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ECONOMIC
FORUM

Clean Skies for Tomorrow

Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation

INSIGHT REPORT

NOVEMBER 2020

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Contents

Foreword

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The World Economic Forum's *Clean Skies for Tomorrow* (CST) initiative, established in 2019, is a coalition across aviation's value chain working to facilitate the transition to net-zero flying by mid-century. In partnership with ambitious senior leadership across industry, government, and civil society, this public-private partnership is driving a shift to zero-emissions aviation through sustainable aviation fuels (SAF) and other clean propulsion technologies.

SAF is a necessary step in aviation's decarbonization pathway, especially with next-generation technologies like electric flight and hydrogen-powered propulsion still years away from application at scale. The CST coalition is working to address the chicken-and-egg scenario whereby producers and consumers of SAF are both either unwilling or unable to carry the initial cost burden of investing in new technologies to reach a scale where they are more cost competitive with existing fossil fuel-derived options.

The aim is to break this impasse and advance the commercial scale of viable production of sustainable low-carbon aviation fuels (bio and synthetic) for broad adoption in the industry by 2030. This report, developed in close consultation with the CST coalition, serves to provide a fact base on which swift and bold actions should be taken by public and private sector leaders alike.

The COVID-19 pandemic, however, continues to have profound effects on society, economies and the aviation and travel industries especially. With many international borders closed and mandatory quarantines imposed, airline passenger volumes are down approximately 60% and gross operating revenues have dropped nearly $400 billion for the year.[1] This sudden crisis for the industry has resulted in thousands of job cuts among airlines, airports, manufacturers and others.

Many have received significant government financial support to remain in business, while others have collapsed or declared bankruptcy. Recovery is expected, albeit slowly. As public health experts learn more about the SARS-COV2 virus, international travel standards will improve. When governments reopen borders and consumer confidence returns, air travel will again become commonplace.

But in the meantime, climate goals must be met and the clock is still ticking on this decade of delivery. Encouragingly, CST's stakeholders have shared that both individual and corporate customers are demanding more sustainable travel options. In line with the Forum's Great Reset initiative, guiding decision-makers along the path to a more resilient, sustainable world beyond coronavirus, CST continues to accelerate the energy transition of the aviation sector. As the International Organization for Public-Private Cooperation, the World Economic Forum is the ideal platform to inform, support and accelerate this transformation.

Along this journey, we are consistently encouraged by the CST coalition members and partners who through their engagement reinforce their commitment to achieve sustainable and climate-neutral flying even in this challenging time. Together with the Energy Transitions Commission and the Rocky Mountain Institute, the Forum's partners in the CST coalition secretariat, we commend the commitment of our ambitious community and look forward to continued partnership on the global race to zero.

Executive Summary

A transition to carbon-neutral flying is possible and sustainable aviation fuels are the most promising decarbonization pathway in the near term.

Climate change is one of the most urgent challenges of our time and requires collective action to solve, embodied in a shared vision and collaboration across government, industry and society. The decade until 2030 is our window of opportunity to shift the global trajectory to a sustainable future. Indeed, the actions taken now will determine the ability of future generations to sustain themselves on this planet.

The United Nations Framework Convention on Climate Change's (UNFCCC) Paris Agreement, signed in 2016, was a watershed moment by demonstrating a global consensus on the threats of climate change and commitment to act. In charting strategies to meet the goals of the agreement – namely limiting climatic warming to 2 degrees Celsius and aiming for 1.5 degrees – governments have outlined their own plans to contribute to the shared goal, some more ambitiously than others. Corporations are also announcing their own ambitious goals and strategies to reduce their environmental footprint and overall GHG emissions, although additional commitments and greater speed of action are needed to succeed.

Aviation is one of six hard-to-abate sectors which, along with cement, steel, plastics, trucking and shipping, represent approximately 30% of global annual carbon emissions. According to the European Commission, by the middle of the 21st century demand for flying could increase aviation's GHG emissions by more than 300% over 2005 levels, although this increase has been temporarily slowed by the COVID-19 pandemic.

The economic and social benefits of air travel are undeniable, providing global access to goods and services and opportunities to experience new places and cultures. The aviation industry has played a large part in enabling the benefits of globalization as well as the risks, such as the ongoing pandemic. It is in this context that the aviation industry and its entire value chain is today confronting the challenge of how to continue to deliver benefits in an environmentally sustainable way.

As travel picks up in the wake of the pandemic, aviation will return to producing its share of about 3% of total global GHG emissions – with overall impacts on climate change even higher as a result of climatic-forcing mechanisms. Hybrid-electric and hydrogen-powered aircraft could significantly help the industry reach the next efficiency horizon, but development and deployment at scale could take 10 to 20 years and the technology will be initially limited to smaller, shorter-range aircraft.

The CST coalition aims to scale SAF as the most promising option to reduce the aviation industry's carbon emissions in the near term. Synthesized from sustainable, renewable feedstocks, such as municipal waste, agricultural residues and waste lipids, SAF has already fuelled more than 250,000 commercial flights.[2] It is fully compatible with existing aircraft and fuelling infrastructure.

A transition to SAF is in reach. From a feedstock perspective, enough raw material is available to fuel all aviation by 2030.[3] To ramp up production, the industry will need to scale new technologies that run on less constrained feedstocks. To create commercial quantities of power-to-liquid fuels or e-fuels, made only from CO_2 and green electricity, technology will need to mature and much more renewable electricity must become available.

In 2019, fewer than 200,000 metric tons of SAF were produced globally, amounting to less than 0.1% of the roughly 300 million tons of jet fuel used by commercial airlines.[4] If all SAF projects that have been publicly announced are completed, capacity will scale to at least 4 million metric tons in the next few years, reaching volumes just over 1% of expected global jet fuel demand in 2030. In the near term, fuels produced from used cooking oil and other lipids will contribute most of the capacity build-up, but smaller companies are now testing and refining alternative pathways. These will take time to scale up, but investment decisions for larger demonstration plants need to be made now for these pathways to contribute.

SAF today is more than double the cost of conventional fuel but costs will decline with further innovations and efficiencies of scale as production increases. Facilities will scale, technologies will mature and inputs such as green electricity will become less costly. There is no "silver bullet", however. No single feedstock or production pathway will be practical in every geography or yield enough SAF to meet all demand. Even as costs fall, SAF will almost certainly remain more expensive to produce than fossil fuel, although a rising carbon price may enable parity in the 2030s. Some stakeholders propose to conduct business as usual and wait for a technological miracle, but climate change is already under way. Hope is not a strategy.

To scale production and make SAF economically viable and scale production, several advances will be required: technological challenges must be overcome; a supportive regulatory framework needs to be installed to stimulate demand from corporate and private customers; and innovative solutions to finance the transition have to be implemented. The CST coalition is debating how to meet these challenges and help aviation earn its right to keep growing.

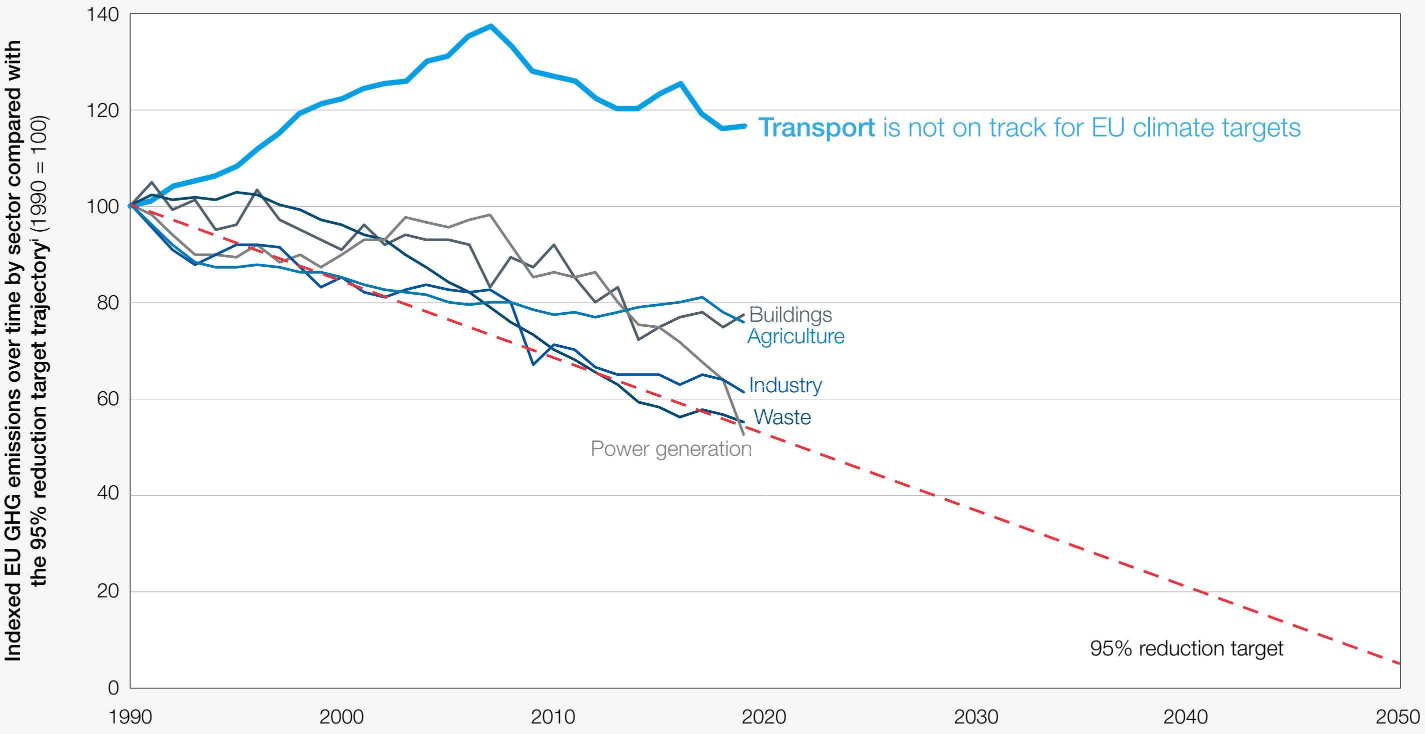
This report, created with the contributions of coalition members, describes feedstock availability and sustainability, production capacity and technology maturity, and quantifies expected costs of the most promising SAF production pathways. It thus provides a fact base for stakeholders, including industry decision-makers, as they build a more sustainable future.

Introduction

Closing the gap to a 1.5-degree pathway, as outlined in the Paris Agreement, will require rapid decarbonization in every industry. Transportation, which contributes nearly a quarter of total energy-related CO_2 emissions,[5] is far behind climate targets. Even within the European Union, which has strict guidelines and metrics for cross-sectoral decarbonization – and a variety of intermodal transportation options – the industry as a whole is entirely off-track for Paris-aligned climate goals.

FIGURE 1 **The transportation sector is next on the list for decarbonization**

After other sectors successfully started decarbonizing, attention is shifting to aviation, shipping, trucking



i. 2017-2019 data extrapolated based on German greenhouse gas emission

Source: European Federation for Transport and Environment; adapted from EEA, approximated EU greenhouse gas inventory 2016; Transport & Environment from Member States' reporting to the UNFCCC (1990-2015 data) and EEA's approximated EU greenhouse gas inventory (2016 data)

All industries are increasing their efforts to reduce emissions. As public pressure rises, the focus in transportation is shifting to harder-to-abate sectors including long-distance trucks, shipping and especially aviation. A 2019 analysis by Goldman Sachs[6] confirmed that aviation emissions present special challenges. The industry's average carbon abatement costs, for example, are more than five times higher than those in power generation or agriculture. In addition, aviation is a global industry with airlines from around the world competing across borders. Due to its inherently global nature, localized and non-standardized regulatory schemes lead to market distortions instead of a "level-playing field" required for smooth operations. Also, fleet-renewal cycles are slow, with commercial aircraft being used for 25 years or more.

Reducing the industry's GHG output is especially important, as aviation is likely to grow faster than other modes of transportation. Demand for aircraft fuel could increase by more than 50% until 2050 compared to pre-COVID levels despite the steep decline in air travel during the pandemic.[7]

FIGURE 2

Annual kerosene demand expected to exceed 400 million tons by 2030 and 500 million tons by 2045

Numbers include COVID-19 impact[i]

Assumptions[ii]

A

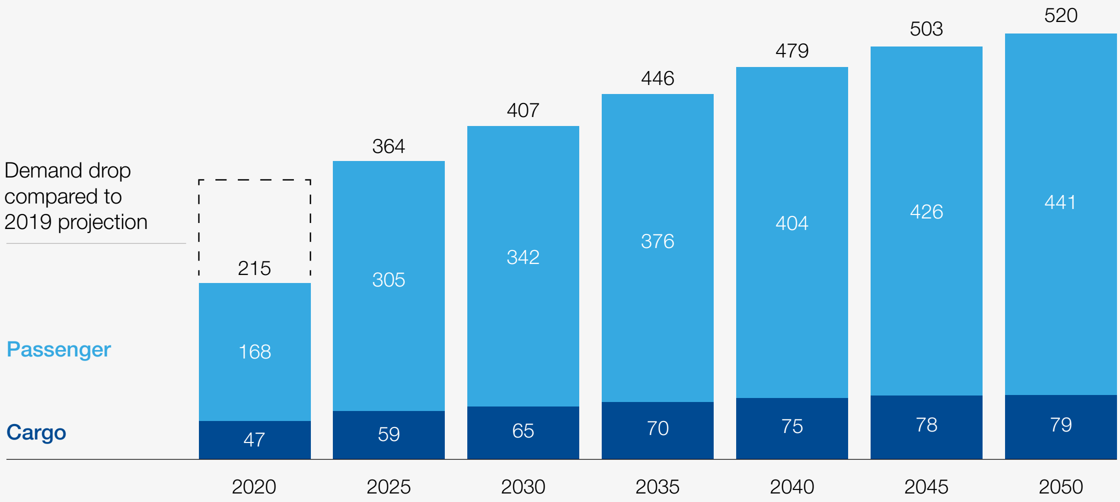
Fuel efficiency improves by 1% annually through 2050, based on historical trends

B

Fuel mix of 100% kerosene[iii] in 2050, with no commercial electric or hydrogen planes

Global aviation energy demand projection (million of tons of jet fuel per year)

Equivalent global CO_2 emissions[iv] **assuming 100% fossil jet** (billions of tons)	**0.7**	**1.1**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**



i. Shifted 2019 projections of 429 million tons in 2030 and 546 in 2050; **ii**. According to Global Energy Perspective Reference Case; ICAO anticipated 20-25% smaller numbers in 2019 based on more aggressive efficiency assumptions; **iii**. Including blend-in fuels; **iv**. Assuming 3.15 tons of CO_2 for every ton of jet fuel

Source: Energy Insights' Global Energy Perspective, Reference Case A3 October 2020; IATA; ICAO

> **❝ The human influence on the climate system is clear. The more we disrupt our climate, the more we risk severe, pervasive and irreversible impacts. We have the means to limit climate change and build a more prosperous, sustainable future.**
>
> UN Intergovernmental Panel on Climate Change

Aviation accounts for about 1 billion metric tons or about 3% of global CO_2 emissions annually.[8] Every metric ton of petroleum-based jet fuel burned produces 3.15 tons of CO_2,[9] in addition to other emissions such as nitrogen oxide, soot and other radiative-forcing mechanisms. Research suggests that climate impacts of all propulsion-related emissions could be two to four times larger than those of CO_2 emissions alone. There are a number of efficiency-based and operational changes to reduce climatic effects, such as engine improvements, fleet renewals, lower altitude flying and others.[10] But the science is clear – the industry cannot solve its sustainability challenges through efficiencies and alternative fuels are necessary to make real progress.

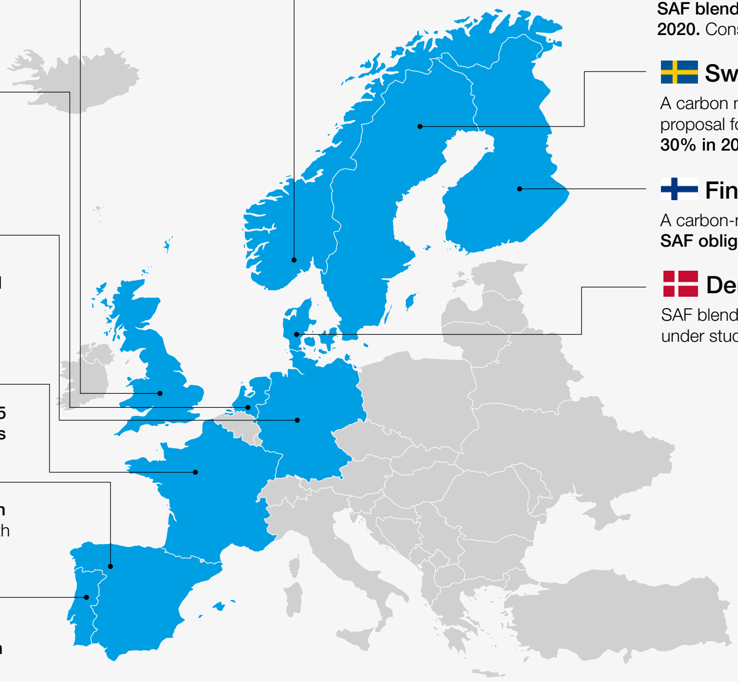
Government leaders and the public recognize the urgency and they're turning up the heat. Norway now requires that 0.5% of aviation fuel in the country must be sustainable, a share that will grow to 30% by 2030, and all short-haul flights must be 100% electric by 2040. In parallel to these SAF or technology-specific policies, over 45 countries have instituted a carbon pricing or emissions trading system, further demonstrating the changing regulatory environment industries need to navigate.[11]

The industry itself has long recognized the need to reduce emissions, yet charting a specific decarbonization course was difficult due to its need for dense energy sources. The International Air Transport Association (IATA), representing almost 300 airlines[12] from around the world, committed to reduce net carbon emissions to 50% of 2005 levels by 2050, seven years before the Paris Agreement was signed at COP21 in 2016.[13] Even though aviation is not part of the Paris Agreement, the International Civil Aviation Organization (ICAO) member states adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) as a market-based measure to achieve net-zero growth of international aviation from 2020 onwards.

More passengers are looking for low-carbon options and some are foreswearing air travel

FIGURE 3 | SAF competitiveness and scale-up – The European landscape

Some decisions pending



The UK

The **Renewable Transport Fuel Obligation (RTFO)** rewards SAF production with the same economic incentives given to road vehicles

The Netherlands

SAF Roadmap under development with a blending mandate at the national or EU level. Focus on **advanced feedstocks**. First SAF plant (SkyNRG) in 2022

Germany

National legislation for **GHG reduction of fuels** (to transpose the RED II) and the German National Hydrogen Strategy **foresee an SAF energetic sub-quota of 2% in 2030 and ONLY for PtL-kerosene**

France

SAF roadmap to reach a SAF supply of **2% in 2025 and 5% in 2030. Focus on advanced feedstocks**

Spain

Climate Change Law: **2% SAF supply objective in 2025**. Several new bio-refineries under planning with special **focus on wastes and residues**

Portugal

Roadmap for Carbon Neutrality (RNC2050) – integrated approach to **transport decarbonization including aviation**

Norway

SAF blend 0.5% mandate started in 2020. Considering a 30% target for 2030

Sweden

A carbon neutral country by 2045. Legislative proposal for **SAF blend ratios from 1% in 2021 to 30% in 2030**. Fossil-free Sweden industry initiative

Finland

A carbon-neutral country by 2035 – **increasing SAF obligation to reach 30% in 2030**

Denmark

SAF blend obligation under study

Source: SENASA

> **We need to build back better in the aviation sector. We are innovating and collaborating with our partners, aiming for a net-zero-carbon aviation sector in 2050. To realize this ambition a sustainable aviation fuels blending mandate and carbon pricing are key policy measures.**
>
> Dick Benschop, President and CEO, Royal Schiphol Group

entirely. In a 2019 consumer survey of more than 5,000 fliers, more than half of respondents said they were "really worried" about climate change and those under age 35 were more likely to be concerned, suggesting that demands for action will continue to rise.[14] 2018 witnessed the first of "flygskam" or "flight shaming", and this has driven both consumers and governments to demand higher sustainability standards.

Whether the coronavirus is a catalyst of change or causes delay in the world's energy transition remains to be seen. The World Health Organization reports that well-over 1 million people have died as a result of COVID-19 at the time of writing and the economic impacts could endure for years. The blow to the airline industry has been unprecedented, with airlines cutting capacity by about 75% in April 2020 compared to the year before. Global demand will likely begin to reverse the negative trends by mid- 2021, but a full return to pre-crisis demand may take several years. During this time, the industry will likely undergo major changes, including consolidation and unprecedented government support.

While the downturn will present profound difficulties for the airline industry's employees, customers and companies, opportunity still remains to speed progress towards a climate-neutral future. In 2019, IAG and Qantas declared net-zero by 2050 commitments and easyJet began offsetting all flights. In 2020, even during the pandemic crisis, all 13 airlines within the One World Alliance made the same commitment with more to follow, indicative of a quickly growing trend of dedicated climate action. Others like Air France-KLM and Austrian Airlines have committed to increased decarbonization targets within the context of recent state aid. While specific strategies to achieve these goals vary, carriers throughout the industry are retiring older, less fuel-efficient planes in favour of lower-cost and lower-polluting aircraft, such as the Airbus A350 and Boeing 777X enabling fuel efficiency gains of up to 25%.[15] Some are relying on offset purchasing schemes, while others are taking more progressive stances to immediately reduce actual lifecycle emissions through voluntary SAF use.

The pandemic has in many ways forced industry, government and society to re-examine priorities and operational strategies. Given the lead time required to scale decarbonized transportation technologies, it must continue to plan for the future even while the industry adapts to a COVID-19 world. This requires both partnering throughout its value chain and obtaining public policy support to ensure future operational capacity is ready.

The Forum's *Clean Skies for Tomorrow* Initiative

The Forum's *Clean Skies for Tomorrow* initiative is a purpose-built platform for leaders throughout aviation's value chain to facilitate the transition to net-zero flying by mid-century. With dedicated resources and collaboration through this project, more solutions can be delivered faster. Through this partnership, the coalition is working hard to see commercially viable SAF production at scale for industry-wide adoption by 2030.

CST leverages the convening power and expertise of the World Economic Forum together with that of the Rocky Mountain Institute, the Energy Transitions Commission, McKinsey & Company, and the initiative's Advisory Partners. Dedicated to decarbonizing aviation, it is accelerating global SAF development via innovative demand, financial and policy mechanisms. This platform rallies collective action and enables risk-sharing among stakeholders in the entire aviation ecosystem.

Established in 2019 with eight Founding Champions, CST has grown to over 80 corporations, international organizations, industry associations, think tanks, NGOs and academic institutions around the world. The initiative includes regular workshops, dialogues, analytical reports and strategic guidance to engage actors throughout the aviation value chain and related industries, including mobility, energy, chemical, agriculture, climate and financial sectors.

The project is strategically structured to focus on key impact areas, including demand-signal stimulation, public policy alignment and transition finance, each informed by an analytical foundation. This report presents the findings of the first impact area: the assessment of SAF feasibility and sustainability. It describes feedstock availability and sustainability, production capacity and technology maturity, and it estimates the costs of the most promising production pathways.

FIGURE 4 **The *Clean Skies for Tomorrow* coalition is pursuing five impact areas to help scale the production of sustainable aviation fuels**

	Groundwork to create a fact base		Enablers for scale-up		
	1 **Assess SAF feasibility and sustainability**	**2** **Democratize global SAF supply**	**3** **Align on an industry-backed policy proposal**	**4** **Create a scalable SAF marketplace**	**5** **Develop a blueprint for financing**
Context	The industry needs a broadly accepted fact base but some SAF studies convey partially conflicting messages and leave key questions unanswered	States with access to substantial sustainable biomass or low-cost power can benefit from a global energy transition	Global scale will require policy interventions to trigger learning-curve effects and economies of scale that could benefit the rest of the industry	US corporate flyers seem willing to pay a premium for SAF, translating into a 10% SAF blend that will require a scalable SAF marketplace	Funding must be mobilized for R&D and SAF supply chain scale-up, and investments must be aligned to shifting investor portfolios
2020 ambition	Refine and strengthen analyses on feedstock availability, technology readiness and production costs into a concise synthesis	Design a specific, comprehensive and actionable approach to scale up SAF in India and create blueprints for other regional pilots	Align on proposed policy interventions to trigger learning-curve effects and economies of scale that could benefit the rest of the industry	Design an SAF marketplace and make a first wave of transactions, design/pilots in 2020, first wave of transactions in 2021	Develop a blueprint for financing the transition to SAF, based on dialogues between aviation players and the finance community

🟩 Focus of this document

Despite technological improvements, aviation-based GHG emissions are expected to substantially rise through mid-century. And with today's sense of urgency on addressing climate change, the industry faces significant social, regulatory and financial headwinds. CST was established as a means to solve these challenges, focused on working within existing structures where possible and enabling innovative solutions where necessary.

CORSIA, led by ICAO – a CST Advisory Partner – is an effort for out-of-sector carbon offsetting. It has shown that industry-wide collaboration is possible, but more efforts are needed to meet internationally agreed climate goals. This requires additional proactive multistakeholder collaboration including diverse perspectives, especially in the run-up to determination of ICAO's long-term aspirational goals in 2022.

While alternative energy sources like hydrogen and electric-based propulsion have incredible long-term potential, they have significant technical limitations over the near term, necessitating other decarbonization routes. To meet decarbonization goals, efforts need to begin today, but technologies like hydrogen-based fuels and battery-electric flying still require years of development. Because new aircraft entering the market have long lifespans and will likely operate through at least 2040, SAF is the most achievable and most effective pathway to reduce aviation's lifecycle emissions in the immediate future and it remains a key component to industry sustainability plans.

SAF also offers a significant opportunity for rebuilding the aviation industry by offering an improved product to satisfy quickly changing consumer demands for sustainable flying and new regulatory requirements. This is why SAF remains a main pillar of CST's mandate and coalition focus.

A global public-private partnership like CST increases the likelihood of rapid SAF scale-up because a supportive regulatory framework, active marketplace and mechanisms to finance the transition are needed. These enablers are being addressed in parallel impact areas.

FIGURE 5

The *Clean Skies for Tomorrow* coalition has grown to over 80 organizations collaborating to scale the production of sustainable aviation fuels and decarbonize global aviation

The World Economic Forum's *Clean Skies for Tomorrow* Initiative is run in collaboration with the Rocky Mountain Institute, Energy Transitions Commission, and McKinsey & Company. CST's Advisory Partners include the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA), the Air Transport Action Group (ATAG), Airport Council International (ACI), the United Nations Framework Convention on Climate Change (UNFCCC), and Race to Zero (RtZ).

Chart is not inclusive of all members

Report methodology

> **“ Emirates is participating in initiatives to contribute to SAF deployment, and we welcome this latest report by the Clean Skies for Tomorrow coalition which will be an important resource to help all aviation stakeholders to progress a fact-based dialogue.**
>
> Adel Al Redha, Chief Operating Officer, Emirates Airline

This report was developed over months of research through existing literature and incorporating expert input from across the CST community. CST Coalition members provided insights in their respective fields of expertise including suitable production pathways, technical maturities, and potential challenges, as well as cost indications and expected scaling effects that will impact SAF costs over time. Throughout, this report relies on data triangulation across its various sources.

Public sources were used to the extent possible, such as academic literature, press articles and company announcements. Specifically, this includes data on installed and planned production capacity, availability of municipal solid waste and waste and residue lipids, areas of arable and degraded land, and GHG emissions lifecycle assessments of different feedstocks and production pathways.

McKinsey insights and solutions were used as complementary information sources. The Agriculture Commodity Research Engine (ACRE) tool provides data on global biomass density based on geospatial data with a granularity of 10x10km and was used to provide input on SAF feedstock availability. Data and insights from the Global Energy Perspective (GEP) serve as the basis for future energy consumption across transportation sectors and typical product outputs from different production pathways as well as cost of input factors such as hydrogen, further guiding the analysis on industry trends and fuel use forecasts.

This report relies on robust and predetermined sustainability metrics to evaluate the feasibility and usability of various SAF production pathways and feedstocks, further detailed in later sections. Other decarbonization options such as new technology, carbon removal, or improved intermodal integration should play a central role in reducing CO_2 and are considered complementary to SAF.

Report findings result from analyses across a structured process. Four ASTM-approved SAF production pathways were selected for further assessment based on expected CO_2 reduction, maximum blending ratio with conventional jet fuel, and maturity of technology and commercial readiness. For this subset of production pathways, feedstock was prioritized based on careful sustainability criteria: at least 60% GHG savings compared to fossil fuels (in line with requirements laid out by the Roundtable on Sustainable Biomaterials) and minimizing the risk of threatening food security or indirect land use change (ILUC). Availability of feedstock for these types was further quantified via sustainability filters detailed later in this report, such as excluding feedstock used outside the energy sector.

The resulting practical availability of feedstock was converted into sustainable aviation fuel potential based on industry-standard conversion factors from feedstock to lipids and industry-standard SAF production shares in the production output slate based on input from the CST coalition. Likewise, current production capacity and the expected ramp-up to 2025 is based on public announcements and expert input from the CST coalition.

Potential challenges and roadblocks in SAF scale-up by production pathways result from expert interviews and the findings from CST’s case study work in other markets such as India. SAF production costs were built from the bottom up, starting with pathway considering different feedstocks, production locations and technologies used and include expert input from CST coalition members.

Bio-feedstock costs are based on expert inputs and historic market prices and are assumed constant for the timeline presented. CO_2 cost reduction costs are based on CST coalition expert input. Electricity and hydrogen costs are location-specific and based on Enerdata and McKinsey Energy Insights’ Global Energy Perspective. Hydrogen costs assume hydrogen production from renewable energy sources (green hydrogen) without producing carbon emissions.

Capital expenditure is based on press and academic literature research and expert inputs. Cost reductions enabled through scale-up and learning curve effects are based on CST expert assumptions. Fossil jet fuel costs are assumed to remain constant based on 2019 averages.

The report uses metric tonnes (tons) as the unit of measure. For conversion purposes the following numbers can be accepted:[16]1 metric tonne = 331 US gallon, 1 US gallon = 3.78541 litres, and 1 barrel = 42 US gallons.

Part 1

Sustainable Aviation Fuels as a Decarbonization Pathway

> **To avoid the worst effects of climate change we need to get to net zero by 2050 and aviation is no exception. The Clean Skies for Tomorrow initiative has played a vital role in building a 'high ambition coalition' committed to that goal.**
>
> John Holland-Kaye, CEO, Heathrow Airport

No single approach or technology alone will allow the airline industry to achieve sustainable, zero-emissions flight. Even if (hybrid-)electric and hydrogen-powered planes become practical for short- and medium-haul flights, SAF deployed at scale from a range of sources will be required to decarbonize across the industry.

Carbon offsets, for example, may be beneficial and airlines are on board with market-based measures such as CORSIA, which may advance global reforestation. Reforestation offsetting schemes can cost as little as $5 per metric ton of CO_2 captured, but increasing demand could lead to significant cost increases over time and there remain significant risks and questions over their long-term effectiveness. Other offsetting projects include resource recovery, such as capturing methane from landfills. Geological sequestration may be the most effective option currently available, but it is expensive and is still a nascent technology.

Meanwhile, public debates continue over the effectiveness of offsets in addressing the problem of high-emissions transportation, and customer adoption of offset schemes remains low. More than half of airlines now offer emissions offsets but fewer than 1% of individual passenger customers opt in to pay the premium.[17] As that share rises, offset programmes run the risk of being considered "greenwashing" – they may appear to address climate change challenges but allow purchasers to avoid meaningful steps to reduce emissions at their source. In addition, offsets do not provide an aviation-specific, in-sector solution.

Intermodal integration, such as with trains and buses today and perhaps with hyperloops and electric flying taxis tomorrow, can generate less CO_2 per passenger mile than planes alone and shipping more freight by rail can reduce emissions. Airlines will need to work more closely with rail and bus companies to integrate services, especially for short connections. But the carbon savings of these advances will make only small reductions in overall airline emissions, at least until groundbreaking new technologies emerge.

Efficiency improvements are possible, even using today's technology. But optimizing ground operations and in-flight procedures and using more lightweight materials in aircraft weight have the potential to reduce aviation's total CO_2 emissions by no more than 5%.

Battery and hydrogen technologies are advancing quickly. Smaller aircraft, such as commuter and regional jets, could be the first to transition to new propulsion technologies. However, about 95% of CO_2 emissions are emitted from aircraft in larger segments for which technological challenges need to be overcome. Using current battery technologies, a plane would need more than 50kg of batteries to replace 1kg of kerosene for a maximum range of 500km-1,000km. In addition, battery weight doesn't burn off the way fuel does, so the aircraft would need to carry the full load for the entire flight, requiring additional energy.

Commuter aircraft powered by hydrogen fuel cells could become feasible for flights of up to 500km in the next decade, and an extension to the short-range segment and up to 2,000km might be possible within another decade. For medium- and long-range flights, an evolutionary aircraft design with hydrogen direct combustion is a promising option; Airbus recently announced the plan to develop a narrow body aircraft powered by hydrogen that would enter service by 2035.[18]

FIGURE 6 **Most promising options to make aviation sustainable are new fuels and propulsion technologies**

	①	②		③
Comparison vs fossil kerosene	**Battery-electric**	**H_2 fuel cell**	**H_2 turbine**	**Sustainable aviation fuel**
Climate impact[i]	🟩 100% reduction[ii]	🟩 75%-90% reduction	50%–75% reduction	🟨 30%-60% reduction[iii]
Aircraft design	🟨 Low-battery density limits ranges to 500km–1,000km	Feasible only for commuter to short-range segments	Feasible for all segments except for flights >10,000km	🟩 Only minor changes
Aircraft operations	🟩 Same or shorter turnaround times	1-2x longer refuelling times for up to short range	🟨 2–3x longer refuelling times for medium and long range	🟩 Same turnaround times
Airport infrastructure	🟨 Fast-charging or battery exchange system required	🟨 LH_2 distribution and storage required		🟩 Existing infrastructure can be used

🟩 Major advantages 🟨 Major challenges

i. Including CO_2, NOx, water vapour and contrails ii. Assuming 100% renewable electricity iii. For e-fuels with fully decarbonized supply chain

Source: Clean Sky 2 JU & FCH 2 JU: Hydrogen-powered aviation report (made possible with funding provided by the EU); expert interviews

This leaves sustainable aviation fuel as key to decarbonizing air travel at scale today and in the long run, applicable to all aircraft segments including medium- and long-haul flights that account for the majority of emissions. The single best option for sustainable aviation is the elimination of polluting emissions in the first place. SAF can, in theory, reduce life-cycle emissions by up to 99%, depending on the technology, feedstock and transportation – and they don't require any major changes to airport infrastructure or aircraft.[19] Lastly, SAF could avoid an early retirement and write-off of older aircraft types as it allows all aircraft to reduce their net carbon footprint.

To be clear, the level of CO_2 and other pollutants emitted from the back of the jet engine is largely equivalent between SAF and fossil-based jet fuel. However, the net climate effect is significantly reduced as a result of a more accurate and holistic accounting of all emissions associated with the fuel, including its production methods and feedstock source. Whereas all carbon from fossil fuels is newly introduced to the global carbon cycle due to its extractive origin, SAF carbon sources are from carbon captured, as waste, or as residual biomass, such as used cooking oil or crop residues. These carbon sources are already present in or would otherwise release back into the atmosphere as they degrade. The end result of SAF use is a significantly reduced amount of additional carbon introduced into the global carbon cycle, whereas 100% of the emissions from fossil jet fuel is newly introduced.

The technical challenges surrounding production are manageable. The American Society of Testing and Materials (ASTM) standard D7566[20] defines criteria for the blending of SAF into conventional fossil kerosene. An ASTM-approved blend is considered the same physical product as Jet A/A-1 fuel and can thus be used without further adjustments. The blending rate is limited to 50% today to ensure full compatibility with aircraft engines of all ages, but in its pure form, SAF already meets all requirements of Jet A/A-1 specification except the aromatics content that makes the blending necessary. Experts expect future aircraft and engine generations to be capable of handling 100% SAF.

In short, today's SAF blends are technically compatible with fuel delivery and airport fuelling infrastructure. No investments in delivery or fuelling infrastructure are needed. The scale-up of SAF volumes has already begun and can continue without delay.

In the decades ahead, SAF will be key to the aviation industry's overall decarbonization progress. Depending on region, technology and feedstock type, it could offer many benefits in addition to reducing emissions, including creating thousands of jobs, protecting the land, air and water by reducing the amount of waste in landfills and illegal dumps, and providing a steady new source of income for millions of farmers, including some of the world's poorest.

1.1 ASTM-certified aviation fuels

Sustainable Aviation Fuel (SAF) describes non-conventional (fossil-derived) aviation fuel produced from biological (plant or animal material) and non-biological sources (e.g., municipal waste or waste CO_2). The chemical and physical characteristics of SAF are almost identical to those of conventional jet fuel and they can be safely mixed with the latter to varying degrees.

The American Society of Testing and Materials (ASTM) has approved seven alternative jet fuels for blending with conventional fossil jet fuel up to a certain limit under their standard D7655. The resulting blend meets the Jet A/A-1 specifications (D1655) and can thus safely be used in commercial aviation without further adjustments.

The oldest ASTM-approved fuel, Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK) certified in 2009, requires the conversion of syngas via a Fischer-Tropsch reaction. This report considers two production pathways for syngas and thus FT-SPK: gasification of feedstock such as waste or residues; and electrolysis of CO_2. The maximum blending rate of FT-SPK with conventional kerosene is 50%. It is possible to add synthesized aromatics from the alkylation of non-petroleum-derived light aromatics, primarily benzene, to FT-SPK; the resulting fuel was approved as a separate SAF type SPK/A by ASTM in 2015. Since the blending limit remains at 50%, it is not considered separately here.

Synthetic paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA-SPK) was certified in 2011 with a 50% blending limit. Both the produced aviation fuel and the pathway are usually referred to as HEFA, while the resulting road fuel is called hydrotreated renewable diesel (HRD).

The alcohol-to-jet pathway can convert ethanol, isobutanol or methanol into aviation fuel. Fuel gained via the methanol route is not yet ASTM-approved, and the isobutanol route initially had a blending limit of only 30% when certified in 2016. When the ethanol route was added to the approved fuels in 2018, the blending limit for all alcohol-to-jet synthetic paraffinic kerosenes (AtJ-SPK) was set at 50%. This report focuses on the ethanol route of the AtJ pathway.

Three other fuels, partially resulting from variants of the routes described so far, are ASTM-approved, but are not in focus for this report. Catalytic hydrothermolysis synthesized kerosene (CH-SK), a variant of lipid conversion, turns clean free fatty acids into jet fuel with a blending limit of 50%. It was approved in the first half of 2020; specific feedstock availability is still unclear. Hydrocarbon-HEFA has been developed for micro-algae-based jet fuel, but algae's commercial potential and feasibility for large-scale fuel production is uncertain and the maximum approved blending rate is only 10%. Likewise, synthesized isoparaffins from hydroprocessed fermented sugars (HFS-SIP, also called direct sugars to hydrocarbons), have approved blending limits of only 10%.

Pyrolysis is a promising technology that has yet to receive ASTM approval. It could become a comparably cheap alternative with feedstocks including abundant and inexpensive agricultural and forestry residues and municipal solid waste.

Part 2

Recommended SAF Pathways

Sustainable aviation fuel is typically produced in a purpose-built plant rather than a fossil fuel refinery, using a range of technology pathways and feedstocks described below. This report addresses four pathways that are most likely to scale and attract industry attention: hydroprocessed esters and fatty acids (HEFA); alcohol-to-jet (AtJ); gasification/Fischer-Tropsch (gas/FT); and power-to-liquid (PtL). The resulting aviation fuels are all ASTM-approved for blending of up to 50% today with conventional fossil jet fuel.

FIGURE 7

Each SAF pathway presents specific opportunities and challenges depending on feedstock and technology maturity

	HEFA	Alcohol-to-jet[i]	Gasification/FT	Power-to-liquid
Opportunity description	Safe, proven, and scalable technology	Potential in the mid-term, however significant techno-economical uncertainty		Proof of concept 2025+, primarily where cheap high-volume electricity is available
Technology maturity	Mature	Commercial pilot		In development
Feedstock	Waste and residue lipids, purposely grown oil energy plants[ii] Transportable and with existing supply chains Potential to cover 5%-10% of total jet fuel demand	Agricultural and forestry residues, municipal solid waste[iv], purposely grown cellulosic energy crops[v] High availability of cheap feedstock, but fragmented collection		CO_2 and green electricity Unlimited potential via direct air capture Point source capture as bridging technology
% LCA GHG reduction vs. fossil jet	73%–84%[iii]	85%-94%[vi]		99%[vii]

i. Ethanol route; **ii**. Oilseed bearing trees on low-ILUC degraded land or as rotational oil cover crops; **iii**. Excluding all edible oil crops; **iv**. Mainly used for gas./FT; **v**. As rotational cover crops; **vi**. Excluding all edible sugars; **vii**. Up to 100% with a fully decarbonized supply chain

Source: CORSIA; RED II; De Jong et al. 2017; GLOBIUM 2015; ICCT 2017; ICCT 2019; E4tech 2020; Hayward et al. 2014; ENERGINET renewables catalogue; Van Dyk et al., 2019; NRL 2010; Umweltbundesamt 2016

- **Hydrogenated esters and fatty acids (HEFA):** Feedstocks for this safe, proven, scalable technology are waste and residue lipids, such as used cooking oil, as well as purposely grown oil trees, such as jatropha, grown on degraded land, and oilseed-bearing herbs, such as camelina, used as cover crops.

  Compared to fossil jet fuel, HEFA provides a GHG emission savings potential of 73%-84%,[21] with additional reduction potential when using sustainably produced "green" hydrogen in the hydroprocessing step of the production process. It has a conversion rate of roughly 90% (i.e., total output is 90% of feedstock input), of which nearly 50% results in SAF. (As a reference, this report uses an SAF yield of 46% – 46% of total output is SAF with another 46% being hydrotreated renewable diesel used for road transport, and 8% light ends such as LPG and naphtha. These shares are approximate and represent the values used in subsequent calculations, all for product slates optimized for jet fuel.) The SAF yield could be as high as 70% in a production process optimized for aviation fuel, but the needs of producers and the impact on overall plant economics will likely vary.

- **Alcohol-to-jet (ethanol route):** Feedstocks for this technology, which is now being piloted commercially, include any biomass that can be transformed into ethanol. Sustainable feedstock includes forestry residues, wood-processing and agricultural residues from mills or collected from fields and nature, and purposely grown non-edible energy cover crops such as miscanthus. Industrial waste gas can also be used as a feedstock. This route offers an emissions reduction potential of about 85%-94%.[22] Processing biomass into jet fuel through ethanol requires a lot of feedstock. A consensus estimate is a conversion rate of 13% and SAF yield of 77% of total output, with 6% road fuel in jet-optimized production. If the process is not optimized for jet, SAF yield drops to roughly 25%. Intermediate ethanol is produced today as a road gasoline blend and in the chemicals industry, competing as outlets for sustainable biomass.

- **Gasification/Fischer-Tropsch:** Using similar feedstock as alcohol-to-jet plus municipal solid waste, the feedstock is gasified to produce syngas – a mixture of carbon monoxide and hydrogen – which is subsequently fed into a

Fischer-Tropsch reactor where it is combined into a mix of hydrocarbons in the presence of a catalyst. Special attention has to be paid to control the H_2:CO ratio in the syngas that has an important effect on the reaction output. The pathway, now in pilot stage, offers CO_2 emission reductions of 85%-94%.[23] The feedstock conversion rate to total output assumed is 20%. Jet-optimized SAF yield is 60%, with 22% road fuel, and technology improvements could raise the SAF yield to 70%. Industrial waste gas can skip the gasification step and be fed directly into the process after optimizing the H_2:CO ratio.

- **Power-to-liquid:** This pathway starts with a different method of producing syngas – electrolysis of captured CO_2 either with (green) H_2 and a reverse water gas shift reaction (RWGS) or directly in a co-electrolysis set-up with solid oxide electrolysis cells (SOEC) and renewable electricity. Conversion of syngas into hydrocarbons such as jet fuel is then accomplished by a Fischer-Tropsch reaction, as in the gasification process. The yields to total output of hydrocarbons with both PtL routes are similar at 17%-18%. The SAF yield of the Fischer-Tropsch step with a product slate optimized for aviation fuel is again 60% (and 22% road fuels), or up to 70% with further process improvements.

The carbon used in the PtL process to produce the synthetic fuel can be sourced from three options: (1) as an industrial waste gas from burning fossils such as coal or gas; (2) from sustainable biomass (bioenergy carbon capture and storage, BECCS); and (3) as direct air capture (DAC), a process that extracts CO_2 directly from the atmosphere. Power-to-liquid fuels offer emissions reductions of up to 99% compared to fossil jet fuel when using renewable electricity throughout the production regardless of the CO_2 alternative used. Using captured fossil-origin carbon, however, creates a risk of double-claiming emission reductions.

If the carbon is used as PtL feedstock, the industrial site or power plant originating the CO_2 should not be seen as carbon-neutral. Only DAC and BECSS carbon fully avoid sustainability concerns around double-claiming emission reductions and unintended incentives for continued carbon emission generation. Nonetheless, many of the first PtL projects focus on the industrial fossil-based captured carbon. Since fuel from PtL is not based on primary biogenic feedstock and requires electricity to produce, it's also called electric or e-fuel.

All of these processes yield a product slate containing not only SAF but also a range of other products such as biodiesel, naphtha or chemicals – products commercially relevant in automotive, petrochemical and other sectors.

> **As the global aviation industry begins the long road to recovery, it is crucial that we lay the foundation for a prosperous and sustainable industry for the long term. Central to this should be an increase in the production and availability of sustainable aviation fuels which can make a swift and dramatic impact if facilitated by appropriate regulation, and government policies and incentives.**
>
> Luis Felipe de Oliveira, Director General, ACI World

FIGURE 8

SAF production processes generate substantial quantities of sustainable road fuel

Values represent conversion factors used for analyses

Approximate output shares of jet-optimized production processes

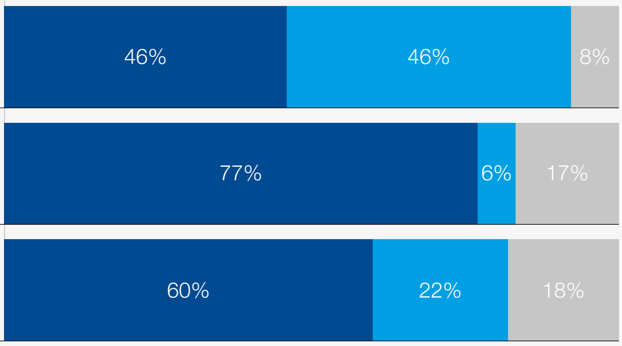
Product slate can be varied, for example, by changing H_2 use and operating conditions

In the long term, technology improvements could raise jet optimal share of SAF output to 70% for HEFA and FT

■ Jet fuel
■ Road fuel[iv]
■ Light ends[v]

Feedstock	Pathway	Conversion rate[ii]
Lipids	HEFA	90%
Biomass (mainly ligno-cellulosic)	Alcohol-to-jet[i]	13%
Biomass	Gasification/FT	20%
CO_2	Power-to-liquid	17%[iii]

Product slate optimized for jet fuel



i. Ethanol route; **ii**. Yield of total output (including aviation and road fuel) relative to feedstock; **iii**. For electrolysis with RWGS; co-electrolysis with SOEC may have slightly higher conversion rate; **iv**. Gasoline or diesel; road fuel resulting from HEFA process is called hydrotreated renewable diesel (HRD); **v**. Light hydrocarbon gases and liquids, e.g., LPG or naphtha;

Source: McKinsey Global Energy Practice; ICCT; International Renewable Energy Agency (IRENA); expert interviews

Part 3

SAF Feedstock Sustainability Guidelines

If production of bio/synfuel is optimized for SAF, advanced and waste feedstock could supply 490 million metric tons of SAF per year, more than the total projected jet fuel demand in 2030. Additionally, about 190 million metric tons of road fuel would result from the production. One of the major challenges in scaling up SAF is obtaining sufficient quantities of sustainable feedstock. The market is complex, with many feedstock types, geographical fragmentation and some disagreement on which resources are ethical, sustainable and compatible with production technologies. This chapter is meant to advance stakeholders' understanding of global feedstock availability.

FIGURE 9

Structured approach to identify sustainable feedstock for analysis

All feedstock must fulfil sustainability criteria

Feedstock type	Feedstock category			Feedstock[vi]	Substantial GHG savings potential[vii]	No fundamental sustainability concerns[viii]
1st gen / crop-based	Edible oil crops			Palm	✗	✗
				Soybean	✗	✗
				Other (incl. sunflower, rapeseed/canola)	✗	✗
	Edible sugars			Sugar cane	(✓)	✗
				Maize	✗	✗
				Other	✗	✗
▌ Advanced and waste	Waste and residue lipids[ii]			Used cooking oil (industrial or private sources)	✓	✓
				Animal waste fat (tallow)	✓	(✓)
				Other (incl. tall oil, technical corn oil, fish oil, POME, PFAD)	✓	(✓)
	Purposely grown energy plants	Oil trees on degraded land		Jatropha, pongamia	✓	(✓)
		Rotational cover crops	Oil cover crops	Camelina, carinata, pennycress	✓	(✓)
			Cellulosic cover crops	Miscanthus, switchgrass, reed cannarygrass	✓	(✓)
	Agricultural residues			Rice straw	✓	✓
				Sugar cane bagasse	✓	✓
				Other (incl. corn stover, cereal residues)	✓	✓
	Forestry residues[iii]				✓	✓
	Wood-processing waste[iv]				✓	✓
	Municipal solid waste[v]				✓	✓
Recycled carbon	Reusable plastic waste				✗	✓
	▌ Industrial waste gas	CO_2 from point source capture (CCS)			✓	✓
		Other (e.g. flue gas from steel production)			✓	✓
▌ Non-biomass based[i]	CO_2 from direct air capture (DAC)				✓	✓

▌ Focus of analysis ✓ Satisfied (✓) Potentially satisfied[ix] ✗ Not satisfied

i. Adjustment of RED II category "Renewable fuel of non-biological origin"; **ii**. Some not included in RED II definition of advanced (e.g., used cooking oil, animal waste fat), while others are (e.g., tall oil, POME); **iii**. Left overs from logging operations, including leaves, lops, tops, damaged or unwanted stem wood; **iv**. By-products and co-products of industrial wood-processing operations, including sawmill slabs, saw dust, wood chip; **v**. May contain up to 20% non-reusable plastics; typically inefficient to separate organics and plastic; **vi**. Algae not assessed due to limited feasibility; **vii**. In line with RSB: >60% based on LCA,; **viii**. Mainly related to food security and land use change; **ix**. Depending on local circumstances

Source: ICAO 2017; RED II; ICCT; Environmental Defense Fund (EDF); expert interviews

Since all SAF types can be derived from a wide range of feedstocks including wastes and residues, the sustainability of any feedstock is always relative to alternatives. Sustainable aviation fuel can live up to its name only if the feedstock fulfils sustainability criteria. Feedstocks meeting high GHG reduction criteria, with no or limited sustainability controversies, should be prioritized while more debatable cases may require local validation.

A two-step approach is used in this report: first identifying those feedstocks that are more sustainable and then quantifying their availability considering additional sustainability criteria. In certain scenarios, it may also make sense to use less sustainable "bridging" feedstocks as older technologies are phased out and new ones advance.

3.1 Identifying the most sustainable feedstocks

No single sustainable feedstock will answer every need; the industry will need to tap into a range of options. However, environmental integrity is key to selecting suitable feedstock. This report includes detailed assessments of an array of potential feedstocks that yield 60% or more GHG savings compared to fossil fuels. This is in line with requirements laid out by the Roundtable on Sustainable Biomaterials (RSB), a multistakeholder organization and CST Knowledge Partner, providing guidance on sustainability criteria of biomass and biomaterial.[24] Additionally, SAF must not threaten food security or spur indirect land-use changes.

For example, if reusable plastics are burned as fuel instead of recycled, they generate more CO_2

than fossil jet fuel over their lifecycle. Edible oils and sugars are excluded because resulting fuels produce more CO_2 than waste and residues-based fuels – and some produce even more CO_2 than fossil jet fuel. Fuelling planes with edible material may also increase demand for land for food and feed. That said, if sustainable local production is possible and does not jeopardize local food security, and other feedstock cannot cover the demand, specific edible feedstocks might be revisited in a local assessment.

Unlike reusable plastic, point-source-captured CO_2 from factory tailpipes and other industrial waste gas may have a positive lifecycle savings but raise other concerns. From a broader sustainability perspective, SAF production should not create a business case for other industries to produce carbon waste and double-claiming must be avoided. In other words, SAF production should not create incentives to continue using fossil fuels if non-emitting alternatives are available. If tailpipe emissions are captured and used for SAF, only the industrial site or SAF producer should get credit from the recycled carbon. Recycled carbons (excluding reusable plastics) could serve as bridging feedstocks, however, to help scale and mature technology until more sustainable alternatives are available at lower costs. An example would be carbon capture and storage (CCS).

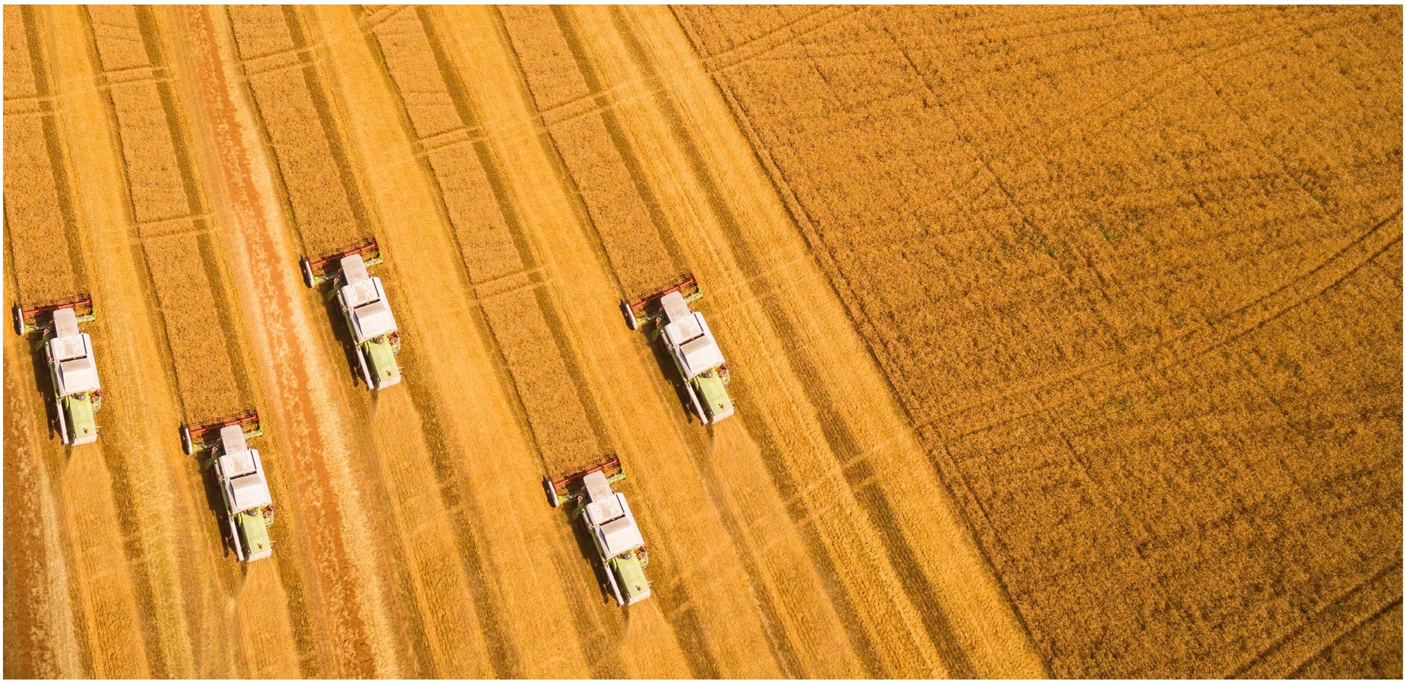
As an alternative, bio-energy carbon capture and storage (BECCS), such as from industrial or power sector use of biomass, provides additional potential. It makes use of the same CCS technology but uses a more sustainable carbon burned first-hand and would mean using this sustainable carbon twice.

Over time, electrification and other process optimization will reduce the availability of fossil carbon to be recycled for combustion. Direct-air-captured (DAC) carbon is widely seen as the most scalable option for sustainable fuels over the long term, despite its high cost today.

3.2 Assessing practical availability

When assessing the practical availability of feedstocks in scope for energy production, including aviation, marine and road fuel, and electricity and heating, the research considered further sustainability criteria. This was based on the standards of the Committee on Aviation Environmental Protection (CAEP) and RSB, ensuring stringent standards that do not include feedstocks with significant ILUC factors or other feedstocks that have significant emissions footprints associated with production. The research also considered competitive uses of feedstocks outside the energy sector, such as for animal feed, which limit the availability of feedstocks for the transport sector.

Feedstock usage filters for this report include sustainability and competing demand, but logistics and viability were considered out of scope for this initial analysis and were excluded as criteria. General sustainability criteria are listed below and specific feedstock related concerns are outlined in their respective sections. As it relates to feedstock assessments, this report is agnostic both on feedstock and technology – as long as they meet the below sustainability criteria. Some governments and non-governmental entities restrict specific feedstocks in principle, but this report restricts feedstocks based on:



Sustainability criteria

– *Conservation*: Feedstocks produced on land protected for biodiversity, conservation value or ecosystem services were excluded

– *Carbon stock*: Feedstocks from primary forests, wetlands, peatlands and other areas with high carbon stock are excluded, including land converted after 1 January 2008, also in line with avoiding high indirect land use change as defined by the European Union's RED II. and other non-governmental advisory standards, such as those from RSB[25,26]

– *Soil health*: Feedstocks that would otherwise put the physical, chemical or biological conditions of soil at risk through removal are excluded

– *Competing demand*: Feedstocks with primary use outside the energy sector are excluded to limit competition with other sectors, including biomass used for animal bedding and feeding and pulp and paper production. But it is important to note that the division of feedstock within the energy sector is not considered at this stage – only its availability for energy production in general, including aviation, marine and road fuel, but also electricity and heating

Logistics and viability

Although logistics and viability are not considered at this stage, these contextual realities may have a significant impact on the overall assessments included in the report. However, these remain outside the scope of this initial assessment and require additional research.

Collection rates and accessibility, for example, vary by feedstock and local circumstances. Feedstocks have varying degrees of fragmentation and specific challenges, in some cases requiring significant logistics for collection. Existing local supply chains are not taken into account for practical availability. Remoteness and geographical conditions such as slope are not considered in availability calculations.

Economic viability can be assessed only at the local level. Some feedstocks can be transported and sold globally, while others do not transport well and thus may provide economically viable options only if concentrations are high close to production sites.

FIGURE 10 **Practical availability assessment based on sustainability and competing demand but not on local logistics and viability**

Sustainability

Availability is assessed against sustainability criteria

- **Soil health:** Amount of feedstock included ensures good physical, chemical and biological conditions of soil
- **Carbon stock:** Land with high-carbon stock (e.g. primary forests, wetlands, peatlands) not used[i]
- **Conservation:** Protected land (for biodiversity, conservation value, ecosystem services) not used

Recycled carbon considered as bridging feedstock until more sustainable alternatives become available

- LCA GHG emission reduction potential clearly exists compared to fossil jet fuel (excluding reusable plastic waste)
- However, from a broader sustainability perspective, existing feedstock use case should not encourage the continued production of carbon waste in the long run

Competing demand

Feedstock used outside the energy sector is not considered available

- Biomass used for animal feed or animal bedding not taken into account
- Biomass used for production of, e.g. chemicals or pulp and paper, not considered

Within the energy sector, division of practically available feedstock not further assessed

- Usage preference for aviation sector versus road (incl. intermediary products like ethanol) and electricity/heat highly dependent on sustainability driven regulation, availability of alternatives and willingness to pay
- Synergetic effects, e.g. from building up feedstock collection systems, exist

Logistics and viability

Current collection rates and accessibility depend on specific feedstock and local circumstances

- Feedstock have varying degrees of fragmentation and specific challenges, in some cases requiring significant logistics for collections
- Current existence of local supply chains not taken into account for practical availability
- Remoteness or geographical conditions (e.g. slope) not factored into availability numbers

Economic viability can only be analysed locally

- Some feedstock can be transported and sold globally
- Others do not transport well and thus may only provide an economically viable option if concentration is high enough close to potential production site

[i] Including land with high carbon stock converted after 1 Jan 2018; RED II also defines high and low indirect land use change (ILUC)

Source: ICAO 2017; Staples et al. 2017

3.3 Technological pathways

In the report, SAF potential is based on the practical availability of each feedstock without considering whether it would be better used for other purposes related to energy consumption, such as road transportation or biomethane production. This raises important policy questions for businesses and governments; the facts presented here may contribute to answering them.

The main feedstock sources included in the assessment are, a) sustainable oils and lipids suitable for HEFA processes; and b) cellulosic waste such as agricultural and forestry residues or municipal solid waste for alcohol-to-jet and gasification/Fischer-Tropsch routes. Their competitive positioning differs by region and time, but most should provide 70%-99% CO_2 reduction compared to fossil jet fuel.

Calculations of the theoretically available total of cellulosic agriculture and forest residue are based on McKinsey's ACRE solution.[27] Filters for sustainability and competing demand described above determine practical availability. The following are detailed results of the feedstock availability analysis.

Sustainable oils and lipids suitable for HEFA processes
(up to 85 million metric tons of SAF)

1. Waste and residue lipids
This HEFA feedstock category includes used cooking oil, animal fat (tallow), fish oil, tall oil, technical corn oil, palm fatty acid distillate (PFAD) and palm oil mill effluent (POME) and other waste and residue lipids. Additional smaller streams exist that are not included in the potential assessed here.

Roughly 11-13 million metric tons of used cooking oil are available each year, and more could become available as growing populations and rising wealth increase the demand for food. Collecting the oil presents challenges, but stricter regulation, for example to avoid health hazards, can improve accessibility.

Animal fats from industry rendering waste represent roughly a third of the global supply of waste and residue lipids – 12-15 million metric tons each year, a figure that should grow as meat consumption rises, especially in Asia. The same holds true for fish oil, although only about 1 million metric tons are available each year.

All other considered waste and residue lipids as described earlier total to about 11-14 million metric tons each year. Total practical availability of this feedstock category thus amounts to roughly 40 million metric tons per year, which translates to roughly 20 million metric tons of SAF and 20 million metric tons of renewable diesel. Converting waste and residue lipids into jet fuel could meet about 5% of total 2030 jet fuel demand.

These numbers are likely a conservative number, since many smaller streams of waste and residue lipids are not included in the analysis.

Sustainability determinations
In general, these feedstocks are considered sustainable, but some cases are subject to debate. Animal fat, for example, is not accepted everywhere as an ethical alternative. The figures in this report include sick animals and BSE-related special risk material such as organs and tallow not consumed by humans according to regulations.

All palm oil-related products – including residue from processing as in the case of PFAD and POME – are controversial in Europe and other parts of the world, and some players prefer not to use them at all, due to the risk of land use change or difficulty in tracing the origin of the feedstock.

Assuming 0.7% oil extraction from raw POME and 5kg of PFAD output for every 100kg of palm oil produced, they total about 5 million metric tons per year and thus 10%-12% of all waste and residue lipids. This research considers palm oil residues only, not palm oil, but the sustainability of palm oil residues is linked closely to the sustainability of palm plantations.

2. Oil trees on degraded land
Feedstock for HEFA is not limited to waste and residue lipids but can be extended by using purposely grown energy plants such as oil trees on degraded land. Z. G. Bai and other researchers define land degradation as the “long term loss of ecosystem function and productivity caused by disturbances from which land cannot recover unaided.”[28] To exclude deforested areas and other negative recent land use changes in this assessment, only 1% of the world’s degraded land is considered in this analysis. On this amount of land, growing jatropha (an oilseed-bearing tree yielding 2.5-3 metric tons of oil per hectare) could produce 85 million metric tons of feedstock and 35 million metric tons of SAF via the HEFA pathway.

Sustainability determinations
As a proxy for degradation, this report used the normalized difference vegetation index, derived from remotely sensed imagery that is closely related to vegetation productivity, the fraction of photosynthetically active radiation absorbed by vegetation, and leaf-area index [29].

3. Oil cover crops
Another way of extending HEFA feedstock base is using oil cover crops. Land under temporary crops (double-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market, kitchen gardens and land temporarily fallow make up 855 million hectares based on the Food and Agriculture Organization of the United Nations (FAOstat).[30] All arable land under temporary crops theoretically benefits from cover crops during rotation phases. Benefits include improved infiltration of water into the soil; reduced erosion, run-off, sedimentation and nitrogen leaching; weed and disease suppression; increases in beneficial insects; gains in soil organic matter; and carbon sequestration.

Cover crops are typically not edible and all benefits can be delivered by purposely grown energy crops. In practice, however, there are barriers to using this land for energy cover crop production. Farmers may not have time or financial incentives to plant and harvest them, for example, and many do not know how to assess the full benefits, based on a survey from USDA’s Sustainable Agriculture Research and Education (SARE) programme.[31]

As a high-level global estimate, 25% of the total arable land is assumed to be practically available for purposely grown energy plants, with 20% planted with oil cover crops and 80% with cellulosic cover crops, since the latter are more industrialized and better fit to most situations. Note that these cover crops are not yet available and would take five to seven years to generate output if production began today.

The availability of oil cover crops is calculated based on 20% of available land planted with the oil herb camelina yielding 1.7 metric tons per hectare. Conversion of 85 million metric tons of feedstock via HEFA would yield 30 million metric tons of SAF per year.

Cellulosic biomass
(up to 405 million metric tons of SAF)

4. Cellulosic cover crops
The availability of cellulosic cover crops is calculated based on 80% of available land planted with miscanthus. Assuming a 50/50 split between gas/FT and AtJ, these crops would yield 120 million metric tons of SAF per year.

Sustainability determinations
There are barriers to using land under temporary crops for energy cover crop production, such as a lack of incentives for farmers, as noted. The high-level global estimate is based on an assumption that 25% of the total arable land is practically available for purposely grown energy plants. This report assumes 20% of this land could be planted with oil cover crops and 80% to grow cellulosic cover crops.

5. Agricultural residues
These include leftovers from harvesting major crops such as maize, cereals, rice and sugar cane, as well as residues from processing them in mills. To maintain the nitrogen cycle, 250 metric tons per square kilometre have been assumed to be left on

the land after each harvest. After excluding residues used in other sectors, such as for animal feeding and bedding, 660 million metric tons of feedstock would be available. Converted to SAF 50/50 via gas/FT and AtJ, they would yield 70 million metric tons of SAF.

6. Forest residues

Forest residues such as branches and other un-merchantable leftovers, when meeting sustainability criteria, offer another cellulosic waste category. These residues originate from forest management and harvesting practices for logging, pulp and paper production, sawmills and domestic fuelwood. Some forest residues are in use today by the pulp and paper industry and power sector for electricity and heat, but much is left unused. Based on ACRE estimates, all biomass is excluded on land with high carbon stock, in primary forests and on protected land. For soil health, about 1,000 metric tons per square kilometre should be left on the ground per harvesting cycle. Thus, 580 million metric tons of feedstock are available to produce 65 million metric tons of SAF, with a 50/50 split between gas/FT and AtJ.

7. Wood-processing waste

Sawmills and pulp plants produce byproducts and co-products such as sawmill slabs, sawdust and wood chips. Applying the same criteria as for forestry residues, 320 million metric tons of feedstock and 35 million metric tons of SAF could be produced using the gas/FT and AtJ pathways.

8. Municipal solid waste

The world produces about 2 billion metric tons of municipal solid waste each year. About half of it is organic, such as food and garden waste. Post-consumer separation of organic waste from mixed waste is inefficient, however, and uncommon. This report considers food and green waste reported by the World Bank to be theoretically available for energy production, if collected in full. Other waste streams include paper and plastics, but their recycling and reuse is assumed to be a preferred long-term alternative. However, non-reusable plastics can be used as feedstock without raising additional sustainability concerns as long as they do not make up more than 20% of overall waste. In total, this report considers 960 million metric tons of municipal solid waste (MSW) available as feedstock. Using the gas/FT pathway, this would yield approximately 115 million metric tons of SAF.

Sustainability determinations

These assessments are built on the assumption that as much as 20% of municipal solid waste is non-reusable plastics. The volumes that are non-reusable and non-recoverable for mechanical or chemical recycling are burned or enter landfills. Given the challenge of separation and alternative uses, the plastics content in mixed waste is considered less problematic and should not prohibit the use of mixed waste for fuel production. In addition, plastics in mixed waste improve the conversion rate from feedstock to fuel.

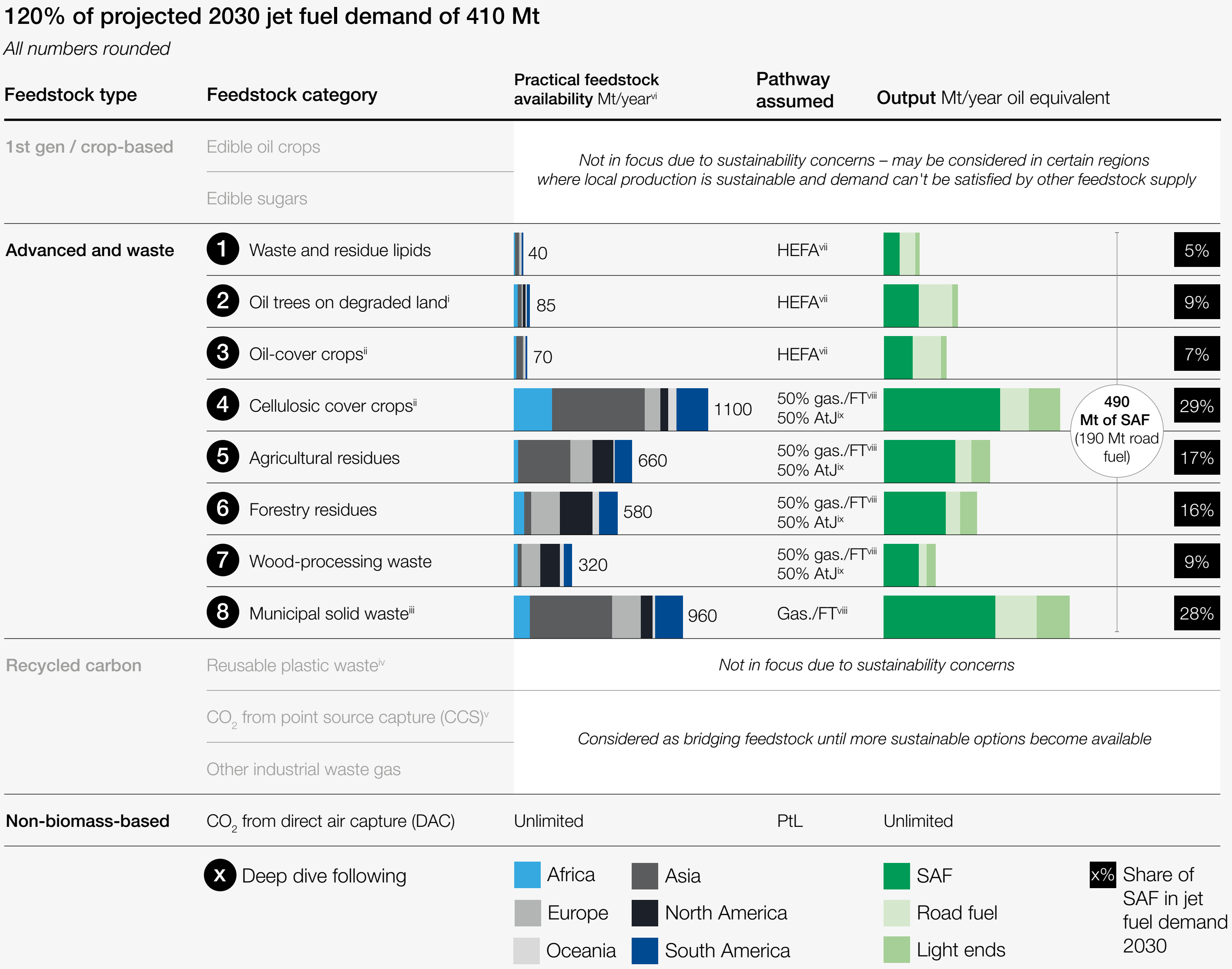
Overall, 500 million metric tons of SAF annually by 2030 is available from advanced and waste feedstock

A global SAF ecosystem would also yield about 190 million metric tons of road fuel or marine diesel (if optimizing fuel production yields for SAF), supporting decarbonization in other sectors. Indeed, although electric vehicle sales are taking off and should grow substantially in the years ahead, demand for sustainable road fuel is likely to continue rising for decades as the size of the total fleet expands along with blending mandates. Global biofuel demand will rise by about 2% annually to roughly 200 million metric tons in 2030, while alternative powertrains such as EVs and fuel cells may eventually reverse the trend.

Scaling up SAF production could benefit the total sustainable energy sector not only via direct road fuel production but also because scaling effective collection systems benefits the economics of all fuel production. Moreover, a surplus of feedstock is available and SAF production will require only a fraction of the total for the foreseeable future.

Every large-scale SAF ecosystem will require abundant, accessible and steady supplies of feedstock. Even without assessments of availability by geography, it is clear that each regional and even local ecosystem will have its own characteristics and dynamics. Some feedstocks, such as lipids, can be sold globally since they can be transported at low cost. The HEFA potential in a region is thus not limited to local supply, as waste and residue lipids from other regions might be available. Bulky feedstocks such as cellulosic residues are more difficult to transport and may, therefore, be most economically viable in locations that provide high feedstock concentration and favourable logistics to production sites.

FIGURE 11 **Advanced and waste feedstock alone could supply almost 500 Mt of SAF per year**



120% of projected 2030 jet fuel demand of 410 Mt

All numbers rounded

Feedstock type	Feedstock category	Practical feedstock availability Mt/year[vi]	Pathway assumed	Output Mt/year oil equivalent	
1st gen / crop-based	Edible oil crops	*Not in focus due to sustainability concerns – may be considered in certain regions where local production is sustainable and demand can't be satisfied by other feedstock supply*			
	Edible sugars				
Advanced and waste	1 Waste and residue lipids	40	HEFA[vii]		5%
	2 Oil trees on degraded land[i]	85	HEFA[vii]		9%
	3 Oil-cover crops[ii]	70	HEFA[vii]		7%
	4 Cellulosic cover crops[ii]	1100	50% gas./FT[viii] 50% AtJ[ix]		29%
	5 Agricultural residues	660	50% gas./FT[viii] 50% AtJ[ix]		17%
	6 Forestry residues	580	50% gas./FT[viii] 50% AtJ[ix]		16%
	7 Wood-processing waste	320	50% gas./FT[viii] 50% AtJ[ix]		9%
	8 Municipal solid waste[iii]	960	Gas./FT[viii]		28%
Recycled carbon	Reusable plastic waste[iv]	*Not in focus due to sustainability concerns*			
	CO_2 from point source capture (CCS)[v]	*Considered as bridging feedstock until more sustainable options become available*			
	Other industrial waste gas				
Non-biomass-based	CO_2 from direct air capture (DAC)	Unlimited	PtL	Unlimited	

490 Mt of SAF (190 Mt road fuel)

ⓧ Deep dive following

Africa, Asia, Europe, North America, Oceania, South America

SAF, Road fuel, Light ends

x% Share of SAF in jet fuel demand 2030

i. Amount of degraded land based on ACRE solution, 1% of this land assumed to be practically available for oilseed bearing trees; **ii**. Amount of arable land under temporary crops based on FAOstat, 25% of this land assumed to be practically available for cover crops; assumed split of 20/80 between oilseed bearing and cellulosic cover crops; **iii**. Availability based on World Bank number for pure organic waste plus 20% of total plastic waste, assumed to be non-reusable; up to 20% of total waste feedstock may be non-reusable plastic without raising additional concerns from sustainability perspective; in practice, complete separation unrealistic; **iv**. Availability based on World Bank number for plastic waste, discounted by 20% for non-reusable plastic; **v**. Availability based on global estimated gasiform CO_2 emissions from manufacturing industries and construction; CO_2 from industrial scale biomass as potentially available alternative (up to 200 Mt); currently, only very limited industrial capture capacity installed; **vi**. Oil equivalent in case of lipids and oil plants, dry biomass in case of lignocellulosic feedstock, CO_2 equivalent in case of gas; **vii**. 90% output yield, 46% SAF share; **viii**. 20% output yield, 60% SAF share; **ix**. 13% output yield, 77% SAF share; **x**. 17% output yield, 60% SAF share; **xi**. Assuming gas can be directly used as syngas with 40% output yield

Source: FAOstat; USDA; ACRE solution (based on e.g. Bai et al. 2008; Gibbs et al.); Energy Insights' Global Energy Perspective, Reference Case July 2020; World Bank; Environmental Protection Agency; IRENA; E4TECH 2020; BEIS 2017; ICCT 2016; EC 142/2011; Greenea; Ecofys; Fischer Solve; Statistik der Verarbeitung Tierischer Nebenprodukte 2016; research articles; press search; expert interviews

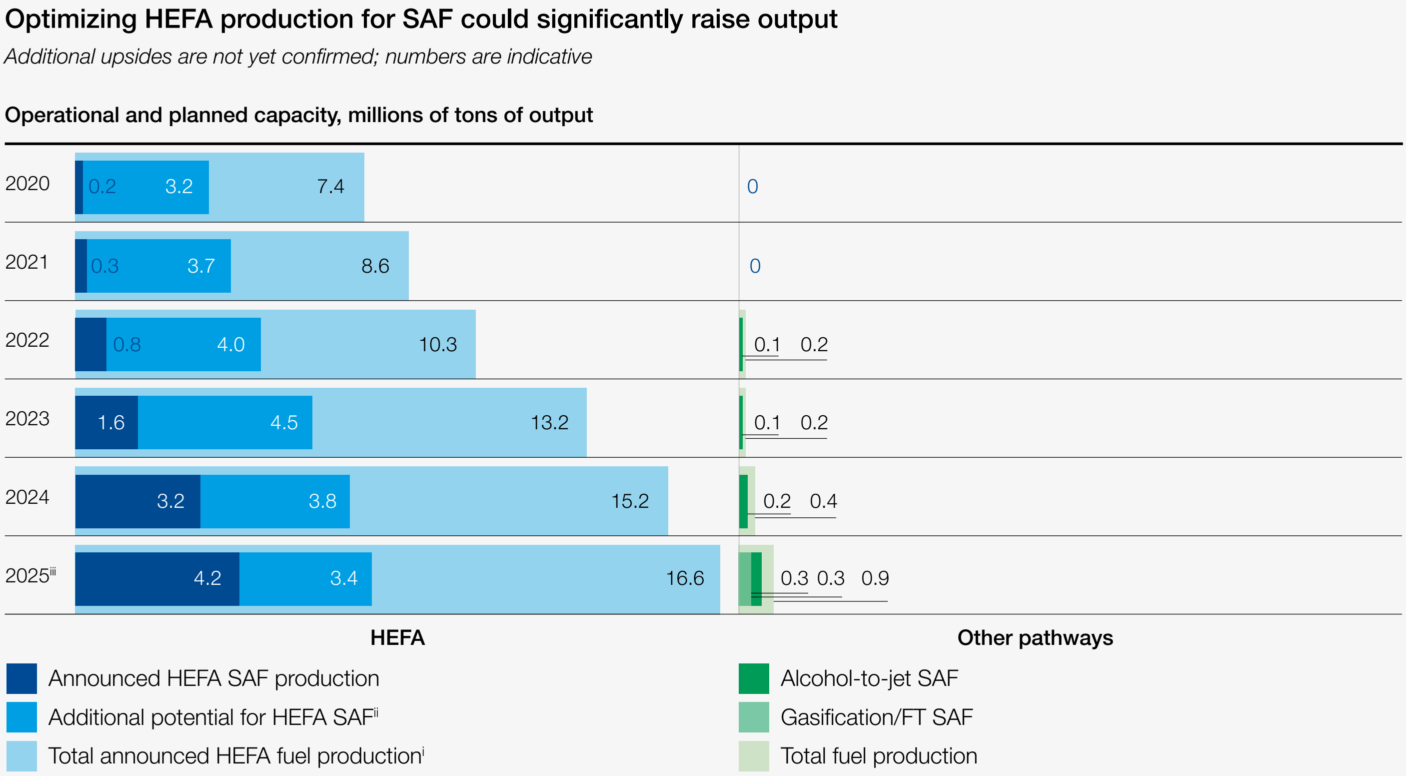
Part 4

Challenges of SAF Production and Technology Maturity

Scaling up each production pathway presents a range of challenges. For example, some feedstocks may be difficult to collect in sufficient quantities and some technologies need additional maturation through research and development to become practical. Demand for SAF would need to rise dramatically in the next few years even though it is likely to remain significantly more expensive than fossil fuel for decades. In short, progress will require not just scientific advances but meaningful and relatively quick changes in attitudes and behaviours around the world – including consumer preference for more sustainable travel options as well as government policy support.

The sustainable fuel industry is still relatively niche, in large part due to its high price premium over petroleum-derived jet fuel. As of July 2020, global capacity of all sustainable fuels (such as those used by aviation and road, regardless of technological pathway, as defined by non-fossil fuels adhering to the sustainability metrics detailed in this report) totalled only 5.5 million metric tons per year and is forecast to grow to 7.4 million metric tons by the end of the year. In the 2025-2030 window, announced production expansions should treble sustainable overall fuel production capacity, but out of this only about 5 million metric tons of SAF will be available in 2025 under current plans, with HEFA being the dominant production pathway. The largest share of the about 18 million metric tons of sustainable fuel in 2025 will be allocated to road transportation. A substantial share of installed and planned HEFA capacity is not focused on aviation fuel and does not have the technical capability to produce a jet-optimized product slate.

FIGURE 12 **Production capacity announced through 2025 will yield only 5 million tons of SAF annually, mostly from HEFA**



i. Including HRD, SAF and light ends; **ii**. If HEFA plants are gradually armed with capabilities for SAF optimized production starting in 2021 with 3-year lead time – additional investments needed; **iii**. Includes plants with no concrete opening timeline

Source: Public announcements

Demand will need to rise sharply to change the calculus of stakeholders throughout the value chain and overcome the challenges of creating a global SAF ecosystem and reaching 2030 decarbonization targets. Today, few major airlines have announced ambitious SAF offtake targets in significant volumes to reduce CO_2 emissions, but regional or national blending mandates, such as those in Norway and Sweden, will stimulate demand and provide additional confidence for further technology and production investment, in time supporting economies of scale.

Fuel producers pursue different production pathways and further scale-up of SAF presents pathway-specific challenges, such as the following.

HEFA fuels are produced today in commercial quantities by Neste, ENI and World Energy. Total production capacity should rise from roughly 200,000 metric tons in 2020 to more than 16 million metric tons by 2025, based on public announcements, mostly by companies such as Neste and SkyNRG. HEFA production plants could be modified to increase the share of jet fuel by adding a refinement unit, albeit requiring lead time and capital investment.

The largest challenge for scaling up HEFA production is the feedstock pool. Today, the world has enough waste and residue lipids to produce roughly 20 million metric tons of SAF, equating to about 5% of estimated 2030 jet fuel demand. While a significant share of this feedstock is already used in industry and other fuel applications, feedstock is scattered widely and difficult to collect in full without a complex infrastructure, resulting in significant unused reserves.

As potential solutions, governments could work with local stakeholders and incentivize waste-lipid collection, which would reduce the pressure on landfills and prevent illegal disposal that can harm the environment. Policy-makers may consider regulation to support collection from more remote areas, potentially harmonizing policies across regions. Additionally, increased production of oil seed energy crops on degraded land, crops with low ILUC factors, and cover crops would provide additional feedstock while potentially providing additional ecosystem service benefits – but such scaling requires lead time of five to 10 years to produce substantial yields, requiring action now for benefits later.

BOX 1

Countries around the world are finding ways to collect used cooking oil

By choosing clear and uniform approaches to collection, transportation, storage and regulation, countries and regions are finding they can collect used cooking oil and prevent it from being illegally blended into virgin oil or disposed of in legal or illegal landfills. Many are also relying on consumer education and using digital tools to solve an old urban problem and transform an environmental and health hazard into a valuable resource. Here are a few examples:

– **India** has adopted a “triple E” strategy of education, enforcement and ecosystem. The Food Safety and Standards Authority began regulating used cooking oils in 2018, using big data to anticipate output across sources, from food stands and restaurants to food factories.

– In **Brazil**, 15 cooperatives in and around São Paulo collect waste vegetable oil from local restaurants, households and central collection sites.

– **China**’s Sustainable Oil Alliance includes government authorities and Shell, who are working on a nationwide collection scheme for used cooking oil

Gas/FT and **AtJ** build on well-known technological processes but have not yet been used at scale for sustainable aviation fuel production and are, therefore, not fully mature. Small gasification/FT sites by Fulcrum in the United States and Velocys in the United Kingdom (one each) are up and running and both companies are building additional production locations. Red Rock Biofuel’s gas/FT factory is close to completion. Lanzatech, a leader in the development of alcohol-to-jet biofuel market, expects to open a first plant in 2022 via its LanzaJet subsidiary focused on SAF production.

Expanding SAF production through this pathway will mean overcoming significant technical barriers. Syngas composition control in gasification/FT and the oligomerization step in AtJ at large-scale pose engineering challenges. Validating the robustness and competitiveness of the technologies in proof-of-concept plants in different regions using feedstocks of varying quality will be central steps in increasing global production volumes.

Producers using this pathway will need robust local feedstock supply chains since lignocellulosic residues are bulky and difficult to transport. Collection and processing systems and incentives are only partially in place today, however. A natural mitigation measure would be to select plant locations carefully based on local feedstock availability and invest in collection and segregation processes, especially of municipal solid waste. Progress will require investments in service providers who collect and segregate residues, especially solid waste.

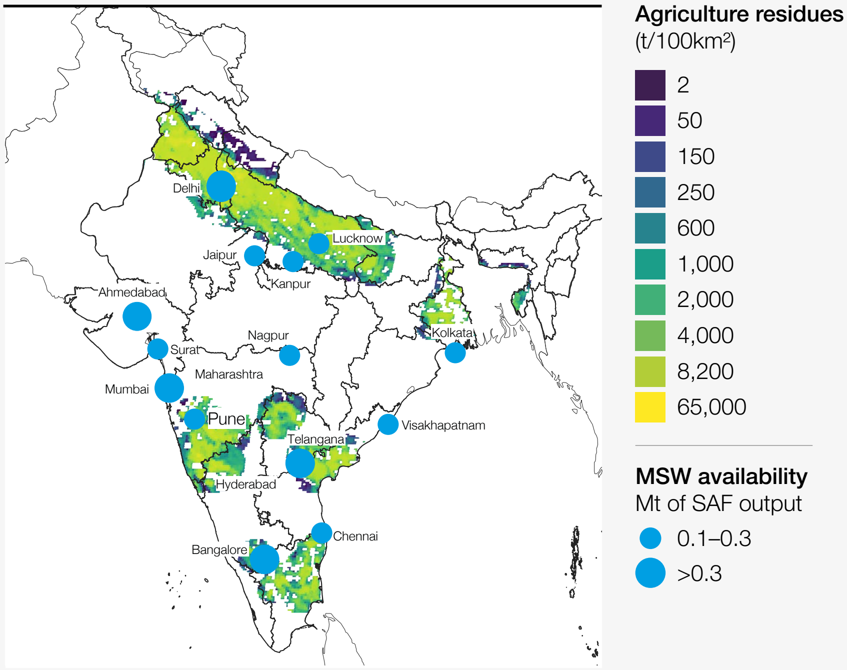
BOX 2 India's SAF potential

- CST's developing market focus includes a significant initial case study evaluation of India's SAF ecosystem potential. Below is an example of the findings, outlining estimated feedstock density by location in India through ACRE. Based on initial analysis, India's concentration of MSW and agricultural residues could provide enough feedstock to produce 11 million metric tons of SAF annually.
- The economic benefits of production grow when considering the commodification of waste, including the increased regional investment required for physical collection and production as well as new jobs created.
- Future CST reports will focus more closely on regional contexts, including India.

FIGURE 13 Scale-up example: India's concentration of municipal waste and agricultural residues could yield 11 million tons of SAF per year

Feedstock availability and concentration allow for significant SAF production

Rough estimates



33 **Potential plants based on municipal solid waste, close to large cities**

80 **Potential plants based on agricultural residues, located in six major hotspots**

11 million tons

Potential annual SAF output[i]

[i]. Asuming average of 77% yield for AtJ and 55% for gasification/FT and total output of 0.15 million tons and about 0.6 million tons of required feedstock per year

Source: McKinsey ACRE solution

> **Through the Clean Skies for Tomorrow coalition, SpiceJet and other industry leaders throughout India's aviation value-chain are collaboratively building a blueprint to produce SAF in India for use in India.**
>
> Ajay Singh, Chairman and Managing Director, SpiceJet

Sunfire, Caphenia and other companies are pursuing the production of SAF from power-to-liquid (PtL) or e-fuels. Sunfire's Norsk e-fuel project is using a SOEC co-electrolysis approach to produce syngas. The alternative route to syngas via reverse-water-gas-shift is also yet to be scaled up. Caphenia runs "power-and-biogas-to-liquid," a variant of the process. The company is building a pilot plant and aims to start production in 2023.

The largest hurdle in the PtL process is gaining access to large-scale sustainable CO_2 and renewable electricity or green hydrogen at competitive costs. Direct air-captured carbon and biomass-based, point-source captured carbon are not yet available at scale and green hydrogen production or co-electrolysis requires more sustainable electricity than is available today at sufficiently localized levels. For both technological routes, production locations should be chosen carefully based on the cost of renewable electricity and availability of BECCS or DAC carbon. One advantage of modular co-electrolysers is that it is simpler than scaling reverse-water-gas-shift set-ups, which are more complex.

Green hydrogen is considered the most sustainable production process for hydrogen. At some locations, blue hydrogen could provide a transitional opportunity enabling cost advantages until electrolysers scale, learning curve effects materialize and energy costs decline. Blue hydrogen costs are mainly influenced by natural gas prices and the cost of capturing and reusing, or storing, carbon emissions.[32]

With targeted support from government and industry as the costs of carbon and hydrogen fall, accelerated proofs of concept could demonstrate processes, help producers standardize plant layouts and blueprints, capture scale effects and inform business plans. For example, CO_2 could be captured from biomass or point sources at strategic locations in high-density industrial clusters. Over time, as the industry climbs the learning curve, the process could be adapted to use direct air carbon capture technology to optimize the sustainability of PtL fuels.

It is not yet clear whether one technology will emerge as dominant. Processes and technologies will likely mature in waves – as illustrated below – but each region will progress to pathways at a different pace, taking into account local sustainability preferences, feedstock availability, input costs and regulatory frameworks and incentives. Importantly, given the drop in capabilities of SAF, the product stemming from each technological pathway is as usable as the next, so there is no inherent need for technological cross-sectoral alignment per se.

Regardless of pathway, ASTM requirements raise the question of where blending will take place. Most producers blend at the refinery, since this is where they have fuel-handling know-how. Most also conduct the fuel certification process at the refinery and the SAF blend can use the same infrastructure as conventional kerosene. Blending mid-way to the airport, such as at a distributor storage location, would require access to a pipeline and additional infrastructure for SAF to be routed there. This would present certification and regulatory challenges to allow the blended fuel to be fed into the existing pipelines.

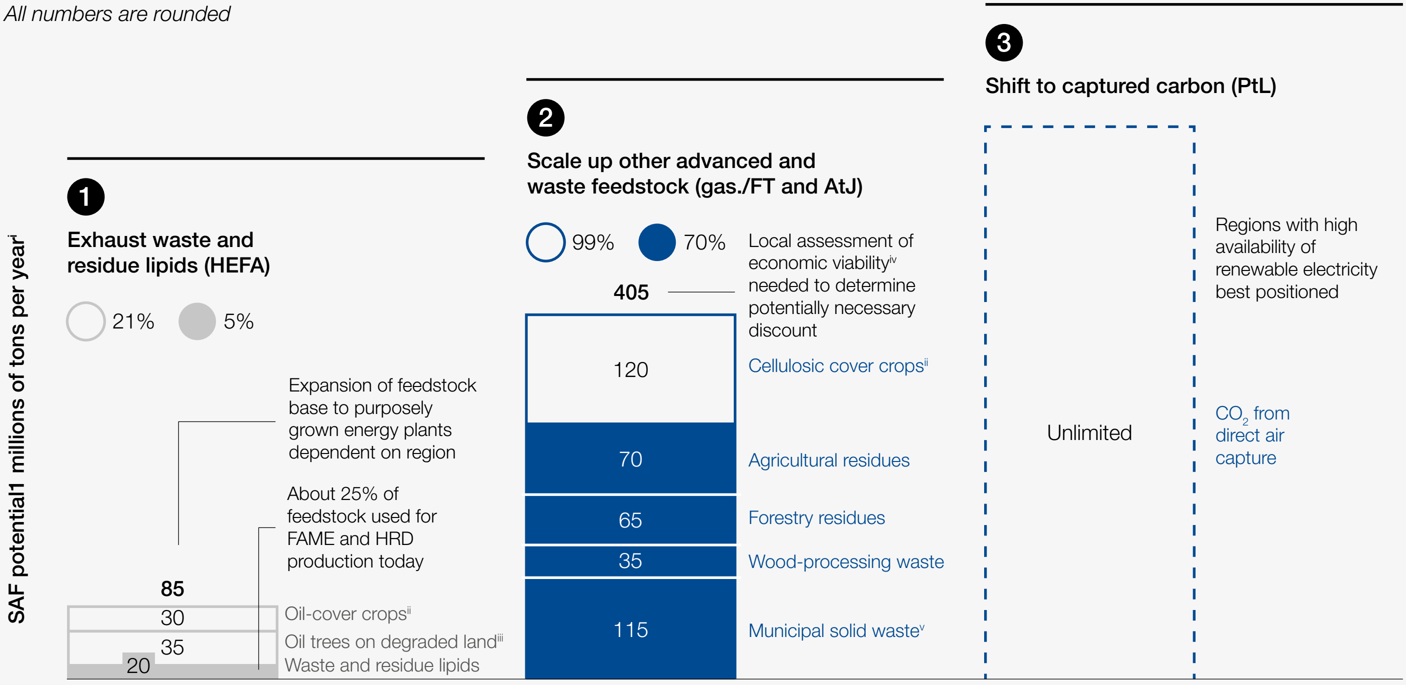
The biggest hurdle for producers focusing only on sustainable fuel production, without any conventional capacity, is supplying conventional jet fuel at a reasonable price. The next chapter takes a closer look at production costs and development over time.

FIGURE 14

There is no "silver bullet:" each region will require a different mix of feedstocks and technology

Development can occur in three main stages, beginning immediately

Excluding biofuels from first-generation/crop-based and recycled carbon feedstocks
All numbers are rounded



i. Assuming exhaustion of practically available feedstock in plants optimized for jet fuel output (HEFA at 46%, AtJ at 77%, gas./FT at 55%); **ii**. From land under non-permanent crops, assuming 5% available for oil cover crops, and 20% available for cellulosic cover crops; **iii**. Assuming 1% of degraded land used for oil trees; **iv**. Including accessibility and collection rates; **v**. Organic waste, may contain up to 20% non-reusable plastic

Source: FAOstat; USDA; ACRE solution (based on e.g. Bai et al. 2008; Gibbs et al.); Energy Insights' Global Energy Perspective, Reference Case July 2020; World Bank; Environmental Protection Agency; IRENA; E4TECH 2020; BEIS 2017; ICCT 2016; EC 142/2011; Greenea; Ecofys; Fischer Solve; Statistik der Verarbeitung Tierischer Nebenprodukte 2016; research articles; press search; expert interviews

Part 5

Managing SAF Production Costs

5.1 Overview

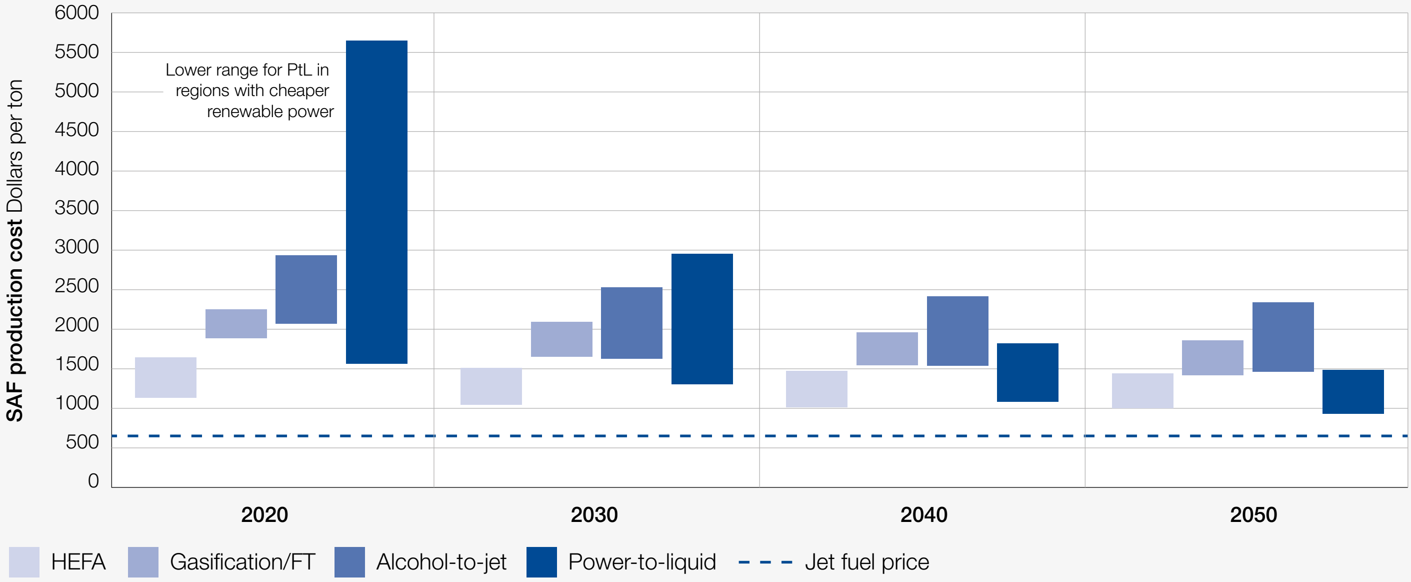
As a result of the varied components required for scaling SAF production – additional research and development, developing feedstock supply chains and building new manufacturing facilities – market costs for SAF are expected to be higher than its fossil-based competition for years to come. Strong demand signals and policy-driven actions are needed to reduce overall costs and, over time, efficiencies of scale and technology maturation will cause prices to drop significantly.

Production costs vary significantly by pathway. **HEFA-produced** SAF will remain the most cost-competitive option until other pathways reach technical and commercial maturity and scale significantly. HEFA costs are driven mainly by the costs of used (waste) oils, which are not likely to get significantly cheaper. PtL is currently far more expensive than any other considered pathway as a result of its nascent technology but is expected to become the most competitive in cost by mid-century.

PtL fuels exhibit the most uncertainty today because of the range of technologies, including reverse water-gas shift (RWGS) versus solid oxide electrolyser cell (SOEC), diverging costs of green electricity such as between Europe and the Middle East, and alternative carbon sources, including point-source capture and DAC carbon. While production costs are high today, synthetic fuels should enable significant cost reduction potential, driven mainly by lower-cost electrolysers and scale effects. The pace of cost reductions will depend on the speed of the global shift to sustainable energy production, such as green electricity and hydrogen.

FIGURE 15 **SAF production costs vary significantly by pathway**

Global SAF production cost for selected feedstocks *Indicative*



Source: Expert interviews

Gasification/FT costs are driven mainly by capital expenditure. In return, the process is highly flexible with regards to the type of feedstock used, including low-cost resources such as municipal solid waste. This flexibility results in a wide range of production costs. Over time, cost savings will rise with scale effects and significant reductions in capex requirements.

AtJ production costs depend mainly on ethanol costs, as with HEFA. While first-generation ethanol is a commoditized and mature market, the conversion of second-generation crops and residues to ethanol is immature – production costs depend on feedstock choices, scale and learning curve effects.

SAF can become commercially viable only if carbon costs rise and/or blending mandates are introduced. Like production costs, carbon costs and mandates could vary by region, but most observers expect them to increase significantly, eventually enabling a break-even between SAF and fossil jet fuel.

Supply and demand dynamics will determine the success of each pathway. In a slow scale-up scenario, HEFA feedstock could be sufficient to

power the industry until low-cost synthetic fuels become available at scale. In an accelerated scale-up scenario, demand requires all pathways to scale before all production technologies have matured and captured their full cost-reduction potential.

SAF can be transported using established infrastructure at relatively low cost – as a “drop-in” fuel, it is effectively itself JET A1. But to maximize efficiency – minimizing both transportation cost and additional transportation-related emissions – SAF should be used as close as possible to production. In regions where demand exceeds local supply, users could buy “virtual” SAF, stimulating production in regions best suited to produce it – as is currently being explored within *Clean Skies for Tomorrow*. This “book-and-claim”-type method would allow for the technologies to scale fastest in locations where they fit best, and as the emissions challenge is a global challenge, emission reductions through SAF occur regardless of their location when used.

This report’s detailed cost assessment is built on insights into more than 30 feedstock types. It provides a holistic and granular overview to help decision makers understand and approximate production costs locally and enable stakeholders to quantify the implications of SAF scale-up in different parts of the world.

FIGURE 16 **Cost drivers and reduction constraints of SAF production vary by pathway**

Pathway	**HEFA**	**Alcohol-to-jet**	**Gasification/ Fischer-Tropsch**	**Power-to-liquid**
Cost drivers	Price of feedstock accounts for majority of production cost and is market-driven based on scarceness of feedstock Cost of (green) H_2 presents the biggest opportunity for HEFA production cost improvement	Refining ethanol into jet fuel presents biggest cost bucket Both steps (ethanol production and jet production) are capex-intensive with decline potential in refining due to learning effects	Gasification-FT production cost is largely driven by capital cost	Costs for both RWGS and SOEC routes are highly driven by cost of electricity either for hydrogen production or co-electrolysis Both PtL routes are also capex-intensive and dependent on price of sustainable CO_2
Cost reduction constraints	Limited supply of feedstock and high hurdles for expanding feedstock base to purposely grown oil energy plants constrains feedstock cost reduction	Opex of refining step likely remains relatively high Ethanol production capex already realized learning rate effects, resulting in relatively little additional potential	Capex to build gasifier remains high even after an expected strong decline between 2025 and 2030	Despite steep decline, cost of green electricity remains substantial Capex for FT+RWGS and FT+SOEC have only limited reduction potential

5.2 Detailed cost breakdown by technological pathway

HEFA

FIGURE 17

HEFA production costs are driven by the cost of feedstock and the 22% decline comes mainly from declining H_2 costs

Key assumptions

Assuming even cost allocation to all by-products. Model based on OECD Europe context.

Ⓐ

Hydrogen
Solar power-based H_2 used at $7.5 and $1.90 per kilo in 2020 and 2050, respectively

Ⓑ

Feedstock
Costs can vary greatly depending on feedstock type – typically from $600 -$950 per ton. *Shown for used cooking oil at $700*

Ⓒ

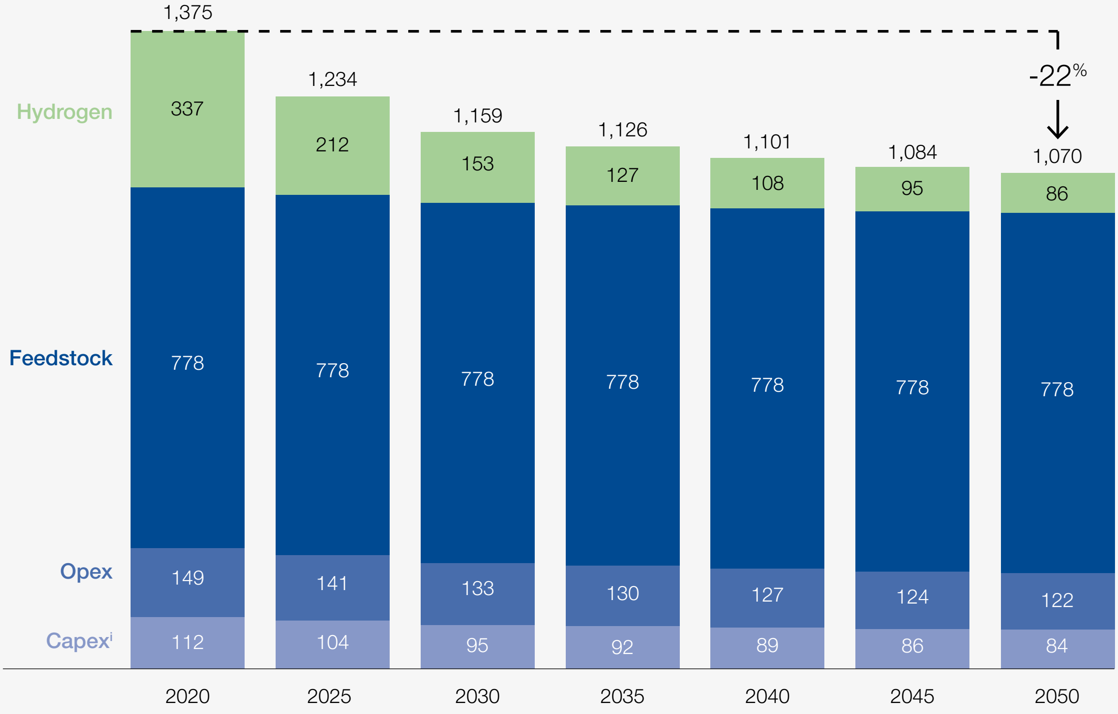
Capex
15% decline by 2030 and about 12% more by 2050

Ⓓ

Yield and jet output
Yield for total product output: 90%
Share of jet in product output: 46%[ii]

SAF production cost US Dollars per ton of jet fuel

Feedstock: Used cooking oil



	2020	2025	2030	2035	2040	2045	2050
Hydrogen	337	212	153	127	108	95	86
Feedstock	778	778	778	778	778	778	778
Opex	149	141	133	130	127	124	122
Capex[i]	112	104	95	92	89	86	84
Total	1,375	1,234	1,159	1,126	1,101	1,084	1,070

i. Greenfield; **ii**. Can go up to 70%

Source: ENERGINET, expert input

HEFA will likely remain the most efficient pathway through 2030. It is the most cost competitive since the proven technology requires relatively little capital investment – the main barrier is the cost of feedstock, a commodity with no big cost-reduction potential. Production costs depend mostly on the cost of feedstock, which today ranges from about $600 to $950 per metric ton. Including the cost of used cooking oil, solar-based hydrogen and operating and capital expenses, which should all decline in the years ahead, total production costs per metric ton of SAF could decrease from around $1,400 today to around $1,100 by 2050 in constant dollars, compared to a steady cost of fossil jet fuel of about $620. Due to falling production costs and availability of sustainable feedstock, by 2030, HEFA produced anywhere in the world could cover 100% of European jet fuel demand at less than 1,500 USD/t.

Gasification/FT

FIGURE 18

Gasification of MSW is capex intensive but has high reduction potential and low feedstock cost

Key assumptions

Assuming even cost allocation to all by-products. Model based on OECD Europe context.

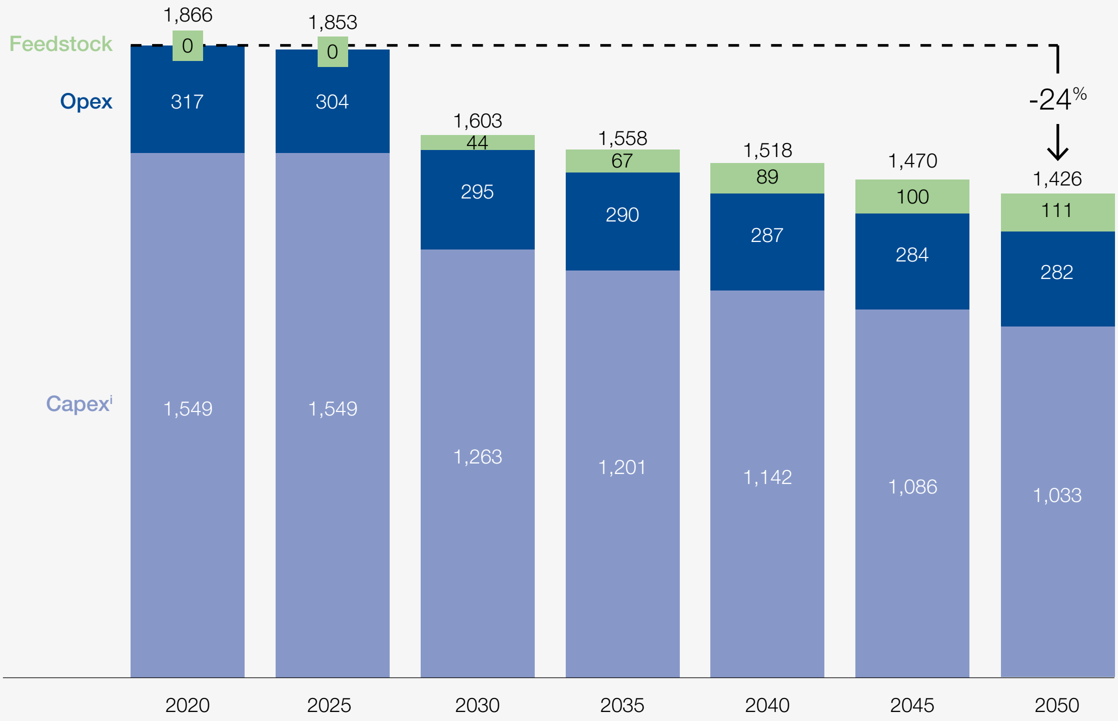
Ⓐ
Feedstock
Cost of MSW assumed to be 0 USD/t, which could change over time

Ⓑ
Capex
4% per annum decline between 2025-2030, 1% decline post 2030

Ⓒ
Yield and jet output
Yield for total product output: 20%
Share of jet in product output: 60%[ii]

SAF production cost US Dollars per ton of jet fuel

Feedstock: Municipal solid waste



i. Greenfield; **ii**. Can go up to 70%

Source: IVL report "Investment cost estimates for gasification based biofuel production systems", expert input

In this pathway today, capex represents more than 80% of production costs when using municipal solid waste as feedstock. This waste is priced at zero today, given the value associated with removing it from urban waste streams. Overall production costs per metric ton should decline from around $1,900 per metric ton today to $1,600 in 2030 and $1,400 in 2050, a 24% decline even assuming that demand for MSW rises until it has a cost.

There are significant benefits to using municipal solid waste as a feedstock. First, solid waste presents growing challenges in urban areas around the world, where land is scarce and residents are concerned that landfill may release methane, CO_2 and noxious odours into the air and pollutants into waterways and aquifers. The UK government, for example, is raising landfill taxes to £95 per metric ton (about $123 per metric ton), resulting in MSW having an effectively negative cost as a feedstock.

Second, in regions where landfill taxes are low or non-existent, especially those without the resources to control the handling or disposal of waste, MSW is generally available free of charge. Regionally specific context will invariably add additional benefits or challenges but, by and large, MSW is a readily available and low-cost feedstock.

Over time, demand may rise for MSW in fuel production and other industrial sectors, which could give it more value and raise costs, possibly in line with competing feedstocks. Steep declines in the cost of renewable power may reduce the appeal of waste-to-energy processes, however, keeping MSW prices low.

Gasification of forestry residues and other cellulosics require smaller capital investments but feedstock costs can vary from $33-$220 per metric ton depending on the region. Production costs per metric ton could fall from about $2,100 today to $1,800 in 2030 and $1,550 in 2050. Adding carbon capture to production could reduce lifecycle GHG emissions to even more than 100% – meaning a negative rate of lifecycle emissions – at a relatively low incremental cost. This process would add about 6% to the cost of fuel. In a typical plant with FT reaction, for example, removing and capturing a share of the CO_2 from syngas is already a process requirement to reduce the size and cost of the FT process step and increase yield.

Alcohol-to-jet

FIGURE 19

Alcohol-to-Jet production costs are mainly in the refining step with a 32% decline driven by ethanol opex and technology capex

Key assumptions

Assuming even cost allocation to all by-products. Model based on OECD Europe context.

Ⓐ

Feedstock
Costs can vary greatly depending on the feedstock type used – from 33 to 220 USD/t Shown for sugarcane bagasse at 33 USD/t

Ⓑ

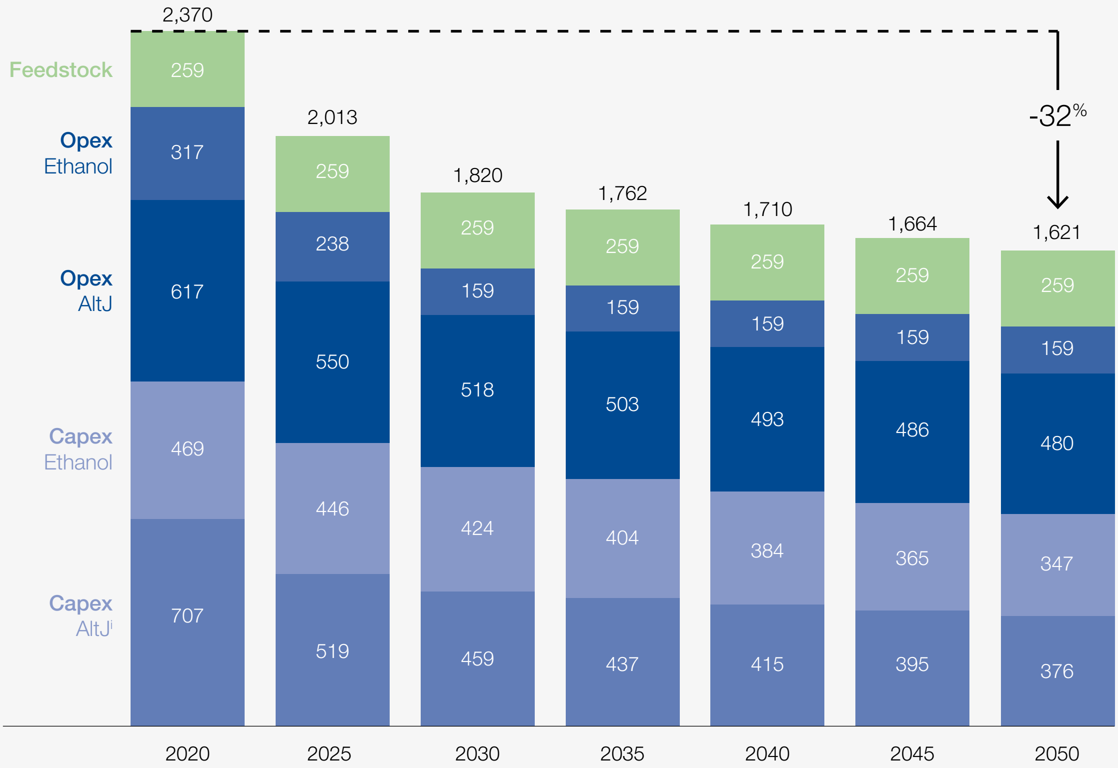
Capex
AtJ – 35% decline by 2030, later 1% per annum
Ethanol production at 1% decline per annum

Ⓒ

Yield and jet output
Yield for total product output: 13%
Share of jet in product output: 77%

SAF production cost US Dollars per ton of jet fuel

Feedstock: Sugarcane bagasse



i. Greenfield

Source: Suresh et. al. "Life cycle greenhouse gas emissions and costs of production of diesel and jet fuel from municipal solid waste“, ENERGINET, expert input

In the AtJ pathway, feedstock costs vary in the same range of $33-$220 per metric ton, driven mainly by the cost of ethanol. Ethanol production costs should fall by about 1% per year and capital expenses by about 35% until 2030 and continue to decline about 1% per year thereafter, lowering SAF production costs per metric ton from about $2,400 today to $1,800 in 2030 and $1,600 by 2050. The cheapest feedstock could be the biogenic part of municipal waste, depending on gate fees, local policies and which cover crops are the most expensive.

Power-to-liquid

FIGURE 20

Water electrolysis and RWGS PtL is driven by H_2 cost with potential of decline of close to 70% by 2050

Key assumptions

Assuming even cost allocation to all by-products. Model based on OECD Europe context.

Ⓐ
Water electrolysis + RWGS
H2 costs can vary greatly by power source and region, shown for solar power-based H2 at 7.3, 3.2 and 1.7USD/kg in 2020, 2030 and 2050 respectively

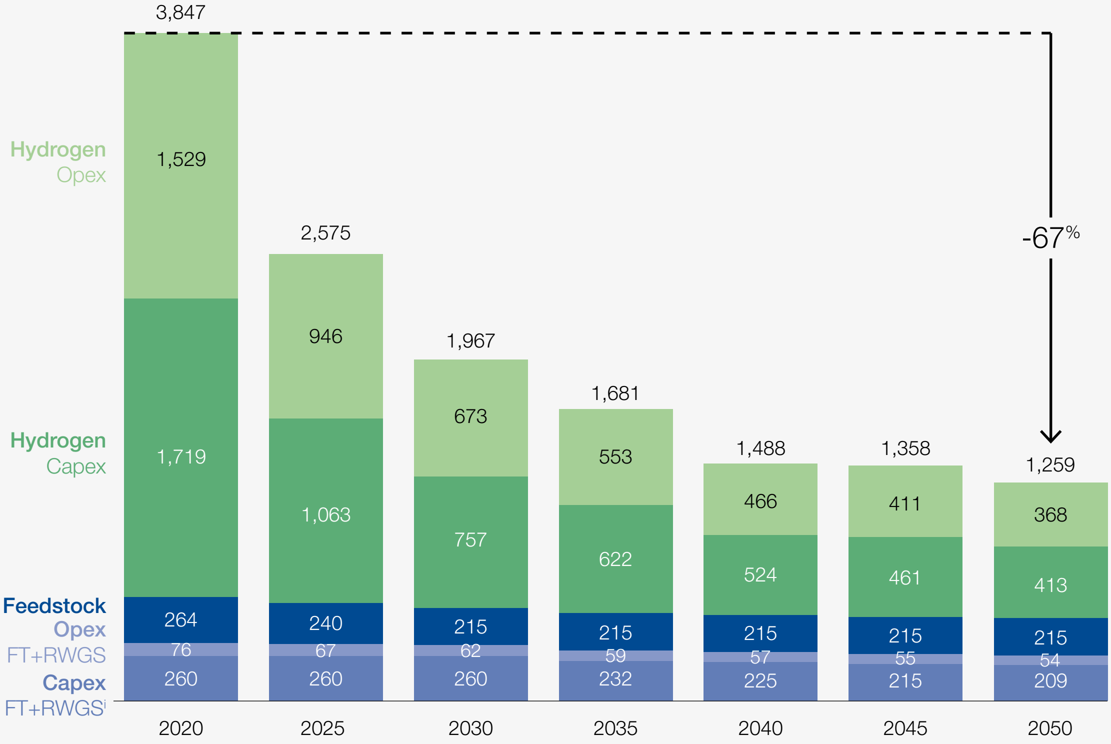
Ⓑ
Feedstock
Industrial CO2 at 81 USD/t, dropping to 66 USD/t by 2030

Ⓒ
FT & RWGS capex
1% decline per annum post-2030

Ⓓ
Yield and jet output
Yield for CO_2: 17%
Share of jet in product output: 60%[ii]

SAF production cost US Dollars per ton of jet fuel

Feedstock: Industrial CO_2, solar power-based H_2



i. Greenfield; **ii.** Can go up to 70%

Source: Energy Insights' Global Energy Perspective, expert input

In PtL pathways, operating and input factor costs represent 80%-90% of production costs today, depending on the specific production process. While reverse-water-gas-shift has very high hydrogen costs based on electricity and capex, co-electrolysis incurs comparable electricity costs directly. These costs vary greatly by power source and region but should fall significantly. The cost of a megawatt hour of solar power is likely to decline from $59 today to $33 in 2030 and $18 in 2050. Hydrogen created by solar power costs $7.30 per kilo today but could fall to $3.20 by 2030 and $1.70 by 2050.

Likewise, industrial CO_2 feedstock needed for all PtL routes now costs about $80 per metric ton but the price could drop to around $65 by 2030. Given these declines in processing and feedstock costs, SAF production expenses in these pathways should fall from more than $3,800 per metric ton today to under $2,000 by 2030 and just $1,300 by 2050.

Conclusion

❝ Even in the current deep industry crisis due to COVID-19, we will not lose sight of the challenge that climate change poses and remain fully committed to our KLM Fly Responsibly initiative and sustainability ambitions.

Pieter Elbers, CEO, KLM Royal Dutch Airlines

Producing sustainable aviation fuel will almost certainly continue to be more expensive than refining fossil jet fuel, but the costs of exceeding the 1.5 or 2.0-degree targets of the Paris Agreement are incalculably greater.

Stakeholders across the aviation fuel value chain agree that SAF are a critical component in the industry's pathway to decarbonization. Similarly, it is widely understood that if the industry wishes to undertake an energy transition, it will require several levers to activate today and in concert for the ecosystem to achieve the scale required to have a lasting and meaningful impact. Making such an industry-wide transition to SAF presents significant yet surmountable challenges.

This report builds a foundational fact base on which global stakeholders can begin to make important decisions on investments, regulatory measures and long-term targets. The transition will require coordinated efforts and a level-playing field for carriers, both of which require sharing of accurate and consistent information. There is no “silver bullet” overarching approach for aviation's decarbonization, but SAF is a necessary asset in the transition. With international certification standards for sustainability, lifecycle emissions reductions, and technical compatibility, every region will be able to develop its own appropriate mix of feedstock and technology pathways.

Through the CST project, the Forum and its partners are supporting aviation's industry transition to climate neutrality. Based on inputs such as this report, the CST coalition and the industry as a whole are developing interventions that will incentivize leaders to act in three key areas.

First, supportive public policies are necessary to inspire swift action. Global deployment at scale requires policy interventions to trigger learning curve effects and economies of scale that would not only drive uptake but also deliver economic benefits to the industry and beyond. A level-playing field is critical due to aviation's global nature and policy-makers must collaborate to design an effective and harmonized system. Decisions will be in many cases regionally determined on respective feedstock availability and technology pathways decisions, but SAF's overall technical compatibility will enable these customizations. A basket of policy and regulatory measures will be necessary to incentivize investment in new technologies and plants. Industry and governments must align on acceptable policy tools to lock in strict sustainability criteria and ensure that SAF development is not counter-productive via negative impacts on land use or other environmental considerations.

Second, a scalable SAF marketplace will drive a strong demand signal. Evidence suggests that corporate flyers are willing to pay a premium for more environmentally-friendly transportation and, specifically, use of SAF in air travel – translating into a significant SAF blend. While this is influenced by feedstock availability and technology pathways, a scalable SAF marketplace could provide consumers with an easily accessible SAF purchase. Incorporating independently validated sustainability metrics and an environmental benefit unit of trade with transferable ownership could further drive uptake. This would enable the industry to directly reduce lifecycle emissions as an alternative to offsetting schemes.

Third, a financing blueprint for the energy transition will enable a rapid evolution. Given the cost differential of SAF, the transition will rely on the creativity and commitment of the financing industry. Together with the aviation industry, investors and lenders must design a blueprint for financing the transition that may include lending guidelines, investment principles, and R&D, project, and both equity and debt finance. This will help forge global collaboration among stakeholders to provide transition financing, mobilize capital and reduce the risks of investment.

Collectively, such a transformation cannot be undertaken by individual organizations or even the aviation sector alone. In order that the vast societal and economic benefits the aviation industry provides continue to be available and for the world to meet its stated climate goals, public and private sector leaders throughout the aviation value chain must collaborate.

The *Clean Skies for Tomorrow* coalition provides a community platform to accelerate these efforts for truly sustainable aviation future and, more broadly, a clean, safe, and inclusive mobility future.

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