", while the Parliament wanted to include all RFNBOs and renewable electricity. The outcome of the negotiations includes renewable hydrogen in the synthetic sub mandate but excludes renewable electricity. Another main uncertainty was related to RCF and low-carbon fuels, and it is now agreed that RCFs are

[6] https://ec.europa.eu/info/%20strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en
[7] https://www.europarl.europa.eu/news/en/press-room/20230424IPR82023/fit-for-55-parliament-and-council-reach-deal-on-greener-aviation-fuels

included in the overall SAF mandate (not part of the sub mandate), while low-carbon fuels are not included. Fuel categories will be discussed further in chapter 3.3.

The provisional political agreement is now subject to formal approval by the Parliament and the Council. Once formally adopted the new legislation will be published and enter into force with immediate effect. These blending mandates will significantly increase the European SAF demand (both biogenic and non-biogenic) towards 2050, and this decision is essential to reduce uncertainty for fuel production projects. Norway is expected to follow up with blending mandates in line with the EU.

Table 3-2: ReFuelEU Aviation proposal, amendments and agreement on definitions of non-biological SAF.[8]

	Original European Commission proposal	European Parliament amendments	Council of the European Union amendments	Agreed definitions (April 2023)
Synthetic aviation fuels	Only drop-in electrofuels qualify	All RFNBOs (e.g. green hydrogen) and renewable electricity	Same as commission	**All RFNBOs (including green hydrogen)** **Not electricity**
Allowing “low-carbon fuels” to count towards the SAF mandates	Not included	Not included	Included	**No**
Allowing RCF to count towards the SAF mandates	Unclear	Unclear	Unclear	**Yes**

3.1.1.2 The Renewable Energy Directive

In the European framework sustainability is defined in the Renewable Energy Directive (RED), first set forth in 2009. The Renewable Energy Directive was revised in 2018 (REDII), but already in 2021, the European Commission proposed another revision to better align with increased climate ambitions. The current timeline for the revision of RED is illustrated in Figure 3-4. On March 30 2023 the European Council, European Parliament and European Commission reached a provisional agreement on the revised REDII, so-called REDIII[9]. This will be submitted to the Committee of Permanent Representatives in the Council and then to the Parliament for approval before it can be formally adopted and enter into force.

[8] https://theicct.org/wp-content/uploads/2022/09/refueleu-definitions-trilogue-sep22.pdf
[9] https://www.consilium.europa.eu/en/press/press-releases/2023/03/30/council-and-parliament-reach-provisional-deal-on-renewable-energy-directive/

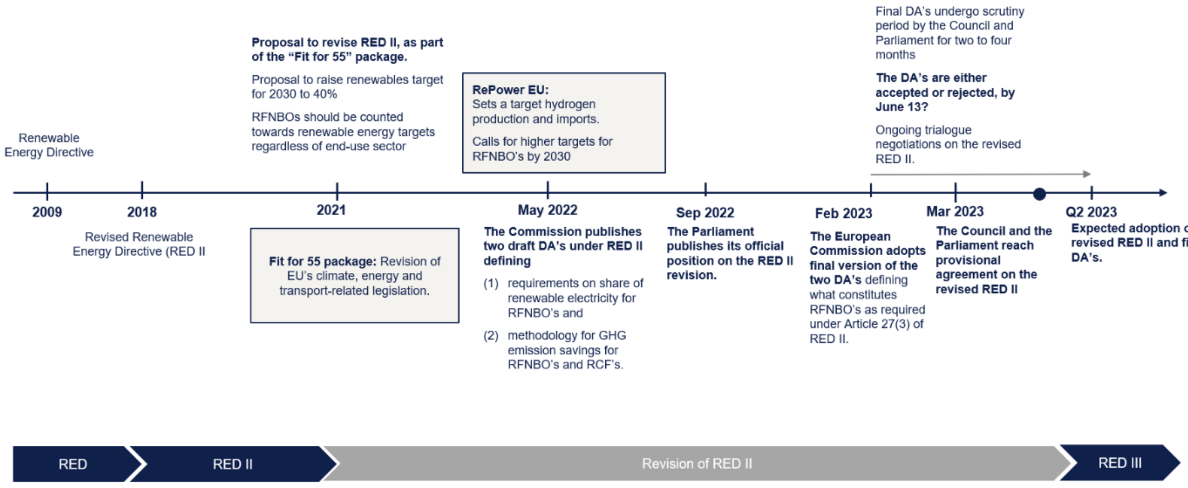

Figure 3-4: Timeline for the Renewable Energy Directive (RED II)

The provisional agreement raised the share of renewable energy in EU's overall energy consumption to 42.5% in 2030 (with an additional 2.5% indicative top up). For the transport sector, the member states can choose between:

- a binding target of 14.5% reduction of greenhouse gas intensity in transport from the use of renewables by 2030
- or a binding share of at least 29% of renewables within the final consumption of energy in the transport sector by 2030

In addition, there is a binding sub-target of 5.5% advanced biofuels and RFNBOs, with a minimum requirement of 1% RFNBOs. This was significantly lower than the European Parliament's proposal of 5.7% RFNBOs in transport. There are no overall EU targets for the use of RCF.

We refer to REDII in this report, but in the future, after the final approval and adoption of the revision this will probably be referred to as REDIII.

REDII defines a series of sustainability and GHG emission criteria for renewable transport fuels. For RFNBOs the criteria is 70% emission reduction compared to fossil fuels[10]. Definitions and criteria for fuel categories are summarised in chapter 3.3.

For RFNBOs and RCFs, Article 27 and 28 of REDII are important. The European Commission last spring published two draft Delegated Acts (DAs)[11] on these articles, and initiated a hearing round which received numerous feedback statements. These DAs present a methodology for determining the GHG savings of RCFs and RFNBOs and criteria for them being considered "sustainable". In February 2023, the European Commission adopted the two DAs and they were submitted to the European Parliament and the Council for approval. The scrutiny period of the DAs is four months where the European Parliament and the Council will have to accept or object the Commission's proposal.[12] The DAs on Article 27 and 28 are strongly connected to the ambitions of ReFuelEU, as they specify how fuels shall be produced to be credited towards the blending mandates. Below is an overview of how the DAs for Article 27 and 28 will impact the RFNBO and RCF market:[13]

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[10] https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

[11] Delegated acts are non-legislative acts adopted by the European commission that serve to amend or supplement the non-essential elements of the legislation

[12] https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_595

[13] Delegated Acts on Art. 27 and 28 explained: How they will shape the PtX market ramp up - PtX Hub (ptx-hub.org)

- The DA on Article 27[14] sets the requirements for renewable electricity used to produce renewable transport fuels. A RFNBO facility can source electricity either through a direct connection to renewable electricity generation, or through the grid. For grid-connected production of RFNBOs, the production can either be located in a bidding zone with more than 90% renewable electricity share or there are specific requirements to additionality, temporal correlation and geographical correlation to fulfil the REDII-criteria.
- The DA on Article 28[15] sets the requirements to the methodology to assess greenhouse gas emission savings from RFNBO and RCF (Article 1), but it also defines the threshold for GHG emissions savings from the use of RCFs at 70% (Article 2), i.e. the same as for RFNBOs. The methodology for assessing GHG emissions savings from RFNBOs and RCFs is based on the emissions from use of fuel, which further is based on the emissions from the supply of inputs, the processing, the transport and distribution, the combusting and potential savings from CCS. It further specifies what types of CO_2 can be considered as “avoided” and be subtracted from the emission calculations (see chapter 3.3.2 for details).

3.1.1.3 Directive on deployment of alternative fuels infrastructure

The EU also has a directive on deployment of alternative fuels infrastructure, but in relation to aviation this is mainly targets for electric charging for stationary aircraft at airports.[16]

3.2 Other environmental and emissions regulation

There are varying definitions of what is sustainable when it comes to aviation fuels. This is especially evident when comparing EU regulations with regulations in other regions, mainly because there are contradictions towards the use of biomass as a feedstock. Two examples for this are that US regulations opens for the use of wheat, and Thailand regulations opens for the use of palm oil. The contradictions in international proposed SAF regulations make it difficult for airlines to make investments and/or carbon reduction strategies, and in turn this also affect the producers. At the moment, this is mostly evident for SAF based on biological feedstock, but similar challenges may occur also for SAF based on non-biological feedstock. The International Civil Aviation Organization (ICAO) is one of the actors that could facilitate common international regulation, and have partly succeeded through the CORSIA, further described below.

ICAO CORSIA

ICAO has through the market-based mechanism, “Carbon Offsetting and Reduction Scheme for International Aviation” (CORSIA), provided high level and general definitions and guiding values for climate effect. For a SAF to be eligible for use within the ICAO CORSIA offsetting-mechanism, it has to meet a set of sustainability criteria. Several of the criteria are related to SAF produced from bio-sources, but there are also criteria that affect non-biological SAF. The criterion related to emissions is:

- Criteria 1.1: SAF (as per the CORSIA definition) will achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis (applicable before 2024)

In addition, there are criteria related to Carbon stock, Water, Soil, Air, Conservation, Waste and Chemicals, Human and labour rights, Land use rights and land use, Water use rights, Local and social development and Food security.

Some of the conversion processes already have CORSIA default Life Cycle Emission values.[17]

U.S Sustainable Skies Act and the Aviation Climate Action Plan

[14] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1087_1_EN_ACT_part1_v8.pdf
[15] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1086_1_EN_ACT_part1_v5.pdf
[16] https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698795/EPRS_BRI(2021)698795_EN.pdf
[17] ICAO 2022 Environmental report https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022.pdf)

The Sustainable Skies Act was introduced to the House of Representatives in May 2021 and to the Senate in June 2021. The Sustainable Skies Act is a bill that "allows a business-related tax credit through 2030 for each gallon of sustainable aviation fuel used by a taxpayer in the production of a qualified mixture (i.e., a mixture of sustainable aviation fuel and kerosene that is sold for use in certain U.S. aircraft)."[18] The bill is targeted for blenders that supply sustainable aviation fuel.[19] The timeline of the adoption of the bill is unknown.

The bill defines sustainable aviation fuel as *"liquid fuel that consists of synthesized hydrocarbons, meets certain recognized international standards, is derived from biomass, waste streams, renewable energy sources, or gaseous carbon oxides, is not derived from palm fatty acid distillates, and achieves at least a 50% life cycle greenhouse gas emissions reduction in comparison with petroleum-based jet fuel."* Further, the legislation requires eligible SAF to utilize the full set of ICAO sustainability criteria as one of the safeguard provisions to ensure its environmental integrity.

In a statement from September 2021, the Biden administration also shared a new Sustainable Aviation Fuel Grand Challenge to increase the production of sustainable aviation fuels to at least 3 billion gallons per year by 2030 and announced new and ongoing funding opportunities to support sustainable aviation fuel projects and fuel producers totaling up to USD 4.3 billion.[20]

In the statement, the US Aviation Climate Action Plan was announced, which was published in November 2021. The action plan follows the goal of net-zero GHG emissions from the U.S Aviation Sector by 2025, and sustainable aviation fuel is one of the key topics. The plan proposes actions to reduce the cost of SAF, enhance the sustainability of SAF and expand supply and end use of SAF on a high level.[21]

The U.S. Inflation Reduction Act of 2022 (IRA)

In the United States' plan to reduce high inflation, a new set of tax credits for sustainable aviation fuel were defined. The inflation act lays down a two-phased plan to incentivize the production and use of SAF, but following the specifications of the plan the SAF should be based on biomass material and is only required to have GHG emissions savings of 50%. The focus on biomass for production of SAF is contradictory to the general development in the UK and EU, where in general the focus is shifting towards production that is not based on biological feedstock.

However, the IRA includes a range of hydrogen support mechanisms, such as the hydrogen production tax credit (PTC), which supports clean hydrogen production with credits ($/kg) increasing with GHG reductions relative to grey hydrogen[22]. Carbon capture and storage is also heavily supported under the IRA.[23]

UK initiatives to stimulate supply and proposed SAF mandate

The UK launched a "Transport decarbonisation plan" in July 2021 that sets the approach to reach the goals of net-zero aviation emissions by 2050 and domestic aviation net-zero emissions by 2040. In the plan, the SAF industry competition, "Green Fuels, Green Skies", is also mentioned as one of the steps to accelerate the production and use of SAF in the UK. The plan further specifies that the UK will mandate the supply or use of SAF by 2025.[24]

In July 2021, the UK Department for Transport ran a consultation with industry actors that lead to a definition of a mandate for the use of SAF in the UK. The consultation concluded that the UK Government will introduce a SAF mandate equivalent to at least 10% (around 1.5 billion litres) of jet fuel to be made from sustainable sources by 2030.[25]

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18 https://www.congress.gov/bill/117th-congress/house-bill/3440/text

19 https://schneider.house.gov/media/press-releases/schneider-introduces-bill-decarbonize-aviation-fulfill-climate-commitments

20 https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

21 https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

22 https://www.nrdc.org/experts/rachel-fakhry/ira-hydrogen-incentives-climate-hit-or-miss-tbd

23 https://www.globalccsinstitute.com/news-media/latest-news/ira2022/

24 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009448/decarbonising-transport-a-better-greener-britain.pdf

25 https://www.gov.uk/government/consultations/mandating-the-use-of-sustainable-aviation-fuels-in-the-uk

The consultation further specifies that the mandate should be operated as a GHG emissions reduction scheme with tradeable certificates and that the mandate will apply to jet fuel suppliers and will begin in 2025.

The UK mandate defines eligible fuels to be waste-derived biofuels, recycled carbon fuels (based on unrecyclable plastic and waste industrial gases) and power to liquid fuels. The GHG emissions savings requirement is 50% relative to fossil jet fuel. Further, the mandate specifies that SAF derived from hydro-processed esters and fatty acids will be capped and a PtL sub-target will be introduced to “encourage the development of strategically important SAF12110 pathways”.

The UK government also has an updated draft legislation for “The Renewable Transport Fuel Obligations” which regulates the renewable fuels used for transport by requiring suppliers of transport fuel to be able to show that a percentage of the fuel they supply comes from renewable and sustainable sources. The legislation is set to affect suppliers with supply above 450 000 litres a year, and the aviation sector is also included. The legislation includes a range of fuels, divided into obligations for development fuels and main obligations, as illustrated below.[26] The RTFO defines a range of feedstocks eligible for use, containing both biological and non-biological types.[27] The development fuel target is related to fuels that are produced through production pathways that are not technically or commercially mature today.

Obligation period (1 Jan – 31 Dec)	Main obligation	Development fuel target	Total obligation
2021	10.679%	0.556%	11.235%
2022	12.599%	0.908%	13.507%
2023	13.078%	1.142%	14.220%
2024	13.563 %	1.379%	14.942%
2025	14.054%	1.619%	15.673%
2026	14.552%	1.863%	16.415%
2027	15.056%	2.109%	17.165%
2028	15.566%	2.358%	17.924%
2029	16.083%	2.611%	18.694%
2030	16.607%	2.867%	19.474%
2031	17.138%	3.127%	20.265%
2032 onwards	17.676%	3.390%	21.066%

Table 2 The obligation trajectory. These percentages are converted to quantities by multiplying them by the obligated amount. The percentages for the 2021 obligation year are provided for information.

Figure 3-5: RTFO obligations for suppliers.

3.3 Definitions and fuel categories

It is important to understand how different fuels are categorized and fit with regulation and SAF mandates. Even after the DAs with the fuel definitions have been adopted, some of the formulations are still vague and unclear. In the “SAF-sphere” terms like “biofuel”, “e-fuel” and “synfuel” are often used interchangeably, and it can be confusing to understand what types of feedstocks and processes are included when the terms are discussed in reports and regulations. In this chapter we define what is meant by the different fuel terms in this report, which is based on the newly adopted EU regulation. Categorizing the different fuels is often complex because they can be based on sources that are a combination of fossil, renewable, biological, and/or non-biological. Section 3.4 highlights this topic and shows an overview of how combinations of different feedstock fit with current EU regulation.

[26] https://www.legislation.gov.uk/uksi/2021/1420/pdfs/uksiod_20211420_en.pdf

[27] https://www.gov.uk/government/publications/renewable-transport-fuel-obligation-rtfo-feedstock-materials-used-for-creating-renewable-fuels/rtfo-list-of-feedstocks-including-wastes-and-residues

3.3.1 Sustainable aviation fuel (SAF)

There is currently no clear international definition of what is considered "sustainable" aviation fuel, but the regulatory bodies are working on establishing definitions and sustainability criteria. In general, SAF is aviation fuel with lower emissions from production and combustion than ordinary fossil-based aviation fuel, and fulfils various sustainability criteria. Consequently, this means that "SAF" includes lower emission fuels with several types and variations of:

1) Chemical compounds
2) Production processes
3) Feedstocks and energy inputs

In the recently agreed ReFuelEU Aviation regulation, SAF is defined as drop-in fuels that are either synthetic or biofuels (see Table 3-2 from the ReFuelEU trialogue negotiations), that fulfils GHG emission reduction criteria from REDIII.

3.3.2 Synthetic fuels

General definition of synthetic fuels:

While fossil fuels are hydrocarbon chains formed naturally underground over millions of years, synthetic fuels are produced by mimicking these processes[28]. Synthetic fuels can be made through various production pathways, which will be presented later in this report. Feedstock can typically be natural gas, coal, biomass or waste, but also CO_2 from industrial flue gases or direct air capture, combined with hydrogen. As such, synthetic fuels can be either fossil, renewable or a combination. Sustainability criteria must be met for a synthetic fuel to be classified as SAF.

EU definition of synthetic aviation fuels:

EU regulation uses a narrower definition of synthetic aviation fuel and uses the term to formulate sub-mandates for SAF. Here, fossil and bio-based fuels are not included in the definition of synthetic fuels. In the original proposal from the European Commission, only "electrofuels" qualified as synthetic aviation fuels, while the negotiations with the European Parliament and Council of the EU resulted in the definition expanding to include all RFNBOs, which also include green hydrogen.

The scope of this report includes RFNBOs, RCFs and low-carbon fuels, which are defined below:

- **RFNBO** – **Renewable fuels of non-biological origin**: Renewable fuels of non-biological origin means *liquid or gaseous fuels, other than biofuels or biogas, which are used in the transport sector, the energy content of which is derived from renewable sources other than biomass* (RED II definition[29]). This means it can be pure hydrogen, ammonia, hydrocarbon gases or liquids. The draft delegated act specifies this further: *As a principle, liquid and gaseous fuels of non-biological origin are considered renewable when the hydrogen component is produced in an electrolyser that uses renewable electricity[30].* Since RFNBOs are based on renewable electricity they are often referred to as **E-fuels, electrofuels, Power-to-X (PtX), Power-to-Liquid (PtL)**, but the benefit of using the RFNBO-definition is that this is in the process of being well defined by EU, which is not necessarily the case for the other fuel names used.
    - **Criteria to be classified as RFNBO:** 70% emission reduction compared to a fossil fuel comparator, which implies a maximum emission of RFNBO = 28.2 g CO_2eq/MJ (REDII).
- **RCF – Recycled Carbon Fuels:** *Liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery* in accordance with Article 4 of Directive

[28] https://synhelion.com/news/synthetic-fuels-explained
[29] https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_595
[30] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=PI_COM:Ares(2022)3836651

2008/98/EC[31] *or from waste processing gas and exhaust gas of non-renewable origin (which are produced as an unavoidable and unintentional consequence of the production process in industrial installations).* The key difference between RFNBO and RCF is that the energy in RFNBOs comes from renewable electricity, while the energy in RCFs comes from fossil waste streams.

The latter regarding energy in RCFs is not explicitly stated in the regulation, and clarifications on this was requested in the hearing round of the Delegated Act, but DNV's interpretation is that only using CO_2 (not containing energy) from industrial processes will not qualify as an RCF. DNV's interpretation is emphasized by the methodology for mixed fuel output being based on the relevant *energy input* qualifying as a RCF source. A statement from ART Fuels forum confirms this. With the current formulation DNV's interpretation is that fuels produced from blue hydrogen does not qualify as RCF since the energy comes from blue hydrogen and not fossil waste streams. If regulation does not require the energy to come from the fossil carbon source, waste incineration will nevertheless not fall under the category of "production process in industrial installations".

- o **Criteria to be classified as RCF:** 70% emission reduction compared to a fossil fuel comparator, which implies a maximum emission of RFNBO = 28.2 g CO_2eq/MJ (REDII Delegated Act, Article 28).

- **Low-carbon fuels:** REDII and the associated DAs do not mention so-called "low-carbon fuels". In ReFUelEU Aviation negotiations The Council of the European Union wanted low-carbon fuels to count towards the SAF targets (see Table 3-2). They described low-carbon fuels as "SAF produced from blue hydrogen and a Fischer-Tropsch process to produce aviation fuel". The Council's proposal states that low-carbon SAF would also need to meet a 70% GHG reduction requirement. **The final agreement within the ReFuelEU does not allow low-carbon fuels to count towards the SAF targets.**

The Delegated Act on Article 28 in REDII sets the requirements to the methodology to assess greenhouse gas emission savings from RFNBO and RCF. Key formulations to understand are what types of emissions can be considered as "avoided", i.e. what CO_2 sources does not have to be included in the emission calculations and can be used to produce an RFNBO. Important formulations in the draft delegated act on Article 28 related to GHG emission calculates are ((details are found in the annex of the DA[32]):

- *Emissions from existing use or fate include all emissions in the existing use or fate of the input that are avoided when the input is used for fuel production. These emissions shall include the CO_2 equivalent of the carbon incorporated in the chemical composition of the fuel that was or would have otherwise been emitted as CO_2 into the atmosphere. This includes CO_2 that was captured and incorporated into the fuel provided that at least one of the following conditions is fulfilled:*

  a) The CO_2 has been captured from an activity listed under Annex I of Directive 2003/87/EC and has been taken into account upstream in an effective carbon pricing system and is incorporated in the chemical composition of the fuel before 2036. This date shall be extended to 2041 in other cases than CO2 stemming from the combustion of fuels for electricity generation; or

  (b) The CO_2 has been captured from the air, or;

  (c) The captured CO_2 stems from the production or the combustion of biofuels, bioliquids or biomass fuels complying with the sustainability and greenhouse gas saving criteria and the CO_2 capture did not receive credits for emission savings from CO_2 capture and replacement, set out in Annex V and VI of Directive (EU) 2018/2001, or;

[31] Article 4 of Directive 2008/98/EC presents a waste hierarchy as a priority order in waste prevention and management legislation. It is not clear on what types of waste are "not suitable for material recovery". An additional element to the definition of RCF is that the emissions from compensating the current use of the carbon source must be accounted for in the emission calculation, e.g. the CO_2 footprint to compensate for produced electricity/heat from waste incineration.

[32] https://energy.ec.europa.eu/system/files/2023-02/C_2023_1086_1_EN_annexe_acte_autonome_part1_v4.pdf

(d) The captured CO2 stems from the combustion of renewable liquid and gaseous transport fuels of non-biological origin or recycled carbon fuels complying with the greenhouse gas saving criteria, set out in Article 25(2) and Article 28(5) of Directive (EU) 2018/2001 and this Regulation; or

(e) The captured CO_2 stems from a geological source of CO_2 and the CO_2 was previously released naturally;

- The above text means that at least one of the conditions above must be fulfilled for CO_2 emissions to be considered as avoided. To reach the 70% emission reduction criteria, most of the CO_2 emissions must be considered as "avoided". Annex I of Directive 2003/87/EC, referred to in (a), lists activities that are included in the EU ETS. CO_2 from activities that are not on this list (such as incineration of MSW or hazardous waste) can not be considered as avoided, not even before 2036/2041. For CO_2 from activities that are listed under Annex I of Directive 2003/87/EC, the DA states that the origin of carbon used for the production of RFNBOs or RCFs is not relevant in the short or medium term as there are abundant sources for carbon, but in the long term, namely from 2041 (or 2036 if from electricity generation), capturing of emissions from non-sustainable sources should not be considered as avoiding emissions.

  This means that, based on DNV's interpretation of current regulation, before 2041 (or 2036 if from electricity generation) fossil CO_2 can be considered as avoiding emissions if the activity is in the EU ETS (or is listed in Annex I and is in another carbon pricing scheme). From 2041 (or 2036 if from electricity generation), the CO_2 must be biogenic, geological and naturally released, come from direct air capture, or from the combustion of RFNBOs or RCFs, to be considered as avoided.

- An additional important element for RCF is also emissions from compensate of current use of source (eg. CO_2 footprint to compensate for produced electricity/heat from waste incineration).

- As mentioned above, it is complex to place fuels in different categories, as they are often based on a mixture of sources, and the definitions of how to qualify as a fuel are still unclear. A fuel can be based on a combination of carbon and hydrogen from various sources, and can then be a combination of fossil, RFNBO, RCF and biofuel. It is important that criteria and guidelines for calculations of emissions and other environmental requirements are well defined in the regulations. The delegated act explains how to calculate the shares of different fuels based on a mix of inputs, i.e. that the share is determined by the energy content of the inputs:

  "3. If the output of a process does not fully qualify as liquid and gaseous transport fuels of non-biological origin or recycled carbon fuel, their respective shares in the total output shall be determined as follows:

  "(a) the fraction of renewable liquid and gaseous transport fuels of non-biological origin shall be determined by dividing the relevant renewable energy input into the process by the total relevant energy inputs into the process

  (b) the fraction of recycled carbon fuel shall be determined by dividing the relevant energy input qualifying as a source for the production of recycled carbon fuels into the process by the total relevant energy inputs into the process."

  The relevant energy for material inputs is the lower heating value of the material input that enters into the molecular structure of the fuel.

  For electricity inputs that are used to enhance the heating value of the fuel or intermediate products the relevant energy is the energy of the electricity."

  In the section below, we describe different hydrogen and carbon pathways, and how we believe selected combinations of these will fall under fuel categories.

- If a process produces a mix of RFNBOs, RCFs and other fuels with the same physical characteristics, all (fuels) should be considering having the same GHG intensity.

3.4 Classification of fuels from different feedstocks

The climate effect of synthetic fuels depends on the origin of the carbon, hydrogen and energy that is used in the production process. The hydrogen and carbon can come from many different sources. We have listed some of the most relevant carbon and hydrogen pathways below. As mentioned above, it can be complex to classify a fuel, as it can be based on a combination of carbon and hydrogen from various sources, and can be a combination of fossil, RFNBO, RCF and biofuel.

Carbon pathways:

- Carbon monoxide (CO) from gasification of biomass or waste (fossil and biogenic)
- Industrial processes where CO_2 is the by-product and used in the industry (e.g. ammonia, urea and fertilizer process)
- CO_2 captured from industrial processes, typically flue gases (e.g. steel, cement)
- Direct air capture (DAC): CO_2 captured from atmospheric air
- Biogenic CO_2 captured from biogenic waste gases
- From gasification of biomass or waste
- Natural occurring CO_2 from ground reservoirs or volcanic activity

The carbon sources have either no energy content, or varying hydrogen and/or energy content (the greater the hydrogen-to-carbon ratio of a hydrocarbon, the greater the energy content). The carbon-containing feedstocks, such as waste, need various amounts of hydrogen dependent on its initial hydrogen and energy content including oxygen, and the purpose of the final fuel product. This ranges from gasification of biomass or waste requiring some extra hydrogen, to CO_2 where all the energy must come from hydrogen added in the process. Some processes are balanced and optimized with both additional hydrogen and CO/CO_2. The different hydrogen pathways are listed below:

Hydrogen-pathways:

- Renewable “green” hydrogen: electrolysis of water using renewable electricity, or thermolysis with electricity and steam
- Low-carbon “blue” fossil based hydrogen: separation of natural gas with CCU and/or CCUS. When using blue hydrogen in hydrocarbon fuel production, hydrogen is split from the fossil carbon and then combined with a more sustainable carbon instead. In this way the fossil CO_2 can be stored and replaced by recycled CO_2 to create a low carbon fuel
- Grid connected “yellow” hydrogen, purple/pink/red from nuclear, green from biomass and -gas, natural “white” hydrogen or a by-product from chlor-alkali processes, pyrolysis “turquoise” from natural gas with black carbon as main product
- Hydrogen produced from gasification of coal or reforming of natural gas without CO_2 capture (grey hydrogen) are the conventional hydrogen production methods today. Depending on the amount of hydrogen needed, this would be a significant contributor to GHG footprint, challenging the possibility to reach the 70% GHG reduction criteria

As mentioned, the categorization is not straightforward. For example, combining CO_2 from industrial waste gases with green hydrogen can give an RFNBO, but also an RCF if part of the energy content is from fossil resources. In comparison, an RFNBO shall not have energy content from biomass or fossil resources, only renewable power. Furthermore, the proposed change in GHG emission counting of fossil CO_2 before and after 2041 (or 2036 if from electricity generation) (see section 3.1.1.2) can make a fuel count as an RFNBO before 2041 (or 2036 if from electricity generation), but fall out of this category after that to become a fossil fuel.

The Department for Transport in the UK has published a Renewable Transport Fuel Obligation (RTFO) Compliance Guidance with the decision tree in Figure 3-6, while for EU and other regions these guidelines are currently not made yet.

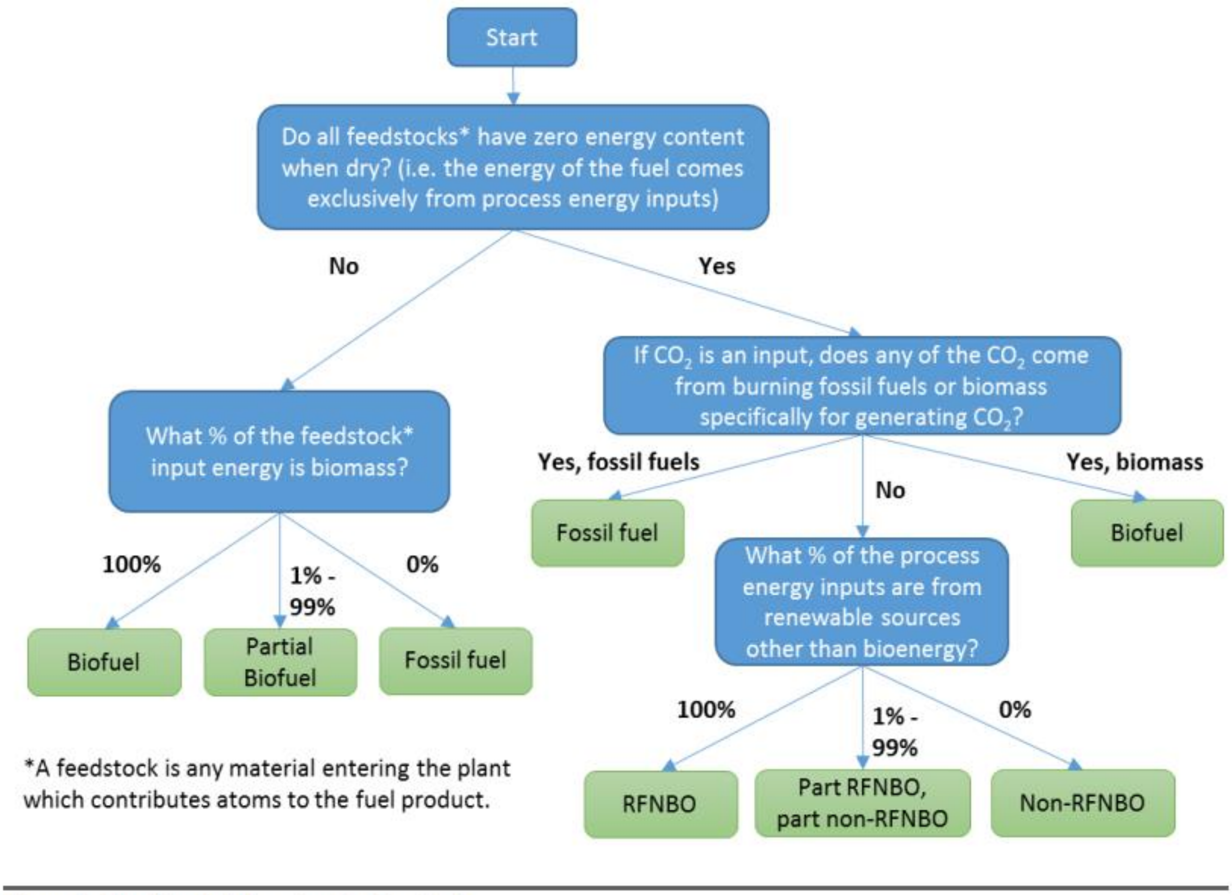

Figure 1 Classifying fuels based on their feedstock

Figure 3-6 Classification of fuels based on feedstock (UK)[33]

The fuel classification process can be divided into two steps:

1. **Do the inputs qualify towards the criteria defined for RFNBO or RCF?**

   RFNBO: Does the energy come from green electricity/hydrogen?

[33] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1042787/renewable-transport-fuel-obligation-compliance-guidance.pdf

RCF: Does the energy come from non-recyclable waste streams or waste gases as defined in the delegated act?

2. **Does the fuel meet the 70% emission reduction target?**

This is where the origin of the fossil CO_2 is important – as it determines whether the emissions can be considered as "avoided" or not.

To summarise the key points based on the latest regulation:

- The hydrogen in RFNBO must be renewable (green). Criteria for renewable hydrogen are defined in the delegated acts..
- The energy source in RCF must be non-renewable waste streams or industrial waste gasses
- Using energy from renewable/biological industrial waste gases will give a biofuel (counts towards SAF targets if GHG emission reduction and sustainability criteria are fulfilled)
- To qualify as either RFNBO or RCF the GHG emission reduction must be 70% compared to a fossil alternative.
- If CO_2 in RFNBO production is from an activity in EU ETS (or is listed in Annex I **and** is in another effective carbon pricing scheme), these emissions are not included in the emission calculation of the fuel before 2041 (or 2036 if from electricity generation). After this, carbon from non-sustainable sources is included in the emission calculation. Emissions costs and accounting will be clarified in different regulatory schemes.
- Blue hydrogen and CO_2 give a low-carbon fuel. The recent ReFuelEU agreement does not include low-carbon fuels in the SAF blending mandates. It is not clear from regulation why a fuel based on blue hydrogen + CO_2 that meets the GHG reduction requirement should not be included in the mandates in line with RFNBOs.

Table 3-3 lists examples of combinations of different feedstocks, and how DNV understands this fit with current EU regulation and fuel definitions (RFNBO before and from 2041 and RCF). While low-carbon fuel now is not considered SAF in the EU, it can be accepted as SAF in other countries and is therefore included in the table.

Cells marked in green are considered as likely, red cells red are considered as unlikely (feedstock qualify, but unlikely to reach GHG reduction target). This is based on DNV's understanding of the categories and emissions reduction potential of the processes. DNV notes that for CO_2 stemming from the combustion of fuels for electricity generation, the time limit is 2036 instead of 2041.

Table 3-3 Mapping of feedstocks sources and fuel categories (current interpretation)

Carbon source	EU ETS due for carbon source (draft interpretation)	(additional) energy/ hydrogen source	RFNBO before 2041*	RFNBO from 2041*	RCF	Low-carbon fuel
Fossil material (coal, oil, natural gas)	**Yes**	None or renewable or low emission hydrogen	No	No	No	No
Solid or liquid mixed carbon waste (renewable + fossil)	**Yes (fossil part)**	None	No	No	Share of fuel equal to fossil energy input, if: 70% GHG reduction, including CO_2 footprint from alternative use in energy production in the source country	
Solid or liquid mixed carbon waste (renewable + fossil)	**Yes (fossil part)**	Renewable hydrogen	Share of fuel equal to energy input share from H2, if 70% GHG reduction including CO_2 footprint from alternative use in energy production in the source country	Share of fuel equal to energy input share from H2, if 70% GHG reduction including CO_2 footprint from alternative use in energy production in the source country	Share of fuel equal to fossil energy input share, if: 70% GHG reduction, including CO_2 footprint from alternative use in energy production in the source country	No
		Low-carbon hydrogen	No	No	Share of fuel equal to fossil energy input, if: 70% GHG reduction, including CO_2 footprint from alternative use in energy production in the source country	Share of fuel equal to energy input share from H2, if: 70% GHG reduction, including CO_2 footprint from alternative use in energy production in the source country
CO_2 in flue gas from processing of fossil feedstocks where purpose is industrial manufacturing	**Yes**	Renewable hydrogen	If: 70% GHG reduction excluding the flue gas emissions	If: 70% GHG reduction including the flue gas emissions	No (but not 100% clear from regulation). DNV's interpretation is that RCFs require energy from the waste stream, not just CO_2)	No
		Low-carbon hydrogen	No	No	No (but not 100% clear from regulation). DNV's interpretation is that RCFs require energy from the waste stream, not just CO_2)	If: 70% GHG reduction
CO_2 in flue gas from processing of fossil feedstocks where purpose is energy production	**Yes**	Renewable hydrogen	If: 70% GHG reduction excluding the flue gas emissions	If: 70% GHG reduction including flue gas emissions	No	No
		Low-carbon hydrogen	No	No	No	If: 70% GHG reduction
CO_2 in flue gas from processing of mixed feedstock (renewable + fossil)	**Yes (fossil part)**	Renewable hydrogen	If: 70% GHG reduction excluding the flue gas emissions	If: 70% GHG reduction including flue gas emissions	No	No

Carbon source	EU ETS due for carbon source (draft interpretation)	(additional) energy/ hydrogen source	RFNBO before 2041*	RFNBO from 2041*	RCF	Low-carbon fuel
where purpose is energy production	**Yes (fossil part)**	Low-carbon hydrogen	No	No	No	If: 70% GHG reduction
CO_2 in flue gas from incineration of hazardous waste	No	Renewable hydrogen	If: 70% GHG reduction including the flue gas emissions	If: 70% GHG reduction including the flue gas emissions	No	No
		Low-carbon hydrogen	No	No	No	If: 70% GHG reduction
CO_2 in flue gas from incineration of MSW	Before 2026: No From 2026: Maybe	Renewable hydrogen	From 2026 if MSW is included in EU ETS, if 70% GHG reduction excluding the flue gas emissions	From 2026 if 70% GHG reduction including the flue gas emissions	No	No
		Low-carbon hydrogen	No	No	No	If: 70% GHG reduction
Solid or liquid pure biogenic materials or waste	**No**	None	No	No	No	No
CO_2 in flue gas from biogenic processing	**No**	Renewable hydrogen	If: 70% GHG reduction	If: 70% GHG reduction	No	No
	No	Low-carbon hydrogen	No	No	No	If: 70% GHG reduction
CO in flue gas from biogenic processing)	**No**	Renewable hydrogen	No	No	No	No
	No	Low-carbon hydrogen	No	No	No	No
CO_2 from Direct Air Capture (DAC)	**No**	Renewable hydrogen	If: 70% GHG reduction	If: 70% GHG reduction	No	No
	No	Low-carbon hydrogen	No	No	No	If: 70% GHG reduction

**For CO_2 stemming from the combustion of fuels for electricity generation, the time limit is 2036*

Figure 3-7 is a simplified illustration of feedstocks and production processes for the different fuels included in the scope of this report. These are examples of combination of feedstocks resulting in fuels in the different fuel categories. Relevant EU regulation is also highlighted in purple boxes. Note that low-carbon fuels are not considered as sustainable according to the recent ReFuelEU agreement on excluded low-carbon fuels from the blending mandates,

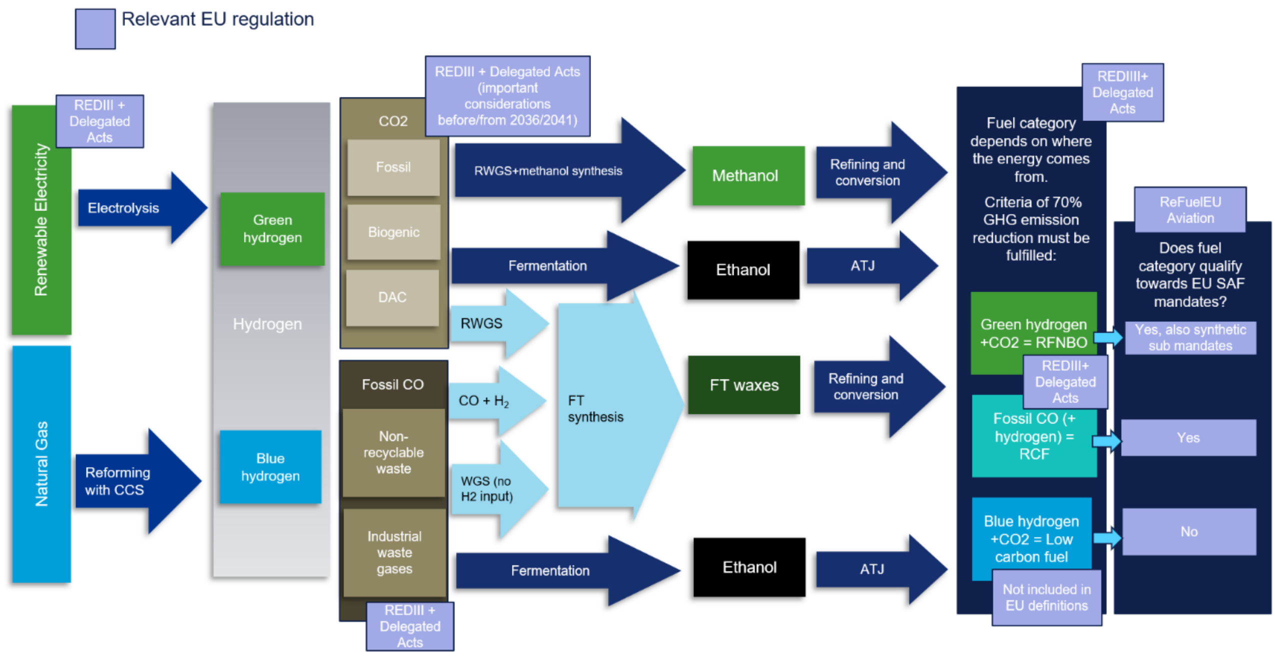

Figure 3-7: Simplified illustration of production processes for non-biological synthetic fuels, including relevant EU regulation.

Figure 3-8 shows an example of how one fuel production process can create a product that can end up being classified as partly RCF, partly RFNBO and partly biofuel. The share of the different end products is based on the share of the energy inputs.

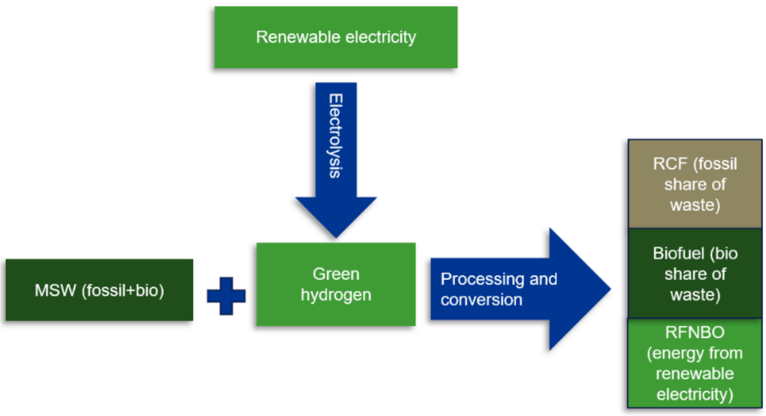

Figure 3-8: Example of a production process giving three different end products

3.5 Testing and certification of aviation fuels (Jet A-1)

ICAO and ASTM regulations

In order for a SAF to be used in commercial flight, it has to comply with ASTM D4054-22, which is the standard practice for evaluation of new fuels and fuel additives, and ASTM D7566[34], which is the standard specification for aviation turbine fuel containing synthesized hydrocarbons.

The International Civil Aviation Organization (ICAO) specifies what conversion processes are approved for SAF production by ASTM International through Annex 16 Vol IV. As of October 2021, seven conversion processes for SAF production have been approved and two co-processing pathways.[35] An important aspect for the approved conversion processes, is that they are based on one or few given feedstocks and a selected process technology. This means that a process that is approved for a certain type of feedstock can not necessarily be used for other types of feedstocks. The qualification of new conversion processes and technologies is time consuming.[36]

UK Civil Aviation Authority (CAA) and Defence Strategic Fuels Authority (DSFA) Def Stan 91-091

The Defence Standard 91-091 specifies the requirements for one grade of kerosene type aviation turbine fuel intended for use in aircraft gas turbine engines. The standard is relevant for aircraft or engines operated by the Crown, or for which the CAA is the certificating agency. The standard refers to ASTM D7566 and its associated Annexes for the requirements for fuels containing synthetic components derived from non-petroleum sources.[37]

34 https://www.astm.org/d7566-22.html

35 Conversion processes (icao.int)

36 Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives (astm.org)

37 http://inaca.or.id/wp-content/uploads/2019/11/Def-Stan-91-091-Issue-11-Oct-2019-Turbine-Fuel-Kerosene-Type-Jet-A-1-NATO-CodeF-35-Joint-Service-Designation-AVTUR.pdf

4 PRODUCTION OF SAF FROM NON-BIOLOGICAL FEEDSTOCKS

This chapter describes the possibilities of producing SAF from non-biological feedstock, including a description of the production processes and pathways, status and plans for production and the corresponding regulatory status related to the utilization of the SAF from these production processes.

4.1 Production pathways and feedstocks

In principle, to produce aviation fuel you need carbon and hydrogen, either as hydrocarbons or in separate molecules, which can come from different sources.

SAF can be produced using several different production processes – and for Jet A-1 there are currently seven production processes or pathways that are approved according to the D7566 ASTM standard[38] to be blended up to 10-50% with conventional aviation fuel, depending on the process. In addition, co-processing in existing refineries is approved up to 5% blending. More processes are under development to be approved. Aircraft and engine manufacturers are currently investigating the effect of increasing the blending limit to 100% for some pathways. This has been tested and industry experts do not expect major hurdles in increasing the blending limits for their newest engines to operate fully on SAF.

Figure 4-1: shows SAF production pathways and certification status. There are mainly two of these pathways that are expected to enable production of RFNBOs and RCFs, that is Alcohol-to-Jet (AtJ) and Fischer-Tropsch (FT). Each SAF-process and plant must use the ASTM D7566 standard to show that they are within the specifications specified in the standard attachments. Another option is to use relevant standards to qualify a new certified route (at fuel readiness level 7), and eventually also demonstrate fuel readiness level 8 and 9.[39]

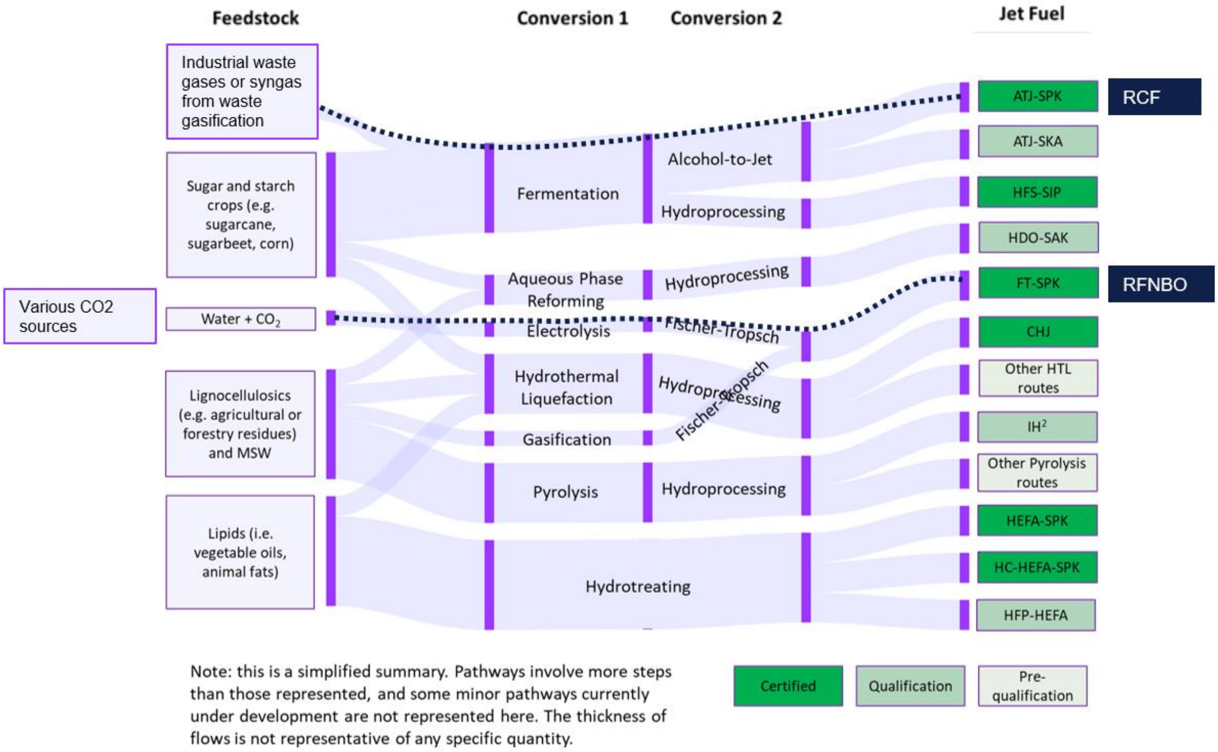

Figure 4-1: SAF production processes and certification status (E4tech, 2020) with DNV adjustments

[38] D7566 ASTM

[39] https://www.caafi.org/information/pdf/FRL_CAAFI_Jan_2010_V16.pdf

All production processes produce a hydrocarbon fuel that can be refined into a mix of different fuels for different purposes. The processes can in many cases have some output flexibility and be adjusted towards producing lighter fractions such as jet fuel, but only up to a certain percentage of the total fuel production volume. Within technical limitations, the share of jet fuel is usually decided by energy prices and offtake agreements with prices, and/or additives which must be added to the SAF to fulfil the specifications in the standard.

Production pathways for RFNBOs, RCFs and low-carbon fuels will be described further in the next sections.

4.2 Production of RFNBO for aviation

As defined in chapter 3, RFNBOs are fuels where all the energy content is from renewable sources of non-biological origin, i.e. from renewable electricity. Figure 4-2: illustrates technology routes to produce RFNBO or e-fuel. Renewable hydrogen and direct use of electricity are also considered as RFNBOs.

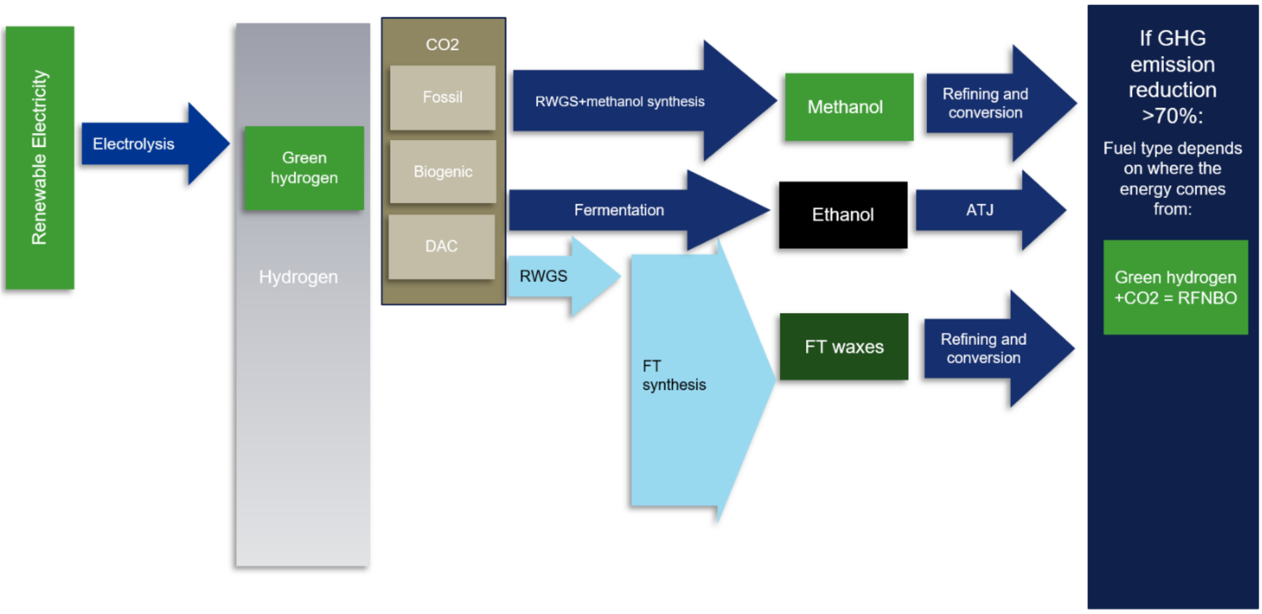

Figure 4-2: Illustration of RFNBO production

CO_2 does not provide any usable energy, all the energy in the fuels must come from hydrogen and the energy to facilitate the reaction between hydrogen and CO_2. While the only hydrogen type relevant for RFNBO production is green hydrogen, current legislation propose that CO_2 can come from any source, such as direct air capture or industrial processes, as long as the fuel's emissions criteria are fulfilled. Proposed EU legislation states that fossil CO_2 (from activities in EU ETS or similar schemes) can be counted as avoiding emissions before 2041 (or from 2036 if from electricity generation), while from 2041 the CO_2 source for RFNBOs is suggested to only include biogenic CO_2, geological CO_2 or direct air capture. It is important that the emission reduction is accounted for only once in the value chain.

Figure 4-3 shows how various e-fuels can be produced from hydrogen and CO_2 through several different production processes. The hydrogen is produced from electrolysis of water using renewable electricity, combined with a CO_2 source to create a syngas, before synthesized and refined to the final fuel product. To produce syngas, hydrogen produced with conventional electrolysis and CO_2 goes through a reverse waster gas shift (RWGS)-reaction, or syngas can be created directly in a co-electrolysis with solid oxide electrolysis cells (SOEC).

E-fuel for aviation (kerosene) can be produced from syngas using different methods:

- Fischer-Tropsch synthesis (PtL FT): Already approved for up to 50% blending with fossil jet fuel
- Via methanol synthesis (currently being tested)
- CO_2 or waste gases fermentation to alcohols with renewable hydrogen, and Alcohol to Jet (qualifying as RFNBO, similar to described for the case at Mongstad where blue hydrogen is used, see part 2 of the report)

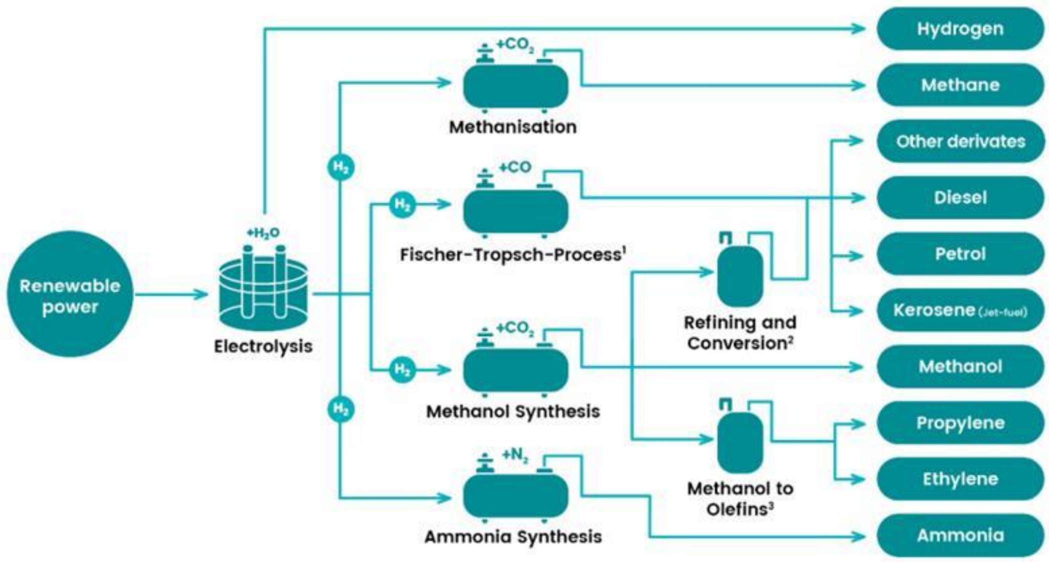

Figure 4-3: Production of various e-fuels. Ethanol and Alcohol to Jet is an alternative route that is not included in the figure.

4.3 Production of RCF for aviation

As defined in chapter 3, *"RCFs are fuels produced from liquid or solid waste streams of non-renewable origin which are not suitable for material recovery or from waste processing gas and exhaust gas of non-renewable origin (which are produced as an unavoidable and unintentional consequence of the production process in industrial installations".* Figure 4-4 illustrates technology routes to produce RCF.

Production and classification of RCFs is not straightforward. Non-renewable waste such as plastics is often mixed with other types of municipal solid waste (MSW). *MSW is highly heterogeneous and can be categorized into a biogenic portion (food waste, greens, woods, paper, and card) and a non-biogenic (fossil-fuel) portion such as plastics, and it is often impossible to fully separate the waste streams*[40]*.* Hence, fuel produced from waste can be partly biofuel, partly RCF and partly fossil fuel.

MSW can be used to produce SAF either through:

- Gasification, which turns the waste or plastic into H_2- and CO-rich syngas. SAF can then be produced from the syngas in a Fischer-Tropsch process.
- Gasification to syngas, fermentation into alcohol and then the Alcohol-to-jet (ATJ) pathway.
- Pyrolysis (with further adequate upgrading processes) could potentially also be used (pyrolysis is done in the absence of oxygen while gasification is done in the presence of controlled/limited amounts of oxygen)

[40] Waypoint2050, *Fuelling Net Zero* (2021)

Furthermore, RCFs can be produced from industrial waste gases, combined with hydrogen and synthesized. As described in 3.3, DNV's interpretation of the current proposed regulation is that the energy in RCFs must come from the waste streams or waste gases.

Plastics and other MSW consists of long hydrocarbon chains. When these are used as feedstock in SAF production, additional hydrogen is needed in the process to get lighter hydrocarbon fractions. It is the origin of the feedstock and energy as well as the overall process emission reduction that determines whether the fuel can be defined as RCF. When green or blue hydrogen is added to the process the end product might end up being partly RCF, partly RFNBO and partly low-carbon fuel. This is important to understand, especially when fuels based on blue hydrogen are not considered sustainable. If blue hydrogen is added to an RCF production process, a share of the end product equal to the hydrogen energy input share is not considered as sustainable fuel (based on DNV's understanding of the regulation).

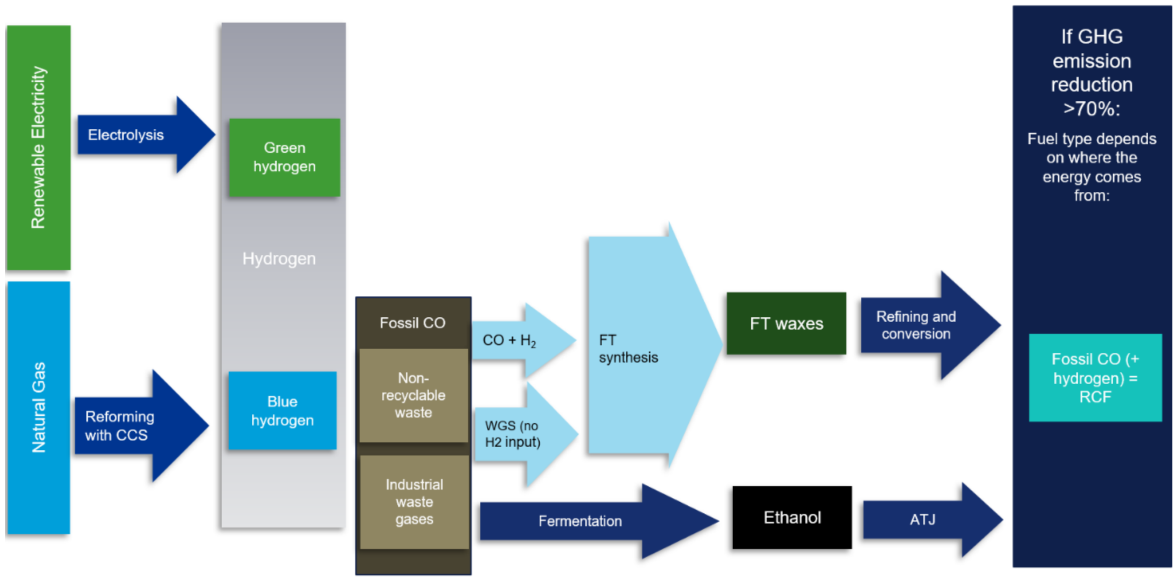

Figure 4-4 Illustration of RCF production

4.4 Production of low-carbon fuel for aviation

Blue hydrogen is often defined as "low-carbon" when below a certain threshold of CO_2 emissions, which means a certain level of carbon capture. For instance, capturing 70 % of CO_2 from natural gas will give about 3 $kgCO_2/kgH_2$, and can be named "low-carbon" in Europe. As described in section 3.3 the Council of the European Union amendments describe low-carbon fuels as produced from blue hydrogen and CO/CO_2 through a Fischer-Tropsch process, and that they must also fulfil the overall 70% GHG emission reduction. Hydrocarbon fuels from blue hydrogen is produced with the same processes as RFNBOs described in Chapter 4.2, except that hydrogen is produced from natural gas with CCS instead of electrolysis. Low-carbon fuels are currently not counted as SAF in the newly agreed blending mandates.

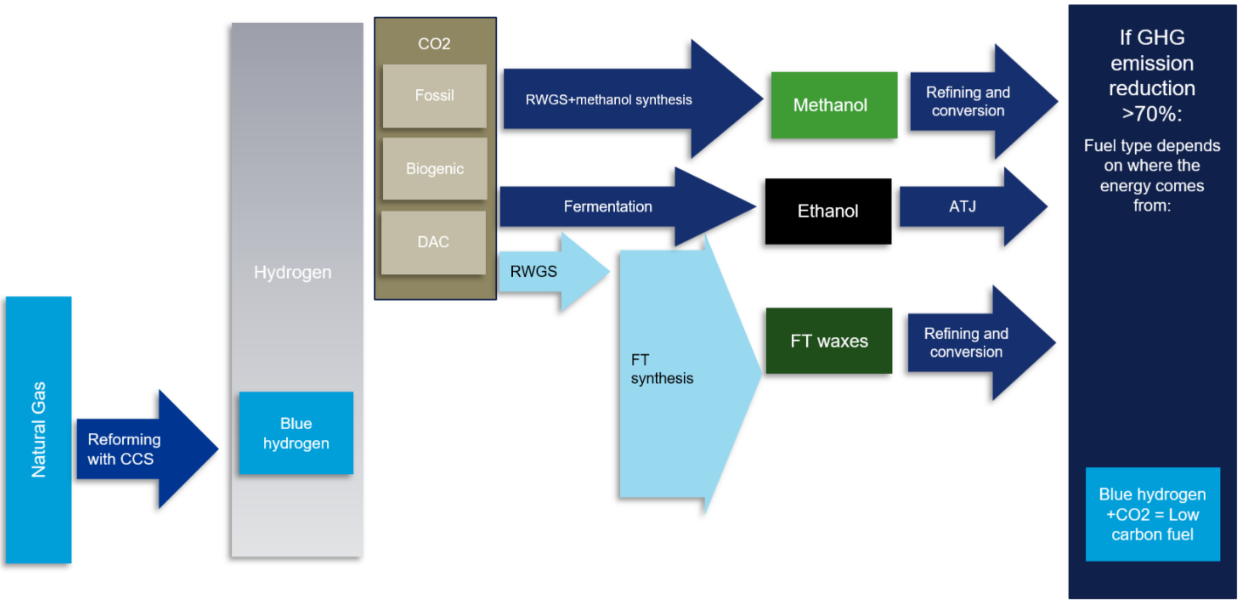

Figure 4-5: Illustration of low-carbon fuel based on blue hydrogen

4.5 Maturity of production processes and feedstocks

A framework for comparing the maturity of the various technologies, processes, and access to feedstocks for fuel is the so-called Technology and Fuel Readiness Level (TRL, FRL). In addition, there is a scale for commercial maturity, the commercial readiness index (CRI), which indicates the extent to which the processes need subsidies and financial support before full commercialization (ARENA, 2014). Different sources indicate different levels of technical and commercial maturity. There are also separate ISO standards that define what is needed to meet a level of maturity.

The Fuel Readiness Level (FRL) scale was developed by CAAFI in collaboration with the Air Force Research Laboratory. It is a fuel development scale allows for parallel fuel research activities and certification activities, and is used by CAAFI to track fuel development and the process of developing, certifying and supplying fuels to commercial aviation. As a result of the FRL, CAAFI developed the Feedstock readiness level (FSRL) tool, for tracking development and availability of the feedstock required to make SAF.

In Figure 4-6:, DNV has placed the different production technologies for RFNBOs and RCFs on an FRL and CRI scale, and the relevant feedstock, i.e. hydrogen, CO_2 and waste, on a FSRL scale.

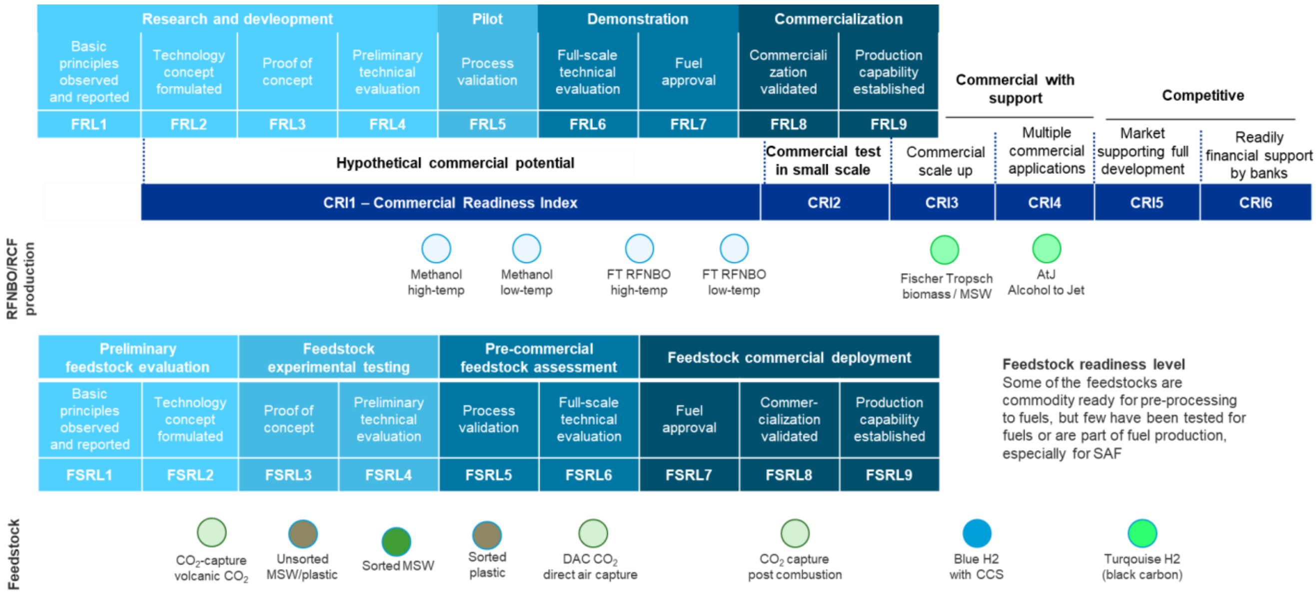

Figure 4-6: Indicative feedstock and fuel readiness for RFNBO and RCF for SAF, including commercial readiness index (DNV team analysis[41])

Figure 4-6: shows that all RFNBO and RCF production processes are below FRL9, while some are at the CRI2 stage. The Fischer-Tropsch technology using MSW is the most mature process included here. E-fuels with renewable inputs generally have a lower readiness level than fossil inputs from established industry. There is increasing activity to test the production of RFNBOs, especially in the automotive industry in Germany.

Partial or full integration is usually named colocation and co-processing. Co-location is defined as a parallel production line for the fuel which blends with full drop-in qualities at the refinery downstream infrastructure. Integration of e-fuel production into existing refineries (co-processing) is being tested, where a complete system integration is at the demonstration stage. Both Fischer-Tropsch and methanol synthesis are high on a TRL scale (TRL 8-9), while Direct Air Capture (DAC) technology is around TRL and FSRL 6-7[42].

Today, pilot volumes of e-fuels are produced from fossil CO_2 side streams, i.e. from fertilizer and methanol production. The first demonstration of using e-fuels in an aircraft was in a KLM flight in February 2021, where a batch of 500 litres e-fuel made of both fossil and biogenic CO_2 and green hydrogen was blended in as 5% of the fuel. This demonstrates that the technology is possible – currently with a limited blending ratio and very small batch volumes. This indicates that e-fuels are at FRL 4-6.

The technology's immaturity and high costs mean that e-fuels are not expected to play a major role until after 2030 without better framework conditions and support. Modelling shows a gradual increase from a few thousand tonnes in 2026 ramping up to expected 570.000 tonnes of e-fuel production in Europe in 2030[43] (DNV H_2 forecast, 2022). This is based on current policies and technology development as of June 2022, and could lead to 4 Mtpa (million tonnes per annum) in 2040 and 6 Mtpa in 2050, see Figure 4-7 below. The potential for improvements in many of the production options lies mainly in the development of fuel cells for electrolysis (especially solid oxide cells) and in developing catalysts for faster and more complete conversion from, for example, syngas to fuel.

41 This overview needs further detailing and a deeper study to quantify the exact levels for each group of feedstocks, as it is also supplier dependent.

42 (LBST – Ludwig-Bölkow-Systemtechnik, 2016) (Schmidt & Weindorf, 2016) (A4E, ACI, ASD, era, canso, 2021).

![DNV logo]

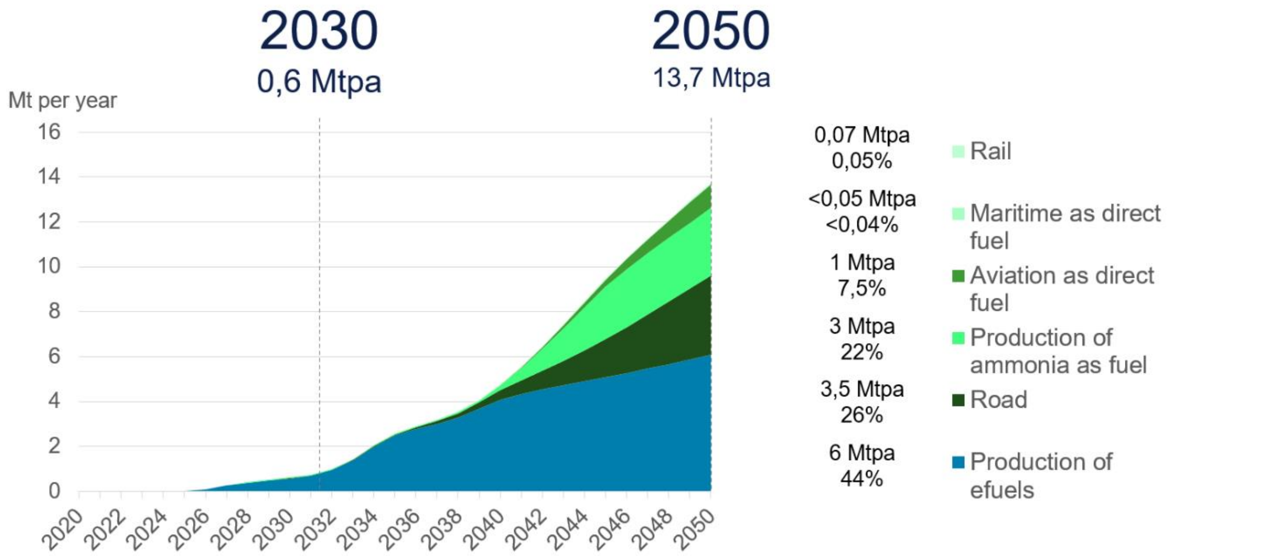

Figure 4-7: Forecast of production of e-fuels and hydrogen for transport in Europe (ETO H_2 forecast, DNV, 2022)

4.6 Status and plans for producing RFNBOs and RCFs internationally

There is currently no industrial scale production of SAF from non-biological resources. Only two SAF pathways (HEFA-SPK and co-processing of vegetable oils in a refinery) have reached commercial technology maturity, but several production projects based on biological resources are scaling up.

Biofuels produced with the HEFA pathway are dominating the SAF market today, but there are an increasing number of initiatives and plans globally for production of SAF from non-biological resources. The map in Figure 4-8 shows that there are 534 large scale hydrogen projects globally, as of May 2022. Many of these projects can be potential e-fuels producers (however in competition with direct uses of hydrogen and ammonia in industry and transport).

Figure 4-8: Global overview of large-scale hydrogen projects (Hydrogen Council, 2022)

Furthermore, several large-scale projects on e-fuels production have been announced globally. The recently updated IEA hydrogen project database lists 26 projects globally for e-fuel production, with a total electric capacity of 17 GW and planned production start dates within the next 10 years. In Europe, several demonstration facilities are expected to be commissioned from 2025. There are also several announced projects on SAF-production from waste – most of them from MSW or biogenic waste, but some are focusing on “hard-to-recycle” waste, such as plastic, that can give RCFs (MSW can also give partly RCF). Table 4-1 lists some planned production projects for SAF from renewable electricity (RFNBOs) or waste (RFCs or biofuel).

Table 4-1: Selected SAF production projects in Europe (from electricity or waste)

Project	Location	Process	Feedstock	Total production volume (mill. Liter)	Planned start-up date	Partners
Norsk E-fuel[44]	Mosjøen Other sites Norway	PtL – FT (SOEC)	Green electricity + CO_2 (industrial and DAC)	50 (phase 1) 100 (full scale)	2026 (phase 1) 2029 (full scale)	Sunfire, Climeworks AG, Paul Wurth SA Valinor, Lux airport
Nordic Electrofuel [45]	Herøya, Other sites Norway	PtL – FT (RWGS)	Green electricity + CO_2 from industry	10 (phase 1) 200 (full scale)	2026 (phase 1) 2029 (full scale)	P2X Europe, Herøya Industrial Park, Eramet, ACT, CO_2 Value Europe, eFuel alliance, Inustrial Green Tech
Green fuels for Denmark[46]	Copenhagen, Denmark	PtL	Green electricity + CO_2	50 000 tonnes	2025	Ørsted, SAS, Copenhagen Airports, A.P. Moller – Maersk, DFDS and DSV
SAS, Vattenfall, Shell, LanzaTech[47]	Sweden	AtJ	Green electricity + CO_2 from district heating	50 000 tonnes	2026/2027	SAS, Vattenfall, Shell, LanzaTech
SkyFuelH2[48]	Sweden	PtL – FT	Green electricity + Biogenic CO_2	N/A	2026	Sasol ecoFT, Uniper
Green Fuels Hamburg[49]	Germany	PtL – FT	Green electricity + biogenic CO_2	10 000 tonnes	2026	Uniper, Airbus, Siemens Energy and Sasol ecoFT
NGO Atmosfair FairFuel[50]	Germany	PtL – FT	Green electricity + Biogenic CO_2 + DAC	350 tonnes	202	Solarbelt gGmbH
Enerkem, Shell, Port of Rotterdam[51]	Netherlands	Gasification + FT	Hard-to recycle waste	80 000 tonnes (up to 75% SAF)	2025/2026	Enerkem, Shell, Port of Rotterdam
Altalto Immingham[52]	UK	Gasification + FT	MSW	60 ML	2027	Velocys/Altalto
Lighthouse Green Fuels[53]	UK	Gasification + FT	Waste + CO_2	180 ML	2027	alfanar

44 https://www.norsk-e-fuel.com/
45 https://nordicelectrofuel.no/what-we-do/#plansandproject

5 DRIVERS AND BARRIERS FOR SAF PRODUCTION FROM NON-BIOLOGICAL FEEDSTOCKS

The main driver for SAF uptake in general is GHG emission reduction compared to fossil aviation fuel (FAF). Compared to other decarbonization alternatives like batteries or hydrogen, the biggest advantage of SAF is that they can be used in existing aircraft, technology and infrastructure (up to a certain blending limit), and the range is the same as existing aircraft. The main disadvantage or barrier for SAF is high production costs compared to conventional FAF and (current) lack of incentives promoting the uptake of SAF.

As SAF from non-biological feedstocks is a relatively new concept, with immature technologies, processes and frameworks, there are several barriers to the establishment of this industry worldwide. Many of these barriers are common and not country-specific, e.g. the barriers related to costs, regulations, standards and technology maturity. Correspondingly, there are also advantages that are general.

Section 5.1 and 5.2 discuss the main disadvantages/barriers and advantages/drivers for non-biological SAF, while section 5.3 focuses on the drivers and barriers for SAF-production specifically in Norway.

5.1 Disadvantages and barriers

High costs, lack of regulation and economical support

Production of non-biological SAF can be more than ten times more costly than conventional fuels. The costs vary for different technologies, production routes and maturity. There is lack of economical support bridging this gap, both upstream and downstream. Without sufficient support mechanism, such as cost of carbon emissions, tax credits, Contracts for Difference (CfD) etc, SAF can not compete with conventional aviation fuel.

Even though the recently agreed EU blending mandates was an important regulatory step there are still unclear aspects, such as how this will be implemented in the EU countries, methodology for LCA/GHG estimates, other environmental impacts, ownership of emissions, guarantee of origin (GoO)-certification and RFNBO certification.. Countries outside of EU lack clear and predictable long term mandates.

Low technology maturity and efficiency

Parts of the production processes still have low technology maturity, such as electrolysers, reverse water gas shift reactor and DAC-technology. In RFNBO production a significant amount of energy is lost in the process and a lot of electricity is required.

High demand for renewable electricity and competition with other electricity consumers

Both electrolysis and direct air capture require a lot of renewable electricity. This requires strong electricity grids and large build outs of wind and solar capacity. Limited availability and surplus of renewable electricity, and establishment of new renewable electricity generation capacity takes time. Areas with electricity deficit need the electricity for other consumption and the possibilities of building out wind and solar generation and grid can be restricted by available areas, government decisions and long approval processes.

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[46] https://orsted.com/en/media/newsroom/news/2022/02/20220204476711
[47] https://group.vattenfall.com/press-and-media/pressreleases/2021/sas-vattenfall-shell-and-lanzatech-to-explore-synthetic-sustainable-aviation-fuel-production
[48] https://www.uniper.energy/sweden/jetfuel
[49] https://www.uniper.energy/news/green-fuels-hamburg-industrial-production-of-sustainable-aviation-fuels-for-climate-neutral-aviation
[50] https://fairfuel.atmosfair.de/wp-content/uploads/2021/10/Short-description_atmosfair_E-Kerosene-plant_EN_092021.pdf
[51] https://www.shell.nl/media/persberichten/media-releases-2021/from-waste-to-chemicals-to-waste-to-jet.html
[52] https://www.wastedive.com/news/waste-jet-sustainable-aviation-fuel-fulcrum-bioenergy-saf/620365/
[53] https://www.greenairnews.com/?p=3277

Limited CO_2 availability

Availability of captured, pure and “ready for use” CO_2 can be limited**.** After 2041 (maybe) only biogenic CO_2 and DAC can be used in RFNBO/RCF production.

RFNBO production require large volumes of water

Both electrolysis and DAC require large volumes of water which has to be demineralized and/or desalinated.

Safety and security

There is lack of standardization and regulation related to safety for hydrogen production facilities. Furthermore, there are unclear national and local procedures for acceptance criteria and documentation of new production facilities.

5.2 Advantages and drivers

Indirect electrification of the aviation industry

RFNBOs is an indirect way of electrifying the aviation industry (with renewable electricity). Furthermore, if waste currently used for electricity or heat generation is replaced with renewable electricity and used for RCF production instead, this is another way to indirectly electrify aviation.

RFNBOs can have the highest climate effect of all SAF

RFNBO value chains may have a theoretical climate effect of 100%, but the most promising are at ~90%. These are based on renewable electricity and CO_2 either from biological sources or DAC.

Do not need the large areas required to grow biomass

Compared to SAF routes based on primary biomass, RFNBOs and RCFs do not need the large areas required to grow biomass, but RFNBOs may require large land areas for wind and solar power, and water for electrolysis (demineralized fresh water or desalinated salt water). Atmospheric CO_2 is “unlimited”, but direct air capture is very energy intensive.

RCFs can utilize unrecyclable waste

Unrecyclable waste and industrial gases can be utilized. RCF can divert waste from landfill or incineration, can give a more effective use of waste, and give GHG emissions savings when used to replace fossil fuel.

RCFs require less electricity than RFNBOs

Finally, an important advantage for RCF production compared to RFNBO is that the electricity demand is lower. While all energy in RFNBO comes from renewable electricity (and there are significant losses in the process), the energy in RCF also comes from the waste or waste gas. However, (renewable) electricity is needed in all the processes in varying quantities, and RCFs (or mixed fuel types) produced from industrial waste gases and green hydrogen will require significant amounts of electricity.

5.3 SAF production from non-biological feedstocks in Norway

In this chapter DNV will provide a high-level overview of drivers and barriers for establishing SAF production from non-biological feedstock in Norway compared with other countries. While these barriers and drivers are not necessarily unique for Norway, such as competition for feedstock and lack of regulation, they are here explained in a Norwegian context.

5.3.1 Barriers for Norway

Figure 5-1 shows the main barriers for SAF production from non-biological feedstock in Norway. Each bullet point is described in further detail below.

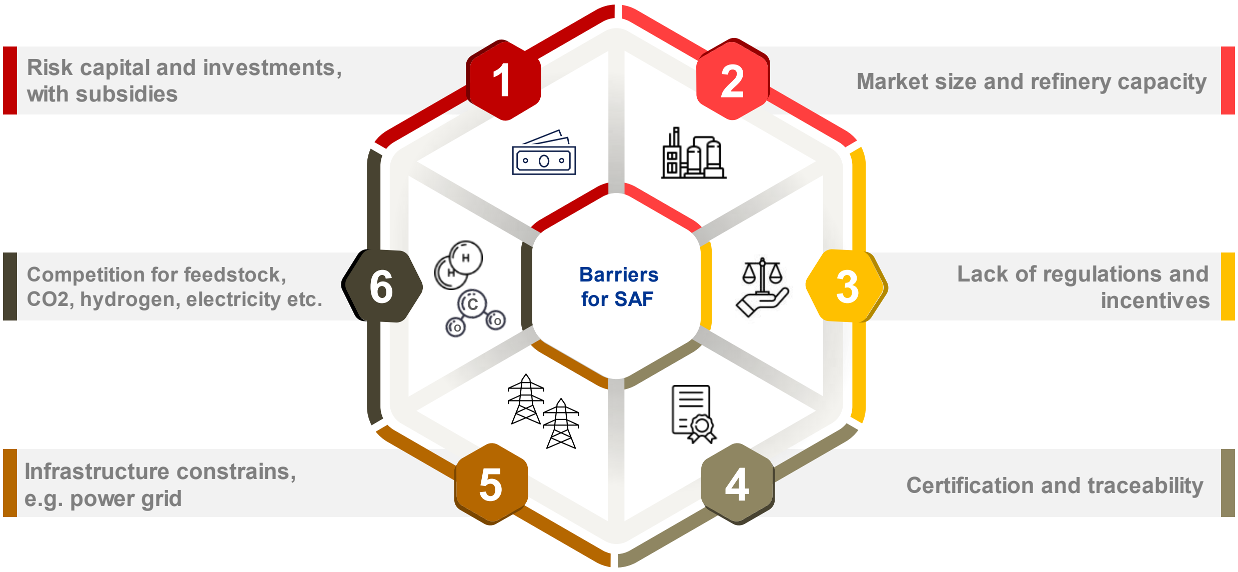

Figure 5-1: Main barriers for SAF production from non-biological feedstock in Norway. Source: DNV.

Market size and refinery capacity

With Norway's relatively small size, the domestic market for uptake of SAF is limited. Profitability in small scale production plants is challenging. An export market is required to establish large production facilities.

Some SAF production processes produce fuels of "drop in" quality, while other processes need to upgrade heavier hydrocarbons to lighter fractions in a refinery. In 2000, the refinery in Sola outside Stavanger was shut down, and in 2021, the former ExxonMobil refinery at Slagentangen in Vestfold was converted into an import-terminal. Today's demand for aviation fuel is covered by only the Mongstad refinery and imports. This means that there currently is only one location in Norway today than can do the refining step to the final SAF-product for the facilities not producing drop in quality fuels. Mongstad is medium-sized in a European perspective. With Mongstad being owned and operated by Equinor, the company has significant control of the future of Norwegian SAF production. Some of the SAF production projects in Norway have announced that they will send their "crude oil" to refineries in Sweden.

Risk capital and investments

Although Norway has a great focus on the transition into renewable technologies and emission reductions, there is a lack of sources for capital and investments into larger renewable technologies and projects associated with high risks, both from the public and the private sector. The public funds such as Enova, Innovation Norway and the Research Council of Norway funds research and pilots, which are important for the green transition. However, the market based (not largely incentivised) investments shows that there still one order of magnitude higher investments in conventional oil and gas, than renewable power, energy and fuels. The proposed contracts for difference and CO_2 emissions taxes may shift this ratio depending on policies.

According to the Norwegian Ministry of Petroleum and Energy, the country has invested significantly in renewable energy over the past decade. Between 2010 and 2019, Norway's total investments in renewable energy amounted to approximately 100 billion Norwegian Kroner ($11.7 billion). However, during the same period, the Norwegian government also invested heavily in oil and gas exploration and production. The total investment in the oil and gas sector between 2010 and 2019 was around 1.5 trillion Norwegian Kroner ($176 billion).

It's important to note that the investment figures for renewable energy in Norway include both public and private investments, while the investment figures for oil and gas mainly refer to the Norwegian state's investments in the sector, so the difference may be even larger. The private sector also invests in oil and gas exploration and production in Norway, but the exact figures are not readily available.

Electricity grid capacity constraints

The Norwegian electricity grid has currently, in general (but this varies from location to location), limited capacity to connect new consumption and there are long lead times and high costs associated with grid upgrades. Over the last years, the pressure on the electricity grid has increased significantly due to increased electrification, establishment of new industries and a general increase in consumption. The grid constraints are evident in both the lower voltage distribution systems operated by the different DSOs and the high voltage transmission system operated by Statnett. The capacity is particularly constrained in the Northern part of Norway[54], but there has also been increased focus on the limitations of the grid in the western part of Norway[55]. The process of reinforcing the grid and building new capacity in Norway can take several years. The limitations in grid capacity impacts the establishment of new industries that have high demands for electricity, e.g. green hydrogen and e-fuels production. In some areas, limited grid capacity can also be an opportunity as it can be commercially attractive to produce e-fuels using "stranded" electricity.

Slow short-term renewable electricity development

DNV's Energy Transition Norway[56] expects Norway to have a net electricity deficit in the period 2026-2030, see Figure 5-2:. Import of electricity can cause higher prices and volatility, removing Norway's competitive advantage of low-priced renewable electricity for power intensive industries. This threatens the establishment of new industries. The deficit is caused by significant increase in electricity demand while production remains quite flat. To avoid the electricity deficit, large scale renewable capacity development must be accelerated, while simultaneously removing grid constraints. DNV expects Norway to have an electricity surplus again from 2031 onwards as offshore wind production scales.

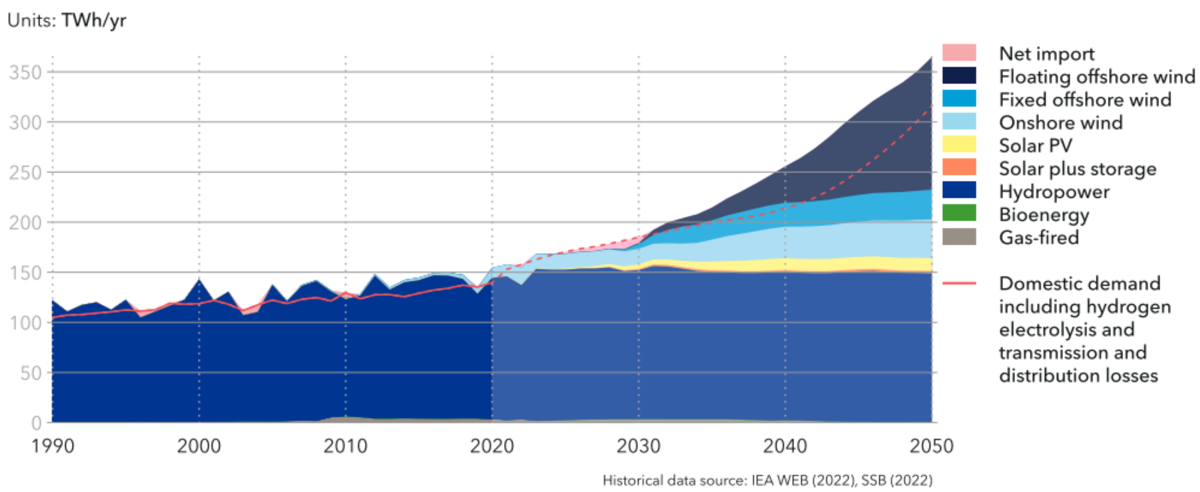

Figure 5-2: Grid connected electricity generation by power station type (DNV, 2022)

54 https://www.statnett.no/om-statnett/nyheter-og-pressemeldinger/nyhetsarkiv-2022/omfattende-forbruksplaner-fyller-opp-kapasiteten-i-stromnettet-i-nord/

55 Regional Kraftsystemutredning for Midtre Vestland, 2022-2042

56 https://www.dnv.no/Publications/energy-transition-norway-2022-235535

Competition for feedstock

Depending on the production process, a significant barrier for production of SAF in Norway is the competition for feedstock. Relevant for this report is competition for municipal solid wastes and plastics, as well as competition for green hydrogen (and the grid capacity required to establish hydrogen production) and biogenic/"low-carbon" CO_2. This barrier also exists in other countries.

According to SSB, the total amount of waste in Norway in 2020 was 11.60 million tonnes. 1.8 million tonnes of this was wetorganic, park- and gardening, wood and sludges, while 2.4 million tonnes was mixed waste. 16% of this came from manufacturing industries, 29% from construction, 13% from service industries, 22% from households and 21% from other sources. Of the non-biological waste in 2020, 225 000 tonnes were plastics and only 131 000 tonnes (58%) of the plastics were recycled. 109 000 tonnes of plastics was incinerated.[57] Norway also has significant volumes of mixed waste that is incinerated, roughly 1 708 000 tonnes in 2020, compared to 170 000 tonnes being recycled. More than 500 000 tonnes of mixed waste is being disposed in landfills or other disposals.

For production of SAF based on MSW, the competition from waste-to-fuel plants could be a barrier in several ways. When the alternative use of waste is to produce heat and electricity, the waste already has a value that drives up the price. This value will vary in different areas. For regulatory and reporting purposes, the alternative use of the MSW/plastics used in SAF production can impact GHG emission savings calculations, as proposed regulations specify that SAF GHG emissions savings must also compensate the emissions savings from alternative use. This means that if the alternative use of MSW/plastics is to produce (renewable) electricity in an area with a high emission electricity mix, it can be more difficult to make the 70% GHG emissions savings threshold than in a country with low emission electricity mix. However, as the regulations for this are not finally decided yet, the impact is uncertain.

On the other hand, Norway is a net exporter of waste, where a significant amount of waste is exported to waste-to-energy plants in Sweden every year. The last 8 years, the total export of waste has been above 1 500 000 tonnes annually.[58] The waste is exported primarily due to lack of capacity in Norwegian waste-to-energy plants (at the same time, some waste-to-energy plants, like the one in Klemetsrud in Oslo, import waste). This represents an opportunity as fuel production using waste could lead to lower export.

Lack of regulations and incentives

Although Norway was the first country to introduce a blend-in requirement for advanced biofuels[59] and one of the few countries that have a CO_2-tax for domestic flights, there are currently few regulations and incentives that succeed to increase the competitiveness of SAF. As described in Chapter 3.5, there's still a significant cost and price gap between SAF and conventional jet fuel, and hence it is only the quite limited blend-in requirements that stimulates the market. According to the Norwegian climate action plan 2021-2030, the carbon tax price is planned to increase towards 2030, but as the cost of SAF is significantly more expensive than conventional jet fuel, the impact of this carbon tax price increase is uncertain. Furthermore, there are also limited regulations and incentives for the establishment of SAF production facilities. The recent Norwegian aviation strategy highlights that the government will stimulate the phase in of SAF through blending mandates[60]. Through the European Economic Area Agreement, most of the regulations for SAF and green fuels that are adopted by the EU (such as the binding SAF blending mandates) are also expected to be legislated in Norway, however with a delay, which can also impact the timeline of new production projects.

[57] (https://www.ssb.no/en/natur-og-miljo/avfall/statistikk/avfallsregnskapet)
[58] https://miljostatus.miljodirektoratet.no/Tema/Avfall/Import-og-eksport-av-avfall
[59] https://avinor.no/globalassets/_konsern/miljo-lokal/miljorapporter/100505_avinor_barekraftig_flydrivstoff_screen.pdf
[60] https://www.regjeringen.no/no/aktuelt/ny-nasjonal-luftfartsstrategi-regjeringen-onsker-a-ta-grep-for-a-ivareta-og-utvikle-norsk-luftfart/id2960859/

5.3.2 Drivers for Norway

There is currently no commercial SAF production in Norway, and all SAF that was sold in Norway in 2021 was imported. However, there are still large advantages for production of SAF in Norway compared to other nations. [61] In the sections below, the identified key drivers are described. Some drivers are more important for certain production processes, such as renewable electricity for RFNBOs, but as this report has shown, RFNBOs, RCFs and low carbon fuels can be combinations of hydrogen and carbon from various sources, and the topics mentioned below can be relevant for all types of fuels. Figure 5-1 shows the main drivers for SAF production from non-biological feedstock in Norway. Each bullet point is described in further detail below.

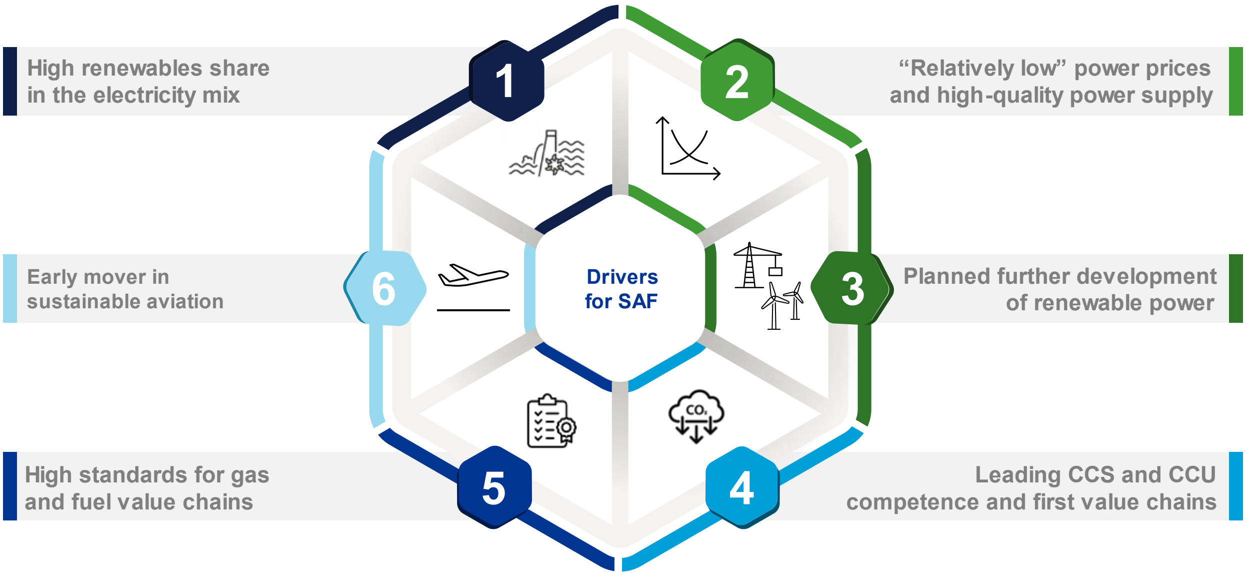

Figure 5-3: Main drivers for SAF production from non-biological feedstock in Norway. Source: DNV.

High renewables share in electricity mix, (relatively) low power prices and high quality power supply

A crucial aspect when producing SAF, which is also evident in the proposed EU regulations for RFNBO and RCF, is that all inputs into the production-process of a SAF should have low (life-cycle) emissions to ensure sufficient GHG emissions savings. Norway has one of the highest renewables shares in the electricity mix in the world and hence the emission factor is low, which ultimately eases the use of electricity and MSW for SAF production. As the renewables share in Norway is typically above 90%, SAF producers in Norway are not reliant on direct connections to renewable energy production or PPAs/guarantees of origin (as defined in Article 27 of the Renewable Energy Directive)[62].

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[61] (https://avinor.no/globalassets/_konsern/om-oss/rapporter/en/programme-for-increased-productrion-and-uptake-of-sustainable-aviation-fuels-2021.pdf).

[62] There are however some unknown effects of the differentiation between the three definitions of renewable electricity. One is that the "renewable-grade" of Norwegian produced hydrogen/RFNBO can be thought to be lower, as it is not 100% green, causing price differentiation. The other is that the producers are not guaranteed an above 90% renewables share from year to year, meaning that some years the production may not be "renewable" if this is not hedged by PPAs and/or guarantees of origin.

In addition to the high renewables mix, Norway is known for relatively low and stable electricity prices. This is a major benefit in production processes with high electricity consumption, e.g. green hydrogen production. Although recent surges in power prices have increased the costs of electricity in Southern Norway significantly, Norway is still, and is expected to continue to be, a high-regarded country for electricity-intensive industry, especially in the Northern parts.

One of the reasons for long lead times for connection of new consumption to the grid in Norway is the relatively strict requirements to the quality and security of supply. This is an advantage for facilities that require high uptimes and stable voltage and frequency levels, but for the production of hydrogen that can be used in SAF, the impact depends on the technology and size of the electrolyser. Figure 5-4: shows DNV's expected hydrogen production in Norway towards 2050.

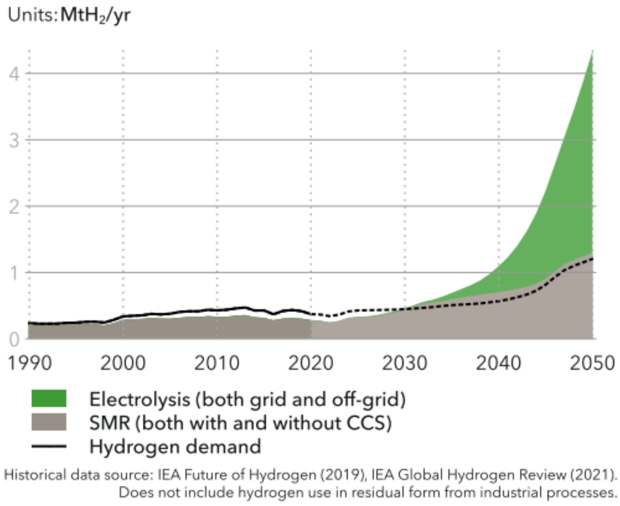

Figure 5-4: Norway Hydrogen production by production route (DNV, 2022)

Significant potential for offshore wind development

Norway's long coastline gives large potential for offshore wind power, and the Norwegian government has announced a target of 30 GW offshore wind capacity by 2040.

Resources and industry

Norway has a large process- and petroleum-industry, with both competence and infrastructure that can be used to establish production of SAF. Norway has a long-distance distribution of jet fuel along the West coast and Northern Norway with relatively high costs. There may be opportunities to produce some of this locally within existing industry clusters, or that partially refined bio- and e-crude can be transported to Mongstad for further SAF refining. There are several local industry clusters with both fossil and biogenic CO_2 emissions and land-locked or bottle-grid low-cost renewable power, which are feedstocks for synthetic fuels which may qualify for blending mandates such as RFNBOs, or other synthetic fuels such as RCF and "low carbon" fuels with a differentiated monetary and GHG value.

Focus on CCS and CCU

Norway has a clear ambition in developing infrastructure for capturing, transporting and storing CO_2. An important project that is a key part of this ambition is Longship. Longship has a total budget of 25.1 billion NOK and seeks to develop a value-chain for CCS, utilizing vast storage resources in the Norwegian continental shelf. Through Longship CO_2 will be captured from the cement-plant of Norcem in Brevik and the waste-to-energy plant of Celsio (earlier Fortum Oslo Varme) in Oslo and then shipped to Kollsnes, where the terminal for storage in the Norwegian continental shelf will be. Holistically, Longship will contribute to building technology, competence and infrastructure for CCS, which can be further commercially developed. Several of the CCS projects are run out of Technology Centre Mongstad, which is utilizing waste gases from the Mongstad refinery-processes and the CHP-plant to pilot CO_2-capture technologies. The focus on CCS and CCU, combined with Norway's vast gas resources, facilitate production of blue hydrogen that can be utilised in production of SAF. Figure 5-5 shows DNV's expected Norwegian CO_2 emissions captured towards 2050.

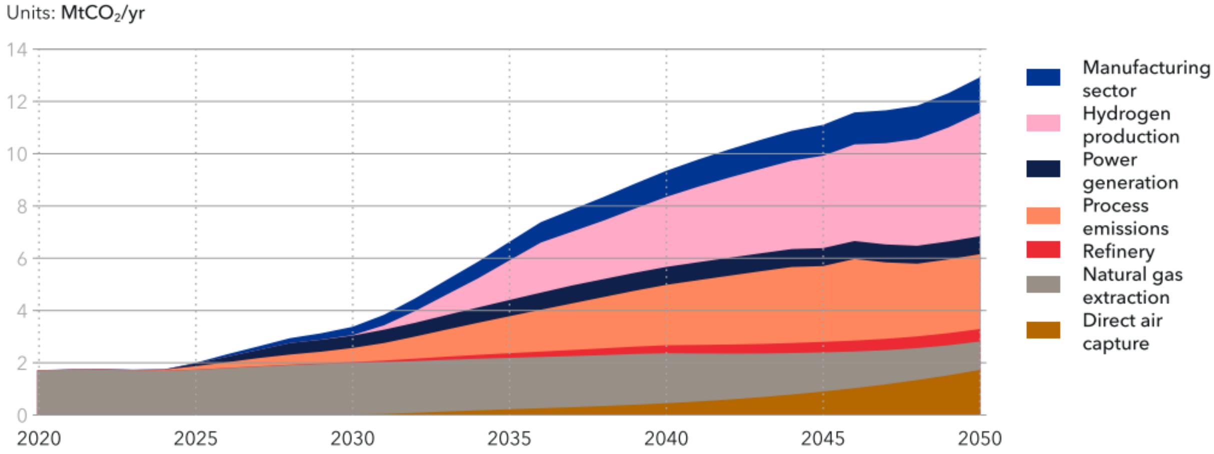

Figure 5-5: Norwegian CO_2 emissions captured (DNV, 2022)

Early mover in sustainable aviation

The Norwegian aviation industry has been an early mover into the uptake of SAF based on biological feedstock.[63] In 2016, Oslo Airport Gardermoen was the first international airport to mix SAF into the jet fuel mix and offer it to all airlines. Norway was also the first country with a requirement to the use of advanced biofuels for the aviation industry (0.5% in 2020). SAS and Widerøe have offered customers to pay for the additional costs of using SAF and together with Norwegian, they have set ambitious target for phasing in SAF in Norwegian airlines.

5.4 The role of national regulation and policy support in the establishment of industrial value chains for SAF

It is clear that national regulation and policies can facilitate the development of industry value chains for SAF. Innovative policies and support schemes are currently being adopted and used to facilitate new green solutions across the US and Europe, examples being the US Inflation Reduction Act, the Contracts for Difference (CfD)-schemes used to fund offshore wind energy production in European countries, and expected for hydrogen and synthetic fuels, and the quota-systems used to promote biofuels in Germany and the Netherlands.

A high-arching requirement for national regulation and policy support to establish industrial value chains for SAF is to provide predictability in regulations and jurisdiction, providing certainty to industry actors, investors and other stakeholders. In addition, there are measures to strengthen the commercial feasibility of SAF projects, including contracts for difference (CfD) schemes, blending mandates and CAPEX support. Blending mandates are expected to be implemented through ReFuelEU, but there are only vague indications of CfD-schemes for hydrogen being implemented in Norway during 2023, and still none for alternative fuels for any sector. There are programs for investment (CAPEX) support from Enova and Innovation Norway for sustainable fuels, but nothing earmarked for SAF.

A key challenge in establishing non-biological SAF production value chains is the supply of feedstock, i.e. MSW and plastic waste. With aviation being a hard-to-abate sector, governments can facilitate the use of waste feedstock for SAF production, if deemed desirable in an emissions- and social-economic context rather than being used for waste-to-energy and district heating.

Norway is well positioned to take a leading role for non-biological SAF production if regulation and mechanisms facilitating update and bridging the cost gap comes into place.

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[63] https://avinor.no/globalassets/_konsern/miljo-lokal/miljorapporter/100505_avinor_barekraftig_flydrivstoff_screen.pdf

6 MONGSTAD AS A LOCATION FOR SAF PRODUCTION

As the only site with aviation fuel production in Norway, Mongstad has been considered as an interesting location for the production of sustainable aviation fuel from waste feedstock during this study. Equinor owns and operates existing infrastructure, logistics and have resources that are necessary for the production of SAF and other synthetic fuels. In addition, there are plans for nearby production of blue hydrogen with carbon capture and CO_2 value chains for storage/sequestration, that could facilitate the SAF production process considered in this study.

In order to produce SAF, many pathways can be chosen (see Chapter 4.1). For this conversion process, using non-biological feedstock, the following SAF production process has been proposed and is assessed in this study.

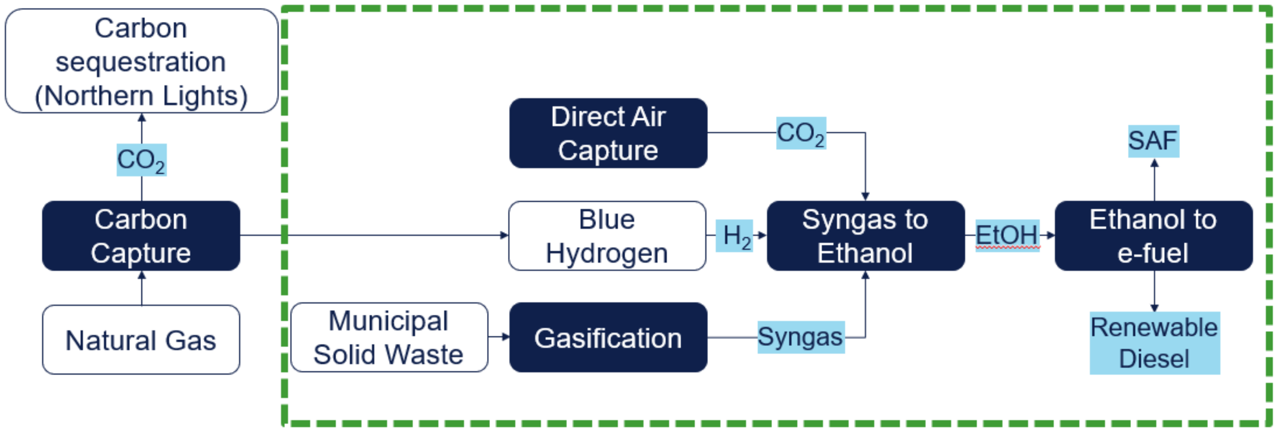

Figure 6-1: Suggested SAF production using Municipal Solid Waste, Blue Hydrogen and Direct Air Capture

The scope of our study is limited to the elements as highlighted by a green dotted line. As such, the sourcing of Municipal Solid Waste feedstock is assessed, as well as the various conversion technologies highlighted in dark blue. In order to assess whether this combination is feasible, the following approach is proposed.

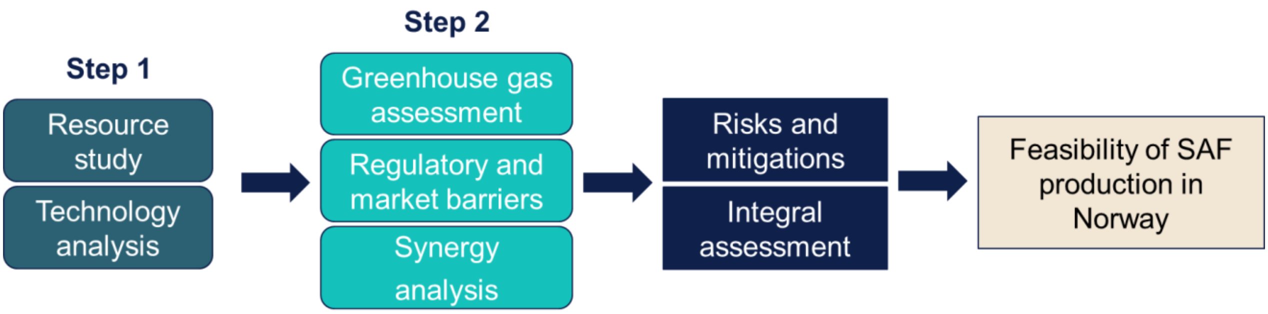

Figure 6-2: Approach for feasibility of SAF production at Mongstad

The study includes an analysis of SAF production to be implemented at Mongstad. The ongoing CCS/CCU project and existing refinery may give beneficial synergies for SAF production with possible co-processing, or a dedicated new plant for e-fuels with a high kerosene and SAF ratio or production slate.

The analysis also includes a specific supplier of DAC technology at Kollsnes, for CO_2 supply to the plant at Mongstad. Synergies with ongoing blue hydrogen projects will be important to utilize the emerging value chains for CO_2 transport and storage. As illustrated in Figure 6-1:, the combination of gasification, blue hydrogen and DAC will be used to produce Ethanol using proprietary technology from LanzaTech, followed by proprietary technology from LanzaJet to produce SAF.

6.1 Assessing risks

In order to quantify the risks related to the production of SAF through the proposed chain of conversion technologies, DNV has assessed the risks by using risk matrices as shown in the figure below. These risk matrices show the probability of the risk occurrence on the horizontal axis and the impact on the vertical axis. Combining the probability and the impact leads to either a green, yellow or red mark on the right-hand side of the risk slides, indicating the risk severity. The risks are defined as a combination of Impact and Probability, using the risk matrix shown below:

H	M	H	VH
M	M	M	H
L	VL	M	M
	L	**M**	**H**

The impact is defined as follows:

- Very high: Material risk with severe impact on costs, time, and/or quality.
- High: Material risk with major impact on costs, time, and/or quality.
- Medium: Impact may be material on costs, time, and/or quality.
- Low: Low material impact on costs, time, and/or quality.

While the probability that a risk occurs is defined as:

- Very high: ≥ 75%
- High: ≥ 50% and < 75%
- Medium: ≥ 25% and < 50%
- Low: < 25%

6.2 Resource study

The available plastic and waste feedstock for Mongstad is assessed in this chapter. This assessment is based on resource prioritization, as well as publicly available data for the collection of residential and industrial waste. While typically the distance between the source and the processing installation (Mongstad) is considered, here the consortium has assumed that the waste will be transported by ship to Mongstad. As such, feedstock sourcing is not limited by the distance from the source to the installation. The inventory of feedstock streams, based on available information, will be used to estimate realistic possible production volumes for SAF in Norway.

In this resource study, a high-level review of the waste streams from municipalities (MSW), land-based industry and the agriculture-, forest- and fishing-sectors are considered.

6.2.1 Prioritizing resource usage

The notion of cascading (see Figure 6-3: pyramid) illustrates that (waste) materials can be converted for many different applications. However, applications can be prioritized, as the feedstock can be used as food, animal feed, fertilizer, fuel, and as an energy source (which is considered the lowest grade, at the bottom of the pyramid).

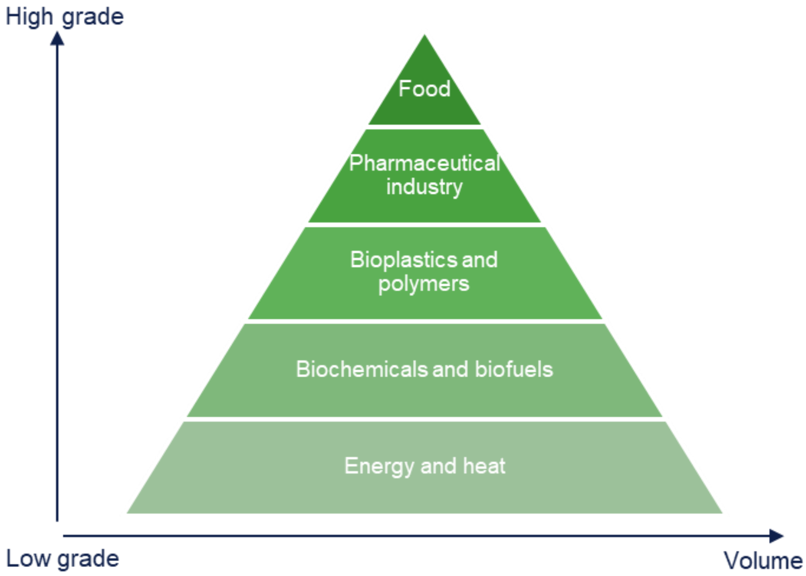

Figure 6-3: Cascading of material application

The types of industrial waste that can be used to produce recycled carbon fuels, according to the Renewable Energy Directive II (RED II), are typically those that are not suitable for material recovery or recycling. This is also highlighted by the Waste Hierarchy, shown in Figure 6-4:.

Figure 6-4: Waste Hierarchy

The Waste Framework Directive from the European Union[64] has an inverse pyramid highlighting which purposes for waste streams are prioritized. The Waste Hierarchy shows that Prevention is the highest, followed by re-use, recycling, recovery and finally disposal. For the application of energy generation using waste streams, recovery is the category that fits the description best. Naturally, aside from EU directives, countries themselves have policies in place, which also strive towards circularity and maximal reuse of resources in waste streams.

From the point of view of sourcing, the centralized collection and aggregation infrastructure in place for waste can be a great opportunity to collect specific waste streams. It can be noted that there are over 27 waste categories, where some are plastic pellets or other refined waste products, now emerging to be commodities, and easy to handle and process due to homogeneous or even standardized properties. Plastic waste from ocean clean ups is one example.

64 https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en

As defined per the scope of this project, the focus is on non-biological feedstock, except biogenic CO_2 with no energy content. It can be noted that if a compound in the reaction has energy content from biogenic sources, a share of the produced fuel equal to the energy feedstock share will accounted as biofuel. The feedstocks that are included as non-biological are hence:

- Waste oils and solvents, which can be converted into transport fuels
- Waste plastics, which can be converted into fuels or chemicals
- Waste gases, such as methane or carbon monoxide, which can be used to generate electricity or heat
- Non-biogenic fraction of municipal solid waste, which can be used to produce energy through incineration or gasification

Industrial waste gases are typically re-used in refinery processes and waste oils are not in large enough volumes, meaning that these have not enough volume to be considered as viable sources to produce SAF at a large scale. According to Equinor, there is limited feedstock available from the industry at Mongstad, meaning that the feedstock must be imported. As such, waste plastics and municipal solid waste (MSW) are the two main feedstocks that can be sourced to produce SAF at substantial scale.

Please note: Typically, MSW is a collection of multiple residual waste streams which are often difficult to separate. Depending on the source, the composition can vary significantly. For this assessment, DNV has assumed that the residual MSW is comprised of 50% of biological waste, and 50% non-biological. As such, the product resulting from the conversion of MSW will count for 50% as biofuel, while the other 50% account for non-biological fuel. While this is our initial assumption, this will have to be verified when reaching out to waste suppliers and analyzing the composition of the specific waste that will be sourced for the SAF installation.

6.2.2 Approach for feedstock inventory

In order to assess the amount of feedstock that can be used for the production of SAF, DNV has opted to use the aforementioned Waste Hierarchy as basis.

Considering that waste re-use and recycling have a higher purpose than the production of fuels, these should be excluded from the sourcing for SAF. In addition, feedstock already processed to become biogas is also excluded. This leaves the incineration and landfill waste, as both of these applications have less added value than to convert to SAF. This is depicted in the diagram below.

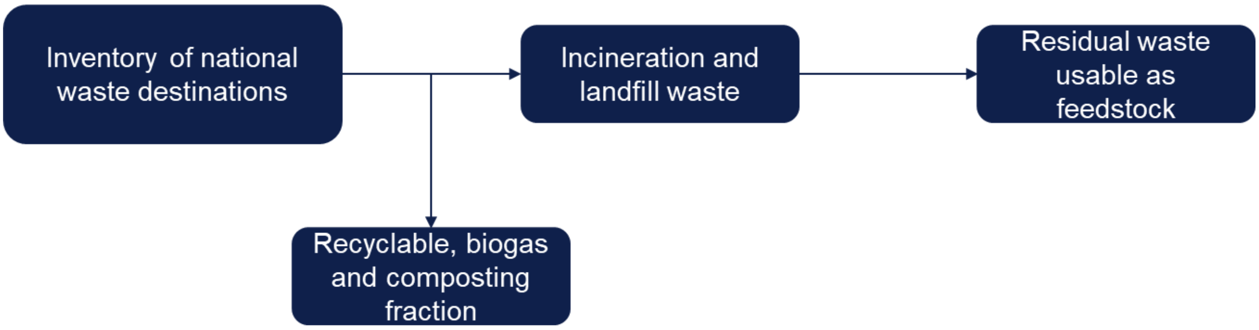

Figure 6-5: Approach to feedstock inventory for SAF

In an ideal case, none of the waste entering the incinerators can be used for recycling or biogas production. While this is strictly speaking not the case because incinerators also process paper and organic matter for example, we will use this as an assumption for our assessment. However, in reality, not all the waste can be sorted in order to serve a recycling or re-use purpose. Figure 6-6: below is an analysis showing the current destination of municipal waste streams.

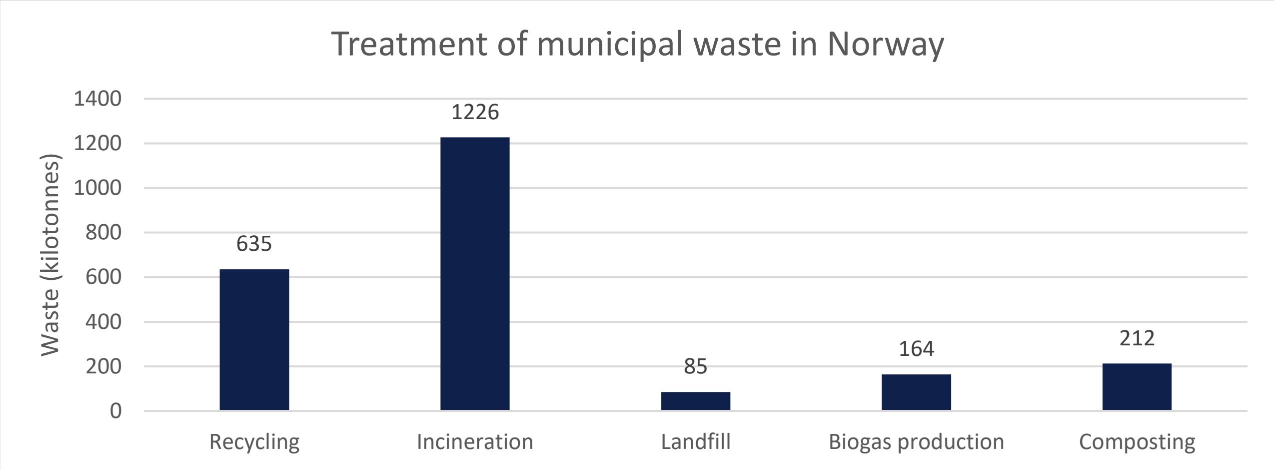

Figure 6-6: Overview of the end-treatment of municipal waste in Norway

As such, the sum for incineration and Landfill across Norway is 1312 kilotonnes of waste. These residual waste streams can be qualified as MSW. However, seeing as recycling and re-use should ideally be prioritized and waste separation improved in the coming years, using the full 1312 kilotonnes of waste is not a sound approach.

An alternative SSB source has categorized the MSW in in Norway in 2021 follows the graph below.[65] The largest category of waste is by far residual waste, followed by food-, wood- and garden-waste.

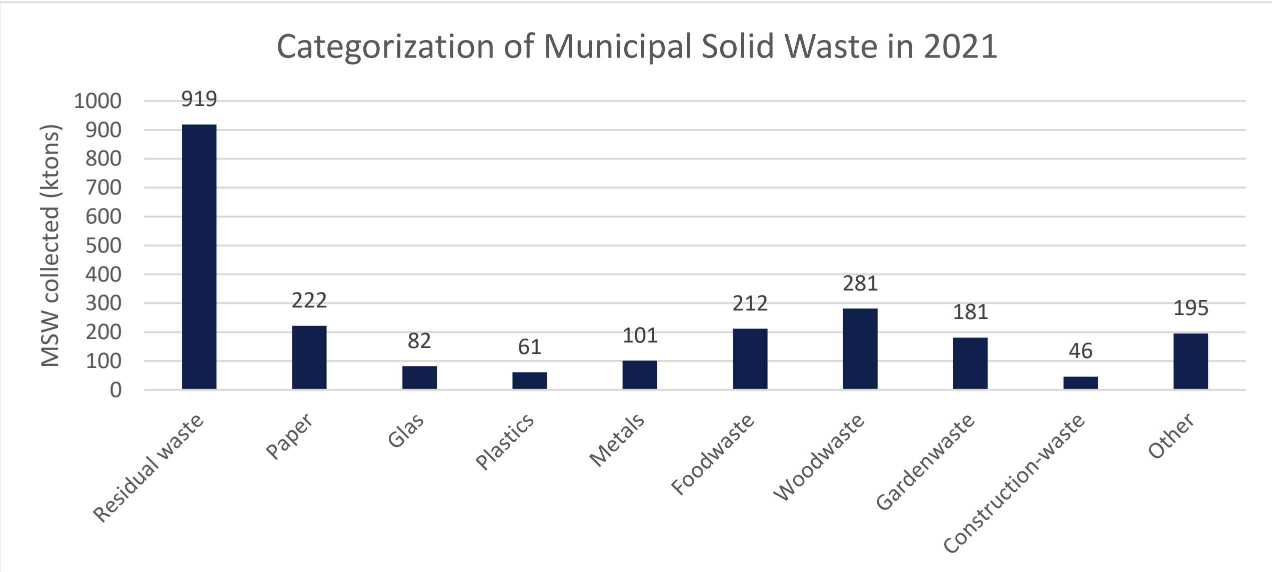

Figure 6-7: Categorization of municipal solid waste in Norway 2021. Source: SSB

Based on SSB data, 39% of the waste mixture in Norway (919 kilotonnes) is residual (non-sorted) waste. The remaining fractions are presorted (glass, metals, textiles, paper, organic waste) and DNV assumes that these can be used for recycling and biogas production. As such, DNV assumes that using only the residual waste is currently acceptable for the SAF production.

For the purpose of this study, residual waste is considered as Municipal Solid Waste (MSW), and as previously stated, is assumed to be 50% biological and 50% non-biological waste. **Following this approach, the feedstock that can be used for SAF production is the residual waste, and amounts to 919 kilotonnes of MSW.**

[65] https://www.ssb.no/natur-og-miljo/avfall/statistikk/avfall-fra-hushalda

6.2.3 Waste from land-based industry, agriculture, forestry and fishing sector

According to the Norwegian Emissions database (Norske Utslipp), the total volume of industrial plastic and rubber waste has been summed up to be 25 kilotonnes of plastic waste and 419 tonnes of rubber waste [66]. Strictly speaking these feedstocks could have added value for the production of SAF. However, industrial plastics and rubbers can for the most part be recycled instead of being broken down to produce fuels.

Similarly for the agriculture, forestry and fishing sector, the amount of plastics totalled to roughly 34 kilotonnes in 2019 [67]. An overview of the purchased, collected and recycled volumes of plastics in the agricultural sector in Norway since 2005 is given in Figure 6-8. The purchased volumes are shown in green (*mengd innkjøpt*), the collected volumes are shown in black (*mengd innsamla*) and the recycled volumes are shown in blue (*mengd materialgjenvunne*). The overview is made by "Grønt Punkt Norge", that maps an estimated 95% of the total volumes in Norway. In 2020, an estimated 13 kilotonnes of plastics was recycled of the 22 kilotonnes that were collected, or 60%.

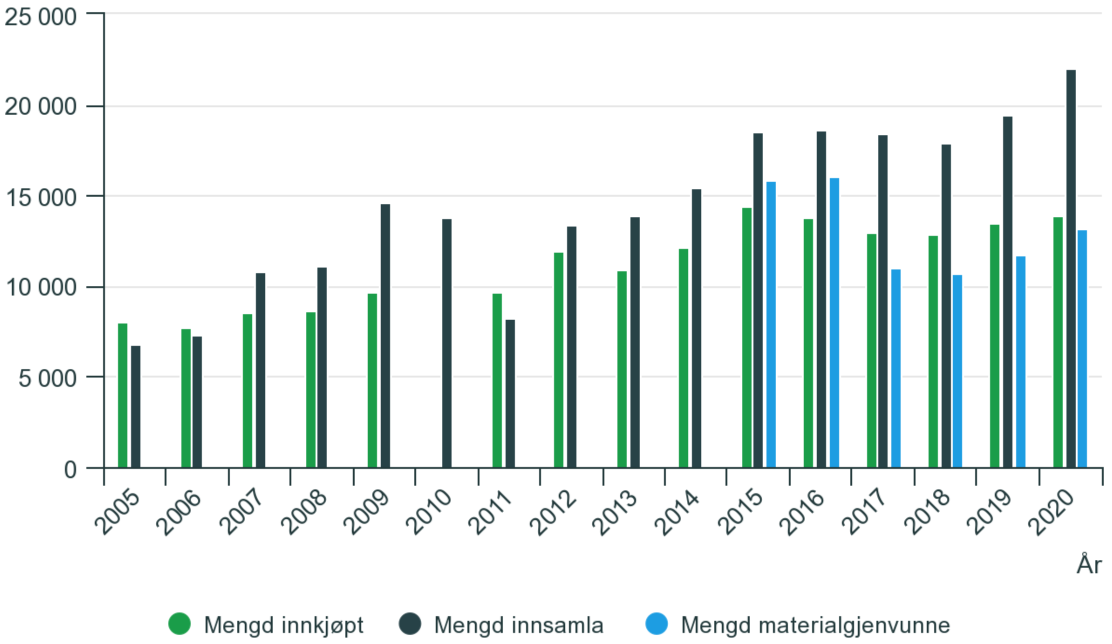

Figure 6-8: Volumes of purchased, collected and recycled plastics from the agriculture sector in Norway. [tonnes] Source: Grønt Punkt Norge

Assuming that 70% of the feedstock stream can be recycled, this leaves 30% that can be used for SAF production, or an estimated 13 kilotonnes of non-recycled plastics.

6.2.4 Waste pre-treatment

In order to proceed with the conversion steps to produce SAF, the (MSW) feedstock needs sorting and separation of metals, stones and glass from the remaining non-biological waste. The waste can then be further pre-processed to increase the energy content per mass and volume, typically in the form of Refuse Derived Fuel (RDF). While there is no universal classification or specification for RDF, it is a fuel produced from the combustible components of MSW. This fuel is in fact a shredded (and possibly pelleted) form of MSW, where non-combustibles are removed. In order to produce RDF, MSW is typically pre-processed by removing glass, stones and metals, followed by shredding and drying,

[66] https://www.norskeutslipp.no/no/Komponenter/Avfall/Plast/?ComponentType=avfall&WasteComponentPageID=63&SectorID=600
[67] https://www.ssb.no/natur-og-miljo/avfall/artikler/plastavfall-og-farleg-avfall-fra-jordbruket

and baled in order to be handled for transport, followed by incineration or alternative thermal conversion processes such as gasification (which will be covered in the next chapter). It should be mentioned that the mechanical pre-processing step converting MSW to RDF is also rather energy and effort-intensive, and has not been taken into account in this assessment. This is due to the fact that the composition and nature of the waste can strongly impact the need and steps of pre-processing.

Conversion to RDF effectively increases the energy density of the transported waste (more MJ per kg of waste). As such, a ship can then transport more waste per trip, making transport more efficient. With the removal of additional inert materials that cannot be processed in the gasification installation, a conservative assumption is that the RDF energy value increases from 8-12 to roughly 18 MJ/kg. It should be noted that depending on the composition of the RDF, the energetic value is reported to be between 11-36 MJ/kg[68] [69], but most reports assume 18 MJ/kg. In a following phase of development, specific waste targeted for Mongstad syngas production will have to look into the energy value of its feedstock.

Following this, the high temperature process (gasification) that will be introduced in Chapter 6.3.1 can take place, converting the feedstock into syngas.

6.2.5 Total feedstock availability

The feedstock streams that can be accounted for, are the residual waste streams (919 kilotonnes), and non-recycled industrial plastics (13 kilotonnes). Based on DNV experience and literature, assuming a 8-12 MJ/kg for the residential residual waste and 30-35 MJ/kg for the plastics are acceptable values. As previously stated, DNV assumes that the inventoried residual waste (MSW) comprises 50% biological, and 50% non-biological. Certainty regarding the fraction of non-biological feedstock will only occur once sourcing and contracting with waste suppliers takes place. Moreover, it should be noted that most incineration installations have long term contracts in place for waste supply. As such, it may be challenging to source the waste pre-destined to incineration for the purpose of SAF production, and using the full 919 kilotonnes of MSW as basis may not be considered realistic.

To summarize, SAF production will not only need to secure large amounts of feedstock, but in order to have an optimal conversion process, will also need to have a constant energy value as well as contractual and logistical challenges. These challenges are highlighted in Table 6-1.

[68] Broz˙ ek, P.; Złoczowska, E.; Staude, M.; Baszak, K.; Sosnowski, M.; Bryll, K. Study of the Combustion Process for Two Refuse-Derived Fuel (RDF) Streams Using Statistical Methods and Heat Recovery Simulation. Energies **2022**, 15, 9560.h

[69] https://doi.org/10.3390/en15249560; https://www.researchgate.net/publication/356434781_Carbonized_Solid_Fuel_Production_from_Polylactic_Acid_and_Paper_Waste_Due_to_Torrefaction

Table 6-1: Summary of risks for feedstock sourcing

Topic	Observations	Implications	I	P	Risk
Fluctuating energy value	A key factor in the continuous gasification process is the sourcing of feedstock with constant calorific value. Seeing as municipal solid waste is based on human consumption, its composition and volume is inherently fluctuating.	Variable feedstock can result maintenance issues and increased costs, as will be discussed in the next chapter. With regards to the seasonal impact and specifications of the gasification process, strict control, pre-treatment (for particle size control) and contractual agreements are necessary. Sourcing of more homogeneous and standardized waste categories can be a solution, also for ease of handling, but higher cost may be the implication	H	M	
Logistical complexity	Sourcing MSW, whether local or international, requires extensive logistics	The processing installation requires a consistent input of feedstock. As such, the plant should have a guaranteed feedstock supply, preferably from multiple locations.	M	H	
Contracting	Supply agreement between waste supplier and SAF production installation (specifically the first step, gasification) is necessary to guarantee specifications of the waste, as well as a continuous supply throughout the year.	Long term contracting is necessary, as waste prices fluctuate. Moreover, competition is projected to increase in the coming years with waste slowly shifting to a resource instead of a burden.	M	L	

6.3 Technical process description

Using experience from multiple Technical Due Diligences on innovative conversion technologies such as gasification, pyrolysis, waste management and Direct Air Capture (DAC), DNV has assessed a DAC technology provider, as well as gasification technologies. In addition to this, various interviews with LanzaTech and LanzaJet have been carried out in order to have a clear understanding of the Waste to Fuel concept, with syngas fermentation to SAF and renewable diesel. These technologies have been assessed on their concepts, including potential implementation, operational and scaling up challenges, their maturity and the track record of the suppliers.

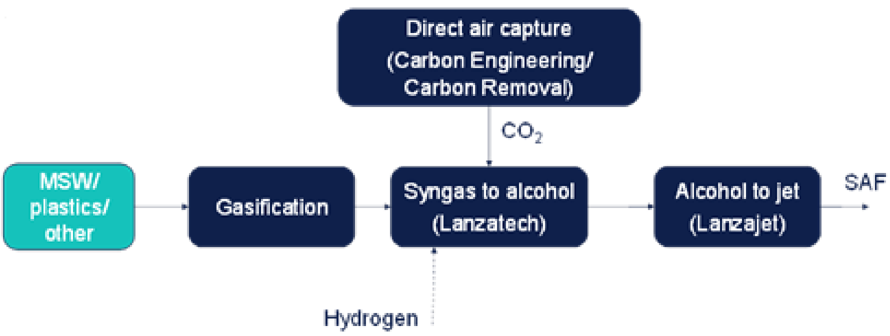

Figure 6-9: SAF production process

DNV has assessed the following processes and suppliers, divided into different subchapters:

Table 6-2: Processes and suppliers assessed

Process	Supplier	Inputs	Output
Gasification	Multiple	Hydrocarbons, partly fossil and biological, typically 50-50% (pre-processed Municipal Solid Waste)	Syngas (H_2, CO, CO_2)[70]
Direct air capture (DAC)	Carbon Removal (Carbon Engineering)	Water, heat, electricity, process chemicals calcium carbonate and potassium hydroxide	captured atmospheric CO_2, process emissions (solid and liquid waste)[71]
Syngas to alcohol	LanzaTech	Syngas (H_2, CO, CO_2)	Alcohol – Ethanol (EtOH)
Alcohol to jet	LanzaJet	Alcohol	Diesel and Kerosene

6.3.1 Gasification

Gasification technology is a thermochemical conversion process that has been explored for a long time, targeting the production of either methane (CH_4) or hydrogen (H_2) as an end-product to produce electricity or one of the feedstocks.

Originally coal was the focus feedstock for gasification, which slowly shifted to biomass and waste in recent years. Gasification is a process whereby carbonaceous organic material is converted into synthesis gas also known as Syngas, which typically consists of a mixture of H_2, CH_4, CO and CO_2. Since the technology is not yet fully mature when using waste or biomass as feedstock, many variants are still present, geared towards products with different characteristics[72].

The conversion steps from feedstock to syngas can be described as follows:

- The entire process of converting waste to syngas typically involves pre-treatment steps to make the preferred feedstock more uniform (drying, grinding).
- The conversion process is carried out in a gasifier at high temperature (600-1200°C), without combustion, where controlled amounts of oxygen and steam are directly contacted with the raw material. Consequently, a series of chemical reactions take place that convert the feed to syngas and char, filtering out impurities. The syngas produced can be further converted to a higher fraction of hydrogen through a Water-Gas-Shift (WGS) reaction and Pressure Shift Adsorption (PSA), thus increasing the yield of Hydrogen. The process also includes a flue gas treatment step, where highly polluting gases are removed.
- It should be noted that while the typical gasification process has an operating temperature between 600-1200 °C, alternative methods such as plasma gasification operate at temperatures up to 10 000 °C (typically between 5-10 000°C in the plasma zone).

[70] As previously mentioned, the biological fraction coming out of the feedstock will be accounted as biofuel, while the other RFNBO and RCF

[71] https://www.cell.com/joule/fulltext/S2542-4351(18)30225-3

[72] https://www.mdpi.com/2813-0391/1/1/11

- Gasification itself can be comprised of different steps, making it challenging to define a single gasification design for this study. Typically, feedstock is broken down through pyrolysis, and further broken down with gasification unit(s). In broad strokes, more gasification breakdown units lead to a higher purity of the end product. This prevents practical issues, increases efficiency and quality of the output, but naturally requires a more intensive investment. It should be noted that since many different gasification concepts exist (depending on targeted input and output) the consumables, use of oxygen in the installation, heating (natural gas) and electricity costs and additional operational costs vary for the different solutions. Our assessment has taken these into account, benchmarked internally together with an extensive literature review in order to arrive to a rough average for the CAPEX and OPEX of a gasification technology. But as such, a future step in the development of this concept will have a different cost from the estimate provided in this report.
- In the gasification process, syngas is produced. Followed by Water gas shift reaction, injecting water in order to increase the hydrogen fraction in the gas. Final purification will then take place in order to exclude potential sulfuric or other impurities which can deter following reactions, such as the productions of fuels for example.

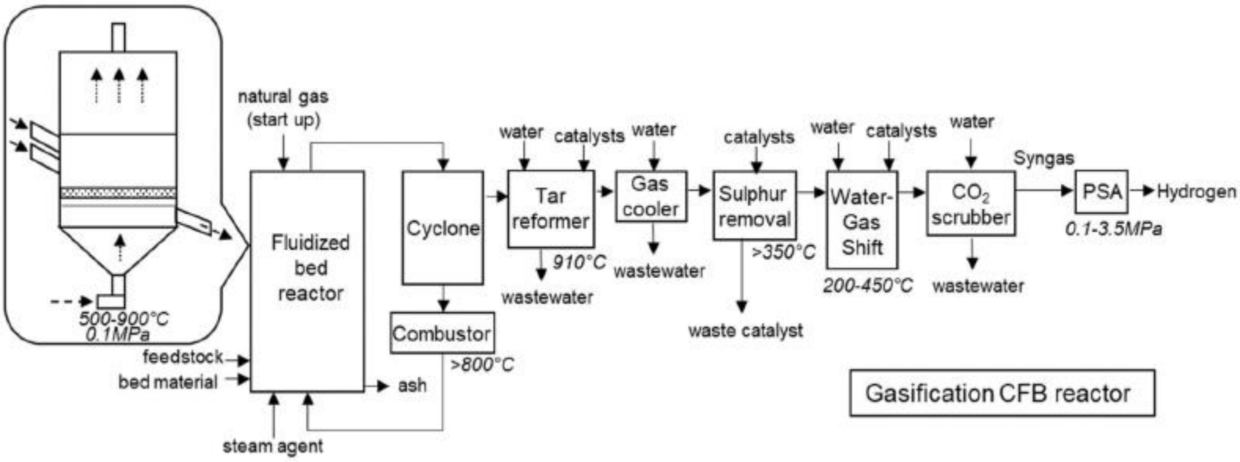

Figure 6-10: Generic process of gasification[73]

Output: As previously mentioned, depending on the different conversion units used, the composition of the syngas at the output will differ, with hydrogen content ranging from 25-50 mol%. For the focus of this study, the next step involved conversion of syngas to ethanol. Based on a case study provided by LanzaTech, the molar composition (amount of molecules of a specific compound) used for the syngas was 40.5% CO, 35.4% H_2, 20.0 % CO_2, 2.2% H_2O and 1.9% other gases, so this will be the basis of our exercise as well.

Parameter control: In the operational environment of the overall SAF production plant, feedstock variation presents a major challenge for large scale implementation. Particle size, consistency and uniformity are essential parameters, as well as temperature control inside the gasification reactor(s). Aside from the temperature control in the conversion technology, the conversion process is comprised of many sub-processes (cracking of longer molecules, separation and purification steps), which all need to be managed well in order to maintain temperature control. If the syngas cools in the system, tars contained in the gas will condense on the walls and ultimately clog the system. Clogging the installation leads to a forced stop, cleaning and start-up again. This is the foremost reason why some demonstration installations for waste/biomass have not been able to be implemented at a large scale. In order to prevent tar formation, temperature control in the installation is essential. While DNV cannot guarantee that this technological development will reach maturity and large-scale implementation relating to the aforementioned hurdles, it is our opinion that the operational challenges can be overcome with an experienced operational team, technical support and learning from past mistakes.

[73] **Lui et. al. (2020)** ***A critical review on the principles, applications, and challenges of waste-to-hydrogen technologies*****. Available at:** https://doi.org/10.1016/j.rser.2020.110365

Table 6-3:Summary of risks for gasification

Topic	Observations	Implications	I	P	Risk
Thermochemical process control	Typical issues relate to temperature control. Varying temperature in the system and at equipment interfaces can result in decreasing yield, as well as tar formation. Tar formation typically originates from methane condensation in the system.	Tar formation is problematic in small piping such as heat exchangers. Heat exchangers improve the thermal efficiency of the process, and clogging then results in the installation having to shut down to clean and replace clogged up parts. [74] Therefore, assuming a typical 8000 operational hours is optimistic according to DNV, and DNV advises to assume a conservative ramp-up for the gasification technology.	H	M	
Maturity	Gasification, while having been investigated for decennia, is an emerging technology when using biomass and waste as feedstock. While the TRL is dependent on the supplier, based on DNV experience the technology can nowadays be considered as TRL 8 (According to the EU classification of TRL[75]).	Unforeseen technical challenges relating to emerging technologies can only be circumvented through continuous practice and years of experience. Lack of understanding of gasification and related operational issues will lead to downtime.	M	M	
Variable feedstock	A key factor in the continuous gasification process is the sourcing of feedstock with constant calorific value.	Variable feedstock can result in clogging and low yields, meaning downtime, maintenance issues and increased costs. Uniform feedstock is an effective mitigation measure to circumvent this challenge.	H	M	
Low calorific feedstock (logistics)	Sourcing feedstock with low calorific value can be a solution when feedstocks with higher CV are in too high demand. But low CV means the installation requires more “fuel” to make the required amount of product.	More transport implies higher costs and potential logistical challenges, to the point where supply of feedstock becomes the bottleneck of the operation.	M	M	
Safety	High temperatures and combustible products are inherent to the gasification technology.	Safety measures on site are essential in order to guarantee good Health and Safety conditions for the operators.	M	M	
Solid waste handling	Logistical waste issues and local regulatory framework need to be investigated in order to understand how the waste by-products from the process have to be treated.	Environmental permits need to be granted by local authorities in order to be able to operate. With the possible gaseous emissions and waste water from the system, these need to be mapped out and controlled in order to be environmentally acceptable.	M	L	

[74] DNV experience also indicates that tar is not the problem for large scale (biomass) gasification. Calcium, potassium carbonate and Sulphur balance control is what is needed to steer, which also avoids clogging. However, since large scale gasification using more challenging feedstocks than coal have not been sufficiently proven, additional testing is necessary.

[75] TRL | EURAXESS (europa.eu)

6.3.2 Direct air capture (DAC)

The DAC technology supplier considered in this study is Carbon Removal based in Norway. However, it must be noted that the DAC technology provider for Carbon Removal is Carbon Engineering that is based in Canada. The DAC plant of Carbon Removal is considered to be located in Kollsnes for the purpose of this study.

The technology description is primarily based on Keith et al 2018, that corresponds to the technology of Carbon Engineering. A schematic of the DAC process is illustrated in the figure below.

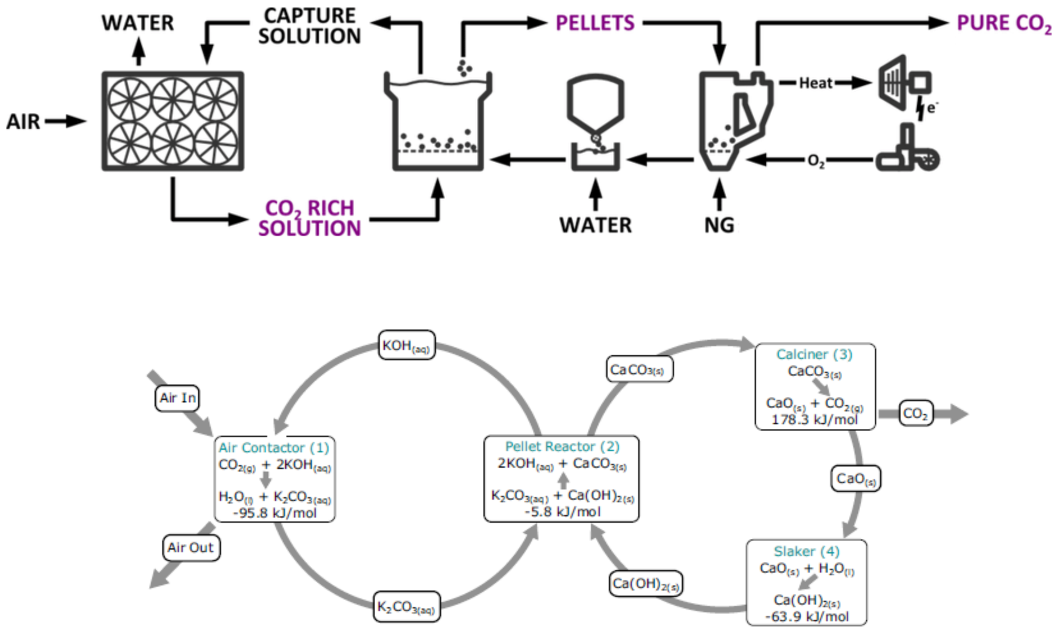

Figure 6-11: Typical DAC system/process (*Keith et al., 2018*)

The DAC system integrates two main cycles:

Absorption cycle: During the absorption cycle air is pulled in through the air contactors and passes over a potassium hydroxide (KOH) solution to capture CO_2 present in air as a carbonate salt according to the following reaction

$$CO_2 + 2KOH \rightarrow H_2O + K_2CO_3$$

The capture takes place at ambient temperature and pressure.

Regeneration cycle: The carbonate salt K_2CO_3 formed flows into the pellet reactor, where the CO_2 dissolved in the capture solution reacts with $Ca(OH)_2$ to form small pellets of $CaCO_3$ that precipitates out of the solution according to the following reaction

$$K_2CO_3 + Ca(OH)_2 \rightarrow 2KOH + CaCO_3$$

This process regenerates the primary KOH capture solution, which is then returned to the air contactor unit. Subsequently, in the most energy intensive step, $CaCO_3$ pellets formed during regeneration step are heated up to around 900°C in the calciner to release CO_2 .

$$CaCO_3 \rightarrow CaO + CO_2$$

In a final step, CaO produced in the calciner is converted to $Ca(OH)_2$ in the slaker, thus regenerating the alkaline solution used in the pellet reactor.

$$CaO + H_2O \rightarrow Ca(OH_2)$$

The DAC process requires two sources of energy inputs:

1) Electricity: to power fans, pumps, CO_2 compressor, electric motors etc.
2) Natural Gas: to provide high temperature heat in the calciner

The energy consumption is quantified at 1460 kWh/tonne CO_2 in the form of natural gas and 366 kWh/t of electricity. It should be noted that the DAC process currently utilizes fossil fuel sources, which emits CO_2 during the capture process, which needs to be permanently sequestered and the rest can be used for the production of e-fuels. However, DNV further understands that Carbon Engineering has ambitions to switch to renewable energy sources for both heat and electricity that will eliminate fossil-based CO_2 emissions and reduce the carbon footprint of the process and improve carbon capture efficiency.

In terms of consumables, the process requires oxygen for the combustion of natural gas for energy demand in the calciner. Oxygen can be bought directly or produced on site in an air separation unit (ASU). However, with intentions to switch to an electric calciner, the need for oxygen could be eliminated. As solvent/sorbent for CO_2 capture, KOH is required and needs to be added to the process to compensate for any losses especially through liquid waste generated. Additionally, $CaCO_3$ needs to be added to compensate for the losses through solid waste. The consumables for this DAC process are base chemicals that are easy to source and are produced worldwide.

Waste generation is a major concern for this specific DAC process. Solid waste is generated as grit (95wt% $CaCO_3$, 5wt% CaO) in the slaker, which consists of impurities and non-converted material from calciner. A liquid waste stream is also generated which consists of water, $CaCO_3$, KOH and K_2CO_3.

According to the knowledge of DNV, the DAC process of Carbon removal/engineering is slightly complex compared to other mature DAC technologies available such as Climeworks that utilize solid sorbent beds. The process of Cabon Engineering/Removal further requires continuous refill of consumables and leads to continuous generation of waste that needs handling. While different DAC processes have their pros and cons, DNV recommends considering a feasibility study for choosing the ideal DAC supplier from the most mature DAC suppliers.

DNV further recognizes that Kollsnes as a location for the DAC plant is attractive due to the availability of natural gas as required by the process and the access to CCS infrastructure.

Table 6-4: Summary of risks for DAC

Topic	Observations	Implications	I	P	Risk
Maturity	Based on the experience of DNV, the proprietary DAC technology developed by Carbon Engineering is considered to have a TRL of 8 according to the EU classification of TRL, given that the actual system has been demonstrated in operational environment.	Given that Carbon Removal in Norway will be using the same concept of Carbon Engineering, it can be deduced that they have sufficient operational experience of carbon engineering to operate it in Norway.	M	M	
CO_2 for use in SAF	The DAC CO_2 and the fossil NG CO_2 has a ratio of 1:0.3 based on a NG emission factor of 0.20 t CO_2/MWh NG.	One has to differentiate between the DAC fraction and the fossil CO_2 which should be sequestered (or used as a fossil carbon source)	H	M	
Heat availability	Electricity and high temperature heating of 900 ºC is needed, which currently comes from natural gas combustion.	Additional CO_2 generated by natural gas combustion needs to be captured to maintain CO_2 balance, unless the heat source is renewable such as renewable hydrogen or, electricity.	H	M	

Waste generation	Generates chemical waste such as: • Grit (95wt% $CaCO_3$ + 5wt% CaO) • Liquid waste (water + $CaCO_3$ + KOH + K_2CO_3) • Brine (if brackish water is used)	Solid and liquid waste need further processing and is energy intensive.	H	M	
Consumables availability	The main consumables used are KOH and $CaCO_3$, which are used as the sorbent for capturing the CO_2.	Consumables are off the shelf components and are easy to source. Usage of logistics from Mongstad is also beneficial here.	L	L	
Land use	Air contactors used in the capture process require sufficient spacing.	A large-scale DAC plant will require significant land availability. Scale up may be hindered by the prioritization of land for other uses.	M	L	
Scalability	Carbon Engineering has a modular approach for air contactors while regeneration cycle (i.e calciner) consists of large-scale modules for cost efficient design. Their scale up ambitions is to build a plant that captures 1 million metric tonnes per annum.	While the modular air contactors are easy for scale up, the large scale modules in regeneration are highly appropriate for large scale applications.	L	L	
DAC plant location	DAC installation is located in Kollsnes, while the SAF production facility is at Mongstad. The liquefied captured CO_2 needs to be transported to Mongstad by either truck, ship or a new pipeline would need to be built.	Transporting either way could negate the potential benefits from capturing CO_2. Alternatively, a pipeline will be a highly costly one.	H	M	

6.3.3 Syngas to alcohol

LanzaTech specialises in the production of ethanol through their patented process. This is comprised of a proprietary gas fermentation process for the conversion of carbon-rich industrial waste gases and syngas to ethanol. It can be noted that ethanol production is impacted by the amount of energy (H_2 and/or CO) and carbon (CO_2 and/or CO) in a gas. LanzaTech has stated to have three plants operating commercially on waste gases from industry and has several demonstration plants that have been shown to operate syngas from gasifiers in the previous decade.

The LanzaTech process can continuously convert gases containing fluctuating levels of CO_2, H_2 and CO to ethanol using a microbial biocatalyst known as an acetogen.[76]

According to LanzaTech, the conversion steps are then as follows:

- The Gas Conditioning Unit removes impurities that impact the downstream process or the Biocatalyst.
- The fermentation process occurs in a bioreactor, where gas is converted using LanzaTech's proprietary biocatalyst. The production of ethanol occurs in a liquid phase broth and produces additional Biocatalyst through growth.
- Once the microbial reactions have occurred, the tailed gases scrubbed and partially looped back into the process. Broth from the bioreactor is sent to distillation for production of fuel or chemical grade ethanol, with water recycled back to the process

[76] Advanced Gasification Technologies – Review and Benchmarking: Task report 2

- Spent Biocatalyst is recovered and sold as a high-protein animal or fish feed supplement called LanzaTech Microbial Protein (LMP).

The yield of syngas to ethanol will vary depending on the syngas composition, with process yield driven by the total volumetric flows of H_2 and CO available (energy containing gases). Selectivity to the target product (ethanol) remains high across a wide variety of gas feedstocks.

Table 6-5: Summary of risks for syngas to alcohol, LanzaTech process

Topic	Observations	Implications	I	P	Risk
Maturity	The proprietary fermentation technology developed by LanzaTech has achieved TRL 9 as the actual system has been proven in an operational environment. However DNV has not been able to assess the TRL themselves. Furthermore, publicly available information suggests that commercial operation of the technology has been ongoing since 2018.	Relating to the strong petrochemical expertise within the company and the proven operational concept, LanzaTech appears perfectly capable of building and operating such an installation. They are in progress to commercialise larger plants.	L	L	
Bioprocessing control	Bioreactor and process are well controlled to support the ethanol production yield and efficiency.	Scale-up is achieved with multiple reactor trains, and performance demonstrated on syngas from gasified-MSW previously so process environment control is nearly identical within the bioreactors.	L	L	
Operation and Maintenance	Some of the bioprocesses are rather complex, and require in-depth knowledge of the biochemistry This is also the case for the maintenance and production of the fermentation bioreactor.	Based on the process description, DNV expects specialist O&M staff will be required. In order to operate this conversion step, LanzaTech personnel will have to educate the operators, provide 24/7 support or operate the installation themselves. Training, support, and monitoring software are all provided by LanzaTech.	M	M	
Purification step	The purification step is typically one of the more important steps in syngas-to-ethanol processes. Both at the in- and output of fermentation, complex mixtures are processed and converted.	LanzaTech utilizes standard distillation methods as seen in first generation ethanol plants (stripping, rectification, dehydration). LanzaTech does not require extractive distillation columns for recovery of ethanol. LanzaTech has also been operating several commercial facilities with this design since 2018 with no redesigns.	M	L	

6.3.4 Alcohol to jet

LanzaJet is a company employing leading and patented technology which converts ethanol to Sustainable Aviation Fuel and renewable Diesel using AtJ (Alcohol to Jet). It has a maximum yield of 90% SAF in the product mixture with the remaining 10% as renewable Diesel (RD), meeting the standards and specifications for Sustainable Aviation Fuel and Renewable Diesel[77]. LanzaJet has indicated having a pilot plant running from 2014, providing extensive operational experience, as well as providing all the kerosene needed for the ASTM testing that eventually resulted in the approval of

[77] According to the LanzaJet website, the process converts ethanol to Synthetic Paraffinic Kerosene (SPK) and Synthetic Paraffinic Diesel (SPD). The process is an approved pathway to produce SAF in accordance with ASTM D7566 Annex A5, which permits blending up to 50% with conventional Jet A aviation fuel.

the AtJ pathway under ASTM D7566 Annex A5. Additionally, LanzaJet is constructing a 10 Million gallon per year installation to be commissioned in 2023. LanzaJet indicates that their modular design is for a 30 million gallons per year product capacity, which converts to 113 million litres of annual SAF + RD production. As such, this unit is used as a boundary condition for this study. It can be noted that LanzaJet is building a 10 million gallon per year installation, meaning this could also be a relatively feasible option. However, considering the fact that SAF uptake is projected to increase over the coming years, the larger capacity of 30 million gallons per year is taken as baseline in this study.

The LanzaJet ATJ process is based on four conversion technologies that have been proven for decades in the petrochemical industry. As such, the whole chain can be considered mature. It should be mentioned that one of the steps discussed below, the catalytic oligomerization, is still in late development phase (considered TRL 7) and will progress after startup of their 10M GPY ASTJ plant in the US (may still require finetuning). The 4 processing steps, which follows ASTM D7566-A5, is illustrated in Figure 6-12 and Figure 6-13 below, and can be described as follows. Dehydration (1) is the process of removing water from the ethanol molecules to produce ethylene and water. The ethylene is then oligomerized (2) (meaning small molecules are combined in order to make longer molecules) into longer carbon chain olefins, followed by Hydrogenation (3) (adding hydrogen) and Fractionation (4), which is the separation of the final product into the desired fraction of diesel and Jet fuel.

It can be noted that the AtJ process can tune the fraction of SAF (or diesel) in the end result, and that it is during the Oligomerization step that this occurs. For example, it can produce 90% SAF + 10% RD, or 25% SAF + 75% RD for a max diesel application. Following this, the third step involves saturating the long olefinic molecules from the second step through a process called hydrogenation. The result is a mixture of paraffins and iso-paraffins and no aromatics. Finally, the mixture goes through a process of fractionation, where the blend is separated into kerosene and diesel.

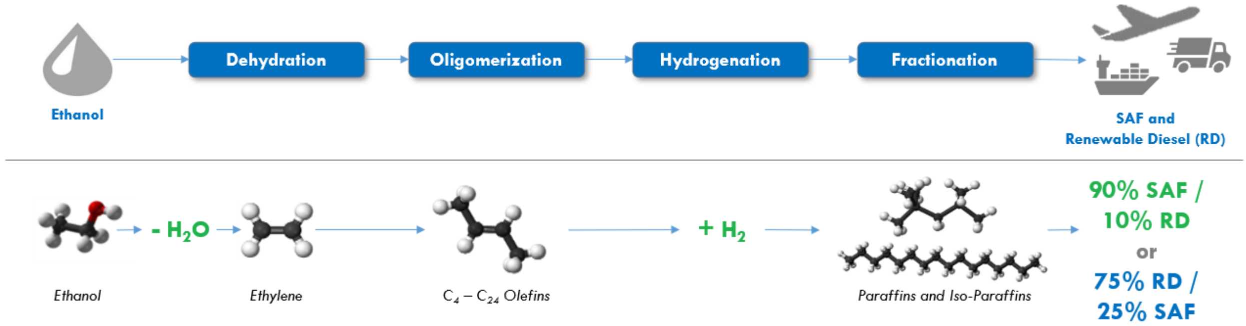

Figure 6-12: LanzaJet alcohol to Jet Process Steps and Chemistry[75]

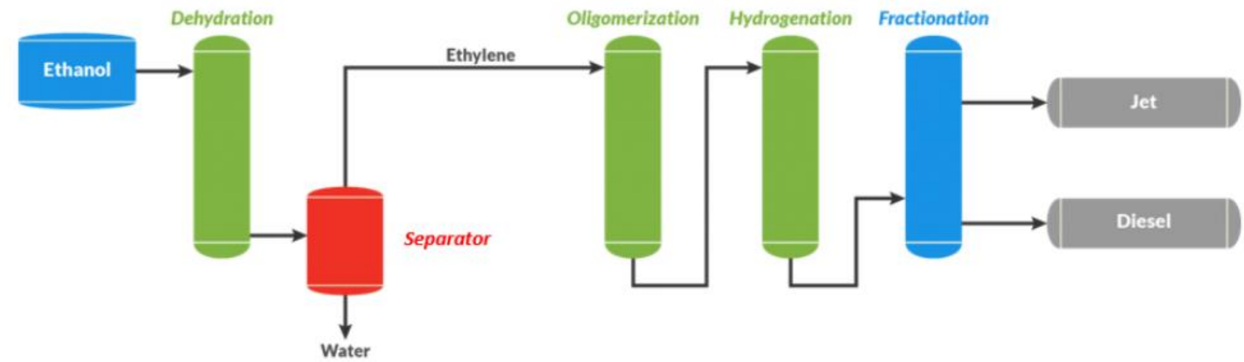

Figure 6-13: LanzaJet Alcohol to Jet Process[78]

As previously mentioned, the technology is comprised of catalytic conversion units that are widely used in the petrochemical industry, where diesel and kerosene yield can be tuned to produce a blend ranging from 90% kerosene –

[78] [https://www.LanzaJet.com/what-we-do/]

10% diesel to 25% kerosene – 75% diesel, without any changes to the installation. LanzaJet indicates that there are no additional by-products aside from SAF and diesel.

Table 6-6: Summary of risks for alcohol to jet, LanzaJet process

Topic	Observations	Implications	I	P	Risk
Cost variability	Since the installation is a modular and pre-engineered concept, LanzaJet can propose a fixed price for a modular installation ATJ process unit	A fixed price means a limited cost overrun, relating to a predictable timeline and concept based on previous experience from the engineering team.	L	L	
Maturity	Almost the entire conversion chain is mature and proven, except for a single unit at TRL 7, called the catalytic oligomerisation of ethylene to jet and diesel range hydrocarbons.	The operational experience for this unit will be gathered in the first years of operation of the 10 Million gallon/year installation. While oligomerization is a well-known process, additional insights may be gathered to optimize further. The low TRL may also lead to unforeseen operational challenges, so a conservative ramp-up is advised, similarly to the previously mentioned gasification ramp-up.	L	M	
Modular	The LanzaJet installation is a standardized module design, built by LanzaJet and includes full Quality Control and factory acceptance prior to shipment on site. It can also be noted that the modularity allows for fast and relatively secure installation.	A reliable, standardized modular design and capacity provides a lot of flexibility in relation to the conceptual design and scale-up needed for the SAF production in Norway across multiple similar units in different locations.	L	L	
Track record	LanzaJet has communicated having built and operated a pilot plant from 2014-2017, as well as a plant being commissioned in 2023 for 10 Million gallons/ year. Several other LanzaJet ATJ units are in various stages of design with capacities ranging from 10 to 300M GPY in numerous geographies and feedstocks.	With only one plant that has operated at a smaller scale, and one plant being commissioned for 1/3 of the Norwegian scale plant, further detail may be needed in order to guarantee that a 30 million production of SAF is feasible. It can be noted project DRAGON in the UK has completed basic design and in the FEED phase for a 30M GPY ATJ unit in the UK for 2025 start up.	M	M	

6.3.5 Blue Hydrogen

Blue hydrogen may be imported locally from the Mongstad facility. This is done to compensate for hydrogen deficiency at the various conversion steps of the process. The hydrogen is needed to maintain the stoichiometric ratio needed to optimally produce SAF. Depending on the value chain and capture rates, SAF may be achieved, with >70% GHG reduction. In this study, DNV has not reviewed the blue hydrogen production pathway in detail. Figure 6-14 illustrates the emissions in the value chain, where very high capture rates are shown to be sure to meet the GHG criteria.

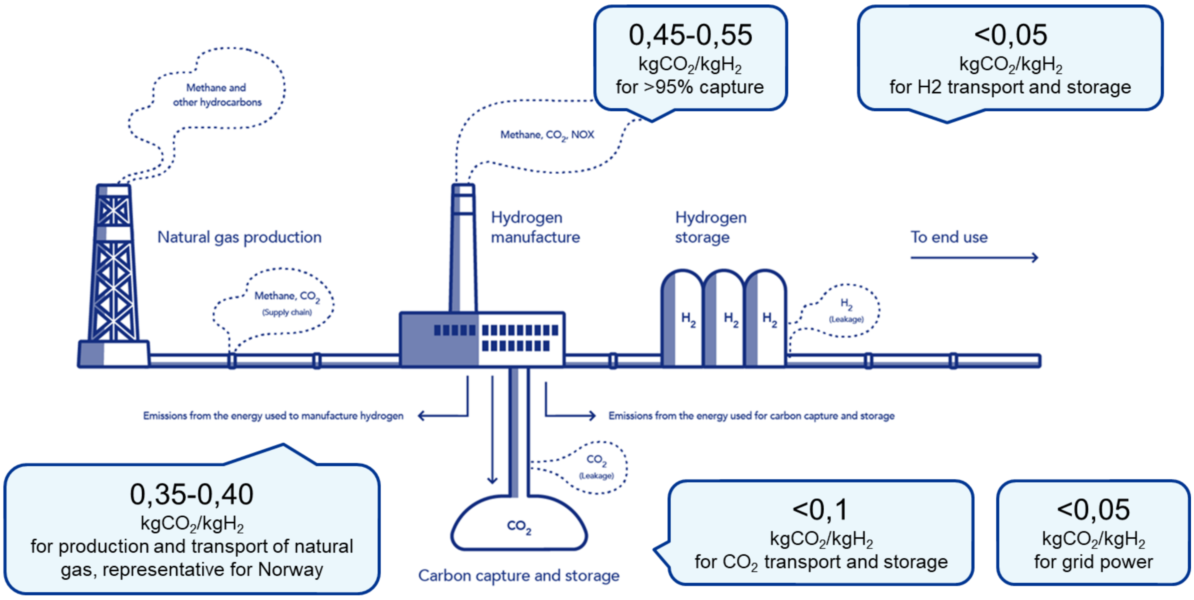

Figure 6-14: Greenhouse gas emission target setting for ultra low-carbon blue hydrogen, <1.0 kg CO_2/kg H_2 (DNV, Blue H_2 White Paper 2022)

6.4 Pathway and Scenario analysis

DNV has followed a pathway-scenario approach to evaluate the SAF production process by taking into consideration the combinations of individual technologies mentioned earlier. In this context, a pathway refers to a stepwise process to produce SAF from a specified feedstock, and/or other components. A scenario refers to variability in external factors, specifically the availability of MSW feedstock and its supply for this study. The pathways and scenarios are explained in detail in the following sections.

As previously stated, MSW is comprised of both biological and non-biological waste. For the purpose of this study, the MSW is comprised of 50% biological and 50% non-biological streams.

6.4.1 Pathways

Two pathways have been identified as described below. The pathways are mainly distinguished by the variations in components (i.e. CO, H_2 and CO_2) fed into the fermentation unit and how those components are sourced.

Pathway 1: Syngas from gasification of MSW

In this pathway, syngas produced from the gasification that consist of mainly hydrogen, carbon monoxide and carbon dioxide is fed to the fermentation process for producing ethanol. While multiple reactions between the different components can take place, DNV has considered the following dominant reactions to happen simultaneously in this pathway based on the information received from LanzaTech.

$$3H_2 + 3CO \rightarrow C_2H_5OH + CO_2$$

$$4H_2 + 2CO \rightarrow C_2H_5OH + H_2O$$

CO and H_2 in syngas are carbon and energy sources for the biocatalyst, while CO_2 is not an energy source and requires H_2 for conversion to ethanol. However, most syngases do not have sufficient H_2 to fully convert the CO_2, therefore, supplemental hydrogen can be added as a co-feed to produce more ethanol. This yield is highly dependent on feedstock availability.

Consequently, under insufficient MSW feedstock circumstances, blue H_2 and CO_2 from DAC would need to be added to the fermentation unit to achieve the targeted SAF production of 113 million liters. As a result, the following reaction is plausible. The impact of feedstock availability on the mass and energy balance is further explained in scenario section.

$$6H_2 + 2CO_2 \rightarrow C_2H_5OH + 3H_2O$$

Hydrogen is always required for the LanzaJet process, and this is considered blue hydrogen as well. The following schematic illustrates SAF production through pathway 1.

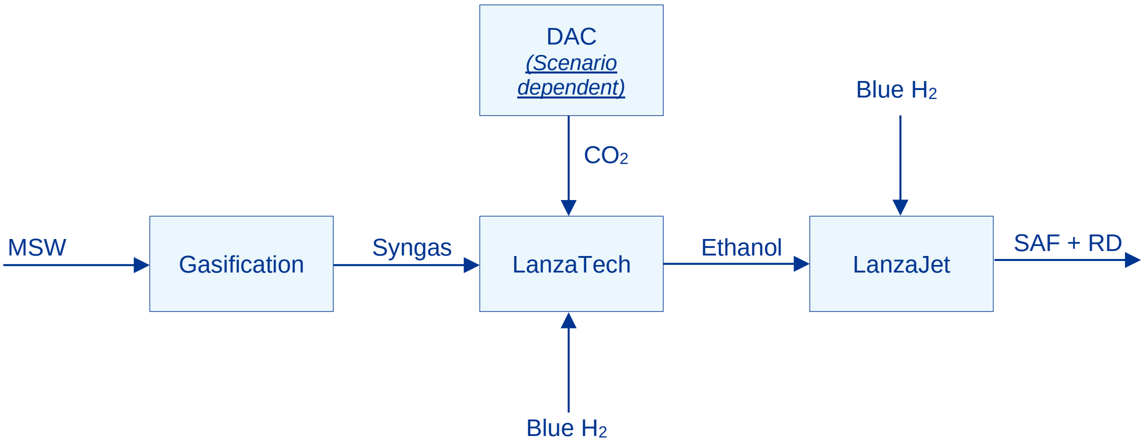

Figure 6-15: SAF production through pathway 1, using Syngas

Pathway 2: Blue H_2 and CO_2 from DAC

In pathway 2, gasification process is completely eliminated and thus the need for waste availability and the SAF production dependency on non-biological feedstock. Blue hydrogen is sourced that reacts with high purity carbon dioxide (>99%) from DAC to produce ethanol. It must be further noted that some CO is always needed for the LanzaTech process to be operational. According to LanzaTech, 25% of the carbon source needs to come from CO. Consequently, a reverse water gas shift reactor (RWGS) would be needed to generate CO from the CO_2 of the DAC process along with blue H_2. The following dominant reaction will take place in the LanzaTech process and the schematic illustrates the SAF production process through pathway 2.

$$6H_2 + 2CO_2 \rightarrow C_2H_5OH + 3H_2O \text{ (main reaction in LanzaTech process)}$$

$$H_2 + CO_2 \rightarrow CO + H_2O \text{ (reverse water gas shift reaction)}$$

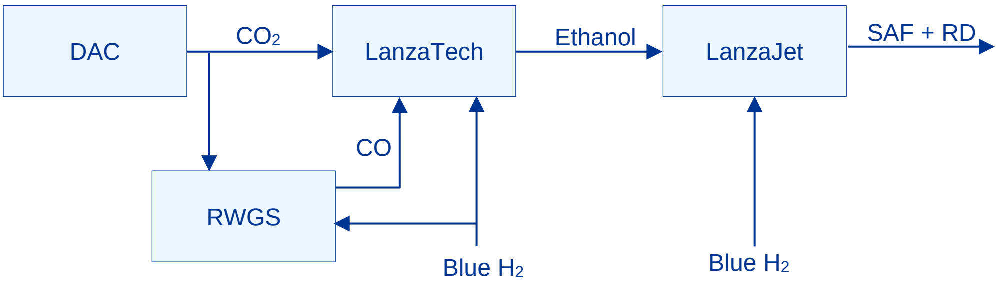

Figure 6-16: SAF production through pathway 2

For the purpose of this study, DNV has performed a detailed assessment on pathway 1, while pathway 2 is proposed as an alternative SAF production route.

It is also worth mentioning that during the project a hub-and-spoke set-up has been identified as a likely more efficient value chain and logistics set-up. This concept is designed and planned as for processing the waste to ethanol in various locations near the waste collection and sorting, and then ethanol is transported to the Alcohol-to-Jet processing plant. It has not been part of the scope to evaluate alternative upstream logistics concepts, but it is recommended that the hub-and-spoke concept is explored as an alternative solution for more cost effective and sustainable SAF production.

6.4.2 Scenarios

Based on the feedstock inventory mentioned in earlier sections, the amount of feedstock necessary for the production of 113 million Liters of SAF + RD is estimated to be around 650 kilotonnes (at 30% moisture) per year of MSW (LHV of 12 MJ/kg). It is noted that if the MSW is treated to make higher-energy Refuse Derived Fuel (RDF), it will improve the overall logistical challenges by decreasing the amount of feedstock required. This improvement is even greater when using plastics, given that the calorific value of plastics is roughly three times higher than that of MSW.

Scenarios are then classified based on the availability of feedstock as well as how they are sourced. Three scenarios have been proposed as follows in order to evaluate pathway 1 described earlier:

1) **Scenario 1: Base case scenario**
    a. **Scenario 1**.1: All required feedstock (650 kilotonnes) to produce 113 million liters of SAF + RD is sourced locally from across Norway
    b. Scenario 1.2: Addition of blue hydrogen to convert excess CO_2 present in the syngas as explained in the description of pathway 1 in previous section, that reduces the quantity of MSW required as in scenario 1.1.
2) **Scenario 2:** All required feedstock (650 kilotonnes) to produce 113 million liters of SAF is imported
3) **Scenario 3:** Realistically available local feedstock is sourced to produce a part of the targeted SAF, and the fermenter is supplemented with additional blue hydrogen and CO_2 from DAC to produce the remaining amount of SAF. The realistically available feedstock is considered to be roughly 1/4 of the total waste streams availability as stated in section 6.2.5.

Scenario calculations have been based on efficiency numbers shared by LanzaTech. Consequently, the following feedstock quantifications are concluded for the aforementioned scenarios.

Scenario	Feedstock (kilotonnes)	Additional information
1.1	650 kilotonnes of MSW	Sourced by ship
1.2	330 kilotonnes of MSW	MSW is sourced by ship + supplementing blue hydrogen
2	650 kilotonnes of MSW	Imported from the United Kingdom, and Italy by ship
3	230 kilotonnes of MSW	Locally sourced by ship + supplementing CO_2 with DAC and Blue Hydrogen

According to the table above, 650 kilotonnes of MSW corresponds to the maximum feedstock that is required based on conversion efficiencies provided by LanzaTech.

The following **assumptions** are made during the detailed evaluation of pathway 1 and its 3 scenarios:

- The syngas composition in the following range is considered:

Syngas component	Mol (volume)%
CO	40-45%
CO_2	14-20%
H_2	30-35%
CH_4	1-4%
H_2O	2-6%

- The mass of wet syngas produced by gasification is higher than the solid plastic feedstock due to the addition of an oxidant. While this can vary widely depending on the gasifier design and type of oxidant, up to 50 wt% increase is expected for plastic feedstocks. However, given that the MSW has lower calorific value than plastic, this increase is considered to be proportionally lower. Notably, the calorific value of syngas is lower than the calorific value of the MSW (including other energy inputs), as gasification is an exothermic process.
- OPEX associated with feedstock, CO_2 and H_2 transport have not been considered in this study, as these costs are highly variable depending on the logistic service suppliers.
- An average hydrogen price of 6.9 EUR/kg is used according to DNV ETO price projections between 2020 to 2030.

6.4.2.1 Pathway 1 – Scenario 1: Ideal scenario – Locally sourced MSW

Scenario 1 consists of two parts as explained in section 6.4.2.

Scenario 1.1

In part 1 of scenario 1, named as scenario 1.1, it is assumed that the 650 kilotonnes of feedstock required to produce 113 million liters of SAF and renewable diesel is locally available It must be noted that this is an ideal scenario as feedstock that can be considered for SAF production is already contracted within Norway. Table 6-7 summarizes the mass and energy balance, CAPEX and OPEX for the production of 113 million liters of SAF+RD.

Table 6-7: Mass and energy balance, CAPEX and OPEX for scenario 1.1

CONVERSION STEP	TECHNOLOGY	CAPEX (MEUR)	OPEX (MEUR)	MASS BALANCE (KILOTONNES OF INPUT)	ENERGY CONSUMPTION (GWH)
MSW TO SYNGAS	Gasification technology	250-300	8-10	650 kilotonnes	150-200
SYNGAS TO SAF	LanzaTech and LanzaJet	300-400	25-35	-	200-300
	OTHER ITEMS				
-	BLUE HYDROGEN	-	5-10	1 kilotonne	-
	TOTAL	550-700	38-55	113M liters SAF+RD	3.5-5 MWh/ t SAF

It must be noted that the blue hydrogen in this scenario is only for the LanzaJet process.

As stated earlier, OPEX associated with feedstock transport have not been considered in this study, as these costs are highly variable depending on the logistic service suppliers. Furthermore, a gate fee for the waste feedstock is considered at 50 EUR/ton. Typically, waste generators are entitled to pay a gate fee for offloading their waste. It is therefore considered as an income at the gasification site, as this waste feedstock is offloaded at the gasification facility. This creates an additional income of 32 MEUR.

The fuel produced in Scenario 1.1 can be classified as a 50% biofuel and 50% RCF, as the SAF production originates from MSW that is assumed to consist of 50% biological and 50% non-biological parts.

Scenario 1.2

In part 2, named as scenario 1.2 the conversion of excess CO_2 present in the syngas to ethanol with additional hydrogen is considered. Consequently, the quantity of MSW will be reduced. It is estimated that additional hydrogen would reduce the MSW requirement by approximately a half, which further reduces the costs and energy associated with the gasification process. Table 6-8 summarizes the costs and energy consumptions for this.

Table 6-8: Mass and energy balance, CAPEX and OPEX for scenario 1.2

CONVERSION STEP	TECHNOLOGY	CAPEX (MEUR)	OPEX (MEUR)	MASS BALANCE (KILOTONNES OF INPUT)	ENERGY CONSUMPTION (GWH)
MSW TO SYNGAS	Gasification technology	150-200	4-6	330 kilotonnes	50-100
SYNGAS TO SAF	LanzaTech and LanzaJet	300-400	25-35	-	200-300
OTHER ITEMS					
BLUE HYDROGEN		-	125-150	20 kilotonnes	-
TOTAL		450-600	151-191	113M liters SAF+RD	2.5-4 MWh/t SAF

The blue hydrogen in this scenario covers hydrogen requirements for both the LanzaTech process and the LanzaJet process. However, as also stated in scenario 1.1, the hydrogen requirement of LanzaJet process is much lower at 1 tonne compared to the 19 tonnes required for the LanzaTech process.

Considering the same gate fee for the waste feedstock at 50 EUR/tonnes creates an additional income of 17 MEUR.

As explained, the SAF production in scenario 1.2 is half originated from MSW (50% biological and 50% non-biological), while the other half is originated from the conversion of additional blue hydrogen and CO_2 in syngas. This leads to a mix of output fuel categorized into 25% biofuel (from the biological part of the MSW), 25% RCF (from the non-biological part of the MSW) and 50% low carbon fuel. However, it must be noted that the 50% low carbon fuel share in this scenario is only due to the use of blue hydrogen as in the definition of low carbon fuels. If green hydrogen had been used, this fraction would have qualified as RFNBO. It should also be noted that it is still unclear how the use of blue hydrogen to increase the conversion of carbon will be dealt with in the EU regulations. With the ReFuelEU provisional agreement from April 2023 on blending mandates and SAF qualifications (see chapter 3.1.1.1) the fuel share classified as low-carbon fuel may not be considered as SAF.

6.4.2.2 Pathway 1 – Scenario 2: Imported MSW

Scenario 2 resembles scenario 1 in most ways, except that there will be additional OPEX items that arise from feedstock transport from abroad. However, as stated earlier due to the variabilities in transport costs, this has not been considered during this study. Table 6-9 summarizes the mass and energy balance, CAPEX and OPEX for scenario 2 and resembles scenario 1.

Table 6-9: Mass and energy balance, CAPEX and OPEX for scenario 2

CONVERSION STEP	TECHNOLOGY	CAPEX	OPEX	MASS BALANCE (KILOTONNES OF INPUT)	ENERGY CONSUMPTION (GWH)
MSW TO SYNGAS	Gasification technology	250-300	8-10	650 kilotonnes	150-200
SYNGAS TO SAF	LanzaTech and LanzaJet	300-400	25-35	-	200-300
OTHER ITEMS					
BLUE HYDROGEN -		-	5-10	1 kilotonne	-
TOTAL		550-700	38-55	113M liters SAF+RD	3.5-5 MWh/ t SAF

Considering the same gate fee for the waste feedstock at 50 EUR/tonnes creates an additional income of 32 MEUR.

The fuel produced in Scenario 2 can be classified as a 50% biofuel and 50% RCF, as the SAF production originates from MSW that is assumed to consist of 50% biological and 50% non-biological parts.

6.4.2.3 Pathway 1 – Scenario 3: Actual available local MSW

In scenario 3, realistically available feedstock in Norway is taken into consideration, which is approximately 230 kilotonnes, determined as 1/4 of the total waste streams available as explained in section 6.2.5. This indicates that there is insufficient feedstock to achieve the targeted SAF production. Consequently, blue hydrogen and CO_2 from DAC are added to the process produce sufficient ethanol that is eventually converted to SAF. It must be noted that this is a similar scenario to scenario 1.1, but takes into account the realistically available feedstock in Norway. Table 6-10 summarizes the mass and energy balance, CAPEX and OPEX for scenario 3.

Table 6-10: mass and energy balance, CAPEX and OPEX for scenario 3

CONVERSION STEP	TECHNOLOGY	CAPEX	OPEX	MASS BALANCE (KILOTONNES OF INPUT)	ENERGY CONSUMPTION (GWH)
MSW TO SYNGAS	Gasification technology	100-120	3-5	230 kilotonnes	50-70
SYNGAS TO SAF	LanzaTech and LanzaJet	300-400	25-35	-	200-300
DAC	Carbon Engineering	50-70	15-25	90 kilotonnes of CO_2	150-180
OTHER ITEMS					
BLUE HYDROGEN		-	165-190	-26 kilotonnes of H_2	-
TOTAL		450-590	208-255	113M liters SAF	4-5.5MWh/ t SAF

It can be deduced from table above that, for scenario 3 CAPEX is dominated by the LanzaTech and LanzaJet process for converting ethanol to SAF, as H_2 is treated as over-the-fence. The total CAPEX is lower comparatively to scenario 1 and 2 as a result of a smaller gasification unit for processing only 230 kilotonnes of feedstock. OPEX is dominated by the blue hydrogen purchase followed by OPEX associated with DAC plant. A gate fee income of 12 MEUR is estimated.

It must be noted that the DAC technology original supplier Carbon Engineering's scale up ambitions at this point is to build a plant that can capture 500,000 tonnes of CO_2 from the atmosphere annually, with the capability to scale up to one million tonnes per annum. The CO_2 requirement in the third scenario falls within this scale up ambition and demonstrates that scenario 3 is plausible for its realization.

Scenario 3 leads to a mix of fuel categories, whereby 18% is biofuel which corresponds to the biological part of MSW, 18% is RCF which corresponds to the non-biological part of the MSW and 64% is low carbon fuel due to a much larger SAF production share coming from blue hydrogen and CO_2 from DAC conversion. It should be noted that it is still unclear how the use of blue hydrogen to increase the conversion of carbon will be dealt with in the EU regulations. With the ReFuelEU provisional agreement from April 2023 on blending mandates and SAF qualifications the fuel share classified as low-carbon fuel may not be considered as SAF.

6.5 Greenhouse gas assessment

6.5.1 Feedstock transport

Regarding the GHG emissions relating from transport of feedstock, emissions from transport by maritime was considered. Further, for the different scenarios feedstock supply from the following locations have been considered:

1. Scenario 1 (both scenarios 1.1 and 1.2): MSW collection is anticipated from all across Norway and transport by ship to Mongstad with an average distance of 1300 km

2. Scenario 2: MSW is considered to import from UK (1060 km from Hull UK to Mongstad) and Italy (6120 km from Napoli Italy to Mongstad) (based on documentation from a partner, including a Letter of Intent), and transported to a centralized handling facility before being transported to Mongstad.
3. Scenario 3: MSW collection from all across Norway by ship to Mongstad is considered with an average distance of 1300 km. CO_2 transport from Kollsnes to Mongstad by ship is also considered (~120 km)

It must be noted that the initial collection step is not included in the analysis.

Compiling various GHG emission sources for transport emissions [79] [80] [81] [82], where Figure 6-17 is a prime example of such analysis, CO_2 emissions per ton.km have been used in order to roughly quantify the emissions relating to transport of feedstock. This unit relates to the grams of CO_2 for 1 to**nnes** and 1km of transport.

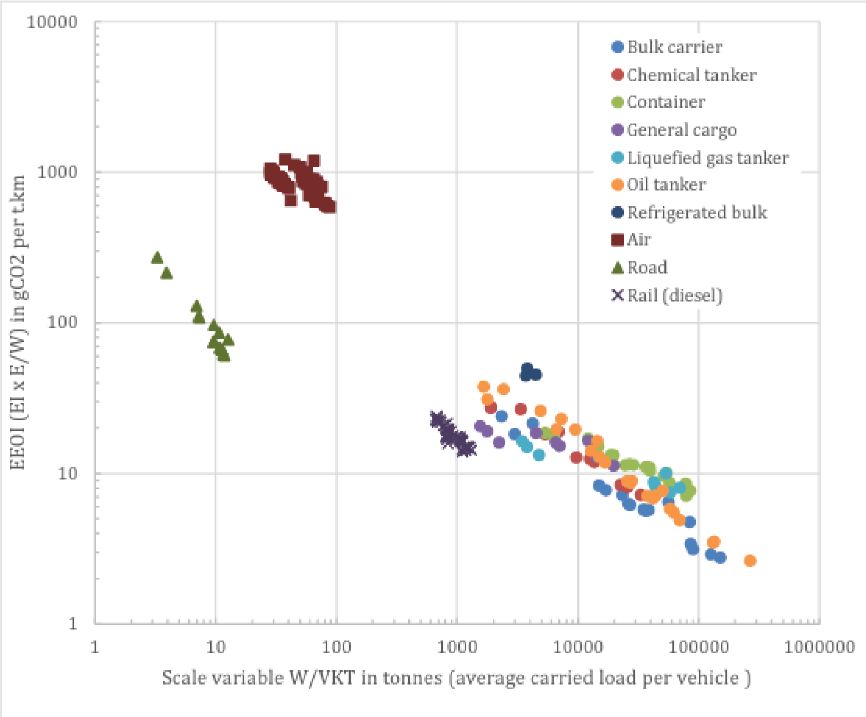

Figure 6-17 Analysis of the emissions of various modes of transport[83]

According to the illustrated figure, a CO_2 footprint of 10 g CO_2 per tonne kilometre, is considered for maritime transport. This is considered as an important part of the scope 3 emissions.

Scenario	Scope 3 emissions (t CO_2)
1	8,500
2	24,000
3	4000

[79] https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/MEPC%2068%20INF%2024%20REV1%20The%20existing%20shipping%20fleet%20CO2%20efficiency.pdf
[80] https://www.proquest.com/openview/556c9f2e9f36ccbdf2967c7aaa4e461e/1?pq-origsite=gscholar&cbl=2048152
81 https://www3.weforum.org/docs/WEF_Net_Zero_Challenge_The_Supply_Chain_Opportunity_2021.pdf

82 https://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf

83https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/MEPC%2068%20INF%2024%20REV1%20The%20existing%20shipping%20fleet%20CO2%20efficiency.pdf

It can be deduced from the table that scenario 2 has a higher CO_2 footprint due to the CO_2 footprint associated with shipping the feedstock from abroad. In scenario 3, the CO_2 footprint is comparatively lower due to the transport of only 230 kilotonnes of feedstock.

6.5.2 SAF Production

The CO_2 footprint calculations for the technologies in the SAF production are performed for the three scenarios of pathway 1. Table 6-11 summarizes the CO_2 footprint for the three different scenarios taking into consideration the following assumptions:

- Scope 1 emissions: Natural gas emission factor = 0.20 t CO_2/MWh (source: DNV Energy Transition Outlook, ETO)
- Scope 2 emissions: Electricity grid emission factor for Norway = 0.008 t CO_2/MWh (source: Norwegian Water Resources and Energy Directorate - NVE)
- Scope 3 emissions: Maritime = 10 g CO_2/km tonnefeedstock, Truck = 80 g CO_2/km tonnefeedstock (source: refer to section 6.5.1)
- Blue hydrogen related CO_2 emissions: 0.9 kg CO_2/kg blue H_2 (source: refer to section 6.3.5)

GHG emissions for fossil comparator (source: RED II) = 94 gCO_2eq/MJ

Table 6-11: CO2 footprint of the three scenarios

Process	Unit	Scenario 1.1	Scenario 1.2	Scenario 2	Scenario 3
MSW to Syngas	gCO_2eq/MJ	8.4	4.4	8.4	3.1
Syngas to SAF	gCO_2eq/MJ	11	11	11	11
DAC	gCO_2eq/MJ	-	-	-	5.9
Blue hydrogen	gCO_2eq/MJ	0.3	4.6	0.3	6.9
Transport	gCO_2eq/MJ	2.3	1.3	6.1	1
Total	gCO_2eq/MJ	22	21.2	25.9	27.9
SAF GHG >70% reductions “qualified”	%	77%	77%	72%	70%

The carbon footprint of the defined SAF production scenarios range between 21.2-27.9 gCO_2eq/MJ of SAF. This corresponds to a CO_2 emission reduction in the range of 70-77% in comparison to the fossil fuel comparator. These estimates are for the direct and indirect emissions, and are high level and rough estimates, and not detailed Life Cycle Assessments (LCA), including all CO_2 equivalents, but an indication. The margin for the threshold of >70 GHG reduction compared with the fossil fuel comparator is likely reached, but based on simplified assumptions and with some uncertainty.

6.5.3 Captured CO_2 supply to Mongstad

Apart from the important traffic that will be generated by transport of non-biological waste, the CO_2 captured using the DAC technology in Kollsnes will also require transportation to Mongstad in scenario 3, which will result in an additional

CO_2 footprint. Three methods are identified to transfer the CO_2 from DAC facility in Kollsnes: pipeline, truck, maritime shipping along with an alternative method whereby DAC supplier at Mongstad itself is considered.

- **Pipeline:** Based on the emergence of this technology, DNV does not foresee that installing a pipeline at this early stage would be feasible. A proof of concept for SAF production from non-biological waste feedstock is necessary first. However, based on a high over investment range, the cost of setting a pipeline is roughly 3.1 MEUR/km[84] onshore, and including a factor of 1.96 to have a range for offshore, this results in a cost of 6.1 MEUR/km. Using a distance of 30 km from Mongstad to Kollsnes (straight line), this results in an estimated cost of investment of 182 MEUR.
- **Truck:** The distance between Kollsnes and Mongstad by road is approximately 120 km for the transportation of CO_2 by truck.
- **Maritime shipping:** Shipping between port of Kollsnes and Mongstad could enable faster transport of CO_2 captured. The approximate distance between the two locations is 60 km.
- **DAC at Mongstad:** DNV is aware of other DAC suppliers building CO_2 capture facilities at Mongstad. Contracting them for supply of CO_2 can fully eliminate any costs associated with the transport of CO_2 from the currently considered DAC supplier in Kollsnes.
- **Transfer of CO_2 certificates:** If CO_2 is captured at Mongstad for transportation (to Kollsnes) and storage, a book-keeping / certificate transfer could be an alternative given that this is accepted by regulations. This can avoid the use of energy (and additional CO_2 emission) for transportation of CO_2 in both directions. In such a scenario CO_2 captured at Mongstad should be used directly instead of double transfer of CO_2.

6.6 Regulatory and market barriers

In Chapter 5, a high-level overview of drivers and barriers for establishing SAF production from non-biological feedstock in Norway is given. This chapter focuses specifically on the technologies and production processes proposed for Mongstad.

Norwegian regulatory environment regarding gasification and DAC

The regulatory context for gasification and DAC in Norway is closely linked to EU regulations. The EU regulations are indicated to be EEA-relevant and it is expected that they will be adopted in Norway, but the structure of this adoption is uncertain. The EU regulations concerning gasification and DAC is thoroughly described in Part 1 of the report. Gasification and DAC are both relevant in the regulations concerning RFNBO, RCF and low-carbon fuel. Gasification is one of the key technologies proposed in several of the production pathways for synthetic fuels. As DAC is considered to be a net remover of CO_2, the CO_2 provided by DAC into production of fuels is considered to be avoided, giving positive GHG effects.

There is today proposed, but still no legally valid regulatory framework for DAC in Norway or Europe, or even globally.[85] There are also large uncertainties related to the regulations revolving gasification processes. This leads to significant uncertainty to what requirements facilities using these technologies need to comply with. The regulatory uncertainty is considered to be a major barrier for establishment of projects, as this reduces the commercial attractiveness significantly. An additional issue for projects in Norway is that the timeline and implementation of EU regulation is even more uncertain, with possible delays and changes to the adoption.

[84] https://www.gem.wiki/Oil_and_Gas_Pipeline_Construction_Costs
[85] Industrien kan fjerne CO_2 med nye virkemidler - Miljødirektoratet (miljodirektoratet.no)

SINTEF and Vista Analyse recently conducted a review of direct air capture of CO_2, and concluded that the main obstacle to large-scale development of DAC is the lack of a market for the removed CO_2. The credits from the CO_2 removed can not be used by industries that are part of the EU ETS, and the non-ETS industries still have to pay the CO_2 tax for their emissions, regardless of the CO_2 removal credits.[86] This is important for DAC-projects that capture CO_2 for fuels production, because with today's standard DAC-sizes, fuel production is likely to only be a side-stream. This means that there needs to be market for captured CO_2, also outside fuel-production, for DAC to be feasible.

For the production processes addressed in this report, the regulatory framework regarding RCF is most relevant. As mentioned in Chapter 3.1 ReFuelEU came to a provisional agreement on SAF categories and blending mandates, which included RCF but excluded low-carbon fuels. This presents a significant risk, which is particularly relevant in Norway: whether the production of RCF using blue hydrogen as an input to the process will be allowed, even if the product achieves the GHG emissions savings threshold. DNV's understanding is that the energy in an RCF must be from a fossil non-recyclable waste source (see definitions in chapter 3.3). This means that using blue hydrogen as an input will give an end product that is partly low-carbon fuel, which does not qualify as SAF, even if GHG emission savings are >70%. The regulatory formulations on this are still unclear.

Market for SAF in Norway

Norway was the first country in the world with a SAF blending mandate: a 0.5% blending requirement for SAF was introduced in 2020. This is carried out on a country level mass balance basis with the majority of the SAF delivered at Oslo Gardermoen, with all airlines paying a fee for the 0.5% mandated volume of SAF. This means that smaller airports do not need to deal with acquiring and delivering SAF. From the introduction of the mandate from 1st January 2020 to January 2023, around 2 billion litres of jet fuel have been delivered in Norway of which 10 million litres would be SAF. Assuming an average cost over this time of 20 NOK/litre[87] this would equate to a value of 200 million NOK. It is worth bearing in mind that jet fuel sales in Norway have still not recovered to pre-pandemic levels.

Major buyers of aviation fuel (and therefore SAF) are the major airlines operating in Norway. Based on company reports, Norwegian Air Shuttle bought 524 tonnes of SAF, SAS bought 1060 tonnes, and KLM bought 4171 tonnes in 2021. This would represent 2.7 times the amount of SAF sold in Norway assuming the 0.5% mandate applied to all fuel sales in 2021. It is likely that some volumes are purchased outside of Norway or that fuel hedging results in more or less than 0.5% SAF being purchased in any given year. SSB do not currently differentiate SAF and fossil jet fuel in their statistics.

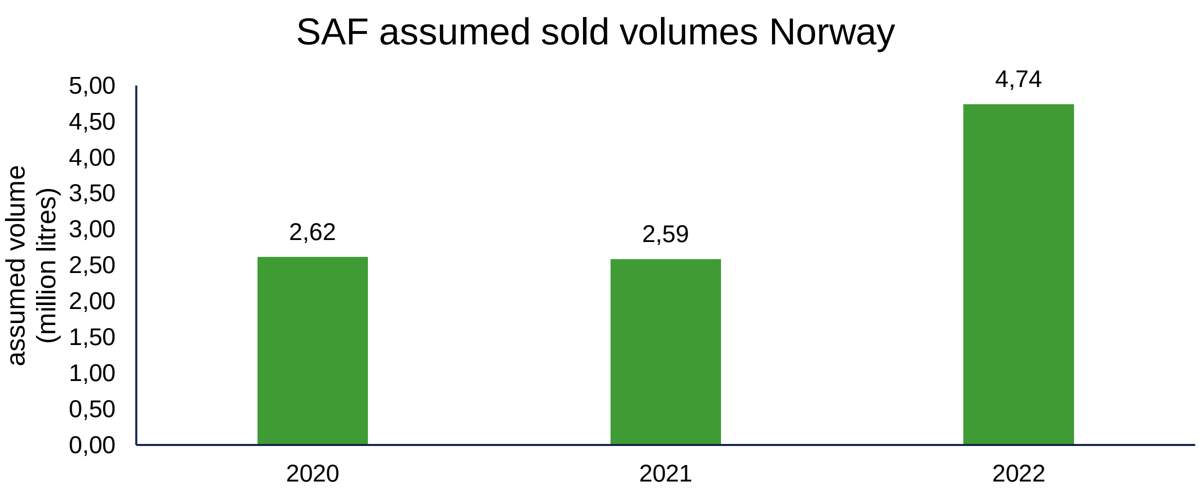

Figure 6-18: Expected SAF volumes (SSB)

86 https://www.miljodirektoratet.no/publikasjoner/2023/mars-2023/direct-air-capture-of-co2/
87 Prices - Aviation Fuelling Services Norway (afsn.no)

According to DNV's Energy Transition Norway report (DNV 2022) Norway's aviation sector is expected to recover to pre-pandemic levels by mid 2024. The number of air trips is expected to increase towards 2050 - fuel use will grow, but not at the same pace due to energy efficiency gains. Currently, 70% of the flights from Norwegian airports (route, charter and freight) are domestic, and 30% are international flights. However, the energy demand for international aviation takes a much higher share. The Energy Transition Norway report (DNV 2022) estimates 80% of aviation energy demand in Norway is for international aviation (based on a methodology where international fuel demand is split between countries based on GDP, rather than on current fuel sales on Norwegian airports). Norway can be a front-runner globally in electrification of short haul flights, but SAF will be the main contributor to aviation emission reduction. The exact mix of low and zero carbon solutions is uncertain.

Based on current jet fuel sales, forecasted demand increases and proposed EU blending mandates SAF demand in Norway will be 216 million litres in 2035 and 840 million litres in 2050. SAF demand in Norway can accelerate significantly if the Norwegian government decide on more ambitious national targets (30% in 2030), or if there are other incentives for increasing SAF uptake. However, it is expected that Norway will follow EU mandates going forward.

The regional distribution of SAF demand is not expected to be even. Specifically regional and local airports (airport category D and E) are expected to have a higher share of electric (and potentially hydrogen) aircraft than international airports, and hence a lower SAF uptake compared to today's jet fuel volume distribution.

Based on DNV's knowledge, there are 4 companies planning SAF production in Norway within 2030 (in addition Silva Green Fuel are planning biofuel production that is currently targeting other sectors but could also produce SAF). Most of the companies have announced potential future upscaling beyond their first plant, but there are no clear plans. DNV has made upscaling assumptions from 2030 based on available information, but the timeline and volumes are uncertain.

The share of the sustainable fuel production capacity that will go to aviation fuel depends on the production technology and the market. Refineries will always have some heavy and some lighter fractions. Production can be optimized for SAF, giving a SAF output of up to 50-90%. The production facilities can either include the refining/upgrading step as part of the facility or send their product to an existing refinery for upgrading to SAF.

Based on the theoretical maximum SAF share for the given production pathways and conversations with the companies, the maximum potential SAF production volumes reach almost 900 million litres in 2030 and >1400 million litres in 2035. However, **realistic volumes are significantly lower** as there are several challenges yet to overcome, such as technology development and testing, costs, unclear regulation and incentives, competition with other offtake sectors (maritime and road transport) and long fuel certification processes.

Even with the expected volumes of SAF, there is today a lack of incentives to make SAF production projects based on non-biological feedstock commercially feasible, as the costs of this SAF will be significantly higher than conventional jet fuel.

6.7 Synergy analysis

Mongstad is Norway's biggest industrial cluster[88] , including Norway's largest oil refinery operated by Equinor, Technology Centre Mongstad (TCM) and Mongstad supply base (Asset Buyout Partners).

Synergies with neighbouring companies relates to the following aspects:

- **Technical resources and knowledge:** Mongstad is part of a larger industrial cluster centred around Fensfjorden. It is home to Equinor's refinery, but also multiple maintenance, supply and service companies close by. As such, the technical knowledge as well as spare parts, knowledgeable maintenance staff and

[88] https://www.mongstadindustrialpark.no/

supply companies are all within the area. This is a strong asset for the operation, maintenance and potential scale-up of SAF production and other renewable fuels in Norway.

- **Utilities:** The electricity, water, chemicals required in order to operate the entire chain of SAF production from MSW present a substantial volume of resources. Direct Air Capture has a large requirement of Natural gas (or an alternative heat source), and could also benefit from residual or waste heat from neighbouring processes. For the gasification process, pure oxygen as oxidant has to be fed to the gasifier. This is typically a gas that is already supplied through a pipeline on a petrochemical installation such as what is present at Mongstad. As such, the SAF production installation can and should make use of local water, heat, energy and chemical supply which is already present on site. Given the extensive use of hydrogen in several of these processes, any future large scale production of blue hydrogen at Mongstad could create a major asset and synergy for a SAF initiative.
- **Infrastructure:** Utilities previously covered also require infrastructure. The Mongstad area has large superficies of land, which may be necessary when storing Municipal solid waste on site, or storing the produced kerosene. Companies putting down cables and pipelines are most likely also on site, having to carry out maintenance on existing operations, which is something that the SAF production will also require.
The port facilities located at Mongstad present a great asset for the location, and the implementation of SAF production. The port at Mongstad is Norway's largest in terms of tonnes over quay, and one of the largest energy ports in Europe. It has a central position in the North Sea basin (Fensfjorden Basin) for international cargo transportation along the Norwegian coast, making it an attractive location for industries relating to energy, service logistics and supply companies.
- **Feedstock supply or by-product usage**: The petrochemical industry at Mongstad may have waste oils or plastic streams that can be used as calorific input for the gasification part, hereby increasing the energy content of the feedstock. This would result in higher syngas output and increase the overall process efficiency. It should be noted that this is only acceptable if the supply and consistent quality of the calorific feedstock can be guaranteed. Otherwise, this may have a detrimental effect on the gasification installation, as lack of calorific stability and lack of composition stability will degrade the installation.

6.8 Assessment of alternative locations for industrial value chains (in Norway)

As a location for SAF production, Mongstad benefits from existing logistics, energy delivery (gas and electricity), space and storage facilities for the installation and ancillaries relating to it. It is essential for any alternative location to fulfil the same criteria. DNV has conducted a high-level analysis of alternative locations for industrial value chains.

Alternative locations for industrial value chains require established logistics such as a local port, railway station or road network in order to transport feedstock on location, as well as dispose of potential waste products such as chemicals and waste water. The following locations have been assessed:

- **Kollsnes** is a gas processing plant close to Mongstad, also operated by Equinor.
- **Øra** is an industrial site located within the Fredrikstad urban area, about 100 km southeast of Oslo. It is an industrial area producing soy meal, paint pigments and chemicals.
- **Slagentangen** is the location of the old oil refinery of Esso (ExxonMobil), close to Tønsberg. The refinery was shut down for commercial operations in 2021.

The locations are assessed across six categories, shown in Table 6-12, with colours indicating the potential (green=high, yellow=medium and red=low). As there are a significant amount of factors impacting the challenges and opportunities with different locations for industrial value chains, DNV recommends a more detailed study to be conducted.

Table 6-12: Assessment of locations for industrial value chain

Locations	Refinery	Logistics	Energy	Feedstock – natural gas	Feedstock – Waste products	Feedstock - electricity
Mongstad						
Kollsnes						
Øra						
Slagentangen						

7 CONCLUSION

The production of Sustainable Aviation Fuel (SAF) from non-biological feedstock was assessed in this report, using information and documents provided by the client, interviews with potential technology providers, as well as confidential DNV information from previous projects. The following insights have been obtained:

“Qualified” as SAF: according to >70% GHG reduction, and legislative definitions:

- The process and scenarios have direct emissions of 21.2-27.9 gCO_2eq/MJ of SAF, this is a 70-77 % reduction of GHG emissions. These estimates are for the direct and indirect emissions, and are high level and rough estimates, and not detailed Life Cycle Assessments (LCA), including all CO_2 equivalents, but an indication. The margin for the threshold of >70% GHG reduction compared to the fossil fuel comparator is likely reached, but based on simplified assumptions and with some uncertainty.
- The fuel that is originated from MSW is categorised as a combination of biofuel and RCF and is hence eligible for the overall SAF-mandate of ReFuelEU Aviation, but not the synthetic sub-mandate. It should be noted that it is still unclear how the use of blue hydrogen to increase the conversion of carbon will be dealt with in the EU regulations. With the ReFuelEU provisional agreement from April 2023 on blending mandates and SAF qualifications the fuel share classified as low-carbon fuel may not be considered as SAF.

Feedstock: Based on DNV calculations, along with input from the partners of the project, the following insights can be derived from feedstock sourcing:

- Non-biological feedstock may be mainly MSW, as well as smaller fractions of industrial and agricultural waste, when excluding the biological fraction. A uniform feedstock is key for the next steps of the process, and a higher calorific value is strongly preferred. The variability of the feedstock composition can lead to fluctuations in the syngas composition and process efficiency. It should be noted that typically, MSW is a collection of multiple residual waste streams with varying composition. DNV has assumed that the residual Municipal Solid Waste is comprised of 50% of biological waste, and 50% non-biological. As such, the product resulting from the conversion of MSW will count for 50% as biofuel, while the other 50% account for non-biological fuel. This assumption will have to be verified when reaching out to waste suppliers and analyzing the composition of the specific waste that will be sourced for the SAF installation.
- **Based on our assessment, local sourcing of Municipal Solid Waste (MSW) is deemed not to be enough to produce the targeted amount of SAF, 113 million litres per year (LanzaTech standard plant).** A smaller plant could be built, but the costs of production would be relatively higher than building a larger plant (more costs per litre of SAF), due to the need for a custom design. As such, the feedstock can be either be imported, or the local feedstock will have to be compensated using local blue hydrogen and CO_2 from DAC, and are considered feasible. Three scenarios according to pathway 1 have been adopted in this study. These scenarios make use of components from different origins, but will go through the same chemical conversion, described below.
- A hub-and-spoke set-up has been identified as a likely more efficient value chain and logistics set-up. It is recommended to study this in more detail.

Gasification: Gasification decomposes MSW or other hydrocarbons to shorter molecules such as CO, CO_2 and H_2. Consequently, these components become the building blocks to produce the targeted SAF. A generic gasification technology cannot be defined due to several reasons. The technology is emerging, and many designs are currently being developed and commercialised. These are typically geared towards the type and quality of a selected feedstock, as well as the targeted product as output. Based on the various insights DNV has from previous due diligence projects, literature reviews and documents provided by partners, we have derived a general conversion to syngas, along with expenses and energy consumption. The following should be noted:

- Higher calorific value feedstock, with a stable energy content throughout the year, are parameters that gasification installations strive to have in order to have stable operations. This is a typical pitfall that has been observed repeatedly in the past. As such, MSW must be pre-treated in order to provide a uniform and dry RDF feedstock (Refuse Derived Fuel) with a higher calorific value than wet MSW. A higher and more constant calorific value of the input guarantees better yield.
- Despite the technological developments for over 30 years, gasification is not considered mature. This is due to the fact that gasification was originally done using coal, which has recently shifted to waste and biomass conversion. These are much more challenging feedstocks, and lessons learnt are continuously being distilled. A notable example of challenge relates to the variability of feedstock. The process is highly sensitive to feedstock fluctuations and is finely tuned to optimize the conversion process. Strong fluctuations mean the gas composition in the output varies, potentially leading to tar formation, which can cause increased clogging in the syngas cooling train. This in turn, will decrease the availability of the plant, leading to higher operating cost and lower income and reduced lifetime.

Direct Air Capture: For the third scenario, whereby the sourcing of local MSW is considered at realistic levels, requires further addition of locally sourced blue hydrogen and CO_2 from Direct air capture to compensate for the limited amount of syngas produced from the limited feedstock. DAC is a rather energy intensive process, but the main caveat is that the DAC installation is located in Kollsnes, while the SAF production facility is at Mongstad. This is far from ideal, seeing as the liquefied CO_2 captured from the air will be transported to Mongstad by truck. This negates potential benefits from capturing the CO_2. A pipeline is also an alternative, but a very costly one.

- Similar to gasification, DAC is not yet mature and is still in the process of being scaled up. As such, both technologies should be considered in the final stages of development, and DNV expects both to be able to play a significant role in the production of SAF in the coming 2-5 years.

Syngas to Ethanol to SAF: Once the syngas with suitable hydrogen and CO_2 as input have been provided, the proprietary technology from LanzaTech and LanzaJet convert the syngas to ethanol through biochemistry, followed by a petrochemical process producing SAF and Diesel. Based on the extensive experience in the Oil and Gas industry from these two teams, this step is not seen as the bottleneck of the value chain.

Regulatory: there are proposed (and recently provisionally agreed and adopted) policies, acts and directive amendments relevant for SAF, use of fossil CO_2, "unavoidable fossil" waste gases containing CO_2 and CO, as well as atmospheric and biogenic CO_2. There are also emerging guidelines and standards, while detailed regulation is still lacking. Depending on the definitions and certification schemes, e.g. RFNBO and RCF, and tax or credits, e.g. EU ETS or US IRA tax credits, the technology and value chains have to adapt to either store the CO_2 or use it for the different synthetic fuel definitions. The risks are high before delegated acts are voted upon and implemented in the legal system, both at EU and national level. When the legal train has been completed and implemented, the regulatory risk is drastically reduced.

Symbiosis: Mongstad as a location presents a beneficial growth area for emerging concepts such as the presented SAF production. It offers benefits such as existing infrastructure, transport (import and export) facilities, as well as technical expertise which may already be familiar with similar concepts, and can offer maintenance and spare parts if needed.

8 RECOMMENDATIONS

8.1 Determination of SAF and regulatory definition

When the regulation is fully defined and ready for national implementation, it is recommended to make an assessment for if the mentioned value chains still qualify for the SAF definition, as RFNBO or RCF.

8.2 By-product income

Depending on the gasification solution chosen as well as the feedstock, the by-product char can be used as a source of income. This has purposefully not been included in this report, as the gasification conversion method has not been fixed, and the feedstock choice can also impact the end business case.

In Biomass-to-Hydrogen plants, the by-product is Biochar. This char can be marketed as a carbon sequestering compound (i.e. a carbon sink) that can increase soil fertility to increase agricultural productivity. Biochar is being sold at high prices, ranging between USD 200–1000/tonne. It should be mentioned that while this by-product looks attractive, biochar as a fertilizer enhancer can only be produced using "clean" Biomass (not containing glue, paint, etc.), as harmful compounds should not end up in the ground. Other Waste to Hydrogen production methods choose instead to form chars or vitrified (glass-type) products that can typically be mixed in construction materials such as asphalt.

8.3 Sourcing waste, plastics or ethanol

8.3.1 Pre-sorted plastics

Managing to source 350 kilotonnes of (shredded and pre-sorted) plastic instead of 650 kilotonnes of MSW can greatly increase the economics of the gasification installation.

- **For sourcing**: Transporting half the weight of feedstock decreasing the CO_2 emissions for transport, as the energy density per transport is doubled. Plastics have a roughly estimated calorific value of 30-35 MJ/kg, while RDF has a calorific value of 15-18 MJ/kg (and unsorted MSW ranges from 8-12 MJ/kg).
- **For gasification:** Using MSW instead of plastics or higher calorific value materials means more processing is required to convert the same amount of energy into a syngas, while the remaining compounds (other than the produced syngas) are by-products such as char or inert material. This implies that higher throughput (more tonnes of feedstock input per hour) would be required for MSW instead of plastic, thus requiring a larger installation (so a higher CAPEX and OPEX) for the same result.

In summation, the higher the calorific value, the more cost-effective the installation can be.

8.3.2 Ethanol – commodity or a hub-and-spoke logistics value chain

Ethanol can be sourced from various sources or other locations, either biobased or other synthetic pathways. This could be explored, for adding sufficient volumes of alcohols when there is not enough waste as a feedstock.

During the project, a hub-and-spoke set-up has been identified as a likely more efficient value chain and logistics set-up. This concept is designed and planned as for processing the waste to ethanol in various locations near the waste collection and sorting, and then ethanol is transported to the Alcohol-to-Jet processing plant. It has not been part of the scope to evaluate alternative upstream logistics concepts, but it is recommended that the hub-and-spoke concept is explored as an alternative solution for more cost effective and sustainable SAF production.

8.4 Adding Hydrogen to the LanzaTech fermentation

Hydrogen addition to the fermentation step can result in additional conversion of excess CO_2 present in the syngas from gasification into ethanol. Hydrogen typically doubles the ethanol production from a given syngas, so the feedstock requirement would be cut in half along with the capacity of the gasification unit. According to LanzaTech, a rough estimation for this scale would be of 3 tonne/h addition of Hydrogen to produce the same amount of ethanol, while cutting in half the MSW feedstock needed. Essentially, what hydrogen does is to increase the carbon efficiency of the process, meaning that less CO_2 is lost as flue gas.

As described in Chapter 3 and throughout this report the ReFuelEU blending mandates and clarifications around including RCFs but excluding low-carbon fuels are important to understand for this project. Adding blue hydrogen to an RCF production process can make a share of the end product a low-carbon fuel, which is not considered SAF. This agreement still has to be formally approved before entering into force.

8.5 Considering the alternative SAF pathway

With pathway 2 explained earlier the gasification process could be eliminated and thus the dependency on waste availability as a non-biological feedstock. If this pathway can be further supplied with CO_2 from a DAC facility in Mongstad, this pathway could potentially lead to economic benefits by eliminating CAPEX/OPEX associated with gasification.

An additional possibility would be to purchase CO_2 from a DAC supplier ideally in Mongstad, that could eliminate the CAPEX and OPEX associated with DAC. However, the economics of purchasing CO_2 would then need to be considered.

8.6 Removing redundant steps

This initial pre-feasibility study does not take into account various optimisation steps. In an optimized plant, heat sources are looped back to increase the thermal efficiency, waste products from one step can be used for another. For example, LanzaTech has a gas conditioning step that removes impurities from the previous syngas production step. However, a stand-alone syngas installation also integrates various purification steps. As such, one of these purification units could be removed, or both can be integrated and geared towards the specifications of LanzaTech. Such optimisations will have to be implemented once a complete design is drawn up and engineered.

9 ABBREVIATIONS

GHG	Greenhouse gas
SAF	Sustainable aviation fuel
CCU	Carbon capture and utilization
DAC	Direct air capture
ASTM	American Society for Testing and Materials
ICAO	International Civil Aviation Organization
RFNBO	Renewable Fuels of Non-Biological Origin
RCF	Recycled Carbon Fuel
DA	Delegated Act
MSW	Municipal Solid Waste
RED	Renewable energy directive
RWGS	Reverse water gas shift

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