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Australian e-SAF for the German Aviation Sector

Bilateral opportunities for synthetic aviation fuel for Germany and Australia

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Background and Acknowledgement

The German and Australian governments have been formally cooperating on energy issues since 2017. Early collaboration was focused through an energy working group with a formal energy partnership signed in 2021.

Over time the work has been expanded into energy and climate work. In September 2024 the Germany-Australia Energy and Climate Partnership was signed, which includes an emphasis on hydrogen, energy efficiency, energy security and climate leadership including multilateral cooperation.

Germany and Australia's hydrogen cooperation culminated in the signing of a Joint Declaration of Intent to establish a joint EUR400 million H2Global tender under the Energy and Climate Partnership in September 2024. The cooperation between the governments is supported by the Australian Hydrogen Council (AHC), the German-Australian Chamber of Industry and Commerce (AHK) and adelphi.

The report explores the opportunities for Australia-Germany collaboration on e-SAF and does not represent the views of the Australian government or Australian SAF market.

The potential for e-SAF trade has been a topic of particular interest for stakeholders in both Australia and Germany and this report seeks to outline the main frameworks and opportunities. The report has been funded by the German Federal Ministry for Economic Affairs and Energy (BMWE).

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Contents

Introduction

Executive Summary 11

1 Introduction 13

2 SAF Production Pathways 15

2.1 SAF and e-SAF 15

2.2 SAF: Hydro Processed Esters and Fatty Esters 16

2.3 SAF: Alcohol-to-Jet Synthetic Paraffinic Kerosene 17

2.4 e-SAF: Fischer-Tropsch (FT) 17

2.5 e-SAF: Methanol-to-Jet Pathway (MtJ) 17

3 Regulatory Context in the EU and Germany 18

3.1 EU Regulation 18

3.1.1 ReFuelEU Aviation and the Renewable Energy Directive 18

3.1.1.1 Definitions 18

3.1.1.2 Obligations and obligated parties 20

3.1.2 EU ETS 22

3.1.3 Other EU SAF and e-SAF Initiatives and Funding Instruments 22

3.2 German Regulation and Funding 22

4 Regulatory Context and Feedstock in Australia 24

4.1 Australian Regulation and Funding 24

4.2 Renewable Power and Green Hydrogen 25

4.3 Australian Carbon Sources for e-SAF Production 26

4.3.1 Direct Air Capture (DAC) 29

4.3.2 CO_2 Extracted from Biomass 29

4.3.2.1 Sugarcane residue 29

4.3.2.2 Kelp 30

4.3.2.3 Landfill/Municipal Waste/Abattoirs 31

4.3.2.4 Forestry and Wood Waste 31

4.3.3 Industrial Point Sources 32
4.3.3.1 Liquified Natural Gas (LNG) Production 32
4.3.3.2 Ammonia 33
4.3.3.3 Iron and Steel 33
4.3.3.4 Cement & Lime 34
4.3.3.5 Natural Gas Power Plants 34
4.3.3.6 Pulp & Paper 35
4.3.3.7 Alumina and Aluminium 35
4.3.3.8 Summary of Australian CO_2 Sources 35

5 Opportunities for Bilateral Trade 39
5.1 Germany's and the EU's Need for e-SAF Imports 39
5.2 Willingness to Pay and Green Premium in Germany and the EU 41
5.3 Insights from the German Aviation Sector 43
5.4 International Supply of e-SAF in the Short Term 45
5.5 Strategic Considerations for e-SAF Trade 49
5.6 Fostering German and Australian Innovation and Pilot Projects on e-SAF 49
5.6.1 Germany 49
5.6.2 Australia 51
5.7 Australian Hydrogen and e-Fuel Projects 51
5.7.1 ABEL Energy: Bell Bay Powerfuels and Townsville Powerfuels 51
5.7.2 HyGate Initiative: SM1 Project 52
5.7.3 Intercontinental Energy: Australian Renewable Energy Hub (AREH) and Western Green Energy Hub (WGEH) 53
5.8 Building an Australian Supply Chain 53

6 Recommendations for Bilateral Cooperation 56

7 References 60

List of Figures

Figure 1: SAF & e-SAF Production Pathways 16

Figure 2: EU quotas and corresponding e-SAF volumes 2025-2050 21

Figure 3: Map of Australian biogenic and industrial CO_2 sources 28

Figure 4: Comparison of projected aviation fuel prices 43

Figure 5: Fundamental barriers to the e-SAF market ramp-up in Germany 45

Figure 6: Overview of potential large-scale e-SAF producers excluding Australia 48

Figure 7: CO_2 cycle for the production of e-SAF 54

Figure 8: CO_2 from Australian Safeguard Facilities and EU and Australian e-SAF demand 57

List of Tables

Table 1: EU requirements for CO_2-sources 20

Table 2: Overview of Australian CO_2 sources 38

Table 3: Overview of e-SAF projects in EU, Norway and Iceland 41

List of Abbreviations

ACARE	Aviation Research and Innovation in Europe
AD	Anaerobic Digestion
Aireg	Aviation Initiative for Renewable Energy in Germany e.V.
AREH	Australian Renewable Energy Hub
ASTM	American Society for Testing and Materials
AtJ	Alcohol-to-Jet
BDL	German Aviation Association
BImSchG	Bundes-Immisionsschutzgesetz
BMWE	Federal Ministry for Economic Affairs and Energy
CEFC	Clean Energy Finance Corporation
CH_4	Methane
$CO_{2\text{-eq}}$	Carbon Dioxide Equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CfD	Contracts for Difference
DAC	Direct Air Capture
DCCEEW	Department for Climate Change, Energy, the Environment and Water
Dena	German Energy Agency
DG	Directorate General
DLR	German Aerospace Center
DRI	Direct Reduction of Iron
EASA	European Union Aviation Safety Agency
EEA	European Economic Area
ETS	Emissions Trading System
e-SAF	Synthetic Sustainable Aviation Fuel
FID	Final Investment Decision
FT	Fischer-Tropsch
GDP	Gross Domestic Product
GHG	Greenhouse Gas
H_2	Hydrogen
HEFA	Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IRENA	International Renewable Energy Agency
Kt	kilo tonne
LCLF	Low Carbon Liquid Fuel
LNG	Liquefied Natural Gas
Mt	Million tonnes
MtJ	Methanol-to-Jet
MSW	Municipal Solid Waste
MW	Megawatts
MWh	Megawatt hour
PPA	Power Purchase Agreement
PtL	Power-to-Liquid
RCF	Recycled Carbon Aviation Fuel
RED	Renewable Energy Directive

ReFuelEU	Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport
RFNBO	Renewable Fuel of Non-Biological Origin
SAF	Sustainable Aviation Fuel
SAFAANZ	Sustainable Aviation Fuel Alliance of Australia and New Zealand
SMR	Steam Methane Reforming
SPK	Synthetic Paraffinic Kerosene
SWIS	South West Integrated System
T&E	Transport and Environment
UBA	Umweltbundesamt (Federal Environment Agency)
UCO	Used Cooking Oil
WGEH	Western Green Energy Hub

Executive Summary

The aviation sectors in Australia and Germany are among the largest globally, making both countries' net zero targets highly significant. E-SAF produced with green hydrogen and sustainable carbon feedstocks offers a particularly attractive decarbonization solution for the aviation industry, as its feedstocks are nearly unlimited and its usage potentially carbon neutral. Australia has tremendous potential as an e-SAF producer and exporter, while Europe and Germany are important markets, due to existing, ambitious e-SAF quotas. This study outlines e-SAF production pathways, existing regulation in Australia, the EU, and Germany, the willingness-to-pay in the EU/ Germany, the potential for an Australian supply chain, and recommendations to overcome current hurdles to e-SAF trade between these countries.

For Australia and Germany to reach their climate neutrality goals decarbonising their respective aviation sectors is key. Both the EU and Australia are key players in the international aviation industry, with Australia being the 8th largest consumer of kerosene while the EU demands 15% of global kerosene demand. Within the EU, Germany is the largest consumer.

In the near term, SAF and e-SAF are the most viable options for decarbonizing aviation, with e-SAF being especially attractive because its feedstock is essentially unlimited. This is recognized by the EU, which has introduced ambitious quotas to incentivise the production and uptake of e-SAF. Specifically, the EU prescribes 1.2% of aviation fuel supply to be in the form of e-SAF by 2030, increasing to 5% in 2035 and 35% in 2050.

Meeting the EU e-SAF quotas will require imports. Despite the stringency of the quota and penalty for non-compliance, fuel suppliers in the EU are thus far lacking behind in the development of or investment in e-SAF projects. In fact, none of the announced e-SAF projects in the EU has thus far reached FID. If the three most promising projects do so in 2025, there would still be a shortfall of 320,000 tonnes e-SAF in 2030.

Australia has a huge potential and an intrinsic interest in becoming an exporter of e-SAF to the EU and Germany. This is because Australia has abundant renewable sources and space to develop renewable energy sources for the production of green hydrogen, a key input to e-SAF. Many parts of the value chain are supported by government policies and funding already. Additionally, Australia has diverse CO_2 feedstock availability, another key input to e-SAF. Since Australia also has a domestic need for both SAF and e-SAF, both to meet its climate targets and to reduce its current reliance on fuel imports and increase its energy security, there is a strong case for the development of both SAF and e-SAF production projects.

Yet, international competition for supplying e-SAF to the EU can be expected to be high. While an uncertain regulatory environment currently obstructs the development of the EU e-SAF market, the EU's core policy for e-SAF, ReFuelEU, will create a clear business case for fuel suppliers and by extension airlines to take up e-SAF and meet the quotas to avoid high penalties. Calculations show that non-compliance would increase aviation fuel costs for fuel suppliers and consequently airlines by 6% in 2030 rising to 20% in 2035 whilst not buying them out of the obligation to comply. Several countries, including the US, China, UK, Brazil, and Morocco, among others, can therefore be expected to target the EU as an attractive export market.

To enable the trade of e-SAF between the EU and Australia in the short-term, this study recommends the following actions:

1. **Provide regulatory certainty regarding ReFuelEU and RFNBO criteria.** Regulation regarding e-SAF and its inputs (H_2 and CO_2 feedstocks) is stringent and ambitious, but the review scheduled for ReFuelEU in 2027 creates uncertainty resulting in a wait-and-see approach by industry, making it increasingly less likely that the quota for 2030 can be met. Uncertainty around RFNBO criteria also reduces investments in

international projects. This should be addressed, in addition grandfathering provisions could increase investor confidence.

2. **Signal need for e-SAF imports to meet German and EU e-SAF demand.** Explicit communication in this direction is thus far lacking but is recommended in light of the limited projected domestic production capacity in 2030. Strategic sub-targets for countries of origin could ensure a diversified import portfolio.
3. **Provide certainty for Australian projects with regard to industrial point sources.** Australia is home to many potential industrial point sources as feedstock for the production of e-SAF. The EU sunset clause limiting their use until 2040 poses a challenge for projects relying on this CO_2 feedstock to take FID. The Australian government could provide guarantees or pathways for these to transition to domestic demand after 2040 provided this does not unnecessarily prolong the lifetime of the industrial point source.
4. **Develop Australian demand to advance decarbonisation and decrease dependency on imports.** Australia has an interest in entering the e-SAF market beyond the opportunity to export to Europe. A domestic e-SAF quota would stimulate project development and thus help both the domestic and international market ramp-up.
5. **Provide planning security for Australian projects using biogenic CO_2 sources.** Biogenic sources are relevant to a number of industries, creating a risk for competition. To reduce this risk and develop a comprehensive strategy, the Australian government should take stock of all available biomass and analyse future bioenergy needs.
6. **Provide financing support for projects.** While the EU quota and penalty create a market for e-SAF, the current slow development of projects suggests that this may not suffice to incentivise offtake agreements and thus FIDs. Further financial mechanisms to bridge the cost gap between e-SAF and kerosene are therefore needed. Supplementing this with non-price-based import criteria favouring market-based trusted trade partners like Australia may help diversify the supply base. This could take a range of forms, including quotas, import subsidies or the introduction of explicit risk premiums for countries of origin with higher political and economic risks.
7. **Facilitate availability of sufficient quantities of low-cost renewable power.** While Australia's renewables potential is tremendous, the build-out of renewable capacity, storage and transmission needs to accelerate to support both the decarbonisation of the existing and future power demand and potential hydrogen and e-SAF production at scale. Availability of low-cost power is currently one of the main concerns for project developers of renewable hydrogen projects.

1 Introduction

To limit global warming to well below 2 °C in accordance with the Paris Climate Agreement, emissions must be reduced globally. The aviation sector, a key contributor to CO_2 emissions, faces unique challenges in decarbonising as it relies on high-energy-density fuels. The International Air Transport Association (IATA) has committed to reducing 50% of CO_2 emissions by 2050 compared to 2005. However, emissions continue to rise, reflecting the urgent need for scalable solutions.

In 2024, global energy-related CO_2 emissions grew by 0.8%, to reach a new record high of 37.8 Gt CO_2 (International Energy Agency [IEA], 2025). Emissions by international aviation alone increased by 13.5% (Canadell et al., 2024). Since the early 2000s, the global number of flights has grown consistently, reaching 38.9 million in 2019. Although the COVID–19 pandemic temporarily reduced flight numbers, they rebounded quickly and are estimated to reach a new peak of 40.1 million by 2024 (Statista, 2024b). The EU is one of the largest global aviation markets, with nearly 1 billion passengers in (Statista, 2024a), consuming approximately 50 million tonnes(Mt) of kerosene annually, thereby accounting for up to 15% of global kerosene (Future Clean Architects [FCA], 2024).

In 2024, flights departing from European airports produced 187.6 Mt of CO2 emissions, a 8% increase compared to 2023 and an almost recovery (98%) compared to pre-pandemic levels. Emissions from intra-European flights (EEA + UK) even exceeded their pre-pandemic levels (European Federation for Transport and Environment [T&E], 2025). Within the EU, Germany had the largest aviation fuel consumption in 2023 kerosene (FCA, 2024). Due to its large size, Australia also has a significant aviation industry with domestic flights carrying 59.59 million passengers in 2024, reflecting a 3.5% increase from the previous year (Australian Bureau of Infrastructure and Transport Research Economics [BITRE], 2025a). For international travel, Australia saw 39.55 million passengers in 2024, marking a 27.8% rise compared to 2023 (BITRE, 2025b). In total, Australia is the eighth-largest consumer of kerosene in the world (Alsop, 2024; The Global Economy, n.d.).[1]

Government and industry are actively working on ways to reduce emissions in the aviation sector. Sustainable Aviation Fuels (SAF) and synthetic Sustainable Aviation Fuels (e-SAF) are regarded as the only viable way to reduce direct emissions at scale in coming decades, with the prospect of hydrogen propulsion for large aircraft remaining distant, and battery electric likely to be limited to short range (potentially with SAF range extension generators). Aviation requires fuels with high energy density, good cold flow properties, thermal stability, and a low freezing point (Hari et al., 2015). The fuel needs to be compatible with the present design of the aircraft engine and existing infrastructure, which e-SAF as a drop-in fuel is able to provide.

While countries like Australia may be able to capitalise on their natural resources for biogenic SAF production, biogenic sources are finite and subject to competition from other sectors/end-uses. This limits their scalability, as compared to e-SAF, where feedstocks are potentially unlimited. Importantly, , e-SAF presents a more promising solution for global carbon emission reduction as it can be produced at very large scale with renewable energy while being almost (99%) carbon-neutral when direct air capture (DAC) becomes more widely available (McKinsey, 2020).

In the long-term, Germany will not be able to supply all of its SAF and e-SAF without imports. And while Australia will have a significant domestic need for e-SAF as well, its potential for large-scale renewable hydrogen production can support domestic and international e-SAF consumption. Australia's near-unlimited access to wind, solar, and land resources enables the development of a strong renewable hydrogen industry, which can serve as a critical input for power-to-liquid (PtL) fuels like e-SAF. Moreover, Australia has already demonstrated its commitment to hydrogen development, with ambitious production targets of 0.5–1.5 Mt/year by 2030 and 15–30 Mt/year by 2050, supported by initiatives like the Hydrogen Production Tax Incentive. As a trusted

[1] using the measure of a barrel to be 159 litres

trade partner of Germany, Australia is therefore in a good position to support German and European energy security through e-SAF exports.

The interest of Australia in entering the e-SAF market is two-fold: First, Australia's aviation industry is a relevant sector both to the economy and emissions. Entering the e-SAF market therefore promises to expand the industry into new fields of activity, adding new jobs and A$13 bn to Australia's GDP (Messent, 2025). By producing domestically, Australia also decreases its dependence on fuel suppliers and creates greater fuel security. Given the size of the aviation sector in Australia, it is also relevant to Australia achieving its goal of net zero emissions by 2050. e-SAF can make an important contribution to this. Second, e-Fuels are a convenient export good, thus expanding Australia's export portfolio. Australia could become an important supplier to the APAC region and beyond. Since e-SAF is easier and cheaper to transport over long distances than for instance hydrogen, e-SAF production could be a valuable means to make the most out of Australia's low-carbon hydrogen potential. With the supply market only just emerging, Australia now has the opportunity to be among the early movers.

However, as of now, the e-SAF industry is still largely theoretical in Australia, with active projects lacking, Even if projects come online in the next few years, it will take time for production to reach economies of scale (including the production of green hydrogen as an input) and reduce capital costs, which will be essential to reducing the green premium and becoming cost competitive with conventional aviation fuel.

This study explores the potential and challenges of bilateral trade in e-SAF between Australia and Germany. The aim is to analyse the regulatory frameworks and economic perspectives for a long-term partnership. It focuses on Australia's potential as a producer of e-SAF, leveraging renewable energy and CO_2 sources, as well as Germany's growing demand for imported e-SAF. The study seeks to provide actionable recommendations for stakeholders to support the development of a sustainable and competitive supply chain for e-SAF. To this end, adelphi and AHK Australia interviewed experts, conducted research, and looked at three Australian projects potentially suited as suppliers, with different carbon sources.

The recommendations of this study build on a long-standing cooperation between Australia and Germany in research, policy and business. Cooperation on hydrogen has been a key focus topic underneath the bilateral Australia-Germany Energy and Climate Partnership, culminating in the announcement of a bilateral H2Global funding window that is currently being developed. A set of diverse German companies, including the aircraft operator Lufthansa, was engaged in the joint German-Australian research project HySupply investigating the feasibility of hydrogen trade between Germany and Australia. Another notable cooperation that is specifically targeted at the production of SAF is the partnership between the European aircraft company Airbus and the Australian aircraft operator Qantas. In 2022, the two companies committed US$200 million to the funding of projects related to the production of SAF in Australia (Airbus, 2022). In March 2024, for instance, the two companies together with the Japanese oil refining company Idemitsu Kosan provided A$29 million to Jet Fuel Australia to support its SAF project in Australia (Reuters Media, 2024).

2 SAF Production Pathways

At present, the utilisation of SAF is the most effective way to reduce CO_2 emissions in aviation. This chapter examines the four SAF types, their pathways, and their advantages and challenges. From chapter 3 onwards, this study concentrates on the opportunities for e-SAF production and trade, which are the production pathways described in chapters 2.3 and 2.4.

2.1 SAF and e-SAF

The term SAF includes both biogenic SAF as well as synthetic, or electricity-based, e-SAF. The energy content of biogenic SAF originates from biomass as the feedstock. Synthetic aviation fuel, or e-SAF, also referred to as the power-to-liquid (PtL) pathway, uses electricity rather than biological feedstocks. Power-to-liquid fuels are synthesized using feedstocks such as CO_2 captured from industrial point sources, biogas, directly from the atmosphere through direct air capture (DAC), or from sustainable/carbon-neutral biomass via gasification. This captured CO_2 is combined with hydrogen (H_2), produced through electrolysis, and processed either through a reverse water gas shift reaction or co-electrolysis to produce syngas (McKinsey, 2020).

Advantages include that both SAF and e-SAF can substantially reduce aviation emissions, e-SAF can be almost (99%) carbon-neutral when using renewable electricity and green hydrogen. SAF and e-SAF represent a solution compatible with existing engines and infrastructure. When burned, they emit fewer harmful pollutants (such as sulphur oxides) than conventional aviation fuel. SAF and e-SAF are an efficient hydrogen carrier, as it is much simpler than storing and transporting hydrogen itself, which is a difficult fuel to handle in both its gaseous and liquefied forms due to low energy density and storage challenges.

SAF production is more cost-intensive than kerosene production but much cheaper than e-SAF production in the near to medium term. The primary disadvantage of e-SAF is the cost. e-SAF is still in the development stage and can be more than eight times the cost of fossil-based fuel, as well as two to three times the cost of SAF made from Hydro Processed Esters and Fatty Acids (HEFA) (Globalair.com, 2021). In addition, the use of fossil-origin carbon as feedstock can pose sustainability risks like double-counting emissions reductions, as well as the risk of not reducing the use of fossil materials (McKinsey, 2020).

The primary limitation to SAF production is the availability of biogenic feedstock. In contrast, while e-SAF production still needs a CO_2-source, this doesn't have to be biogenic. Still, a challenge for both SAF and e-SAF production is that some of the same biomass feedstocks are also used in other industries. This could cause competition between different industries, likely resulting in higher feedstock prices in certain locations. This is already an issue for producers of biodiesel and renewable diesel, although this is exacerbated in their case by the fact that they rely on a narrower range of biogenic feedstocks than do producers of renewable methanol.

e-SAF has advantages over SAF in terms of much lower demand for water and land use. Additionally, biomass is often scarce, geographically dispersed, and logistically challenging to transport. This often results in smaller SAF production plants being the more feasible option, both economically and from a emission-reduction point of view, as transporting low-energy-density biomass over long distances using fossil fuels can negate some of the climate benefits. By contrast, when utilizing renewable electricity, e-SAF can be almost climate-neutral and does not face similar limitations in scalability (Agora Verkehrswende & International PtX Hub, 2024; Federal Environmental Agency, 2022).

In 2023, over 1.3 billion litres of SAF were produced worldwide, twice the amount of SAF produced in 2023, and making up 0.3% of global aviation fuel production (IATA, 2024). According to the Centre of Competence for Climate, Environment and Noise Protection in Aviation (CENA Hessen), the predominant production process among running and announced SAF projects in the HEFA pathway. Every third project uses or will use this production process.

An almost equal number of projects plans to use the PtL (FT) pathway. These projects, however, usually are at a much earlier stage (e.g. project idea) and of lower capacity. The Alcohol-to-Jet pathway is the third most common production pathway with a global share of 15%. Only 3% of projects seek to use the Methanol-to-Jet pathway, while 9% of projects do not disclose their planned production pathway (Centre for Competence for Climate, Environment and Noise Protection in Aviation [CENA Hessen], 2024).

Figure 1 summarises the production pathways that are described in the following sub chapter.

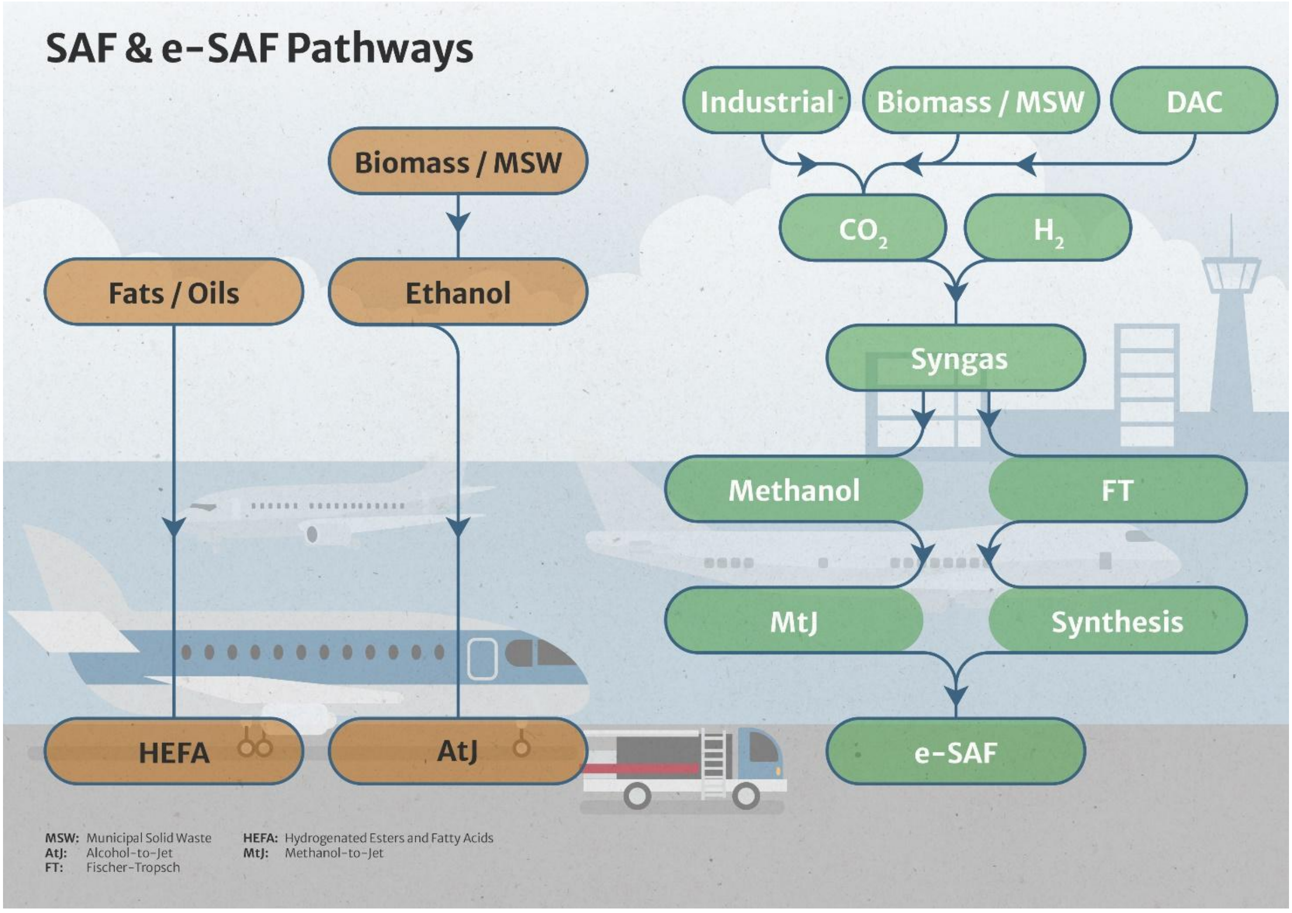


Figure 1: SAF & e-SAF Production Pathways

2.2 SAF: Hydro Processed Esters and Fatty Esters

Hydro processed esters and fatty acids (HEFA) are the most widely produced SAF type. Around 540 million litres of HEFA were produced in 2023.

The HEFA pathway uses edible and non-edible oil, used cooking oil, animal fats, and algae oil. The oils and fats undergo hydro processing, in which free fatty acids are extracted and hydrogenated to remove double bonds. The oxygen content is removed through hydrodeoxygenation or decarboxylation, and the resulting paraffins are further processed to meet aviation fuel specifications and gain synthetic paraffinic kerosene (SPK). This SPK has the right freeze point, flash point, and cloud point to make it suitable for the use in aviation (Ng et al., 2021).

One of the process's key advantages is its flexibility. It can produce both SAF and renewable diesel and can be designed in a way to maximise one product over the other depending on the market demand. The production of HEFA is a well-established technology and is presently the only SAF production method in commercial operation. It therefore is a more near-term solution for decarbonisation than e-SAF, which is still scaling up (Commonwealth Scientific and Industrial Research Organisation [CSIRO], 2023). However, HEFA relies on oil-based feedstocks, which can cause competition with food production, loss of biodiversity (e.g. palm oil), and can provide a negative incentive to cook virgin plant oil to sell as used cooking oil (UCO) at a premium (Ng et al., 2021).

2.3 SAF: Alcohol-to-Jet Synthetic Paraffinic Kerosene

SAF can also be produced through alcohols from biomass via fermentation or thermochemical conversion. The resulting synthetic paraffinic kerosene (SPK) made from Alcohol (AtJ-SPK) can be blended with traditional aviation fuel (Ng et al., 2021).

One key advantage of AtJ-SPK is that it can utilize abundant and diverse feedstocks. However, conventional ethanol is made from corn, sugar beets, and sugarcane that require large amounts of land to grow as well as fertilizers, pesticides, and fossil-fuelled farm equipment. Hence, an expansion of the production of AtJ can contribute to soil erosion, deforestation, and salination.

Another disadvantage of growing feedstock crops for AtJ is the risk of floods and bushfires through droughts, a frequent occurrence in Australia. Also, fermenting and distilling requires heating fuel, and the fermentation process emits CO_2 as a by-product (Bettenhausen, 2023). The disposal of waste and fermentation liquors entails environmental problems, such as polluting rivers and surrounding areas (Xie et al., 2024).

The biggest challenge in Australia is that unlike in the US and the EU, the ethanol industry is very small, with only two plants operating at an estimated 40% capacity factor, producing high-cost ethanol. This ethanol already costs more than fossil aviation fuel, and the subsequent processing steps of dehydration, oligomerisation, and hydrogenation add approximately another three times the cost. The resulting fuel costs approximately three times as much as kerosene with little prospect of significant cost reductions in the longer term (Lloyd, 2025).

2.4 e-SAF: Fischer-Tropsch (FT)

For the Fischer-Tropsch production route, the syngas is converted into hydrocarbons through the Fischer–Tropsch synthesis. This step is similar to the synthesis process used for the Methanol-to-Jet fuel process outlined below. The Fischer-Tropsch pathway produces almost 100% hydrocarbons, but only up to 80% can be refined into e-SAF (Emerging Fuels Technology, 2021). The rest is naphtha and light hydrocarbons, which can be used for other products such as e-diesel and processed or recycled (Geologyscience, 2023).

Advantages of FT e-SAF include that Fischer-Tropsch is a well-established technology and is an American Society for Testing and Materials (ASTM)-certified process for SAF production. Large-scale plants exist today, although currently only operated with fossil-based feedstock (Agora Verkehrswende & International PtX Hub, 2024).

2.5 e-SAF: Methanol-to-Jet Pathway (MtJ)

Another production pathway for e-SAF is the Methanol-to-Jet (MtJ) process, which consists of two established methods. Both begin with syngas to produce methanol, followed by its conversion into either dimethyl ether or olefins. In one method, methanol is transformed into dimethyl ether and then further processed into hydrocarbons suitable for aviation fuel. In the other method, methanol is converted into olefins, which are subsequently oligomerised to produce other hydrocarbons (World Intellectual Property Organization [WIPO], 2014).

Using methanol to produce e-SAF has several advantages. For one, the e-methanol has several end uses and could be directly used, for example as a shipping fuel, as well. Methanol is a widely produced and traded feedstock, although so far fossil based. One option could be the production and export of e-methanol in Australia with subsequent refining to e-SAF in Europe.

On the other hand, the infrastructure for methanol-based fuels, especially its storage and distribution, is less developed than for traditional fossil fuels (except in China). Like most fuels methanol is highly flammable and toxic if ingested, so handling it requires safety measures, which are however well known from the existing conventional methanol industry. The MtJ production pathway is currently not mature and only pilot plants exist. The production route is also not ASTM-certified, but the certification process is currently underway.

3 Regulatory Context in the EU and Germany

EU regulation plays a pivotal role in shaping German national policy, as Germany, being a member state of the European Union, is bound by EU laws and directives. Accordingly, much of the German climate and energy policy originates at the EU level. Therefore, this chapter will look at EU regulation first.

3.1 EU Regulation

EU regulation on SAF and e-SAF in particular is one of the most advanced globally. Europe's vision for a sustainable aviation sector is outlined in the strategy paper "Fly the Green Deal" published in 2022 by Aviation Research and Innovation in Europe (ACARE), an advisory council on aviation in the EU, set up as a public-private partnership between the DG for Transport and Energy of the European Commission and industry actors. The strategy paper sets the framework for the EU's aviation sector by outlining short- and medium-term actions required to align the aviation sector with the goals of the Green Deal (Advisory Council for Aviation Research and Innovation in Europe [ACARE], 2022). In 2023, this was followed up on with the publication of two pivotal pieces of regulation, ReFuelEU Aviation and the two delegated acts of the Renewable Energy Directive (RED) II, which define standards for Renewable Fuels of Non-Biological Origin (RFNBOs) including SAF and e-SAF. These two key pieces of regulation are supplemented by the EU ETS, which is pivotal for creating demand for SAF and e-SAF, as well as other legislative and funding initiatives.

3.1.1 ReFuelEU Aviation and the Renewable Energy Directive

ReFuelEU Aviation is the EU's centre piece of regulation on the decarbonisation of the aviation sector. It was passed in October 2023 and forms part of the Fit-For-55 package, which entails a wide range of regulations all aimed at reaching the EU's target of reducing emissions by 55% by 2030. In principle, the regulation mandates set quotas for SAF and e-SAF and defines clearly which characteristics SAF and e-SAF products have to fulfil to be able to count towards these quotas.

3.1.1.1 Definitions

According to Article 3(7) of the ReFuelEU Regulation the following products qualify as SAF within the EU:

- Synthetic aviation fuel produced from renewable hydrogen and captured carbon (only in the form of liquid drop-in fuels)
- Aviation biofuels
- Recycled carbon aviation fuels (RCFs) (from liquid or solid waste streams of non-biological origin unsuitable to material recovery or from waste processing gas and exhaust gas of non-renewable origin)

Definitions are based on the provisions in the Renewable Energy Directive (RED) II and its associated delegated acts. The directive was transposed into German law in 2021 (Deutscher Bundestag, 2021).

The RED II established sustainability standards for Renewable Fuels of Non-Biological Origin (RFNBOs), which entail e-SAF. According to the directive, a fuel qualifies as an RFNBO if its lifecycle emissions are 70% lower than the reference value of $94gCO_2/MJ$ and it is produced with renewable energy that meets the requirements of additionality and temporal and geographical correlation[2]. To accommodate the market ramp-up, there is a delayed enactment of both the temporal correlation (monthly until 2030, hourly after) and the additionality requirement (will only apply from 2038 for projects coming online before 2028). At the moment there are ongoing discussions between the EU Commission and the German government as to whether to postpone these requirements even further, adding considerable

[2] The EU follows a well-to-well approach in the calculation of emissions from RFNBOs. This means that emissions ranging from the extraction or cultivation of raw materials serving as input to the fuel to the use of the fuel are included. Accordingly, the emissions from e-SAF will vary depending on the feedstock and production process used. As long as the overall emissions stay below the benchmark of $94gCO_2/MJ$, the fuel will qualify as an RFNBO (Directive (EU) 2018/2001, 2018).

regulatory uncertainty (Deutsche Energie-Agentur GmbH [dena], 2025).

Fuel suppliers are obligated to calculate the emissions of their product using the formulas provided in Annex V and Annex VI of RED II and to enter this, alongside with information on the quantity of fuel supplied, the conversion process, the origin of the feedstock and the percentage volume of aromatics and naphthalenes as well as the percentage mass of sulphur, in the Union database. Further, their product must be certified by voluntary schemes that are recognised by the EU Commission and regular third-party audits must be performed by accredited bodies to verify the emission data and sustainability practices. Thus far, the EU has recognised three certification schemes (CertifHy, REDCert, and ISCC). All EU member states must set up national authorities that enforce these requirements. In Germany, the Federal Ministry for the Environment, Climate Protection and Nuclear Safety is responsible for the oversight of aviation fuel suppliers (European Commission [EC], 2025).

ReFuelEU also recognises for the fulfilment of the obligations outlined under 2.1.1.2:

- Renewable hydrogen for aviation
- Low-carbon hydrogen for aviation
- Synthetic low-carbon aviation fuels (produced from low-carbon hydrogen and captured carbon as opposed to renewable hydrogen in the case of synthetic aviation fuel)

The requirements for low-carbon hydrogen and synthetic low-carbon aviation fuels are outlined in the EU's gas market package (Directive (EU) 2024/1788, 2024). Similar to RED II, the gas market package requires an emissions savings threshold of 70% for low-carbon fuels. Thus far, the methodology for calculating these emissions savings has not been published. However, the EU Commission is obligated to do so by August 2025 (EC, n.d.–a). This study will concentrate on the opportunity that arises from bilateral trade and cooperation of renewables-based synthetic aviation fuel (e-SAF). [3]

Additional requirements arise with regard to the allowed CO_2 sources, which are outlined in the second delegated act of RED II: Biogenic sources must comply with the sustainability and certification criteria for RFNBOs outlined in RED II and the associated delegated acts. CO_2 from industry point sources may be used if a CO_2 pricing system (similar to the EU ETS) is in place in the producing country over the whole duration of the production cycle. CO_2 may also be supplied from direct air capture, for which no specific requirements exist (Commission Delegated Regulation (EU) 2023/1185, 2023; Directive (EU) 2018/2001, 2018; Thorsten Herdan, 2024). An overview of the requirements per CO_2 source can be found in Table 1 below.

CO_2 Source	EU Requirements
Biogenic	– Must comply with the sustainability criteria laid out in Article 29 and the certification requirements outlined in Article 30 of RED II as well as the associated delegated acts – Must not have received credits for emissions savings from CO_2 capture and replacement – Not permitted[4]: biomass from food and feed crops (except for waste and residual products when

[3] EU acceptance of other certification schemes, for instance Australia's Guarantees of Origin Scheme – either via translation using an intermediate mechanism or by direct recognition– is key to enabling trade as it will significantly reduce regulatory and administrative burden of producers and consumers. However, it also presents a challenge as not only do emissions accounting methods need to be satisfactorily comparable, but additional sustainability and governance requirements and regulations must be demonstrated to be met. Increased interoperability, and mutual recognition arrangements may be beneficial to reduce duplicative certifications and to help producers meet specific jurisdiction sustainability requirements.

[4] Unless stated otherwise in Annex IX of Directive (EU) 2018/2001, 2018.

	monitored for impact on soil quality and soil carbon), intermediate crops, palm fatty acid distillate materials, soy-derived materials, soap stock and its derivatives, drained peatlands, highly biodiverse areas including primary forests and nature reserves, areas with high carbon content, and illegal logging
Industrial Point Source	– An effective CO_2 pricing system must be in place in the country where the CO_2 has been captured – Captured carbon from gas power plants permitted until 2035 – Captured carbon from energy-intensive industry facilities permitted until 2040
DAC	– No requirements

Table 1: EU requirements for CO_2-sources

At the moment of writing, only countries within the EU ETS, Switzerland and Great Britain are recognized by the EU Commission to host an effective CO_2 pricing system (NOW GmbH, 2025). "Effective" is defined as meeting the following criteria: Robust monitoring, reporting and verification (MRV) process; binding on its participants; stable; apply the carbon price at least on the whole sector producing the RFNBOs or RCFs; stringent enforcement and government-led. Countries other than Switzerland and the UK can request recognition of their carbon pricing system by Directorate General (DG) ENER, which will assess the request together with DG CLIMA.

In the case of Australia, the Safeguard Mechanism would need to be recognized as effective. Similar to the EU ETS, the Safeguard Mechanism covers large industry. In contrast to the EU ETS, the Safeguard Mechanism only covers facilities with emissions higher than 100,000 tonnes CO_{2eq} per year (Department of Climate Change, Energy, the Environment and Water [DCCEEW], n.d.–c). The EU ETS allows member states to apply for the exclusion of installations with emissions of below 25,000 tonnes CO_{2eq} (excluding emissions from biomass) per year (or, if the installation is engaged in combustion activities, with a rated thermal input of below 35 MW). However, for the exclusion to be permitted, the member state must show that alternative measures are in place to ensure that the facility achieves equivalent emission reductions (Directive 2003/87/EC, 2003, Art. 27). Whether the Australian Safeguard Mechanism qualifies as effective nevertheless and meets the other criteria would need to be discussed with DG ENER and DG CLIMA.

3.1.1.2 Obligations and obligated parties

The key lever of ReFuelEU for establishing a more sustainable aviation sector in the EU is the setting of the below outlined quotas for shares of SAF and e-SAF in total aviation fuel consumption from 2025 to 2050. The quotas apply to all fuel uplifted by airlines from all EU airports, for both flights within the EU as well flights outside the EU (International Air Transport Association [IATA], 2024). In total, more than 95% of all flights that depart from an airport within the EU will be covered by ReFuelEU[5] (EC, n.d.–b).

Figure 2 summarises the quotas for e-SAF and denotes the corresponding volumes in kt from 2025 to 2050.

[5] Excluded are flights for military, humanitarian, repatriation and returns operations.

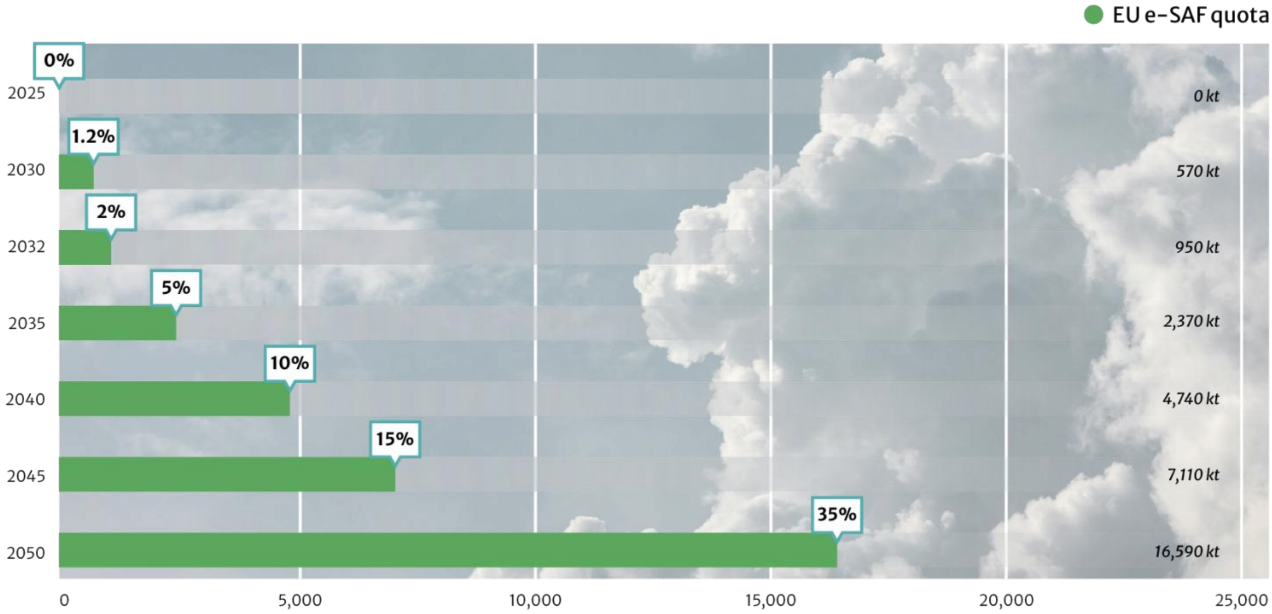


Figure 2: EU quotas and corresponding e-SAF volumes 2025-2050

Sources: Agora Verkehrswende & International PtX Hub, 2024; Regulation (EU) 2023/2405, 2023; Directive (EU) 2018/2001, 2018

ReFuelEU includes obligations for fuel suppliers, airports (airport managing bodies) as well as airlines (aircraft operators) as the end-user of SAF and e-SAF:

- Fuel suppliers operating at EU airports must ensure that the quota of the ReFuelEU is met and that the mandated share of SAF and e-SAF is blended into the fuel supply. To this end, they must enter the supplied quantities of SAF and e-SAF in the EU's Union database. If the fuel suppliers fail to meet these quotas a penalty of at least two times the price difference between fossil kerosene and SAF must be paid (the calculation method is similar for SAF and e-SAF, with the EASA yearly technical report serving as the price input). The exact penalty is to be determined by the member states, who were required to publish their penalties by the end of 2024. However, no member state has thus far published its penalty. In addition to paying the penalty, the fuel supplier still has to fulfil the quota for the period of non-compliance, which means the cost of non-compliance will be much higher than complying with the obligation (T&E, 2024). This is intended to result in a very strong incentive for compliance. To ease the pressure initially, a transitional period until 2034 has been put in place, which allows fuel suppliers to meet the quota as a weighted average within each member state (i.e. some airports will surpass the quota, while others miss it). Additionally, if fuel suppliers miss the e-SAF quota in 2030 and/or 2031 they have until 2035 to compensate for this shortfall (supply obligations for that period however remain in place). If the quota is missed in 2032-2035, the obligations may be fulfilled until 2036, with supply obligations for that period again remaining in place (IATA, 2024).

- Airports are obligated to facilitate the supply of SAF and e-SAF from fuels suppliers to airlines. Individual penalties to be set by EU Member States.

- Airlines on the other hand are required to be fuelled sufficiently, when departing from EU airports to prevent tankering, i.e. the circumvention of the quotas by refuelling outside the EU (European Commission, n.d.; Regulation (EU) 2023/2405). To this end, they are required to refuel at least 90% of their annual aviation fuel used in the EU when departing from an EU airport. Penalties apply for non-compliance. They are also required to submit annual reports containing verified information outlining compliance with the anti-tankering obligation and the SAF and e-SAF quotas (IATA, 2024).

In reality, the costs of non-compliance with SAF and e-SAF quotas that are borne by the fuel suppliers will be passed on to airlines through higher fuel prices as suppliers adjust pricing to cover the fines. This cost transfer means that, while airlines are not directly penalized for e-SAF shortfalls, they will bear the financial burden through increased fuel costs, impacting overall operational expenses. Therefore, airlines should have a strong incentive to cooperate with fuel suppliers or at least motivate them to secure future e-SAF supply. In some cases, airlines act as fuel suppliers themselves though and are mandated to fulfil the quota.

While many European airlines have made voluntary emission reduction commitments and customers, particularly large cargo customers, are increasingly demanding sustainable fuel options, the mandatory quotas are a strong instrument for ensuring demand for SAF and specifically more expensive e-SAF in a legally binding manner, thus encouraging production and supporting the market ramp-up.

3.1.2 EU ETS

The EU ETS is a second means for creating demand for SAF and e-SAF in the EU. The aviation sector was integrated into the EU ETS in 2012, meaning that airlines have been required to buy certificates for flight routes within the European Economic Area (EEA)[6] and, since 2024, from the EEA to Switzerland as well as to the UK. In 2026, the Commission is planning to review whether offsetting under CORSIA is sufficient for meeting the goals of the Paris Agreement. If not, the ETS may be extended to apply to international flights as well. In 2025, the European Federation for Transport and Environment (T&E), a European NGO working on sustainable transport and energy policies, estimated that the regional focus of the ETS and the continued availability of free allowances resulted in 70% of CO_2emissions from the aviation sector not being covered by the ETS. This is because currently the EU ETS only applies to flights within the EEA and outbound flights to Switzerland and the UK (T&E, 2025). The expansion to international flights would therefore constitute an important expansion of the EU ETS.

To date, airlines have received a large number of free allowances, but this practice is to be reduced from 2024, with all allowances to be auctioned from 2026 onwards. SAF and e-SAF use by airlines are incentivised in two ways: First, the use of SAF and e-SAF can be claimed to reduce emissions of airlines, including the SAF and e-SAF that is required underneath ReFuelEU (IATA, 2024). Second, between 2024 and 2030 airlines can access 20 million free allowances if they use SAF or e-SAF on routes that are covered by the EU ETS. With this the EU intends to encourage the uptake of SAF and e-SAF (Council of the EU, 2022). However, since e-SAF is likely to enter the market at a significantly later point than SAF, it is likely that these free allowances will be used-up by the SAF sector, thus having little to no effect on the production of e-SAF. From 2025 onwards, airlines will need to report non- CO_2 emissions as well. In 2028, regulation on the pricing of these emissions is to be drafted by the Commission (Implementing regulation (EU) 2024/2493, 2024).

3.1.3 Other EU SAF and e-SAF Initiatives and Funding Instruments

The EU has established several more, smaller-scale initiatives that add to the overall regulatory and funding framework for sustainable aviation fuels. Among these are funding through instruments such as Horizon Europe, the Innovation Fund and InvestEU as well as easier access to funding for SAF due to the establishment of the EU taxonomy; the Flight Emissions Label, which seeks to support more informed decision making by EU citizens with regard to the climate impact of their flights; and the set-up of the SAF Clearing House, which is designed as a one-stop-shop for support to SAF producers in acquiring ASTM D4054 approval, fulfilling sustainability criteria as well as the successful external communication of SAF benefits to the wider public (EC, n.d.–b; European Union Aviation Safety Agency [EASA], n.d.).

3.2 German Regulation and Funding

While Germany is firmly embedded in the EU framework and will have to comply with all provisions outlined above, it has also introduced national-level regulation to encourage a more sustainable aviation sector within the Bundes-Immissionschutzgesetz (BImSchG) and the Greenhouse Gas (GHG) Reduction Quota (THG-Quote) system. In 2021, the German government announced the introduction of a national PtL-SAF

[6] The EEA consists of the Member States of the EU and three countries of the European Free Trade Association (EFTA) (Iceland, Liechtenstein and Norway; excluding Switzerland).

quota, which would have required that 0.5% of total kerosene sales come from the sale of e-SAF by 2026 (Agora Verkehrswende & International PtX Hub, 2024). The new government announced in its coalition agreement that this quota will be abolished to avoid undue burdens for German airlines and fuel suppliers (CDU & CSU und SPD, 2025).

Further, the new government plans to use half of the national revenues from the EU ETS to support the development of SAF and to reduce taxes, fees and charges in the aviation sector more broadly (CDU & CSU und SPD, 2025). This will add to the state aid that the German government has thus far been providing in the context of the European Projects of Common European Interest (IPCEI), which aim at increasing the EU's competitiveness creating jobs, economic growth and supporting the green and digital transition. This funding programme is embedded in the EU's state aid law and allows member states to offer state aid to projects without violating EU competition policies. Thus far, the European Commission has approved four IPCEIs related to the production and usage of low-carbon hydrogen, and German companies are involved in three of these. As part of the IPCEI Hy2Move, which specifically targets the application of hydrogen (technologies) in the transport sector, the German government is, for instance, providing state aid to Airbus Germany (EC, 2024). The state aid provided in the context of other IPCEIs for the production of green hydrogen in Germany can additionally be seen as an indirect source of funding to the e-SAF sector, as this kickstarts green hydrogen production and the creation of a market.

Additionally, national funding programmes supporting the production of green hydrogen or the implementation of CCS-technologies are indirectly encouraging the production of e-fuels including e-SAF. One example is the Federal Fund for Industry and Climate Action, which offers €3.3. billion to small- and medium-size enterprises that reduce their emissions by at least 40%. Module 1 of the programme supports companies in the industry sector to either electrify processes or use hydrogen for process heat or as a fuel. Module 2 supports the installation of CCS and CCU technologies as well as related research. Module 2 therefore can contribute towards the availability of CO_2 from point sources for the production of e-SAF (Kompetenzzentrum Klimaschutz in energieintensiven Industrien [KEI], n.d.).

In the context of the German-Australian Energy and Climate Partnership, a Joint Declaration of Intent was signed in 2024 to establish a joint H2Global funding tender, where each government provides EUR 200 million over the next ten years to support the production and trade of renewable hydrogen between the two countries. Negotiations on the detailed auction design are in a final stage; the auction is expected to start in the first half of 2026. The auction will be exclusively open for Australian producers that sell their hydrogen products to the German market. The price gap is covered equally by both partner countries.

4 Regulatory Context and Feedstock in Australia

This chapter looks at the regulatory context for e-SAF in Australia as well as the potential for renewable power and hydrogen production, although not extensively as they have been well documented elsewhere. It also includes an assessment of CO_2 sources for e-SAF production.

4.1 Australian Regulation and Funding

In August 2024, the Australian government published its Aviation White Paper in which it outlines the future path for the aviation sector in Australia. The paper clarifies that the aviation sector will need to take action to contribute to Australia's transition to net zero emissions by 2050 and the uptake of SAF is one of the identified measures to do so. The paper also summarises existing instruments, which while not targeted at (e-)SAF production exclusively are supporting their production.

One such instrument is the Safeguard Mechanism. Scope 1 emissions from the aviation sector, including for instance emissions from the "combustion of fuels on the aircraft to drive the propulsion system" are covered by the mechanism. Accordingly, aircraft operators with emissions above 100,000 tonnes of CO_2 per year are required to limit their emissions to the baseline set by the regulator each year. This baseline is calculated for each company by multiplying its emissions generating product output (in the case of aviation this is inter alia fuel usage) by an emissions-intensity value, which reflects the average of Australian industry emissions performance. If an aviation company's emissions exceed this baseline, it must buy carbon credits, one for each tonne of excess CO_2 emissions (DCCEEW, n.d.–c; Fowler, 2023; Qantas Group, 2024).

The baseline declines each year by 4.9% which creates an ever more stringent emissions limit for the sector, thus constantly increasing the attractiveness of switching to SAF or e-SAF. However, the effectiveness of this mechanism crucially depends on the initial baseline and the carbon unit price relative to the price of using e-SAF. For the year 2023-24 the default prescribed unit price is A$33.19. Qantas Group and Virgin Australia as well as occasionally one to two smaller airlines are covered by the mechanism. However, thus far, these airlines have not taken up e-SAF as a means to meet their baselines, for which there are two interrelated main reasons. First, their initial baselines have been set quite high, so that, secondly, they can meet them relatively easily by making fleet adjustments (e.g. aircrafts that burn less fuel) and by purchasing carbon offsets. In this way, Qantas has thus far easily been able to stay below its baseline of 4.47 Mt CO_{2e} for 2024 and expects to be able to do so with the two more cost-effective approaches outlined above in the years to come, even as the baseline declines. However, independent of the Safeguard Mechanism, Qantas has set itself the target to have SAF account for 10% in its fuel mix by 2030 and for 60% in 2050 in order to meet its net-zero target in 2050. Already today, Qantas is using SAF in its Heathrow flights. There are no targets for e-SAF specifically (Qantas Group, n.d.). Hence, SAF is incorporated into the airline's sustainability strategy, but this cannot be attributed to the Safeguard Mechanism (Fowler, 2023; Qantas Group, 2024). Likewise, Virgin Australia has to date been able to meet its baseline of 2.17 Mt CO_{2e} without buying carbon credits (Clean Energy Council, 2025; Fowler, 2023).

The Australian government has legislated the Hydrogen Production Tax Incentive, which will provide A$2 per kilogram for eligible renewable hydrogen produced between 2027-28 and from 2039-40 for up to 10 years per project. This will reduce the costs of input for e-SAF projects and thus support their production significantly (Australian Government, 2024).

Financial support is also provided through the National Reconstruction Fund. The Fund was established in March 2023 to help transform Australian industry an economy by providing A$15 billion in the form of loans, equity investment, and guarantees to projects in seven priority areas including transport and renewables and low emissions technologies[7] (Department of Industry, Science and Resources, 2022). This is supplemented by three indirect funding opportunities. The Hydrogen Headstart program aims to accelerate the production of renewable hydrogen in Australia. This program will provide operating funding support to large-scale renewable hydrogen projects through a competitive, merit-based application process administered by the Australian Renewable Energy Agency (ARENA). All end uses of hydrogen or hydrogen derivative products are eligible. A second indirect funding avenue is by the Clean Energy Finance Corporation (CEFC), which supports early-stage and demonstration projects related for instance to the production of hydrogen and bioenergy projects (Clean Energy Finance Corporation [CEFC], n.d.). Lastly, as mentioned in chapter 3.2., the Australian government provides funding over the next ten years under the joint H2Global funding window with Germany to support the production of renewable hydrogen.

This will be supplemented by several measures announced in the 2024-25 budget. Here, the government has allocated A$1.7 billion to ARENA's Future Made in Australia Innovation Fund for priority sectors, including A$250 million for Low Carbon Liquid Fuels (LCLFs), and A$18.5 million to the expansion of the Guarantees of Origin scheme to include LCLFs (DCCEEW, n.d.–b; Minister for Infrastructure, Transport, Regional Development and Local Government, 2025). Australia's Guarantee of Origin Scheme was established in 2024 and serves as the country's voluntary certification scheme for low-emissions products and renewable electricity (Department of Climate Change, Energy, the Environment and Water (DCCEEW) (n.d.–b)). To enable international trade, for instance with the EU and Germany, mutual recognition of the respective certification schemes will be crucial.

A$1.5 million have been allocated to a regulatory impact analysis on the costs and benefits of introducing demand-side measures such as non-mandatory targets, trading schemes connected to low-carbon fuels standards and mandates. Additionally, the government has already initiated an industry consultation on the most suitable tool to provide further support to the production of low-carbon fuels projects. Instruments under discussion include competitive grant-based production incentives such as Contracts for Difference or a fixed grant amount per production unit or a production tax incentive in the form of a time-limited incentive per unit of LCLF. In addition, the Australian Government has provided support for research and innovation through the Emerging Aviation Technology Program (Australian Government, 2024).

Early feedback in the context of the regulatory impact analysis and the industry consultation on supply-side tools from Brisbane Airport, the Government of New South Wales, Western Sydney Airport, Australian Airports Association, SkyNRG, Qantas Group, Board of Airline Representatives of Australia, and Business Council of Australia points to the desirability of additional demand-side measures, particularly the introduction of mandates for the use of SAF, while using a mix of supply-side tools to ensure the demand can be met. Feedback from the Sustainable Aviation Fuels Alliance of Australia and New Zealand (SAFAANZ) suggests a regulated demand side lever, tied to intensity (Department of Infrastructure, Transport, Regional Development, Communications and the Arts [DITRDCA] & DCCEEW, 2024).

4.2 Renewable Power and Green Hydrogen

Australia is uniquely positioned to become a global leader in renewable energy and green hydrogen production, thanks to its exceptional solar and wind resources. The country's vast open spaces and extensive coastline provide ideal conditions for large-scale renewable energy projects, including hybrid systems that combine solar and wind to optimise energy generation. With 21 times the land mass of Germany but only one third of the population, Australia could potentially supply all of Germany's energy demand multiple times over. Using just 3% of Australia's surface area for the production of hydrogen could cover Germany's non-electricity energy consumption 10 times over (Australian Embassy, 2021).

Over the past 12 months, renewables accounted for 40% of Australia's total electricity supply, with significant variation across states. Tasmania leads with 95% renewable energy, followed by South Australia at 75%, while Queensland lags behind at 29%. New South Wales stands at 36% and Victoria

[7] The other priority areas are medical science, value-add in agriculture, forestry, and fisheries sectors, value-add in resources, defense capability, and enabling capabilities.

has a 40% renewables share. Western Australia is special as large parts of the state are not grid connected. The South West Integrated System (SWIS) represents the largest grid and stood at 39% (Open Electricity, 2025). This disparity highlights the importance of state-level policies and investments in driving renewable energy adoption.

Although the expansion of renewables has been relatively slow in recent years, 2024 saw an uplift with investments in renewables at levels that hadn't been reached since 2018 (Clean Energy Council, 2025) This development reflected improving economic conditions, the introduction of the federal Capacity Investment Scheme, an underwriting scheme for 32 GW of renewable and storage capacity, and improvements to grid connection and planning processes. However, investor confidence has been shaken in Queensland due to unexpected state government decisions following the state elections in October 2024, underscoring the need for stable and supportive policies.

Looking ahead, the Australian federal government aims to achieve 82% renewable energy by 2030, with 48% likely by the end of 2025 (Coorey, 2024). Many more projects will need to be committed and come online to meet the renewable energy target that first and foremost targets decarbonisation of the existing power consumption. Challenges remain for renewable hydrogen and e-SAF projects, which require access to low-cost renewable power. Network charges, a shortage of low-cost Power Purchase Agreements (PPAs), comparably high costs of building independent renewable infrastructure in Australia as well as bottlenecks in the construction of renewables and storage could limit the scalability of these projects in the short to medium term.

Nevertheless, Australia's National Hydrogen Strategy does set ambitious targets for green hydrogen production for 2030 to 2050 (DCCEEW, 2024a).

- 2030: 0.5 – 1.5 million tonnes
- 2035: 3 -5 million tonnes
- 2040: 5 - 12 million tonnes
- 2045: 9 – 20 million tonnes
- 2050: 15 – 30 million tonnes

If all the hydrogen targeted for 2030 were refined into e-SAF and assuming that one tonne of e-SAF requires 0.45 tonnes of hydrogen, this would result in 1–2.2 million tonnes of e-SAF in 2030, scaling up to 30–60 million tonnes by 2050. To put this into perspective, replacing just 10% of Australia's aviation fuel with e-SAF would require 770,000 tonnes[8], demonstrating the potential for Australia to meet both domestic and export demand.

4.3 Australian Carbon Sources for e-SAF Production

This chapter investigates different carbon sources and their potential use as CO_2 feedstock for e-SAF in Australia. Four main feedstock types are useable as carbon sources, the first being the capture of pure CO_2 directly from the air. The second source is CO_2 as a byproduct from heavy industries, for example: ammonia, aluminium, paper, liquefied natural gas (LNG), cement production, and steel manufacturing. The third potential carbon source comes from biogenic materials that contain carbon, which can be extracted primarily through gasification. These biogenic materials are municipal solid waste (MSW), abattoir waste, kelp, sugar cane, and agricultural and forestry residues. Another developing sector, which is not looked at below due to a lack of data, is biogas occurring at landfills and anaerobic digesters, with individual facilities being small scale, but collectively a large potential supply.

The following questions form the basis for the research into carbon sources, and in some cases estimates or predictions are made. However, not all questions can be answered for each potential source:

- How much carbon can each source provide?
- How can the carbon be extracted?
- What infrastructure is needed to extract and use the carbon?
- Is the carbon/carbon source already needed for other products?
- What are the market dynamics around the carbon source?
- Is the extraction of the carbon commercially viable?

[8] 2019 consumption 9,39 billion litres; 10% converted to tons = 769,401 tons

- How sustainable is the carbon source?

The map in Figure 3 gives and overview of the different industrial and biogenic CO_2 sources and their distribution across Australia.

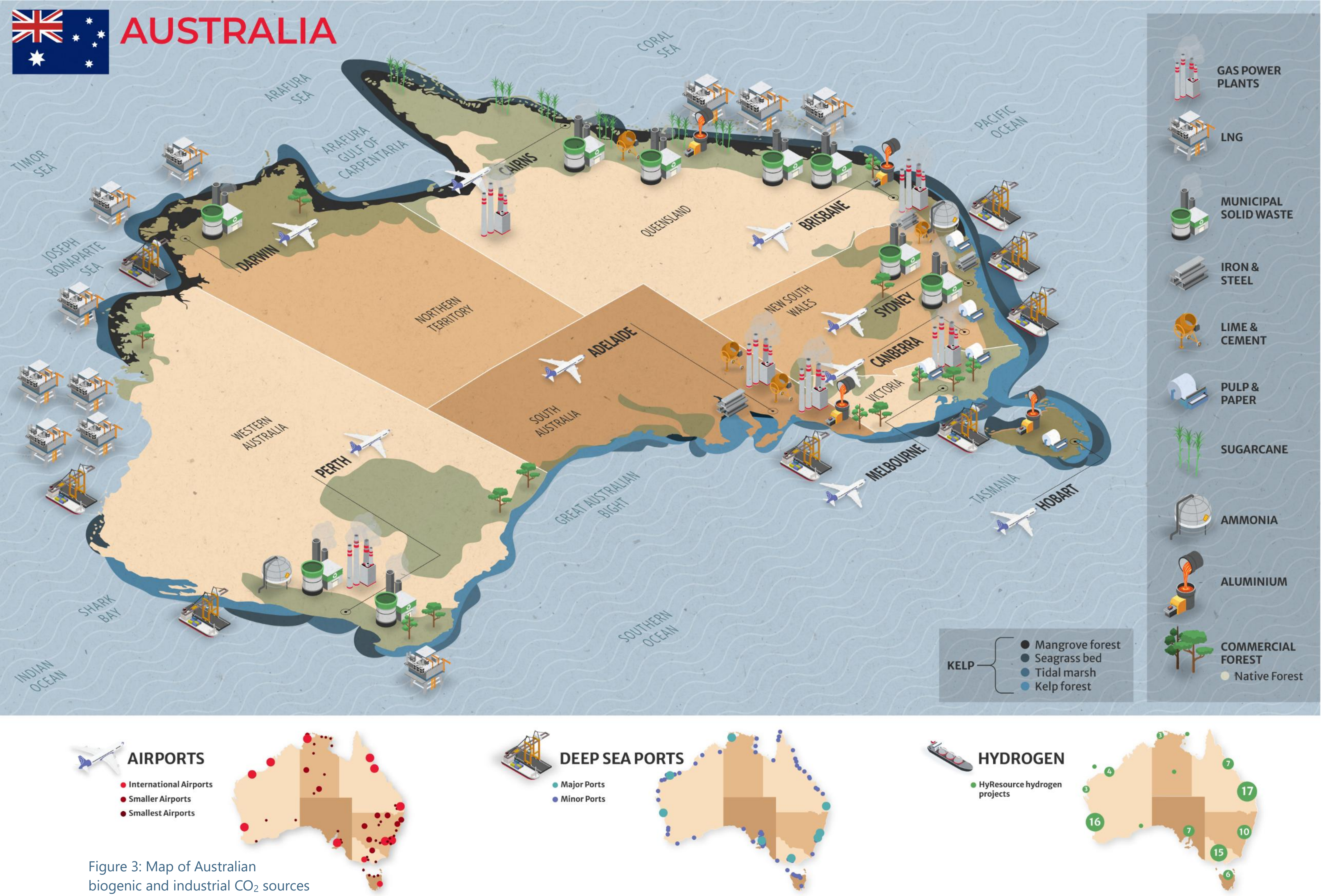


Figure 3: Map of Australian biogenic and industrial CO_2 sources

4.3.1 Direct Air Capture (DAC)

With the amount of carbon dioxide present in the atmosphere today, capturing CO_2 right from the air is the most immediate idea for a carbon source. However, this proves to be more technically difficult than first imagined. DAC requires moving large volumes of air through devices that trap the CO_2 in either solid absorbents (S-DAC) or aqueous solutions (L-DAC) but both approaches are presently energy-intensive and therefore expensive. The most energy-intensive step in DAC operation is the re-release of CO_2 after capture, and research is currently ongoing to make this aspect of both S-DAC and L-DAC more energy efficient.

Moving large volumes of air through the devices also requires a lot of energy as CO_2 constitutes only 0.04% of the atmosphere and is therefore comparatively much more diluted than a point source. For example, flue gases coming from cement production contain around 20-25% of CO_2 (Majeed & Svendsen, 2018), Finally, another factor for creating efficiency is in the operating temperatures of L-DAC and S-DAC (IEA, n.d.). As they are designed to use both electricity and heat to operate, the utilisation of waste heat streams can bring down the overall energy usage of a DAC system.

Around 1.32 billion tonnes of CO_2 will be needed annually to produce enough e-SAF to replace the amount of aviation fuel consumed globally in 2019[9] (Agora Verkehrswende & International PtX Hub, 2024). To produce this volume of CO_2 from DAC, the implementation of large-scale facilities will be necessary requiring a large amount of land and the development of supporting infrastructure and technology. Other challenges exist around producing a consistent supply of e-SAF using DAC as a carbon source, as well. For example, effective and efficient storage of the captured CO_2 may be required, or transportation to the location of e-SAF production if it is not co-located. Consequently, if the supply of CO_2 is interrupted so will be the production of e-SAF.

According to the IEA, twenty-seven DAC plants with a combined annual capture capacity of nearly 0.01 Mt CO2 have been put into operation worldwide to date. (IEA, n.d.). Climeworks estimates that developing a DAC plant from concept to commissioning takes around six to ten years, indicating that it will take some time before enough projects exist to match the required supply of CO_2 for E-SAF production (Climeworks, 2024). With the price of air-captured CO_2 currently around US$600, without substantial progress, it does not seem that the price will get below US$100/tonne even in the most optimistic scenarios in the longer term (Evans, 2017).

However, despite these challenges, the IEA estimates that 63.6 Mt of CO_2 could be captured by 2030 if all projects under development and in the concept and feasibility stage are completed (IEA, n.d.). Various DAC projects exist in Australia, such as the Ambient CO2 Harvester (ACOHA), AspiraDAC, Heirloom, Skytree projects, CSIRO projects and Fugu.

4.3.2 CO_2 Extracted from Biomass

CO_2 extracted from biomass is another potential carbon source for producing e-SAF. Some of the following biomass feedstocks contain some hydrogen, which is also usable for e-SAF. This chapter analyses biomass coming from feedstocks, such as sugarcane/bagasse, landfills/municipal solid waste/abattoirs, kelp/algae, and forestry residue/wood waste.

The process of gasification is the only way to extract the CO_2 from biomass. Gasification converts organic materials like MSW, kelp, or bagasse at high temperatures, and without combustion, oxygen, or steam into carbon monoxide, carbon dioxide, and hydrogen. Afterward, a water-gas shift reaction initiates a reaction between the carbon monoxide and water to produce more hydrogen and CO_2 (U.S. Department of Energy, n.d.–a). Gasification is made up of five discrete thermal processes: *Drying*, *Pyrolysis*, *Combustion*, *Cracking*, and *Reduction* (ALL Power Labs, n.d.).

The current price for CO_2 extracted from biomass is approximately A$100-300 per tonne (Queensland Economic Advocacy Solutions, 2019). This price is driven up by competition for the biomass feedstocks needed to produce e-SAF, compared to captured CO_2, as well as the inefficiency of the technology used for CO_2 extraction.

4.3.2.1 Sugarcane residue

Sugarcane residue, also known as bagasse, is one of the various CO_2 sources that are suitable for producing e-SAF in Australia. Australia produces 4.5

[9] Global consumption of 331 million tonnes of kerosene in 2019 multiplied by 4kg of CO2 needed for the production of 1 tonne of e-SAF.

million tonnes of raw sugar annually from crushing around 30 million tonnes of sugarcane (Queensland Economic Advocacy Solutions, 2019). This sugarcane is produced on 378,000 hectares of land, 95% of which is located in Queensland due to the more tropical climate conditions favourable for growing the plant. Sugarcane takes between 9 and 18 months to grow, binding carbon inside itself during this process. After being crushed to extract the juice for sugar, approximately 20% of the sugarcane's mass remains as bagasse (Melati et al., 2017). At 24.7%, the carbon content in sugarcane bagasse is quite high (Kalderis et al., 2008).

Bagasse is often used to generate energy in sugar mills with one tonne producing around 2MW of electricity (International Renewable Energy Agency [IRENA], n.d.). When burned in high quantities, it can power a typical sugar mill and produce excess energy which can be fed back into the electricity grid. However, sugarcane can be gasified to extract the carbon out of the plant material, which could then be used to produce e-SAF. If alternative renewable energy solutions powered the sugar mills, it would be possible to access around 50% more bagasse for producing aviation fuel.

According to the CSIRO roadmap, the top two available feedstocks for (e-)SAF production in Australia in 2025 will be agricultural residues and a combination of sugarcane and bagasse. Using the ethanol-to-jet pathway, 10% of Australia's current raw sugar production and 25% of bagasse production could be used to produce 988 ML of aviation fuel in 2025 (CSIRO, 2023). However, CSIRO predicts that by 2050 most SAF will be produced with the PtL pathway as e-SAF (McClure, 2023). According to their Roadmap, 10% of projected sugar production and 40% of projected bagasse production through 2050 would be enough to produce e-SAF (through gasification and the Fischer-Tropsch process) to meet 10% of the SAF demand in Australia.

As a disadvantage, producing sugar emits a lot of CO_2 in the form of scope 2 emissions. Approximately 32% of sugarcane's CO_2 footprint originates from farm machinery use, while 15% comes from fertilizer production. Additionally, growing sugar cane produces a lot of nitrous oxide, which has a 265 times stronger global warming effect than CO_2 (CarbonCloud, n.d.). To maintain and improve healthy ecosystems, the sugar cane industry needs to implement a range of sustainable initiatives, which could also benefit the social acceptance of sugarcane. One of these sustainable initiatives can be using sugarcane to produce SAF or e-SAF.

4.3.2.2 Kelp

Algae, especially kelp, is another potential CO_2 source for producing e-SAF. Microalgae are single-celled photosynthetic microorganisms, whereas macroalgae are multicellular aquatic plants containing differing amounts of carbohydrates, fats, and proteins. Kelp is a type of macroalgae, that uses photosynthesis to absorb CO_2 and grow biomass with water and sunlight, up to 61 cm a day (Gerretsen, 2021).

Kelp can be used for HEFA biofuels and biogas through anaerobic digestion, animal feed, or carbon storage (CSIRO, 2023). The process of gasification is used to extract the carbon from the kelp. Otherwise, kelp can be processed through drying, freezing, ensiling, or fermenting. With kelp's carbon content being approximately 30% when dry, 1 tonne of dried kelp could produce up to 1.1 tonnes of CO_2 (Bayley et al., 2017).[10] Some of the key environmental advantages of growing kelp for fuels is that it does not compete for existing agricultural land and its growth requires little to no fresh water, pesticides, or fertilisers (Thomas et al., 2024).

The largest kelp forests in Australia are found along the southern coast and around Tasmania. According to a study published in *Nature,* 30% of the carbon sequestered in the oceans around the Australian continent is found in the kelp forests of the Great Southern Reef (Filbee-Dexter & Wernberg, 2020). However, with global warming, the volume of kelp forests has decreased, especially in the seas around Tasmania (Wild, 2024).

A few organisations and projects, like the Tasmanian Giant Kelp Restoration Project, are developing methods to restore large-scale kelp forests (The Nature Conservancy Australia, 2025). Commercial seaweed farms are also being planned, which intend to use the crops as pharmaceuticals, human food, and carbon storage. The commercial projects are still in the developing and planning phase but are estimated to start growing kelp at the end of 2025 (Becker & Gregory, 2022). These seaweed farms and

[10] CO_2 Yield (at 30% carbon content) = Carbon Weight / 0.27 = 300 kg / 0.27 ≈ 1,110 kg. The conversion factor of carbon dioxide to carbon is 0.27.

restoration projects are located around the Tasmanian coast and New South Wales.

It is very difficult to estimate the volume of seaweed farms because there are factors such as limited data from large-scale operations, environmental variability, technological challenges, and seasonal variations (Kite-Powell et al., 2022).

4.3.2.3 Landfill/Municipal Waste/Abattoirs

In Australia, around 13.5 million tonnes of municipal solid waste MSW were generated in 2022 – 2023. Of this, 5.9 Mt were either reused or recycled. The highest amount of waste was generated in New South Wales (28 Mt), Victoria (16 Mt), and Queensland (15 Mt), while the highest waste recovery rates can be found in Southern Australia (82%), followed by the Australian Capital Territory and New South Wales (73% each). MSW is a potential CO_2 source to produce e-SAF through the processes of incineration, gasification, or anaerobic digestion. Each process has advantages and disadvantages, with some pathways better suited for specific outcomes (DCCEEW and Blue Environment Pty Ltd., 2025).

Incinerating one tonne of municipal solid waste emits between 0.7 and 1.7 tonnes of CO_2 which, when captured, can be used to produce e-SAF (Zero Waste Europe [ZWE], 2020). The most used CO_2 capture process is the absorption method, in which flue gases are captured during the incineration of MSW, and CO_2 molecules subsequently adhere to a liquid chemical solvent in the absorption column. In there, a thermal process separates the CO_2 molecules from the solvent, which can be reused (Veolia, n.d.).

Less than 20% of the flue gases are made of CO_2, but aiming to extract just the CO_2 from MSW for fuel synthesis without using the embedded hydrogen is inefficient compared to other methods of making SAF from the same feedstock (Warmuzinski et al., 2015). E-SAF would be the most efficient SAF to make from MSW flue gases.

Gasification of MSW, where MSW is heated in a low-oxygen environment until it breaks into molecules, produces syngas containing CO_2 and some hydrogen. Slag or char are the other products of this process. With the addition of green hydrogen, the syngas products are useable for e-SAF through the Fischer-Tropsch process. According to CSIRO, a small FT plant with an annual production capacity of 50 ML SAF would consume 3% of Australia's projected municipal waste for 2025. A large plant with an annual production capacity of 300 ML would consume 17–18% of the municipal waste collected in 2025 (CSIRO, 2023). However, no such plants exist in Australia yet.

It is challenging to establish MSW projects because every council has its policies for waste management, as well as different waste levies and prices. The average levy for all states in Australia is A$107.4. Hence, every council needs to be negotiated with independently and there are other usage competitors from the bioenergy sector. To create supply chains for waste intermediates, and to synthesise SAF, Australia requires technology development and capability demonstrations.

Usually, MSW is deposited into landfills, which can be used later to produce energy. It is also possible to use Anaerobic Digestion of wastewater, organic waste, and MSW to produce biogas, which consists of CO_2 (25-50%), methane (50-75%) and contaminants. The CH_4 and CO_2 can be reformed together with renewable electricity to produce syngas which can then be synthesised into (e-)SAF by the Fischer-Tropsch process to produce FT-kerosene. The resulting fuel is a hybrid with approximately 25% being e-SAF and 75% being bio-SAF (depending on whether allocating by mass or energy) (CSIRO, 2023).

4.3.2.4 Forestry and Wood Waste

Australia has a total of 133.6 million hectares of forest, 98% of which is native forest and a further 1.8% commercial plantations (Australian Bureau of Agricultural and Resource Economics and Sciences [ABARES], n.d.). Forests can store significant amounts of carbon in the wood of trees making the total stock of carbon in Australia's forests 19,417 million tonnes in 2021. The total stock of carbon from harvested wood was 167 million tonnes in 2021 (Montreal Process Implementation Group for Australia and National Forest Inventory, 2024).

Woody biomass, however, yields not only CO_2 but, when co-gasified with oxygen, up to 30% of hydrogen, making it a very attractive feedstock as long as supply lasts (Chmielniak et al., 2024). It needs to be noted that sourcing that biomass from plantations is far from trivial, with tying the harvesting of those residues into the operations of the plantation, noting other restrictions such as weather events, access, parasites etc.

Wood waste from sawmills such as woodchips and sawdust, pulp mill residue such as black liquor and wet wastes and wood wastes from the manufacturing of commercial wood products are also potential carbon sources. According to ABARES, around 5.2 million tonnes of sawmill residue have been produced in 2016-17 (Lock & Whittle, 2018).

4.3.3 Industrial Point Sources

The next section analyses the potential of capturing CO_2 from industries such as iron and steel, liquefied natural gas, natural gas electricity generation, pulp and paper, lime and cement, ammonia, and aluminium.

Australia hosts a range of industries that provide CO2 as a byproduct. While Australia does not have a carbon tax, the Safeguard Mechanism requires industrial facilities emitting more than 100,000 tonnes of CO_2-eq per year to gradually decrease their emissions by 4.9% each year by 2030 (DCCEEW, n.d.–c). Companies are therefore reducing emissions or buying offsets, but large quantities are still being emitted.

Captured, this CO_2 could be used as a carbon source for e-SAF and is cheaper than CO_2 extracted from biomass in almost every industry. The price for captured CO_2 can be below A$100 per tonne of CO_2 (CSIRO, n.d.). This is because there is currently no other use and hence no competition for the carbon emitted.

From a sustainability perspective, using the vented carbon for fuel production offers a second life to the CO_2. Yet, it must be stressed that this usage of carbon is no long-term solution, as heavy industry processes are to be decarbonised. Only as long as the emissions arise anyway and the emitted CO_2 wouldn't be captured and permanently stored, can this be regarded as a sustainable feedstock to produce e-SAF.

4.3.3.1 Liquified Natural Gas (LNG) Production

Australia has been one of the world's largest LNG exporters since 2020. There are ten LNG plants currently running in Australia, which produced around 33.8 million tonnes of CO_2 emissions in 2023-2024 (Australasian Centre for Corporate Responsibility Inc [ACCR], 2023; Future Energy Exports, 2024). The three largest emitters are Gorgon Operations, North West Shelf Project, and the Ichthys LNG Project. Gorgon is estimated by its operators to run until 2056, and the Woodside North West Shelf Project has recently been extended until 2070 (Clean Energy Regulator, 2025; Shackleton et al., 2025).

Those plants will keep emitting CO_2 unless it is stored or utilized. Only the emissions covered by the Safeguard Mechanism and as agreed with the government for particular gas fields are currently being sequestered. With the right incentives, more CO_2 could be stored or re-utilized. Storage is not always the most feasible option and requires careful planning. No two storage sites are the same, and compressing the CO_2 underground requires massive amounts of energy. Utilisation is therefore an attractive alternative.

For example, Bonaparte is a proposed CCUS project off the northwestern coast of the Northern Territory, led by INPEX with TotalEnergies and Woodside as consortium partners. Such a CCUS project could facilitate not only the sequestration of CO_2 from nearby LNG facilities in the Darwin region but also the utilisation of the CO_2 (Total Energies, 2022). One possible off-taker could be TotalEnergies TE H2's Darwin H2 Hub, which is a multi-energy project powered by up to 4.5 GW of solar PV generation coupled with energy storage to provide dispatchable renewable energy and green hydrogen production. The first stage of the project is aiming to feature a 50 MW electrolyser for synthetic hydrocarbon production to demonstrate the viability of e-fuels in Australia (Ho, 2025).

The process of liquefying natural gas already separates the CO_2, which would freeze well before methane becomes liquid (-162 °C) and therefore block the pipes. The majority of the 33.8 Mt of CO_2 emitted by the LNG industry could be used for e-SAF or other carbon-related production pathways. This makes CO_2 from LNG the cheapest and most concentrated option compared to other carbon sources.

As Japan and South Korea are already contemplating utilising synthetic methane from LNG, Australia would need government policy support to utilise recycled CO_2 or syngas as a CO_2 source for e-SAF. If the final product could prove low emissions, then developing an e-SAF export market with LNG as a carbon source would be possible. As the LNG industry is strategically important to Australia and vital for global supply, this source of CO_2 will likely exist for many decades to come.

4.3.3.2 Ammonia

Ammonia plays a vital role as a fertiliser for crop growth and in various chemical applications. It also has potential as a fuel for shipping, for power generation, or as a hydrogen carrier.

Ammonia is synthesized through the Haber-Bosch process where hydrogen is reacted with nitrogen under pressure. In most cases, Steam Methane Reforming (SMR), where natural gas reacts with steam to produce hydrogen and CO_2, is used as the source of hydrogen. When SMR is used, a very pure CO_2 stream is produced as a by-product with approximately one tonne of CO_2 emitted as a byproduct for each tonne of ammonia produced.

Demand for ammonia is likely to remain high due to its use as a fertiliser. In fact, the global demand for ammonia will triple by 2050 relative to 2023 but will increasingly be replaced by green ammonia in the future (S&P Global, 2023). Green hydrogen can be used to produce ammonia, as is being trialled by the Yuri project in the Pilbara, and there are several other large-scale ammonia projects using green hydrogen as a feedstock in development in Australia. Whilst the use of green hydrogen for ammonia production is preferential from the overall perspective of reduced carbon emissions, if ammonia is produced using an increasing amount of green hydrogen, then there will be less of a CO_2 waste stream to be used for e-SAF production. Therefore, the CO_2 emissions, coming from ammonia production, are expected to decrease to 3 Mt of CO_2 by 2035.

However, it will be some time before enough green hydrogen is produced in Australia to replace the need for SMR, so utilisation of the CO_2 waste stream would still be beneficial in the short term. Around0.4 Mt of Australia's annual 0.5 Mt grey hydrogen production is used to make ammonia, emitting around 4 Mt of CO_2 in the process. These emissions are produced across 7 facilities. Wesfarmers CSBP ammonia production produces 955kt of CO2 (Clean Energy Regulator, 2025), 620kt of which is emitted as a pure CO_2 stream after selling a certain quantity.[11] Their facility in Kwinana, Western Australia, emits 600 tonnes of CO_2/day; 50-60 tonnes are sold, the rest is vented.

Yara and Incitec Pivot are further ammonia producers that produced a combined 1.7 Mt of CO_2 in 2022-2023 in Western Australia and Queensland (Clean Energy Regulator, 2025), although Incitec Pivot ceased ammonia production by closing its Gibson island facility in 2023. In the cases where pure CO_2 streams are produced, they could be used directly as the carbon source for e-SAF production.

4.3.3.3 Iron and Steel

Producing iron and steel emits significant amounts of CO_2. These facilities are large, resulting in high operating and maintenance costs, which make capturing CO_2 from iron and steel production expensive. Iron and steel production is among the most carbon-intensive industries, contributing 8% of global CO_2 emissions (Australian Trade and Invest Commission [Austrade], 2024).

Around 11 Mt of Scope 1 CO_2 emissions came from iron and steel production in Australia in 2021 – 2022 (Climate Change Authority, 2025). Bluescope, Liberty, and Infrabuild are currently emitting around 8.3 Mt of CO_2, which is 75% of all Australia's iron and steel-related emissions (Clean Energy Regulator, 2024).

The steelmaking process starts with mining iron ore, a compound of iron, oxygen, and other minerals. On its way to being transformed into steel, the iron ore is reduced to iron by using the blast furnace route, then processed into steel via a basic oxygen furnace. The majority of carbon emissions, between 80% - 85%, come from the reduction of iron ore to iron using coal in blast furnaces, where the CO_2 is separated and emitted.

However, this CO_2 could be captured and utilised. A transition to a direct reduction of iron (DRI), then use of an electric arc furnace to make steel can be expected over time in Australia, but DRI is more complicated for hematite, a form of iron ore more common in Australia than magnetite. According to Australia Minerals, approximately 58% of Australia's iron ore is hematite and 41% magnetite (Australia Minerals, 2024). Technologies to produce DRI from hermatite are being explored by Australian companies (such as Neosmelt by Rio Tinto, Blue Scope, and BHP) but these have a long way to go to become commercial. Additionally, the existing furnaces have long lifetimes, up to 50 years, and are therefore unlikely to be replaced swiftly, even if new technologies become available. On the contrary, BlueScope is currently investing A$300 million into

[11] According to Expert Interviews.

the refurbishment of blast furnace number 6, which has been mothballed furnace since 2006. While being more fuel-efficient, it will not be capturing the several thousand tonnes of CO2 per day, as there are neither storage sites nearby nor a market for the gas.[12]

Nevertheless, the IEA says that emissions from the steel industry will be required to decrease emissions by around 50 per cent by 2050 (Clean Energy Regulator, 2024).

4.3.3.4 Cement & Lime

Cement and lime production account for about 8% of global CO_2 emissions (World Economic Forum, 2024). In Australia, the sector emitted 4.7 Mt CO_2 in 2020-2021. Around two-thirds of the production process's emissions are direct emissions from the raw materials (CSIRO, 2023b). The other third comes from heat, fuel, and electricity and could be electrified or run on green hydrogen. The lime and cement production process begins with the extraction of raw materials, such as limestone and clay. These are crushed and ground into a fine powder, which is heated in a rotary kiln at temperatures reaching up to 1450°C. This phase is the primary source of CO_2 emissions, with approximately 0.5 tonnes of CO_2 released for every tonne of cement clinker produced.

Various studies estimate that emissions from the cement industry could be reduced by between 35 and 60% if CCUS technologies are applied (Kumar et al., 2025). There are several pathways via which emissions could be captured:

- Amine scrubbing, where amine solutions absorb CO_2 flue gases produced during cement manufacturing. CO_2 is then separated from the amines through heating, allowing for compression and transportation.
- A method which is being investigated in, is capturing the CO_2 directly from the calcination process before it gets vented into the atmosphere. Companies such as Leilac are working on solutions to capture the CO_2 through indirectly heated calcination (Leilac, n.d.).
- Other methods to capture CO_2 are calcium looping, cryogenic separation, and the use of membrane systems. Whilst it might be possible to replace the raw materials with synthetic limestone or other materials in the future, it will take a very long time to replace the quantities needed, even if the technology was already mature today (Hills et al., 2016).

However, as the industry strives to decarbonise its production, less CO_2 will be available for capture. The World Cement Association predicts that the industry's global emissions will decline from 2.4 Gt in 2024 to less than 1 Gt in 2050 (World Cement Association, 2024).

4.3.3.5 Natural Gas Power Plants

With 101 gas power plants running in Australia, approximately 33% of Australia's generated energy was produced from natural gas in 2022- 2023 (Clean Energy Regulator, 2024; DCCEEW, n.d.–a).

Natural gas plants generate electricity through the combustion of natural gas in gas turbines or combined cycle systems. In natural gas plants, water and CO_2 must be separated from the final gas stream, as they lower the value of the stream. This results in processed methane, the primary component of natural gas. In open-cycle gas turbines, methane is combusted to produce hot gases that drive the turbine connected to a generator. When using a combined-cycle gas turbine, the heat from the combustion is used to produce steam, which drives a steam turbine.

Australia's total scope 1 CO_2 emissions from natural gas electricity generation amount to 15.8 Mt (Clean Energy Regulator, 2024). Most CO_2 is being emitted when combusting methane, around 0.502 kg of CO_2 per kilowatt hour of electricity, which could be captured. Technologies to capture CO_2 have been implemented at a commercial scale worldwide for natural gas plants, as well as during fertilizer production, and at ethanol plants. Still, there is no one-size-fits-all approach for CO_2 capture and CO_2 is mostly vented into the atmosphere.

In addition to direct emissions are lifecycle emissions from extraction, processing, and transport. Torrens Island Power Station, Longford Gas Plant, and some natural gas fields are already sourcing out CO_2 from their flue gas streams. E.g. Torrens Island emitted 376,000 tonnes of CO_2 in 2024, of which it sold 50,000 tonnes to Air Liquide as part of an

[12] BlueScope's Port Kembla facility upgrade given the green light

ongoing 15-year contract; the remainder was vented (DCCEEW, 2023).

While CO_2 emissions from power generation represents the biggest emission factor, this source is projected to decrease from about 110 Mt CO_2-e globally in 2025 to about 30 Mt in 2035. In Australia, the emissions are projected to decrease from 18 Mt in 2025 to 14 Mt in 2035 (DCCEEW, 2023).

4.3.3.6 Pulp & Paper

Australia produced 2.9 million tonnes of paper and paperboard in 2022- 2023 and approximately 1.6 million tonnes of paper and cardboard are discarded in Australia's landfills each year. The pulp and paper industry accounted for 0.8% of Australia's total emissions in 2019 – 2020. Around 3.367 Mt of CO_2 were emitted, of which 43% were direct scope 1 emissions (Montreal Process Implementation Group for Australia and National Forest Inventory, 2024).

The process of paper production involves a couple of steps, several of which require large amounts of energy and result in significant CO_2 emissions. The process starts with sourcing raw materials, like trees, which get debarked and chipped. The majority of scope 1 emissions are released during the cutting and chipping of trees. The rest of the scope 1 emissions arise from pulping, where around 70 to 90% of the biogenic CO_2 can be captured and utilized (CaptureMap, 2024). The majority of CO_2 emissions during pulping come from the combustion of lignin. The CO2 emitted can be captured using amine scrubbing technology, a chemical separation method that relies on the reaction between amine-containing solvents and the CO2 in the flue gas (slb Capturi, 2024).

Most of the scope 2 emissions come from energy use during chemical/mechanical pulping, as well as when drying the paper with heated cylinders. These emissions could be reduced by using energy from renewable sources or green hydrogen.

4.3.3.7 Alumina and Aluminium

According to the International Aluminium Institute, global demand for aluminium will increase from 100 million tonnes per year today to 190 million tonnes by 2050 (International Aluminium Institute, n.d.).

Australia produced 19.05 million tonnes of alumina in 2023 and is the second-largest producer of alumina worldwide. Australia has six bauxite mines, five alumina refineries, and four aluminium smelters (International Aluminium Institute, n.d.). In 2023, aluminium manufacturing produced around 33.4 Mt of CO_2, 3% of the global aluminium industry emissions.

The production involves three steps: the extraction of bauxite ore, refining the bauxite to alumina, and smelting alumina to aluminium. This last step causes the highest emissions. Around 14.8 Mt of CO_2 emissions in 2023 come from refining the alumina from bauxite using fossil-generated electricity. The most emissions, around 18.2 Mt of CO_2 in 2023, are produced during smelting. The brunt of it comes from indirect emissions (15.1 Mt) for heating (Australian Aluminium Council Ltd., 2022). These could be reduced by using electricity from renewable sources or hydrogen (Zhang et al., 2024). The other part comes from the usage of carbon anodes, which could be replaced by inert anodes, thus eliminating direct emissions. The emissions from smelting are expected to be reduced to 3 Mt of CO_2 by 2035 (DCCEEW, 2023).

As the carbon concentration in aluminium smelters' flue gas is particularly low, capture costs of that part of the process would be very high, "likely two to four times the cost of CCS in iron and steel production and approximately 25 times the cost in natural gas processing, fertiliser, and bioethanol production. [...] Simply switching to clean electricity sources [...] can already lead to a roughly 75% reduction in emissions from the industry globally" (Zhang et al., 2024). It is therefore not the best point source of CO_2 and will not be included as a potential CO_2 source.

4.3.3.8 Summary of Australian CO_2 Sources

With CO_2 constituting five to ten times the weight of SAF relative to hydrogen, while costing a fraction (min. A$25-600/t CO_2 vs A$10,000/t H2, assuming an approximate price of A$10/kg H2), its source plays a critical role in SAF production. In fact, the CO_2 source is widely recognized to be the single most important factor when looking at e-SAF production sites, followed by renewable energy costs and transport infrastructure (proximity to airports or ports).

DAC has the potential to be a source of CO_2 for food production, water treatment, hydrocarbon production etc. as it is ethically uncontested. It would also make e-SAF production geographically independent of the source of CO_2, only requiring large energy input, but so does the production process for hydrogen and SAF in general. However, DAC is still very far from being commercial and may never provide CO_2 as cheaply as point sources and will never deliver large quantities in as concentrated an area.

Biomass is by far the most suitable carbon source for e-SAF, because its gasification yields 20% hydrogen, which is the most expensive component (Lepage et al., 2021; Tucker, 2025b). However, biomass is fraught with limitations, ranging from the CO_2 footprint in its growth and transport to its vulnerability to fires, droughts, and floods. It also competes with other use cases like combustion for heat and power generation. Mainly, its quantities are limited and will only ever cover a part of aviation fuel demand, even if new sources such as kelp can be explored and scaled up.

Industrial point sources are principally a suitable option where these emissions would not otherwise realistically be mitigated for at least the next two decades, which allows enough time to ramp up DAC to provide the quantities necessary in the long-term. Whilst CCS will be needed in the long term for unavoidable emissions, it does not shape up to be an easy or cost-effective pathways in the near-term. Storage sites can be prohibitively remote from originating sites, and the energy required to liquify and inject the CO_2 can be huge.

In particular, where CO_2 emissions are already being captured as part of the process, such as in LNG and ammonia production[13], their usage could be encouraged to prevent venting, especially as long as there are no incentives to invest into mitigation measures or potential CCS sites are too far from the point of generation. e-SAF production based on industrial point sources will require co-location with the point source, as the transport of CO_2 is expensive. The cost of transporting CO_2 in 2019 ranged between US$3-12 per tCO_2 in a 100-mile onshore pipeline with a small flow rate of 1 Mt/year. Depending on the range and flow rate the price may increase even more (Smith et al., 2021).

The utilisation of industrial point sources needs to be carefully evaluated, based on:

- The timeframe in which this industry will continue to emit due to:
    - Regulatory obligations to reduce emissions
    - Alternative technologies being not yet mature (e.g. aluminium, steel)
    - Economic hurdles for immediate replacement of processes being too high (e.g. not all blast furnaces can be replaced by DRI at once), hence transition taking place over several decades
    - Other factors such as long-term supply contracts for LNG

- The availability decarbonization pathways: while for example ammonia production can transition to green hydrogen-based processes, this is not possible for cement production where the emissions are derived from the feedstock.

- The role of the respective industry in the overall decarbonisation scenario, such as gas plants being used as peakers only and not for permanent supply.

Table 2 below presents the assessment of potential carbon feedstock sources for e-SAF production in Australia. For each source, the table details the quantity, access / process of extraction, infrastructure, competition for the feedstock, market, commercial viability and price in so far as this information is available. The data reveals that Australia has approximately 101.96 Mt of carbon available from these sources (excluding DAC, kelp, and aluminium), whereby 29.35 are biogenic and 72.6 are industrial point sources. There is no CO_2 amount for DAC noted as this will not be available on a large scale in the near future. The prices exhibit a wide range from as low as A$0-16 for LNG and ammonia byproducts to around A$600 for DAC.

[13] Wesfarmers CSBP ammonia production produces 955kt of CO_2, 620kt of which is emitted as a pure CO_2 stream after selling a certain quantity. Their facility in Kwinana, Western Australia, emits 600tons of CO2/day; 50-60t are sold, the rest is vented (Jakubik, personal communication, 2025).

	Quantity of feedstock	Access/Process of Extraction	Infrastructure	Competition for Feedstock	Market	Commercial Viability	Amount of carbon source / Scope-1-CO_2 emissions	Price[14] in A$
DAC 	Only research projects, theoretically unlimited	Fans and boxes with solid and liquid absorbents	Only research projects	no	/	High potential but still at an early stage – few commercial projects and plants, but mostly demonstration projects	/	around A$600
Sugarcane /Bagasse 	30 Mt of sugarcane (~30% bagasse)	Gasification of sugarcane or bagasse	Sugarcane farms in QLD and existing sugar mills	electricity production, Sugar industry, SAF production	Strong Sugar Production Industry in Australia	good potential if sugar mills powering replaced by renewable energy	5.8 Mt	A$100-300
Kelp 	/	Gasification of dried kelp	No commercial kelp farms yet	Marine life, food industry, cosmetics	/	Good potential if commercial kelp farms work out	/	
MSW 	13.5 Mt of MSW generated and 5.9 Mt recovered	Gasification of MSW biomass	Good infrastructure for MSW, but rarely for gasification	Electricity production, recycling, SAF production	Strong competition for feedstock in Australia	Good commercial viability, MSW doesn't cost a lot	13.5 Mt of Waste x 0.7-1.7 = 7.75 Mt	A$95- A$126
Forestry 	6.5 Mt of forestry residue and 5.2 Mt of sawmill residue	Gasification of forestry residues and sawmill residues	No infrastructure to collect forestry residue	Wood production, none for forestry residue	Wood products, but no real market	good potential, collecting the forestry residues is not commercial, but using the sawmill residue is	15.8 Mt	A$100- A$300
LNG Production 	33.8 Mt	CO_2 is already separated during the process, can be captured	Projects like Bonaparte already utilize and store the CO_2	/	Potential offtaker close to LNG-plants	Is commercially viable	33.8 Mt	0- A$16

[14] Global CCS Institute (2021); Psarras (2023)

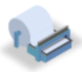
Ammonia 	4 Mt	Pure CO_2 stream is produced as a byproduct during SMR	Can be captured	Will decline as natural gas is being replaced by green hydrogen	/	Commercially viable, as long as not replaced by hydrogen	4 Mt	0- A$16
Iron & Steel 	11 Mt	CO_2 can be captured during the reduction of iron ore	Less emissions as decarbonisation of iron and steel sector progresses	Less CO_2 emitted when using electric furnaces	No market yet	Not commercially viable, if replaced soon -If not, then commercially viable	11 Mt	A$70- A$126, Sinter: A$126- A$182
Cement & Lime 	4.7 Mt	Can be captured during the heating phase	Increasing, e.g. Calix for HyGate project	/	Testing projects	Is commercially viable because the CO_2 comes as a free byproduct during the process	4.7 Mt	A$71- A$95
Natural Gas Plants 	15.8 Mt of CO_2 emitted	Different capture methods during the combustion of methane	CO_2 is already being captured and stored/utilized	/	No long-term solution, but needed till replaced by renewables	Is commercially viable	15.8 Mt	A$111- A$190
Pulp & Paper 	1.5 Mt	CO_2 can be captured during pulping	Capture methods being tested	/	/	Capturing the CO_2 during pulping is viable	3.3 Mt (scope 1 & 2)	
Aluminium 	3-5 Mt	CO_2 can only be captured in very small amounts in off-gas but is very low-concentrated	No capture methods	/	/	Most of the emissions are indirect and come from energy use, as well as low concentrated -> not viable	3-5 Mt / 0	A$284- A$474
Total Maximum: 101.95 Mt (without DAC, kelp and aluminium) **Biomass:** 29.35 Mt (without kelp) **Industry:** 72.6 Mt (without aluminium)								

Table 2: Overview of Australian CO_2 sources

5 Opportunities for Bilateral Trade

This chapter explores the opportunities for trade by examining Germany's and the EU's anticipated demand for e-SAF imports and their willingness to pay. It incorporates insights from German industry stakeholders and evaluates the international competitiveness of Australian e-SAF in meeting this demand. Additionally, the chapter highlights innovations in both Australia and Germany. Finally, it provides an overview of a few Australian hydrogen and e-fuel projects alongside considerations for developing a robust Australian supply chain.

5.1 Germany's and the EU's Need for e-SAF Imports

Calculations by the German think-tank Agora Verkehrswende show that in 2030 the EU quota would require the production of 570,000 tonnes of e-SAF, which is around half of the announced global production. In 2035, it would require the production of 2.4 Mt e-SAF (Agora Verkehrswende & International PtX Hub, 2024).

There are currently 22 commercial scale projects announced in the EU plus Norway and Iceland, adding up to a total production capacity of 1.276 Mt in 2030 (see Table 3). Yet, as none of these projects has reached Final Investment Decision (FID), it remains highly uncertain whether 570,000 tonnes of e-SAF will become available by 2030 (T&E, 2024a). According to T&E, there are three prospective projects that could reach FID by the end of 2025, namely the Arcadia eFuels ENDOR project in Denmark, Norsk E-Fuel's Alpha plant in Norway, and Nordic Electrofuel's E-fuel Pilot plant also in Norway. However, these projects would be insufficient for covering the mandated 570,000 tonnes of e-SAF in the EU in 2030, as their joint potential production of 238,000 tonnes would still leave a gap of around 332,000 tonnes (T&E, 2024a). To reach the quota, around 10-15 e-SAF projects at commercial scale would be required.

Table 3 gives an overview of announced industrial-scale e-SAF projects in the EU, Norway, and Iceland and their production targets for 2030.

Project	Companies	Location	Planned Commissioning Date	Production Target in 2030 (kt)
Project Mosjoen - Alpha, Beta & Gamma plants (Norsk e-Fuel)	Norsk e-Fuel, Sunfire, Climeworks, Paul Wurth, Axens, Norwegian, Gen2 Energy	Norway	2026 -30	160
E-fuel Pilot	Nordic Electrofuel, BPT, Aker solutions, P2X-Europe, Sunclass airlines	Norway	2027	10
IdunnH2	IdunnH2, Icelandair	Iceland	2027	65
BioÖstrand	Biorefinery Östrand AB, St1, SCA	Sweden	2029	100
HySkies[15]	Shell, Vattenfall, LanzaTech, SAS	Sweden	2030	80

[15] Vattenfall (2024)

Hy X	Vattenfall, St1	Sweden	2030	100
Synkero[16]	Sky NRG, KLM, Schiphol Group	Netherlands	2027	50 (currently on hold)
INERATEC-Zenith Energy	INERATEC, Zenith Energy Terminals	Netherlands	2027	26
ENDOR	Arcadia e-fuels, Technip Energies, Haldor Topsoe S/A, Sasol Ltd, DCC/Shell Aviation Denmark A/S, Sunclass Airlines, BNP Paribas	Denmark	2026	68
Green Fuels for Denmark	Copenhagen Airports, DSV, DFDS, SAS, Topsoe, A.P. Moller-Maersk, Neste Shipping Oy, HOFOR, BIOFOS, CTR, VEKS	Denmark	2029	30
Concrete Chemicals	Sasol ecoFT, CEMEX, ENERTRAG	Germany	2027	26
Jangada	Hy2Gen, energy4future	Germany	2028	64
Hykero	XFuels, EDL, Airport Leipzig-Halle, Johnson Mattey, BP	Germany	2027[17]	50
ReUze	Engie, Infinium, ArcelorMittal	France	2028	71
KerEAUzen	Engie, Air France	France	2028	68
Take Kair	EDF, Holcim, IFPEN, Axens, Air France-KLM	France	2028	35
BioTJet	Elyse Energy, Avril, Axens, Bionext, IFPEN	France	2027	38
Hynovera[18]	Hy2Gen, Technip Energies, Bionext, Axens, Airbus Helicopters	France	2027	16
SAF+ / H2V	SA + Consortium, H2V	France	2029	80
The Breogan Project	Greenalia – P2X Europe	Spain	2027	30
Smartenergy, REN, Lipor[19]	Smartenergy, REN, Lipor	Portugal	--	35

16 SkyNRG (n.d.)
17 XFuels GmbH (n.d.)
18 Concertation Hynovera (2024)
19 Smartenergy (n.d.); The Portugal News (2023)

P2X-Portugal	P2X Europe – The Navigator, H%R Group, Mabanaft	Portugal	2027	30
Dimensional Energy	Dimensional Energy	Greece	--	44

Table 3: Overview of e-SAF projects in EU, Norway and Iceland

Traditional aviation fuel suppliers should be leading the development of e-SAF projects, given their market position, infrastructure, expertise and the fact that they are the mandated entities. However, many hesitate to invest significantly in e-SAF, leaving much of the innovation and production to smaller companies and startups. As a result, at this stage e-SAF supply remains highly dependent on emerging players, which face challenges such as financing, scaling production, securing stable off-take agreements and don't have access to the necessary fuel storage and refuelling infrastructure at airports.[20]

This creates uncertainty for airlines, which will face higher kerosene prices as fuel suppliers pass the penalty payment for not meeting their (e-)SAF quotas on to them. Unless airlines act as fuel suppliers themselves (which many do to some extent already depending on the airline's size), they might need to consider a change in strategy to avoid excessive costs, manage supply risks and increase planning certainty. Two possible pathways are to either enter long-term offtake contracts for e-SAF with fuel suppliers, thus enabling the latter to take FID for projects, or to produce or co-invest in production facilities of e-SAF (vertical integration). Both pathways have significant risks attached to them, the former regarding locking in high prices for a specified contract period, the latter diverging from the core business into an area where experience is lacking and uncertainty persists regarding the most promising production pathway (Pechstein, 2022).

Overall, it appears unlikely that the EU will be able to meet its demand through domestic supply alone, at least in the short-term. In addition to too few projects reaching FID in time, most announced projects in the EU rely on biogenic CO_2 sources, as these can be used indefinitely (unlike industrial point sources) and are readily available (unlike DAC, which remains too expensive). However, biogenic sources will face fierce competition from other sectors, including the shipping, chemicals, construction, and agricultural sectors. Therefore, the practical scalability of e-SAF production based on biogenic sources is limited, requiring the scale-up of DAC-based production, which will however take time.

Importing from non-EU countries in the short- to medium-term thus appears as a necessity. Yet, importing these products remains difficult, as demonstrated by the e-SAF pilot auction under the H2Global mechanism in 2023, where no final bid was submitted. This experience shows that for international companies to be willing to invest in e-SAF production aimed at the European market, long-term contracts with relatively high offtake volumes will be required to make the investment bankable. Additionally, the second delegated act of RED II requires a "proportional allocation" of the GHG savings to all products of the Fischer-Tropsch process (e-SAF, diesel, naphtha) which was identified by the final bidder as too inflexible and therefore unfeasible, resulting in its withdrawal from the auction process. Indeed, depending on the production process, 20 to 50% by-products are generated in e-SAF production in refineries. In the worst-case scenario, 50% of the hydrogen used would therefore be attributed to by-products that do not yet receive any financial support (NOW GmbH, 2024).

5.2 Willingness to Pay and Green Premium in Germany and the EU

The market for advanced SAF and e-SAF in particular has yet to develop, and the technology has still to mature. Studies on likely prices for e-fuels more broadly predict these to be four to eight times more

[20] In Germany, the supply and infrastructure for aviation fuel are highly centralized and often controlled by a small number of major oil companies and joint ventures. Most large airports rely on centralized fuel storage and hydrant systems, which are typically operated by a consortium of major fuel suppliers rather than being open-access facilities. This setup creates a de facto monopoly or at least a strong oligopoly, where a few dominant players control access to aviation fuel distribution (Pechstein (2022)).

expensive than conventional fuels. The latest report by EASA estimates production costs for e-SAF to range from €6,600 to €8,700 in 2023. Production costs for e-SAF produced with industrial or biogenic CO_2 feedstocks range from €6,600 to €7,975, while e-SAF costs produced with CO_2 from DAC ranges from €7,300 to €8,700. This compares to a price of €816 per tonne jet A-1 fuel. For now, these e-SAF costs are estimates, as e-SAF is not yet traded on the market (EASA, 2024).

For 2030, studies on the expected cost of e-SAF diverge widely, with more recent studies expecting much higher prices than studies from only two years ago. The range of predicted prices is between €2,135 to €8,951 per tonne (Agora Verkehrswende & International PtX Hub, 2024; T&E, 2024b). The price-range results from assumptions regarding the cost of renewable power, the number of full-load hours, and the cost of the CO_2 source. If renewable power is cheap, full-load hours are high, and the CO_2 is derived from point sources, prices are at the lower end of the spectrum. Medium costs can be achieved if renewable power is cheap, full-load hours are high, and the CO_2 source is expensive as in the case of DAC, or if renewable power is cheap, full-load hours are low, and the CO_2 source is rather cheap. High costs arise if the e-SAF is produced in regions with higher costs for renewable power and DAC is the CO_2 source. By 2050 the costs are predicted to fall to between €1,090 to €2,620 per tonne, with an average price of 1,935€ per tonne. This is still more than double the current jet A-1 fuel price (Agora Verkehrswende & International PtX Hub, 2024).

However, additional developments need to be considered. First, free ETS allowances for the aviation sector are to be terminated in 2026. Therefore, in 2030, all CO_2 emissions by the aviation sector will be priced. The current CO_2 price is at €70/t CO_2 and some forecasts show that it might stay stable until 2030. Predictions by the EU Commission however rather point to a CO_2 price of €85/t CO_2 in 2030, and predictions by the Potsdam Institute for Climate Impact Research (PIK) even expect a price of up to €125/t CO_2 in 2030.

Accordingly, the price for Jet A1 could reach between €1,036,5 to €1,209.75 in 2030 (Mantulet et al., 2023; Pahle et al., 2024; Simon, 2021). Second, not fulfilling the e-SAF quota in 2030 could elicit a penalty of 11,568€ per tonne of missing e-SAF (based on e-SAF price estimates by EASA for 2023), which will create additional costs for the fuel supply. Third, the EU might decide to reform its energy taxes and introduce a tax on kerosene. However, for the moment, this appears to be rather unlikely as the EU Commission further delayed the introduction of a kerosene tax in the summer of 2024. The reasons provided included the limited availability of e-SAF and the worry that introducing taxes would therefore hurt the aviation sector without an alternative being available (Energy News Magazine, 2024; Gruber, 2024). Figure 4 below shows a comparison of all price scenarios outlined.

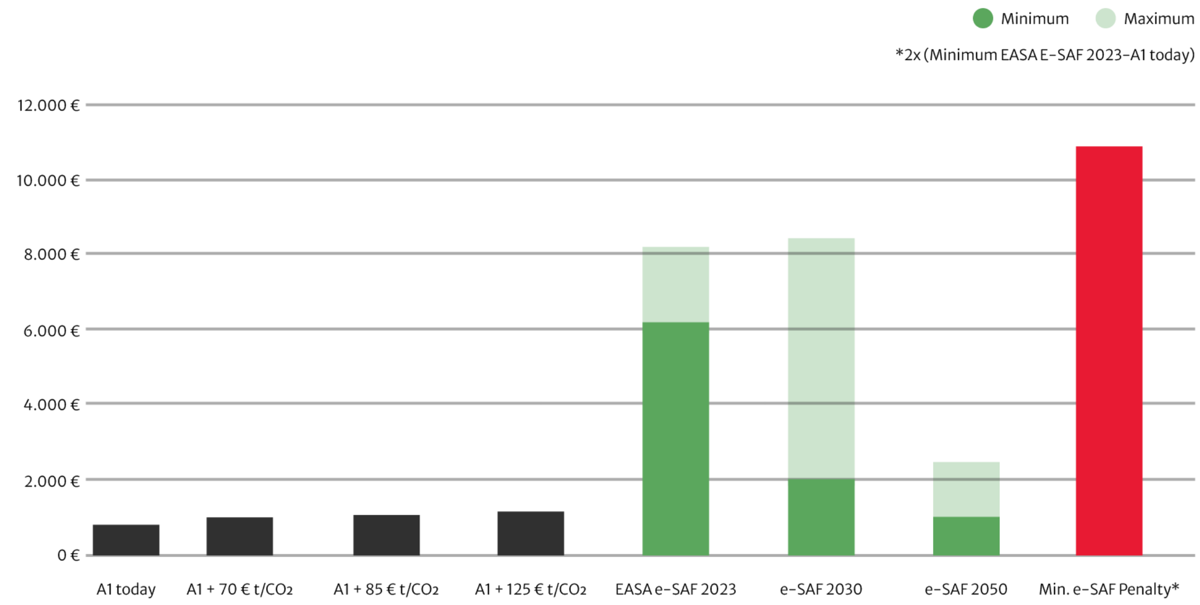


Figure 4: Comparison of projected aviation fuel prices[21]

This shows that in 2030, A1 fuel will remain much cheaper than e-SAF, even if the CO_2 price increases significantly and a kerosene tax is introduced. However, the compliance obligation paired with the penalty payment will induce such high costs on EU and German airlines that it can be expected that airlines will be willing to pay even the highest predicted price for e-SAF.

To illustrate, one might want to consider the implications for a fictional airline with an annual kerosene consumption of 500,000 tonnes that is subject to the obligations under ReFuelEU. Accordingly, of the 500,000 tonnes of kerosene consumed for flights, 6,000 tonnes would have to be in the form of e-SAF in 2030.

If the fuel suppliers of the fictional airline fulfil the e-SAF quota for 2030 and deliver the required quantities to the airline, the costs would be around €575 million (leaving aside the costs for fulfilling the SAF quota), assuming an e-SAF price of €6.600 / tonne, the min e-SAF price of the 2023 EASA report. If the fuel suppliers do not fulfil the quota and have to pay the penalty (here calculated as two times the price difference between €6.600 / tonne and the jet A1 plus carbon price at €85), the costs would be around €608 million. These are most likely to be passed on to the fictional airline entirely. Hence, if the quota is fulfilled, the airline saves €33 million, while non-compliance would increase aviation fuel costs by almost 6% under the 1.2% e-SAF quota.

By 2035, with an increase of the e-SAF quota to 5%, the cost of non-compliance would rise to €138 million, resulting in an aviation fuel cost increase of 20%. It should be noted that this example solely illustrates the development of aviation fuel costs under compliance versus non-compliance scenarios and does not account for other operational costs or shifts in the overall cost structure.

5.3 Insights from the German Aviation Sector

Between October 2024 and March 2025 interviews were conducted with German airlines, aviation associations, and non-governmental organisations to gain a deeper understanding of the practical implications of EU regulation as well as e-SAF market developments.

The general sentiment among the interviewees was that the EU quotas will be challenging to meet due to high costs and limited availability of e-SAF. Generally,

[21] While the exact penalty fee is set individually by EU member states, the fee must at least be double the price difference between the price for a tonne of e-SAF and a tonne of fossil kerosene (T&E (2024b)). As e-SAF price input, the EU Commission names the EASA yearly technical report as the leading document (European Commission (EC) (n.d.–a).).

prices are expected to be higher in 2030 than they were predicted only two years ago. Most interviewees assumed prices to be at the higher end of the e-SAF 2030 bar shown in Figure 4. Additionally, interviewees pointed to a much slower development of the e-SAF market than they had hoped for, resulting in serious doubts concerning the sufficient availability of e-SAF in 2030 to meet the EU quotas. One reason for this slower than expected development is that many fuel supplier and airlines have entered a "wait-and-see" position resulting from the prospect that the EU Commission will review ReFuelEU in 2027. It is therefore a fair assessment to say that the review unintendedly leads to regulatory uncertainty which results in slower progress with projects which in turn results in less available e-SAF, making it more likely that the quotas might indeed need to be scaled back. The fact that no member state has yet published the penalty payment that will be required when quotas are not met contributes further to an overall uncertain regulatory environment. Together with technological uncertainties regarding the scale up of e-SAF production, this has resulted in little investments and only a few small-scale offtake agreements.

In the longer term, interviewees expect e-SAF production to scale up, especially if additional pathways such as the methanol-to-jet route are authorized. Interviewees agreed that more support mechanisms as well as robust financial incentives would need to be implemented. Especially the lack of financial support both for individual projects as well as for covering the green premium was mentioned as problematic.

Further barriers mentioned were difficulties in handling and transporting e-SAF via the established infrastructure although others didn't foresee larger issues with this. Since most e-SAF producers are currently start-ups rather than established fuel providers, they often lack the necessary infrastructure links from their production sites to the airports. Hence, they are likely to rely on established fuel suppliers to close this gap in the supply chain which may further add to the already high production costs of e-SAF. International trade will face additional barriers, particularly the recognition of the trading partner's emissions trading system for CO_2 point sources to be permissible.

Based on these identified hurdles, interviewees made several recommendations for the new German government and EU Commission. All organizations agreed that certainty regarding the e-SAF quota was necessary as soon as possible. The interviewed industry representatives asked for an easing of the quotas, which was, however, rejected by other interviewees, as this would be exactly the regulatory back-and-forth hampering the development of the market. With suitable technologies being available (although further development is required), strong political commitment by the EU Commission and member states paired with suitable financial support would enable the meeting of the quotas as they are.

With regards to CO_2 -point sources, it was recommended to establish grandfathering rules that ascertain that the CO_2 source remains permitted over the entire course of the plant's operation. Only this kind of rule would at this stage enable the usage of industrial CO_2 -sources for e-SAF projects.

Financial support measures could target support for individual projects, the price of e-SAF and the price of kerosene to change incentive structures from both directions. This could include grant funding for pilot projects and/or CfD schemes similar to H2Global for the e-SAF sector[22], while introducing taxes on kerosene would reduce the price gap from that direction. Further suggestions were to reserve SAF allowances specifically for e-SAF to ensure that e-SAF projects benefit from this currently first-come-first-serve support scheme. It was also mentioned that high location costs for airlines in Germany deprive the industry of budget to invest in projects.

Another recommendation includes adjusting the quota increases to a yearly basis instead of having multi-year jumps, which would facilitate a smoother scale-up. The flexibility mechanism, which is currently in place until 2034, and allows the meeting of the quota per fuel supplier instead of per airport, could be extended, so that fuel suppliers can provide e-SAF at airports where this is easiest to implement. Lastly, to enable international trade and thus increase the availability of e-SAF, clear procedures for the recognition of third country emissions trading systems would have to be established.

There are a range of fundamental barriers to the e-SAF market ramp-up, as summarized in Figure 5.

[22] Compare the proposed policy intervention from Project SkyPower to create a government-backed market intermediary.

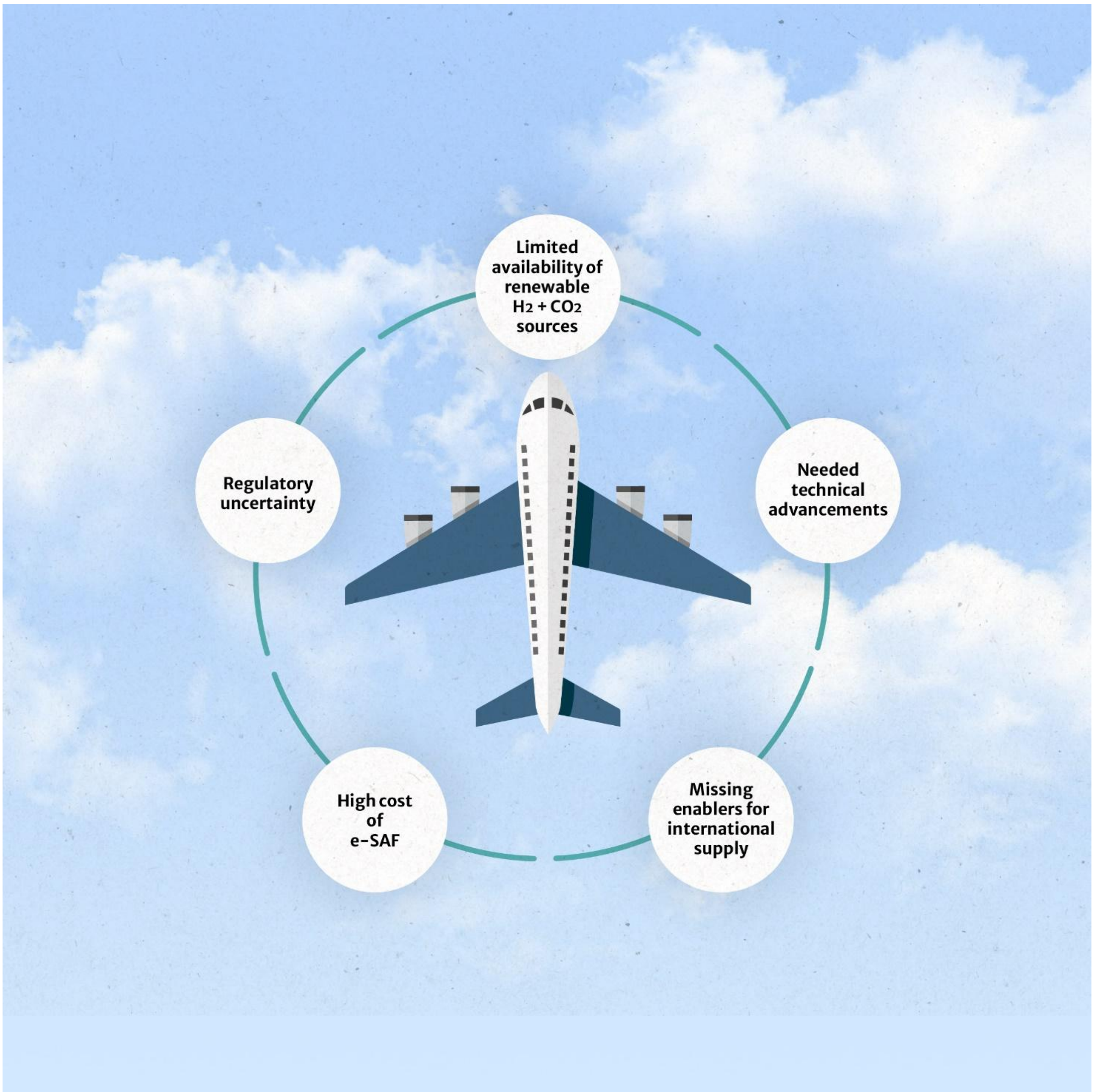


Figure 5: Fundamental barriers to the e-SAF market ramp-up in Germany

5.4 International Supply of e-SAF in the Short Term

A global e-SAF market has yet to emerge, with only a few countries already producing e-SAF in pilot or demonstration projects or planning to do so in the future. However, with quotas in the EU and elsewhere coming into place by 2030, projects need to be developed now to be able to supply on time. Hence, having an idea of what the international landscape for e-SAF production looks like is useful to assess where Australian e-SAF fits in and how competitive it is.

The US is highly active in the SAF market already and has started moving into the e-SAF market as well. However, most projects are still at early development stages (planning and construction). The US's potential to export to the EU is significant although it also has a large domestic demand, which will claim large parts of the supply. Thus far, the AtJ process is dominant, due to abundant and cheap ethanol feedstock availability (Hundt & Antonenko, 2025).

However, other production pathways are also feasible as a wide array of feedstocks including biogenic resources (corn grain, oil seeds, algae, forestry residues, MSW, etc.) as well as industry point sources, especially the cement industry, refineries, and power plants are available (U.S. Department of Energy, n.d.–b). Trade relationships with the EU and Germany are well established and a regulatory framework is present at federal level and in several states (California, Washington, Oregon, and Illinois). At the federal level, examples include the SAF Grand Challenge, which set production targets for SAF for 2030 and 2050 and established a roadmap for the scale-up of various SAF and e-SAF production pathways, as well as tax credit support through the IRA that strongly incentivize production of renewable hydrogen (DCCEEW, 2024b; Pan American Finance, 2024). However, with Trump as the new president, the persistence of this regulatory framework and continued support for the upscaling of the green hydrogen and e-SAF market are uncertain (Hussain, 2025a).

In South America, Brazil, Columbia, and Chile are also well positioned to become exporters of e-SAF including to Europe. Brazil has extensive biomass resources (esp. bagasse from the sugarcane industry) and access to industrial point sources (esp. cement, steel, and ethanol production) as well as ample experience in producing bioethanol and biodiesel. Additionally, it has exceptionally low costs for the production of green hydrogen due to its renewable potential and experience in implementing such projects. The required infrastructure (roads, ports, airports) is in place and well within reach of suitable regions such as the Rio Grande do Norte. The government has set targets for the production of SAF and supports the development of green hydrogen and SAF projects with US$1 billion (Hank et al., 2023; Hussain, 2024b; Lopes, n.d.; Souza Ramos, 2024).

In recent years, Columbia has made significant investments in renewable energy to realize its potential. Production costs are particularly low in the La Guajira region, which has been identified as the only region that is internationally competitive in the study by Fraunhofer ISE. The country's aviation organization Aerocivil has released a roadmap with production targets for 2030 and 2050 and the country's state-owned energy company Ecopetrol plans to invest US$500 to US$700 million to build SAF capacities (Centre for Aviation [CAPA], 2025; Hussain, 2025b); SAF Investor, 4 April 2025).

Columbia has extensive biomass resources, and its cement facilities and oil refineries could serve as industrial point sources. Ethanol production capabilities could be used in the AtJ process (Inter-American Institute for Cooperation on Agriculture [IICA], 2025; Yáñez et al., 2020). The country's current focus is on the production of SAF, but e-SAF could be produced in the long-term (International PtX Hub, 2023a).

Chile is already home to the production of e-methanol and e-gasoline by HIF Global. It has tremendous potential for the production of renewable electricity and hence the production of green hydrogen. Additionally, plans exist to launch the production of SAF in 2030, with e-SAF being an option for the long-term (Hank et al., 2023; Hussain, 2024a).

In Africa, Marocco and potentially Namibia are promising candidates for the production of e-SAF. Marocco is close to the EU and has great potential for the production of renewables and green hydrogen. CO_2 could be captured from industrial point sources in the cement and phosphate industry. Additionally, Marocco has abundant agricultural residues (e.g. wheat straw and sugarcane bagasse) that could be used as a CO_2 feedstock as well as livestock manure and landfill biogas in cities (Bhar et al., 2025; Labbi, 2017; United Nations Industrial Development Organization [UNIDO], 2023). In 2024, Marocco hosted the first e-fuels conference by HIF Global, where the company announced its plans to establish production capacities in the country (HIF EMEA GmbH, 2024; Singer, 2024).

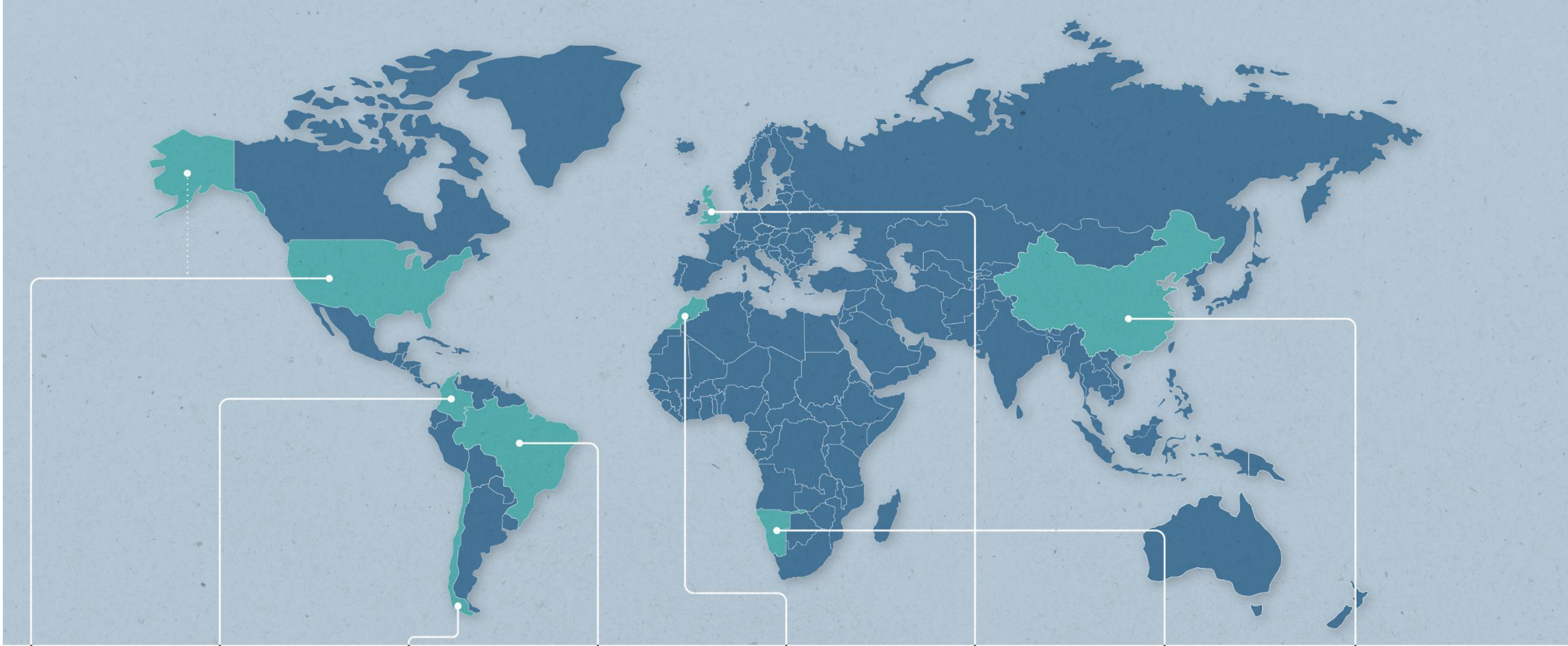
Meanwhile, Namibia also has ambitions to produce green hydrogen, with strong existing interest from European partners due to its strategic export location and great renewables potential. However, renewables and hydrogen production costs in Namibia are in the middle-range, so that international competitiveness is uncertain (Hank et al., 2023). Feedstocks are available from agricultural residues, industrial point sources, municipal waste, and, especially, woody biomass from bush encroachment, which would have the co-benefit of supporting biodiversity preservation efforts in the country (International PtX Hub, 2023b).

While China has entered the SAF and e-SAF market rather late, it has potential to become an important producer as well. Both airlines and the government have set production and offtake targets, and pilot projects for SAF are running (Chua, 2024; Vurdhaan, 2024; wei Neo, 2024). China has ample feedstocks available, especially in the form of used cooking oil, but also from agricultural residues, municipal waste, and industrial point sources (Harrington, 2022). The current focus is on the HEFA process due to the abundance of used cooking oil, but given China's build-out of renewable capacities, potential exists for the country entering the e-SAF market (Pan, 2024; Parolini & Yiran, 2024).

Lastly, the UK, with its closeness to the EU and a firm commitment to PtL production processes is a strong contender in the e-SAF market. The UK has set domestic targets for the uptake of SAF and e-SAF, and funding, including specifically for PtL production processes, is available. With this, the UK is, together with the EU and US, the only country that already focuses on e-SAF and can therefore be expected to be a relevant player in the emerging market. Limited biogenic CO_2 feedstock availability could however become an obstacle in the scaling of the market (Addleshaw Goddard, 2025; Surgenor, 2023).

In a study by Fraunhofer ISE, Australia performs best for the production of e-SAF compared to India, Mexico and Spain. Costs range from around €167/MWh to €340/MWh in the four countries, depending on the regions assessed and whether the e-SAF and all by-products (naphtha, diesel, etc.) can be sold for export or only the e-SAF. The cost estimates assume CO_2 capture via low-temperature DAC for all regions and transport costs to German ports are included. In fact, both India and Mexico are assumed not to be competitive with Australia for exports to Germany (Hank et al., 2023).

In conclusion, the international supply landscape for e-SAF is beginning to take shape, with several countries demonstrating significant potential to become key players. Against this backdrop, Australia stands out as a highly competitive option for e-SAF exports to Germany, with favourable production costs and strong renewable resources. As the global e-SAF market evolves, Australia's ability to capitalise on its advantages will be crucial to securing a leadership position in this emerging industry. The map in Figure 6 summarises the key points for each of the countries mentioned in this chapter.



USA

- Biofuel pathways dominate thus far, some announced e-SAF projects
- Strong CCS sector, several biorefineries
- Regulatory support for e-SAF and SAF quotas at federal and state level, though uncertainties regarding Trump's approach
- Substantial domestic demand might limit export potential

COLUMBIA

- Significant potential in renewable energies, especially wind
- Strong biofuels sector
- Extensive biomass resources
- Ethanol production capabilities could be used in the ATJ process
- Cement and oil refining as industrial point sources
- Current focus on SAF, but could be advanced to e-SAF

CHILE

- Significant potential in renewable energies
- Production of ethanol and e-gasoline by Germany's HIF Global and joint initiative by Chile's Copec and Germany's Ineratec to build a 3,500 tonne PtL plant
- Policy support for the production of green hydrogen and SAF/ e-SAF

BRASIL

- Extensive biomass resources, incl. bagasse and straw from sugarcane industry
- Industry point sources from cement, steel, and ethanol production
- Experience from producing biodiesel and bioethanol
- Regulatory and funding support for SAF and green hydrogen
- Strategic export location to EU

MOROCCO

- High potential in renewable energies and ambitious targets by government
- Industrial point sources (cement and phosphate processing) & abundant agricultural residues (e.g. wheat straw and sugarcane bagasse), landfill biogas, livestock manure as feedstocks
- Closeness to EU
- First e-fuels conference by HIF Global in May 2024

UK

- Several announced SAF / e-SAF projects
- Limited biomass feedstock availability, though industry point sources are available
- SAF quota since 2025, government funding and regulatory support available
- Clear commitment to advanced technologies incl. PtL pathway
- Closeness to EU

NAMIBIA

- Significant potential in renewable energies
- Problem of bush encroachment impacting biodiversity –could be used as a CO2 feedstock
- Industrial point sources (esp. mining industry), agricultural residues and municipal waste as additional feedstocks
- Strategic export location to Europe
- Green hydrogen production costs in the middle-range, other regions, incl. Australia, are cheaper

CHINA

- Limited current capacity: focus on HEFA
- Extensive feedstock availability (used cooking oil, agricultural residues, municipal waste, industrial point sources)
- Production goals for SAF and pilot programme with major airlines
- Entered the market late, behind its potential

Figure 6: Overview of potential large-scale e-SAF producers excluding Australia

5.5 Strategic Considerations for e-SAF Trade

As mentioned above, the import of e-SAF appears as a necessity for the EU and Germany, at least in the short- to medium-term. Similar to hydrogen, for which import targets already exist—including in Germany, where separate targets have been set for hydrogen and hydrogen derivatives—dedicated import targets for e-SAF would be beneficial. These targets would help raise awareness domestically and serve as a strong signal internationally, increasing the likelihood of domestic offtakers and international suppliers to match. This could be supplemented by strategic considerations and potentially sub-targets regarding the country of origin. Unlike in the field of clean tech, where the EU and Germany have become much more selective with notable caution towards imports from China, and formulate the explicit goal to diversify supply in order to reduce dependencies, such a clear strategy has thus far not been communicated with regards to hydrogen and its derivatives, including e-SAF.

Considering the production costs of hydrogen and its derivatives, it increasingly becomes apparent that projects with strong backing from the state, tend to be able to take FID sooner. This is due to more favourable financing conditions leading to lower production costs. Examples of this are the ammonia project in Egypt by Fertiglobe, a strategic partnership between UAE state-owned ADNOC and OCI Global, NEOM in Saudi Arabia and the AMG project in Kakinada in India (Atchinson, 2024; Fertiglobe, 2024; NEOM, n.d.). Hence, a purely price-based approach to the import of hydrogen and its derivatives, including e-SAF, may disadvantage hydrogen imports from countries where projects operate in a market-based environment and could lead to undesirable dependencies. Given that the hydrogen and hydrogen-derivatives market is still emerging, there is the unique opportunity to implement guardrails now to shape the composition of EU and German imports. Establishing import criteria beyond the price of a hydrogen-based product would constitute a strong signal to the international market and facilitate trade partnerships with like-minded countries, including Australia.

From an Australian perspective, establishing a strong e-SAF industry would be highly beneficial as well. The emission saving and economic benefits outlined in Chapter 4 are compounded by energy security considerations. In 2022, Australia imported 80% of is oil products, an increase by 17% from the previous year. This is due to the closure of two oil refineries (in Kwinana and Altona) in 2021 (DCCEEW, 2024c). Hence, this high percentage of oil product imports can be expected to persist. Only three countries are providing 65% of imports, indicating potential risk to supply security (Deloitte, 2024). Establishing an e-fuels, including e-SAF, market would therefore offer the opportunity to become less dependent on fuel imports, increasing the independence of the transport sector. Demand from the EU could serve as an important catalyst to further motivate Australian producers.

5.6 Fostering German and Australian Innovation and Pilot Projects on e-SAF

As there currently is no large-scale commercial production and deployment of e-SAF, fostering innovation on e-SAF is of particular strategic relevance amidst national and global decarbonisation efforts. In terms of bilateral cooperation and potential future trade, innovation can build on the complementary strengths of Australia and Germany and address challenges in the scale up of e-SAF production, the transport and infrastructure, technological pathways as well as the deployment of e-SAF in aviation.

5.6.1 Germany

Within the EU, Germany is home to the largest number of announced e-SAF projects. However, all of these projects are at early development stages (feasibility study, research project, pilot plant).

A noteworthy project is by the German Aerospace Center (DLR), Germany's and the EU's leading research centre on aircraft technologies. The center is currently in the process of building the largest research facility on e-fuels globally in Leuna, called the Technology Platform for Power-to-Liquid Fuels (TPP). On 1 October 2024, construction of the facility has officially begun. The DLR has received €130 million of funding for the construction by the Federal Ministry for Transport (BMV) with more funding planned to be made available in 2028 for research activities. Once operational, the facility will be semi-industrial in scale with a capacity of 2.500 tonnes of e-fuels production each year. Its modular design allows for the flexible expansion of research activities (German Aerospace Center [DLR], 2024b; NOW GmbH, 2023).

Also in 2024, DLR delivered two major insights regarding e-SAF specifically. In June, together with Airbus, Rolls-Royce and SAF manufacturer Neste, it conducted the world's first in-flight study on the impact of using 100% SAF (bio-based) in an A350 commercial aircraft. The results showed that the usage of SAF can significantly reduce non- CO_2 emissions including soot particle emissions and contrail ice crystals. Specifically, the climate impact of contrails could be reduced by 26% using 100% SAF. This is important, as the usage of SAF is therefore useful not only for reducing CO_2 emissions but also for directly reducing the global warming impact of contrails (DLR, 2024a). In October, the DLR continued with performing first of its kind research, when it conducted ten test flights during which a D328 Uplift was fuelled with 100% synthetic, aromatics-free kerosene. This was intended to investigate whether the positive effects shown with biobased SAF regarding non-CO_2 emissions also apply to synthetic SAF (DLR, 2024c).

German companies are also showing innovative activity at the production stage. For instance, the Solarbelt, backed by the German NGO atmosfair, succeeded in producing the first badge of 5 tonnes of e-SAF for commercial use in its pilot facility in Wertle, Germany, which is the world's first industrial scale e-SAF production facility. The e-SAF was produced using renewable energy and DAC-based CO_2. This approach results in the produced e-SAF having 96% lower emissions than conventional fuel, certification is performed by TÜV-Süd. The kerosene can be purchased via book-and-claim and will be made available by the Munich-based travel companies Hauser Exkursionen and Neue Wege Reisen, where passengers can add 0.1% of e-SAF to their flights from next autumn onwards. Additionally, the e-SAF produced in Wertle will be available for purchase on the website of atmosfair. By 2026, atmosfair and Solarbelt aim to produce 300 tonnes per year (atmosfair, 2024).

Meanwhile, the German e-fuel producer INERATEC is working on making green methanol production, needed as an input for e-fuels in the shipping and aviation industry as well as in the chemical industry, more efficient. In its project facility in the chemical park Bitterfeld-Wolfen, Germany, it is, together with the Leibnitz Institute for Catalysis and Creative Quantum, comparing two different production processes, the classic heterogeneously catalysed direct synthesis of e-methanol from green hydrogen and CO_2 and a new homogenously catalysed production process. For the latter, the syngas will be derived from a newly developed co-electrolysis process developed by the University Bochum and lower temperatures (130°C instead of 260°C) as well as pressure (less than half of the usual 80 bar) is required. The Federal Ministry for Economic Affairs and Energy has been providing funding for this project since 2020 (INERATEC, 2024). Earlier this year, INTERATEC'S e-fuel demonstration plant in Frankfurt, which will also produce some e-fuel as part of its 2,500 planned annual production capacity from 2025 onwards, secured a €40 million venture debt loan from the European Investment Bank and a €30 million grant from Breakthrough Energy Catalyst (European Investment Bank [EIB], 2025). Additionally, the DAWN project by Synthelion in Jülich could be key to diversifying e-SAF production pathways. This industrial-scale demonstration project seeks to produce e-SAF using solar heat. The production of 4 kt per year are planned from 2026 onwards (EASA, 2024; Synhelion, 2024).

The overall development of a more sustainable aviation sector in Germany is bundled in the work of aireg, the Aviation Initiative for Renewable Energy in Germany e.V. aireg is a non-profit organisation dedicated to advancing the use of renewable energy in aviation. Founded in 2011, it brings together expertise from industry, academia, and research institutions to promote SAF as a key solution for reducing the aviation sector's carbon emissions. The initiative focuses on fostering innovation in SAF production technologies, improving certification and quality standards, and ensuring the economic and ecological sustainability of renewable aviation fuels.

aireg's work includes supporting the development of industrial SAF production facilities, advocating for regulatory frameworks that encourage market adoption, and facilitating collaboration among stakeholders across the aviation value chain. Its members range from start-ups to large corporations, including airlines, airports, fuel producers, and technology providers. By addressing the challenges of scaling SAF production and integrating renewable energy sources, aireg aims to position Germany as a leader in sustainable aviation and contribute to global climate goals (Aviation Initiative for Renewable Energy in Germany [aireg], n.d.).

5.6.2 Australia

In 2023, the Commonwealth Scientific and Research Organisation and Boeing released their joint Sustainable Aviation Fuel Roadmap for Australia. The roadmap identifies a tremendous opportunity for producing SAF in Australia. According to the roadmap, Australia has the potential to produce around 5 billion litres of SAF by 2025. Alcohol-to-Jet and the Fischer-Tropsch process are identified as the most suitable production processes. While biogenic feedstocks such as sugarcane, municipal waste and sawmill residues are identified as available feedstock in the near-term, hydrogen and CO_2 are identified as feedstocks for the medium- to long-term. Key challenges are the availability of feedstocks, supply chain constraints, and the alignment of international standards and regulation (CSIRO, 2023).

The Australian Jet Zero Council is a body established in 2023 by the Australian Government to work on net zero aviation in Australia through convening key stakeholders from airlines, infrastructure, manufacturing, feedstocks, projects, research and development as well as finance and investment. The council provides recommendations for policy settings, provide leadership and promote industry efforts. Topics that are addressed in this group include SAF sustainability and certification, building SAF literacy and social licence, SAF accounting, investability and the feedstock market (DITRDCA, n.d.).

JetZero Australia, established in 2021, is a bioenergy company that wants to produce Alcohol-to-Jet (AtJ) SAF in Queensland. JetZero Australia has partnered with and received investments or funding from LanzaJet, Qantas, Airbus, Idemitsu Kosan, the Australian Government and the Queensland Government. The company focuses on developing sustainable feedstocks and renewable fuels, such as SAF and potentially e-SAF in the future. The first main project is called Ulysses, a A$600 million facility in Townsville converting bioethanol into SAF and renewable diesel. It includes a front-end engineering design study, to produce aviation fuel via AtJ on a commercial scale, with completion targeted for 2025. It is expected to produce 110 million litres of low-carbon fuels annually and could cut net domestic aviation carbon emissions by 70%, compared to fossil fuel use. The other main project is Project Mandala, a partnership with Singapore's Apeiron Bioenergy to source waste oils and non-edible crops for SAF (HEFA).

5.7 Australian Hydrogen and e-Fuel Projects

While no dedicated e-SAF project is currently planned in Australia, there are many projects that propose to produce renewable hydrogen or e-methanol. For some project developers, the production of e-SAF would be an option in case of sufficient demand and available CO_2 -source. Below five Australian projects are considered, three proposing the production of e-methanol that already have a CO_2 source and two large-scale renewable hydrogen projects that would still need to secure a CO_2 source.

5.7.1 ABEL Energy: Bell Bay Powerfuels and Townsville Powerfuels

ABEL Energy is an Australian green hydrogen and green methanol project developer, with projects that are centred on areas abundant in sustainable wind and solar energy, water, and biomass resources. Their flagship project is Bell Bay Powerfuels located in Tasmania. ABEL Energy's second project is the Townsville Powerfuels project in Queensland, where a feasibility assessment is currently being finalized. When fully developed, each project should produce around 300,000-360,000t of green methanol per annum (van Baarle, 2025).

The Bell Bay Powerfuels project is located at Bell Bay on the site of a decommissioned oil-fired power station. This location has its own existing deep water port infrastructure, a high-capacity grid connection, and access to large quantities of biomass residues as a source of biogenic carbon. According to ABEL Energy, the plant will combine green hydrogen from a 260MW water electrolysis plant with synthesis gas from a biomass gasifier to produce green methanol. ABEL Energy will use oxygen from the electrolysis plant, instead of air, to improve the efficiency of the biomass gasification process (Tucker, 2025a).

The Townsville Powerfuels project is almost a replica of the Bell Bay project. Like Bell Bay Powerfuels, it will abate more than 540,000t of CO_2 per year and aims to improve the local renewable fuel uptake (ABEL Energy, n.d.). It will use biomass mostly sourced from agricultural residues and forestry residues.

Both projects will use a hybrid process for production of renewable/green methanol. By contrast, just using CO_2 and hydrogen (e-methanol) results in over a third of the hydrogen being lost as water. On the other hand, simply gasifying biomass to produce all of the carbon oxides and hydrogen required (bio-methanol) results in much of the carbon being vented into the atmosphere as CO_2. The ABEL projects will overcome these deficiencies by combining gasification of biomass (producing both CO and CO_2 for the carbon input, as well as some hydrogen) together with electrolysis of water (to generate most of the required hydrogen) (Tucker, 2025a). The overall outcome is a lower cost of production with a very high conversion of the carbon in the biomass to methanol, and much less hydrogen being lost as water, thereby reducing the projects' renewable power demand. But by utilising this efficiency, the resulting e-methanol will not fully fulfill the criteria of an RFNBO. Only the part of the e-methanol that will be produced by renewable hydrogen will be able to be recognized as renewable under EU regulation.

A driver for using biomass gasification as part of the methanol production process is to address the concerns of sustainability advocates and potential offtakers. A number of large methanol developers in northern China are proposing to use the same hybrid process and will be commencing production in 2025, underlining the viability of the approach. Global demand for low-carbon methanol will grow substantially and no one region will have the capacity to satisfy that demand. Both China and Australia could be significant producers as they have the land, renewable power and waste biomass resources to make a significant contribution to global supply at a competitive cost.

Both ABEL projects aim to produce the hybrid methanol to use as a fuel in the maritime sector, and potentially as e-SAF for the aviation sector. An e-SAF production unit could even be co-located with a methanol plant (van Baarle, 2025). This has some advantages given that e-SAF has more than twice the energy density of methanol, meaning that only half the volume needs to be transported from the plant to the customer.

5.7.2 HyGate Initiative: SM1 Project

The German-Australian HyGate initiative supports pilot and demonstration projects across the hydrogen supply chain in Australia. It is a joint venture between Australian and German partners, funded by both governments (Australian Renewable Energy Agency [ARENA], 2023).

One of the funded projects is the SA Solar Fuels project in Port Augusta, South Australia, which involves the development of a methanol production plant using renewable energy. It is a partnership between Vast, Mabanaft, Fichtner, and Calix, which is a supplier of CO_2 (CSIRO, 2024). Vast secured up to A$19.48 million from the Australian Renewable Energy Agency, while Mabanaft received up to €12.4 million from Projektträger Jülich on behalf of the German government (Mabanaft, 2024). In May 2024, Vast announced that the project had received planning consent. A study about the exact timeline is coming out soon. In March 2025 it was announced that SA Solar Fuels projects has been awarded additional funding of A$700,000 underneath the Australia-Singapore Low Emissions Technologies (ASLET) initiative (VAST Energy, 2025).

The plan of the project consists of a 10 MW electrolyser to produce green hydrogen with green electricity supplied by Vast and the local grid when the grid is running on mostly renewable energy. The carbon source is captured CO_2 from Calix, a lime and cement producer, which is planning to open a lime plant close to the project (Dronoff, 2025). The green hydrogen with CO_2 from a sustainable source yields green methanol. At full scale, the project will be using 15,000t of captured CO_2 per annum to produce 20t of renewable methanol a day, which would translate to 7,500t of renewable methanol per annum (Dronoff, 2025). Hydrogen input would be around 3,500t and the price would be around A$2000 (Patel, 2025).

The renewable methanol can be used in Australia or shipped to Europe by Mabanaft. It will mostly be used as a fuel in the national and international maritime sector. e-SAF is also being considered and is an option in the future, with scaled-up production and other projects under HyGate (Dronoff, 2025). The project is close to the Adelaide Airport, where the produced e-SAF could be used right away or exported. The SAF or the methanol can be exported from the harbour in Adelaide as well, which has a deep-sea connection.

Another green methanol project, Portland Renewable Fuels by HAMR Energy, is located relatively close to the airport and harbour in Adelaide. Given their proximity, it might be commercially viable to build the needed methanol export infrastructure there.

5.7.3 Intercontinental Energy: Australian Renewable Energy Hub (AREH) and Western Green Energy Hub (WGEH)

InterContinental Energy (ICE) is developing two of the largest renewable energy projects in Australia; the 26 GW Australian Renewable Energy Hub (AREH) together with bp and CWP Global, with the first tranche of green electrons targeted from 2029; and the Western Green Energy Hub, InterContinental Energy's second strategic e-fuels project in Western Australia, which may ultimately be powered by up to 70 GW of solar and wind. With initial production anticipated in the early 2030s and development phased over two decades, at full scale it will be able to produce up to 5 Mt of hydrogen per year, which can then be used to produce e-methanol, ammonia, green steel, or e-SAF (InterContinental Energy [ICE], n.d.).

The full-scale production of 5 Mt of hydrogen will be achieved in 20-25 years, so if ICE decides to produce methanol or e-SAF, a large amount of CO_2 will be needed (Patel, 2025).

The amount of CO_2 and hydrogen consumed in producing 1 tonne of SAF can vary significantly, depending on production method, feedstock used and distillate products ratios. From fully scaled-up production of hydrogen, the possible e-SAF production could be up to 10 Mt which may need up to 40 Mt of CO_2. WGEH is well suited to produce green e-methanol or e-SAF, due to large amounts of energy available for Direct Air Capture (DAC), and potential captured CO_2 from other sources.

5.8 Building an Australian Supply Chain

Early projects such as ABEL Energy and HAMR Energy will be able to deliver methanol from 2030, others will follow. With the current attention on fuel supply security, this topic is gaining a lot of traction in defence forces on both sides of the globe. As a consequence, companies like Santos that are already planning to produce e-methane at their Moomba site – with excellent renewable energy potential, a water basin as well as production water from their oil and gas operations, and carbon dioxide in large quantities - could switch or complement their operations to e-SAF instead, seeing as this only changes 5-10% of the production process and is easily done, depending on customer demand.

According to Agora, the cost of e-SAF is mainly dictated by the cost of renewable electricity (28-49%) (Agora Verkehrswende & International PtX Hub, 2024). Australia has the potential to excel not only in this area, given its monumental potential for renewable electricity generation, but also in the sectors of electrolysis, by co-locating to desalination plants or oil and gas extraction, which not only produce significant amounts of wastewater, but also industrial CO_2 emissions that can be used as point sources as well as "benefits, such as economies of scale in electricity supplies, maintenance workforces and land use permitting" (Lloyd, 2025).

Figure 7 shows the potential evolution of the Australian e-SAF supply chain, moving from the current situation where CO_2 emissions from Australian industry are directly emitted, to a short-to medium term situation where industrial and biomass point sources are used while DAC technologies are being scaled up. In the long term, the goal should be to fully abate industrial emissions so that these are either no longer emitted or captured and stored permanently. Instead, biomass sources and DAC should become long-term sources of CO_2, with DAC being the preferred option.

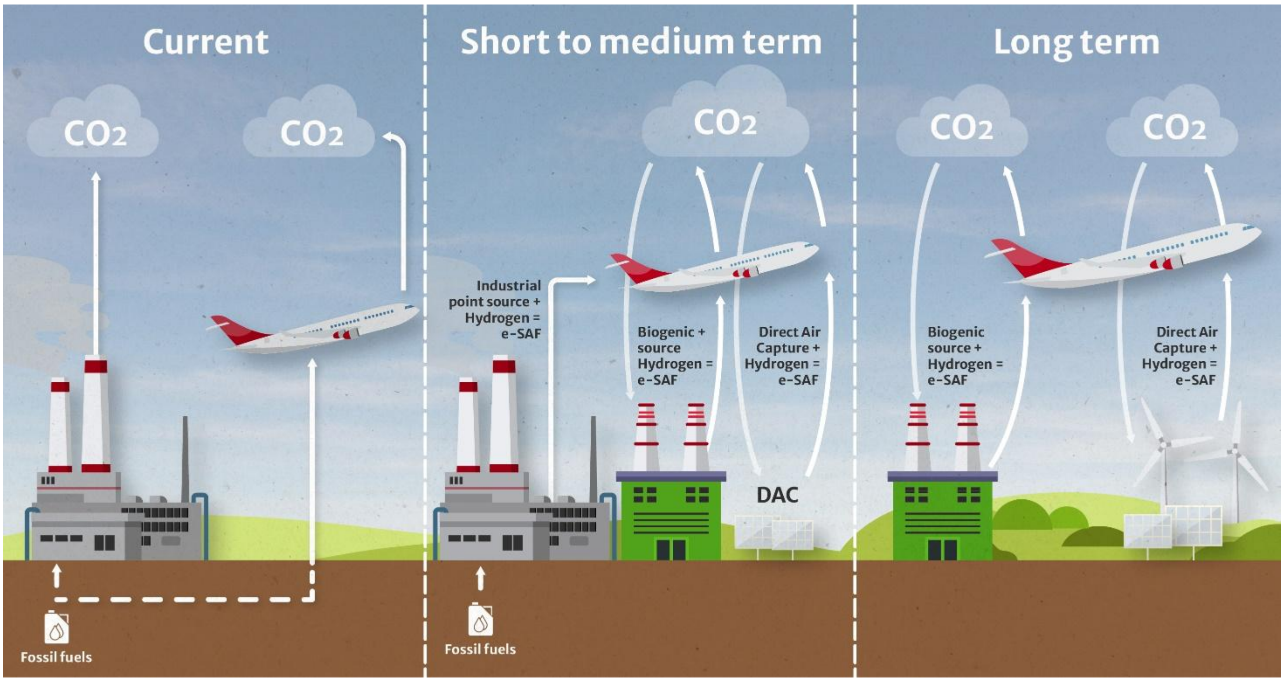


Figure 7: CO_2 cycle for the production of e-SAF

Concretely, Australia could start producing e-SAF in select regions that:

- Co-locate **LNG** for CO_2 source, renewable energy from solar and onshore wind, a (potential) desalination plant or wastewater from gas extraction plants in areas like the Pilbara with its massive space, irradiation factor, wind potential and existing ports. For example, TE H2 could provide the energy and utilize the captured carbon from the Ichtys LNG plant, process into e-SAF and ship out of Darwin port. With this CO_2 source, there would be an Australia-wide potential of 34.6 Mt of CO_2 to tap into, translating to potentially >10Mt/year of e-SAF, which would require about 50GW of electrolysis and about 75 GW of renewable energy. Simultaneously, this could provide a pathway for the utilization of (parts) of the emissions from LNG plants for the next decade(s).

- Co-locate **limestone** for CO_2 source when processed into lime for the cement industry, or alternatively **DAC**; renewable energy from solar and onshore wind, a (potential) desalination plant in limestone-rich areas like Southern WA; with DAC being supported by the off-heat of the electrolysis or even PtL process. A port would have to be built.

- Co-locate **biomass** for CO_2 source especially when coming from biogas or AtJ plants where it is a by-product that is currently under no obligation to be captured or offset, with renewable energy from solar and onshore wind, existing water sources and ports; e.g. in Northern Tasmania, South Victoria, Northern Queensland, or Oakajee, WA. Projects such as ABEL Energy, HIF Global, HAMR Energy are already leveraging forestry residues to make e-methanol; ABEL potentially providing >150,000 and HAMR 100,000 tonnes e-SAF/year. In Northern Queensland, Bioenergy Group is projecting 150,000 tonnes of surplus biogenic CO_2 extracted from biogas by early 2028. This surplus biogenic CO_2 could be turned into e-SAF (est. 50,000 tonnes) whilst the biomethane from the biogas produces biogenic SAF through Fischer-Tropsch (Bioenergy Group, n.d.).

Generally, any carbon captured, even from smaller sources such as municipal waste or gas plants and co-located with smaller electrolyser plants, could be used to make e-SAF, but this would be more applicable for domestic use, especially for defence aircraft, than for export. With specialised companies such as Caphenia for syngas and Emerging Fuel Technologies, such plants could be operating near sources such as bigger cities or dairy processing plants.

Offtakers such as SEFE and Mabanaft are already looking at or are involved in Australian projects. German ports such as Hamburg but also other European ports (Rotterdam, Antwerp to name the most important ones) are already equipped to receive kerosene shipments.

6 Recommendations for Bilateral Cooperation

Germany and Australia have a unique opportunity to establish a long-term partnership in the development and trade of e-SAF, leveraging their complementary strengths to meet the challenges of decarbonising the aviation sector. Germany's growing demand for sustainable aviation fuels, driven by ambitious EU quotas, aligns well with Australia's abundant renewable energy resources and its potential to become a global leader in hydrogen and e-SAF production.

As has been outlined in this report, the EU quotas for e-SAF, coupled with the penalty and no option to buy your way out of compliance, are a strong foundation for market creation. By 2030, 570,000 tonnes of e-SAF will be needed in the EU, of which a significant part may need to be imported. Looking at the project pipeline in Europe suggests that the shortfall could amount to over 300,000 tonnes. As the e-SAF quotas increase in 2032 and 2035 and 5-yearly increments after that, the demand will increase accordingly, up to 16,590 kt in 2050. Germany will have a significant demand for e-SAF, too. German airlines will require around 128.000 tonnes of e-SAF in 2030 and 533,000 tonnes by 2035 based on the current legislation. As argued above, scale up of production has been lagging, partly because of the 2027 review of the quota creating uncertainty.

Australia has tremendous potential for renewable power and the production of green hydrogen. As has been discussed above, by 2030, Australia could produce one to three million tonnes of e-SAF, if all hydrogen targeted in the National Hydrogen Strategy would be used for this purpose. By 2050, this could amount to 30-60 Mt. Only a fraction of this could cover the whole EU demand for e-SAF.

To produce these amounts of e-SAF, large quantities of CO_2 will be needed. Assuming that 4 kg of CO_2 are needed for 1 kg of e-SAF, fulfilling the EU's e-SAF quota in 2030 would require 2.3 Mt CO_2, increasing to 66.4 Mt CO_2 in 2050. Germany would need around 0.4 Mt of CO_2 in 2030 increasing to 12.7 Mt CO_2 in 2050 to fulfill the e-SAF quota for the country's entire kerosene consumption[23]. Australia had a slightly lower kerosene consumption in 2023, requiring comparable amounts of CO_2 to replace with e-SAF.

Our investigation into CO_2 sources has demonstrated that Australia has significant potential for both biogenic and industrial sources, although there are limits to and stronger competition for biogenic sources. A maximum of 102 Mt of CO_2 excluding DAC, kelp, and aluminium is available in Australia (see Table 2). A glance at the industrial point sources that are going to occur until climate neutrality in 2050 illustrates that significant emissions could be utilized for e-SAF production.

Looking at the projections for CO_2 emissions from facilities covered by the Australian Safeguard Mechanism highlights their potential to significantly contribute to global e-SAF production. This is noting of course that Australian safeguard facilities manage their own emissions reductions pathways and may pursue carbon capture if it makes sense from a decarbonisation and business perspective. Figure 8 illustrates that if these emissions were used, they could generate enough e-SAF to meet the EU's e-SAF mandate until the late 2040s, by which time DAC is expected to become more widely available. Naturally, Australian demand for e-SAF must also be considered. Assuming the same quotas as the EU has implemented were implemented in Australia, and that 50% of the e-SAF required to fulfil the EU's e-SAF quota is sourced from Australia, the emissions from Australian Safeguard Mechanism facilities could cover this combined demand until approximately 2048.

[23] Based on an annual kerosene consumption of 9.04 Mt in Germany in 2024 and assuming that consumption levels remain stable until 2050 (Eurostat (2025)).

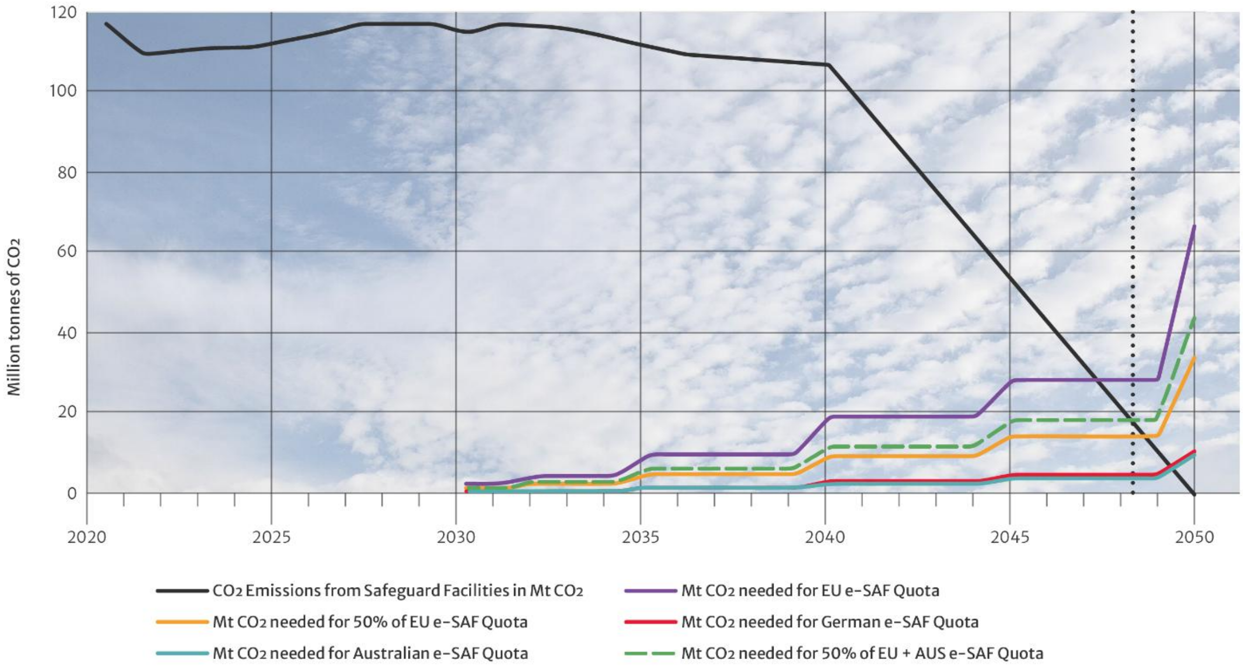


Figure 8: CO_2 from Australian Safeguard Facilities and EU and Australian e-SAF demand

While this study does not recommend extending the timeframe in which industrial point sources are allowed as eligible CO_2 sources within EU regulations on ReFuelEU, this analysis does illustrate that there are significant amounts of industrial CO_2 emissions that can be utilised for e-SAF production until 2050 and particularly in the short to medium term. Overall, the potential for bilateral trade of e-SAF between Australia and Germany / the EU can be looked at in three distinct timeframes:

- **Short-term**: the EU has e-SAF mandates in place from 2030 that will generate a market and demand that likely can't be met by projects in the EU and neighbouring countries Norway and Iceland. This would enable Australian e-SAF projects to lock in demand and export to the EU.

- **Medium-term**: as the Australian aviation sector also experiences pressure to decarbonise, the ability to export large quantities to Germany and the EU may be limited amid domestic climate targets.

- **Long-term**: once renewable energies are built out on a very large scale and the commercialisation of DAC technologies takes place, Australia is well-positioned to become a key global supplier of e-SAF, including to Germany and the EU.

To unlock this potential in the short-term, the following recommendations are made.

Provide Regulatory Certainty Regarding ReFuelEU and RFNBO Criteria

As outlined in this report, there is significant uncertainty around the persistence of certain elements of the ReFuelEU as well as the requirements for RFNBOs. For one, many organisations expect the review in 2027 to make changes to the quota as the current e-SAF quota is widely regarded as unattainable. In addition, the national penalties for non-compliance haven't been announced yet. There has also been much discussion around the RFNBO requirements pertaining to additionality and temporal correlation. As long as fuel suppliers and airlines in the EU are not completely certain that the quota and penalties will hold, it is unlikely that offtake agreements with and investments into Australian e-SAF projects take place to avoid any first-mover disadvantages. Similarly, the requirements and frameworks for RFNBOs need to be robust. To increase investment security for project developers and offtakers, grandfathering provisions could be established that ensure projects can continue operating under the rules at the time of their investment decision, even after new regulations or requirements are introduced.

Signal Need for e-SAF Imports to Meet German and EU e-SAF Demand

Germany and the EU should explicitly communicate the necessity of e-SAF imports to meet the ambitious quotas, particularly as domestic production alone will not suffice. This will encourage global producers, including those in Australia, to actively seek long-term offtake agreements that will enable them to invest in e-SAF projects, ensuring a diversified and reliable supply for the EU aviation sector. This could be supplemented by strategic considerations and potentially sub-targets regarding the country of origin to diversify supply in order to reduce dependencies. A purely price-based approach to the import of hydrogen and its derivatives, including e-SAF, may disadvantage hydrogen imports from countries where projects operate in a market-based environment as opposed to projects with state backing. Establishing import criteria beyond the price of a hydrogen-based product would constitute a strong signal to the international market and facilitate trade partnerships with like-minded countries, including Australia.

Provide Certainty for Australian Projects with Industrial CO_2 Point Sources

As demonstrated in this report, there is a large amount of industrial point sources in Australia that could be utilised for the production of e-SAF. To enable Australian projects to use industrial CO_2 point sources for e-SAF that is destined for the EU, the Australian Safeguard Mechanism would need to be recognised as eligible under EU regulation. Aligning the Australian Safeguard Mechanism with EU sustainability standards would facilitate trade and create opportunities for collaboration. In addition, it also needs to be ensured that the interoperability of certification schemes in Australia and the EU enables Australian hydrogen producers to proof RFNBO compliant production.

The EU sunset clause, which limits the use of industrial CO_2 point sources for e-SAF production to 2040, poses a significant challenge for projects aiming to reach Final Investment Decision (FID). This restriction creates uncertainty for investors, as projects relying on industrial CO_2 will not be able to recoup their investment costs for a carbon sequestration unit in that timeframe. To address this, governments could implement mechanisms or guarantees that ensure that Australian projects looking at export to the EU can transition to domestic demand after the sunset clause takes effect, providing a clear pathway for continued operation.[24] Alternatively, projects could be allowed to offset their reliance on industrial CO_2 by investing in emerging technologies like Direct Air Capture (DAC), enabling them to meet sustainability criteria while maintaining operational continuity. These measures would provide the necessary planning security to attract investment and ensure the long-term financial viability of e-SAF projects. In the case of cement and likely parts of the LNG industry, it can safely be assumed that their emissions will outlive any carbon sequestration plant built today.

Develop Australian Demand to Advance Decarbonisation and Decrease Dependence on Imports

Australia’s heavy reliance on imported fuels poses a significant risk to its energy security, particularly for critical sectors such as defence and aviation. Developing a robust domestic demand for SAF and e-SAF is essential to advancing decarbonisation efforts while reducing this dependence on imports. By introducing a domestic e-SAF quota or an emissions intensity aviation fuel standard that is balanced with the requirements underneath the Safeguard Mechanism, Australia could stimulate local production, that can then both serve the domestic and international markets. This would not only enhance the resilience of Australia's aviation sector but also drive innovation, create jobs, and position the country as a leader in clean energy.

Provide Planning Security for Australian Projects Using Biogenic CO_2 Sources

[24] This could tie in with the proposal by CORSIA to distinguish between „real zero“ and „low carbon“ SAF. CORSIA proposes to establish these terms for SAF meeting certain thresholds.

To support projects utilising biogenic CO_2 for e-SAF, Australia should take stock of all available biomass, conduct a full analysis of the future bioenergy needs and establish a clear strategy for the distribution and preferred end uses of biomass. This will help limit competition between industries, ensure sustainable feedstock allocation, and provide Australian producers with the planning security needed to scale up (SAF and) e-SAF production. "Australia's Bioenergy Roadmap" from 2021 noted that while bioenergy already contributes a significant share of Australia's energy, there remains potential for growth. However so far, there isn't enough knowledge about the size of sustainable and economically viable biomass, so that an assessment of the resource potential is needed. A national coordinator role could be established to oversee biomass resource assessments, align stakeholders across industries, and develop policies that prioritise sustainable and equitable biomass allocation.

Provide Financing Support for Projects

Even though an e-SAF quota coupled with a penalty creates a strong driver for demand, financial mechanisms are still crucial to bridge the cost gap between e-SAF and conventional aviation fuel until e-SAF production costs decline over the next few decades. Price gap bridging mechanisms as proposed in Project SkyPower can reduce the green premium and make e-SAF projects economically viable. These measures will attract private investment and accelerate the development of a competitive e-SAF industry. As the scale up of e-SAF production facilities is still needed, grant-based funding for strategic first-mover projects is also an option. Additionally, it should be considered to incentivise imports from reliable trading partners such as Australia. As outlined above, a purely price-based approach to the import of e-SAF might disadvantage imports from projects operating in a market-based environment such as Australia. Import criteria beyond price, such as quotas or import subsidies, could be established to ensure that Australian e-SAF is imported into Germany and the EU and has an advantage that can translate into better financing conditions. Another way would be the introduction of explicit risk premiums for imports into the EU that reflect higher risks related to political and economic factors and would further highlight the economic advantage of e-SAF produced in Australia.

Facilitate Availability of Sufficient Quantities of Low-Cost Renewable Power

Australia's renewable energy resources are vast, and its potential to produce green hydrogen and e-SAF is tremendous and underscored by ambitious goals at the federal and state level. However, the expansion of renewable energy infrastructure must accelerate to support both the decarbonisation of the existing and future power demand and potential hydrogen and e-SAF production at scale. Currently, the availability of low-cost power is one of the main concerns for project developers of renewable hydrogen projects.

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