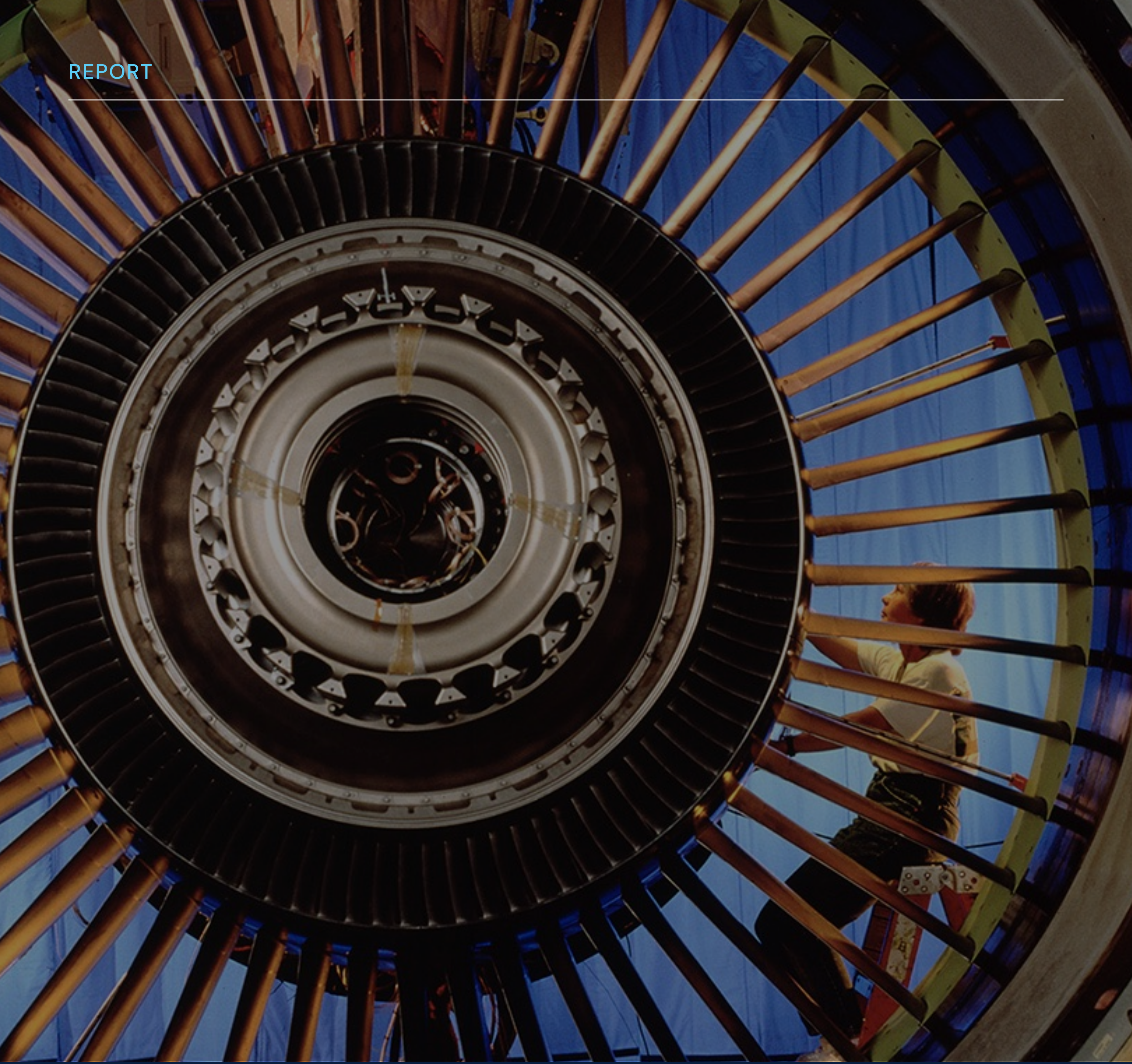
REPORT



Fueling Net Zero

How the aviation industry can deploy sufficient sustainable aviation fuel to meet climate ambitions

WAYPOINT2050
AN AIR TRANSPORT ACTION GROUP PROJECT

An ICF Report for ATAG Waypoint 2050

September 2021

ATAG AIR TRANSPORT ACTION GROUP

ICF

Contents

Summary of key findings

- The second edition of Waypoint 2050 estimates that 330–445 million tonnes of sustainable aviation fuels (SAF), alongside technological and operational improvements, will be required for the global aviation industry to achieve net-zero carbon emissions by 2050. This report investigates the roadmap to deploy sufficient SAF capacity, evaluates the feedstocks and technologies required and estimates the necessary investment and the cost to airlines.
- Aviation will be able to access bioenergy sufficient for 41%-55% of the total SAF required. While 30-110 exajoules (EJ) of sustainable bioenergy is available per year, multiple sectors will compete for its use. As a particularly hard-to-abate sector, aviation should be prioritized but should not expect exclusivity, and this study estimates that aviation will be able to access 20 EJ, sufficient for at least 180 million tonnes of SAF production per year.
- Renewable electricity can be used to produce SAF through the Power-to-Liquids approach. This approach uses hydrogen from electrolysis and carbon captured from the atmosphere as feedstock and is therefore not limited by bioenergy availability. While expensive today, developments across renewable power generation, hydrogen production, and direct air capture will reduce costs. Industrial waste gases can serve as a transitionary feedstock to accelerate deployment.
- Most production is likely to use the Alcohol-to-Jet (AtJ) and Fischer-Tropsch (FT) pathways. While almost all production today uses the HEFA pathway, feedstock constraints will limit this to 6%-8% of required capacity. The first commercial FT and AtJ facilities are expected to start production in 2021 and 2022 respectively, building the foundations for the industry to scale production.
- Rapid technology developments will reduce the price premium for SAF. By 2050, the average cost is estimated at $760-$900 per tonne SAF. This is well within the historical cost range of fossil fuels, although slightly higher than the historical average.
- Improvements in supply chains, production processes and installation of carbon capture and sequestration (CCS) will increase the carbon reduction achieved by the SAF. This analysis has limited fuels to net-zero carbon, but this may prove conservative with designs in-process to offer carbon-negative fuels. SAF also provides non-CO_2 climate benefits, such as reduced Sulfur dioxide and particle emissions. Greater carbon reduction and consideration of these non-CO_2 benefits will further support the value of SAF compared to fossil fuels.
- The industry will require 5,000 – 7,000 renewable fuel refineries by 2050. These will typically be built close to the feedstock supply, with an average capacity of ~32 million gallons (100,000 tonnes/pa), equivalent to just 0.001% the size of current oil and gas refineries. While over 90% of oil and gas production is located in just 22 countries, the SAF industry will need to leverage feedstocks across almost every country, improving energy security, independence, and resilience for many nations.
- Building this infrastructure will require 1,080 – 1,450 billion US dollars. Per year, this represents ~6% of the historical annual oil and gas capital expenditure. The level of investment will be increasingly achievable as additional specialized producers enter the market, fossil infrastructure is increasingly available for retrofitting and investors look to decarbonize portfolios.
- This investment will create or sustain an estimated 13.7 million jobs. Investments in bioenergy are highly effective at job creation, with 23 people employed today for every $1m invested in bioenergy over the last decade, compared to just 2.7 jobs per $1m invested for solar investments and 1.1 for wind power.

A pathway for global SAF deployment

In just 100 years, the aviation industry developed from the first powered flight to a global network connecting over 1.5 billion people. Passenger numbers continued to climb as tickets became ever more affordable, and by 2019 over 4.5 billion people boarded aircraft to visit friends and family, explore distant countries, and conduct international business.

Rapid technology development has been crucial to this growth. Aircraft have become quieter and remarkably more efficient, with the CO_2 emissions per passenger-kilometer reducing by more than half since 2000. The average aircraft passenger in Europe now emits less CO_2 for a kilometer traveled than the average car passenger[1].

In the continued pursuit of lower costs and reduced carbon emissions, the industry is increasingly turning to more exotic opportunities. Billions of dollars have been invested in electric, hydrogen and hybrid propulsion systems, innovative turbojet architectures are in development, and radical aerodynamic improvements such as blended bodies and strut-braced wings are increasingly discussed as the next step. Operational improvements will enable smoother, more efficient flights and ground operations, and increased load factors will continue to drive down emissions per passenger.

Electric and hydrogen propulsion systems will initially be deployed on smaller aircraft flying short routes. As the technologies improve, their range and power could increase, and by 2050 scenarios 3 of the W2050 analysis expects hydrogen, electric or hybrid propulsion to be deployed on aircraft up to 150 seats, operating flights less than 120 minutes. These routes represent 27% of current industry CO_2 emissions[1], with the remaining 73% of emissions from larger aircraft flying medium and long-haul routes.

Sustainable Aviation Fuels (SAF) offer a potential solution for these routes, and a complement to hydrogen and electric technologies on shorter flights. The low weight and volume required to store energy as kerosene make SAF ideal for the rigors of flight, particularly over longer distances where the reduction in weight as fuel is consumed becomes an important factor. As a drop-in fuel, SAF can also be used with minimal change to the infrastructure and aircraft used today, allowing use as an interim solution while electric and clean hydrogen powertrains are developed, tested and deployed, and while the ground infrastructure is built out.

In 2020, just 50,000 tonnes of SAF were used by the aviation industry, representing less than 0.1% of total fuel consumption. Rapidly increasing production of SAF will be essential to the continued decarbonization of aviation and the immediate requirements to build infrastructure, develop commercial partnerships and establish processes are clear. The long-term requirements are more complex, driven by the growth of the industry, the level of climate ambition, and the expectations around alternative clean technologies.

The Waypoint 2050 analysis provides a central estimate of 3.1% compound annual growth rate from 2019 to 2050 – representing over 10 billion passengers by 2050, flying a distance of more than 22 trillion Revenue Passenger Kilometers. If the aviation industry continued to operate the same fleet as today, in the same manner as today, this level of activity would consume over 620 million tonnes of kerosene and emit ~2,000 million tonnes of CO_2 every year.

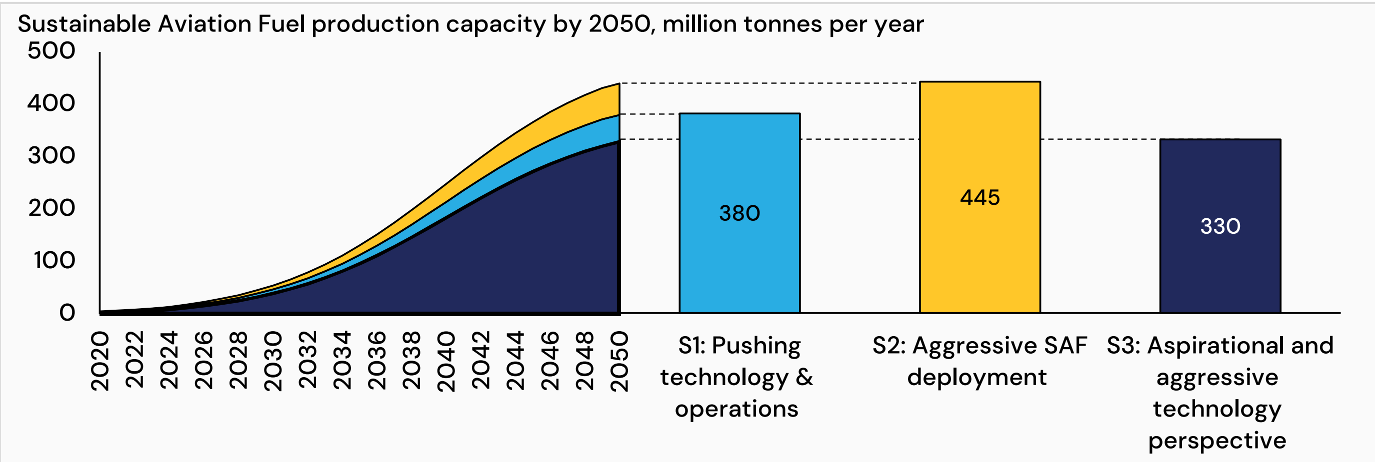
[1] https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/

In 2009, the aviation industry became one of the first global sectors to establish a comprehensive climate ambition. Since then, focus and efforts have continued to intensify, and this report's analysis is based on an ambition of net-zero emissions globally by 2050. This is aligned with the 1.5°C stretch goal of the Paris Agreement, which the Intergovernmental Panel on Climate Change has identified is needed to avoid some of the worst impacts of climate change.

The aviation industry will need to leverage every possible advantage to achieve this, including developing aircraft technologies, improving operations, and increasing SAF use. Delivering on the ambition will require a departure from the historical trends, and consequently there is considerable uncertainty in the possible contribution from each approach. This analysis considers this uncertainty across the same three scenarios as the Waypoint 2050 report, each considering a different future:

- Scenario 1: Pushing technology and operations
- Scenario 2: Aggressive Sustainable Fuel development
- Scenario 3: Aspirational and aggressive technology perspective

Three scenarios are investigated for achieving net zero by 2050



Source: Waypoint 2050, Assuming ERF increasing from 70% to 100% by 2050, 90% of fuel replacement by SAF by 2050

These scenarios provide a range of sustainable fuel volumes required to meet the aviation industry's climate ambitions, given the expected level of growth. The first scenario, pushing technology and operations, represents an ambitious increase in aircraft efficiency, use of alternate propulsion and operational improvements, supported by the use of 380 MT of SAF by 2050. In the second scenario, the deployment of SAF is prioritized over alternate propulsion systems, resulting in a requirement for 445 MT SAF by 2050 – the highest of all three scenarios. The third scenario considers aspirational development of alternative propulsion technologies coupled with their aggressive deployment, greatly reducing the requirement for sustainable fuels to just 330 MT SAF by 2050.

Achieving these volumes of SAF is ambitious but possible. Pioneering efforts have built a solid foundation for the SAF industry. Over 365,000 flights powered by SAF have proved their safety and operational feasibility. Some airports already offer SAF on an ongoing basis, demonstrating their use as drop-in fuels that can use existing infrastructure. Seven different technology pathways have achieved regulatory approval through the American Society of Testing and Materials (ASTM), allowing future production to use a wide range of feedstocks, from used cooking oil to agricultural residues, municipal solid waste, and renewable electricity.

The first of these pathways has already been commercialized, converting waste lipids (like used cooking oils and waste fats) into SAF through the Hydroprocessed Esters and Fatty Acids (HEFA) pathway. Considerable infrastructure is already under construction to scale this pathway, particularly in the United States, where federal and state regulations provide strong incentives. This pathway is attractive due to the ease of converting the feedstocks into fuels and proven technologies. However, there are limited volumes of these feedstock available and continued scaling of the SAF industry will need to draw on a greater variety of feedstocks and pathways.

Pioneering organizations have been working for years to commercialize other production pathways, and the first of these facilities is nearing commercial service. In July 2021, Fulcrum announced the completion of construction at its Sierra facility, which aims to produce SAF from municipal waste as early as the end of this year using the Fischer-Tropsch (FT) production pathway[2]. LanzaJet is building a facility in Freedom Pines[3] to convert alcohol to SAF using the Alcohol-to-Jet (AtJ) pathway, with a target set to come online in 2022. Other leading companies are developing facilities and technologies that will revolutionize SAF production. These are expected to greatly increase the feedstocks that can be used and reduce the cost of SAF, allowing the industry to scale in earnest.

There is a great deal of biological feedstock available that these pathways can use, and these production pathways will not be limited by feedstock availability for several decades. However, the long-term climate targets of the aviation industry are ambitious, and as the SAF production capacity increases to several hundred million tonnes each year, even these pathways will be increasingly constrained by the availability of sustainable feedstock supply. This is compounded by competing uses for these feedstocks, such as use as materials for construction or bioplastics, and by other industries seeking low-carbon sources of energy. While the difficulty of decarbonizing aviation favors the industry as a key sector for these feedstocks, it will not be their sole consumer.

The increasing availability and reducing cost of renewable electricity will support the transition from the biological feedstocks to the use of low carbon electricity as the primary feedstock, alleviating the constraints on bio-feedstock availability. In this approach, called Power-to-Liquids (PtL), hydrogen and carbon monoxide are produced with renewable electricity and used as the feedstock for SAF production. Their conversion into SAF uses the same technologies as bio-feedstocks (such as FT and AtJ), allowing the PtL approach to leverage the cost reductions developed as these production pathways scale using the bio-feedstocks.

While the most visible development will be the progression through feedstocks – from the waste and residue lipids today to the wide range of bio-feedstocks and ultimately to PtL – each pathway will also be incrementally improved, reducing costs and further reducing the emissions produced.

The HEFA facilities will see continued cost reductions as additional infrastructure is built, particularly as fossil fuel facilities are adapted to produce renewable fuels and the production process is further optimized

[2] https://fulcrum-bioenergy.com/wp-content/uploads/2021/07/2021-07-06-Sierra-Construction-Completion-Press-Release-FINAL.pdf
[3] https://www.lanzajet.com/where-we-operate/

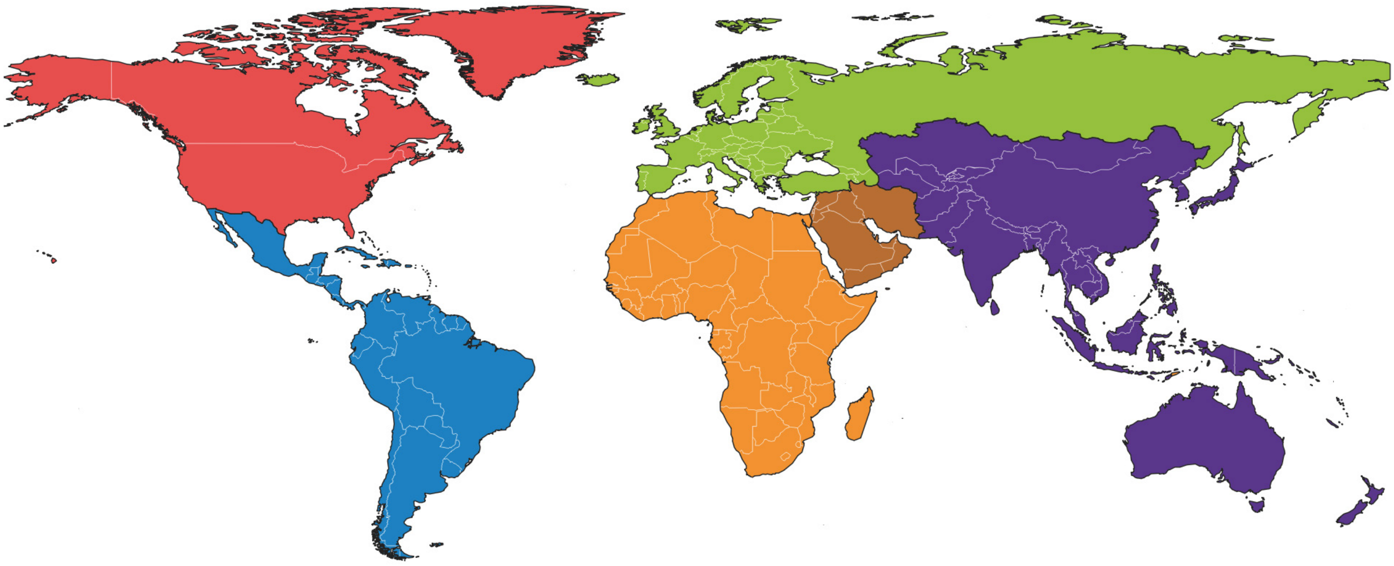
These improvements will be incremental however, with much of the technology already mature and well proven. By contrast, the AtJ and FT facilities under construction today are first-of-a-kind plants, and their future cost of production will decrease rapidly as the lessons learned are incorporated into future designs. This will be complemented by improving operations for feedstock acquisition, transportation and processing, and improvements across the supporting activities. PtL production is costly today, and only proven on a limited scale by PtL leaders such as Sunfire[4] and Shell[5]. Developments across a range of industries, including continued expansion and cost reductions for renewable electricity, improvements to electrolysis technology for hydrogen production and cheaper carbon capture from Carbon Engineering[6] and Climeworks[7], will all contribute to reducing the cost for the future requirement from PtL.

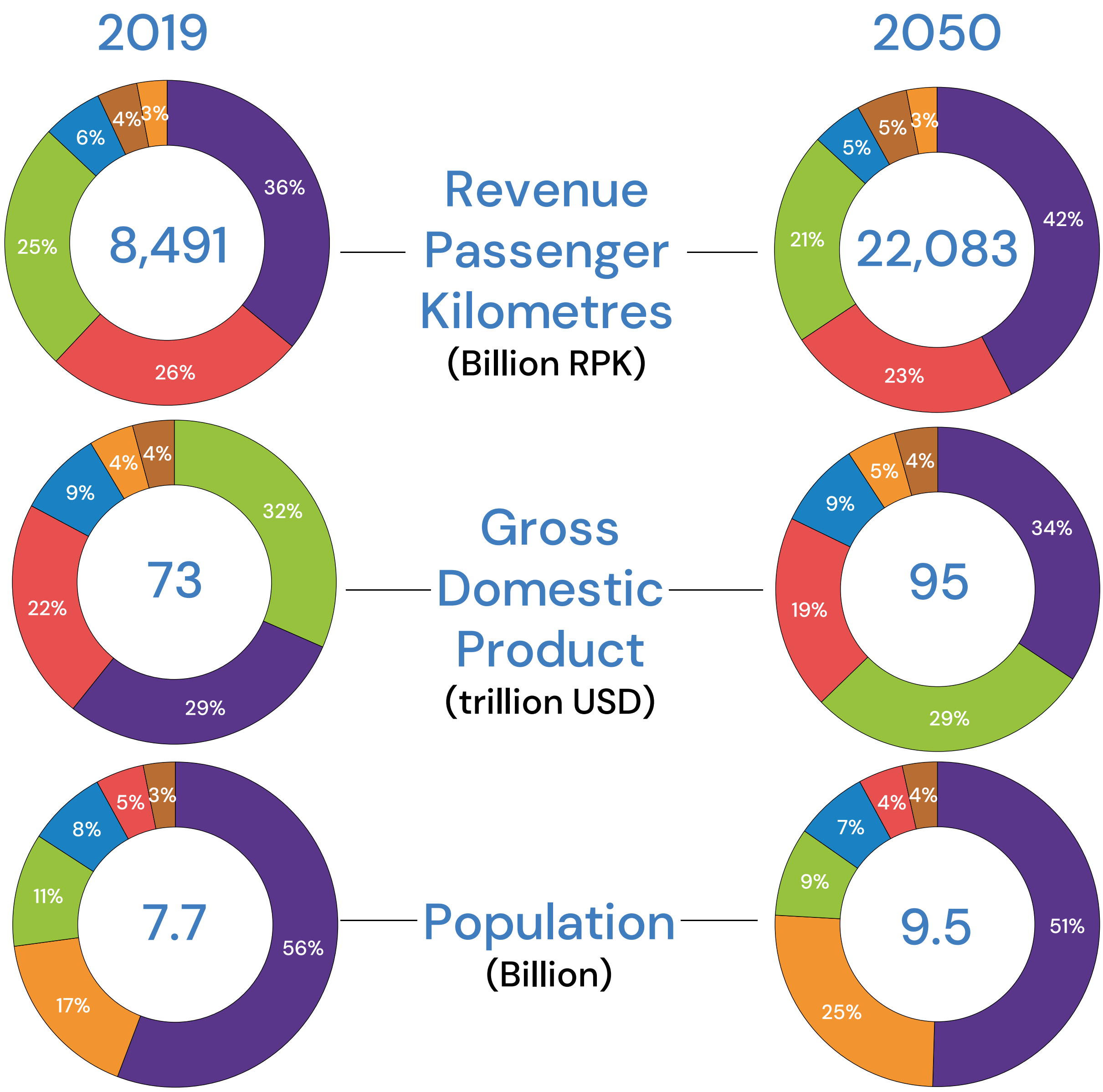
As advanced technologies and SAF are deployed it will be increasingly necessary to consider emissions on a full life cycle (well-to-wake) principle. This ensures all emissions during the production, transport and consumption of fuels are counted, providing a fair comparison between technologies. For example, the emissions for electric and hydrogen aircraft should consider any emissions created during the generation of the electricity and hydrogen consumed. This is particularly important for SAF, which can be manufactured from a wide range of feedstocks, such as waste lipids, agricultural and forestry residues, and renewable electricity. The emission reduction for SAF is seen over this full life cycle, with carbon absorbed during the growth of the feedstocks, offsetting the carbon emitted when the fuels are combusted. For example, when agricultural residues are used as feedstock, the carbon utilized has recently been extracted from the atmosphere as the plants grow, and the release of the same carbon during combustion adds little additional carbon to the atmosphere. Therefore, the carbon used for SAF is already in active circulation while for fossil fuels the embodied carbon has been sequestered underground for thousands or millions of years, and the entire carbon emitted during combustion is additional to the atmosphere.

Measured across the life cycle, each feedstock and pathway provides a different reduction in carbon emissions. Individual producers can use a range of approaches, such as use of renewable electricity, low-carbon hydrogen (where required) and operational efficiencies, to further increase the environmental benefits. The use of carbon capture and sequestration (CCS) can further increase the carbon reduction, and the current SBTi guidance[8] is to include the CCS benefits associated with fuel production when establishing targets. This analysis limits the carbon reduction to 100% (carbon neutrality), but this may transpire to be a conservative assumption, with several producers already planning facilities that can produce carbon-negative fuels. SAF also provides benefits beyond the CO_2 reduction, with reduced particulate, sulfur oxides and nitrogen oxide, and possibly reduced contrail formation[9]. As the warming effect and the benefits of these reductions are better understood, the value of SAF will be further confirmed.

[4] https://www.sunfire.de/en/home
[5] https://www.bloomberg.com/news/articles/2021-02-08/klm-makes-first-regular-flight-with-sustainable-synthetic-fuel
[6] https://carbonengineering.com/
[7] https://climeworks.com/
[8] https://sciencebasedtargets.org/sectors/aviation
[9] https://www.euractiv.com/section/aviation/opinion/the-benefits-of-sustainable-aviation-fuel-go-beyond-co%E2%82%82/

Regional definitions and statistics, aligned to ATAG Aviation: Benefits Beyond Borders





How many facilities will be required?

The transition from fossil fuels to sustainable production will represent a radical change for the jet fuel industry. While current production is centralized in huge refineries, most SAF production will be distributed to collocate facilities with feedstock supply. The facilities will be small – this analysis estimates the average SAF facility will be just 0.001% the size of current oil and gas refineries. This mirrors the electrical transition from centralized fossil fuel plants to distributed wind, solar and hydro installations.

5,000 – 7,000 renewable fuel refineries will be required by 2050 to meet the climate ambitions of the aviation industry

The necessary range of feedstocks and technologies will result in a diverse industry. The facilities using high energy density feedstocks, such as waste lipids, will be able to economically consolidate feedstock across broad, potentially international catchment areas, allowing the construction of large facilities that can leverage economies of scale. However, the limited availability of HEFA feedstocks will constrain these facilities to just 6-8% of total SAF production. By contrast, facilities using low energy density feedstocks, such as agricultural residues or municipal waste will be most economical when close to their feedstock supply.

This will drive a divergence in SAF facility size, with the HEFA facilities producing 100 million gallons per year (0.31 MT/pa) of fuels[10], while smaller AtJ and FT facilities are built to match the local feedstock availability and produce 20-60 million gallons per year (0.1 – 0.2 MT/pa).

Each sustainable fuel facility will produce renewable syncrude, which must be processed into a range of products such as SAF, renewable diesel, and light ends. The product slate for each will require careful selection, considering the technology, yield and market for each product. In this analysis, it has been assumed that the product slate is optimized for a blend in the early years with an increasing focus on SAF as other consumers turn to electric vehicles.

This results in an average capacity per facility of ~32 million gallons (100,000 tonnes/pa), producing 22 million gallons of SAF (65,000 tonnes/pa). These are substantially smaller than fossil refineries: for example, the average oil and gas refinery in North America[11][12] in 2021 had a capacity of 2,142 billion gallons per year, nearly 67,000 times larger than the average expected sustainable fuel facility. These fossil fuel plants have grown to such size in order to leverage the considerable economies of scale during the refining process and transport logistics, while the sustainable fuels plants will be tailored to highly variable feedstocks that are costly to transport. Renewable fuel plants also require greater volumes of feedstock for a given level of production – while in conventional refineries the weight of fuels produced is close to the weight of crude input (and actually higher in volume due to processing gain), the mass yield for renewable fuels is far lower: from 90% when converting lipids to fuels to 20% for MSW[13]. Consequently, up to 5 tonnes of feedstock may be required for every tonne of fuels produced, increasing the importance of the feedstock logistics and cost.

[10] There will be significant variance around this: some facilities will be far larger
[11] https://www.eia.gov/petroleum/refinerycapacity/
[12] https://www.oilsandsmagazine.com/projects/canadian-refineries#canadian-refineries
[13] Depending on the composition of the waste

Table 1: Required number of facilities, globally and by region

	Scenario	**Global**	Africa	Asia & Pacific	Europe	Latin America & Caribbean	Middle East	North America
1	Pushing Technology and operations	**5,904**	410	2,270	1,256	726	217	1,025
2	Aggressive SAF deployment	**7,026**	464	2,661	1,525	843	279	1,254
3	Aspirational & aggressive technology perspective	**4,964**	355	1,940	1,027	623	172	847

The distribution of facilities has been calculated to minimize the production costs, considering the regional availability of feedstocks and renewable power. The actual development of infrastructure is likely to vary due to the pattern of demand, regulations, and market for intermediaries.

This analysis assumes global demand and regional production, supported by the development of a book-and-claim mechanism. This aims to separate the market for the environmental attributes from the physical fuel, allowing the demand for SAF to be digitally matched to the availability, reducing the need to transport the physical fuel. Combined with distributed production, the SAF industry is expected to reduce the cost and environmental impact of transporting fuels. As SAF becomes a larger share of the fuel pool the distributed production should have an increasing benefit, although some fuel may need to be transported to match the demand and supply profiles.

Regulations such as incentives and carbon expenses are instrumental to the development of the SAF market. The current patchwork of regulation creates a fragmented market, with both the high-value HEFA feedstocks and finished SAF transported internationally. Strong incentives may result in a higher share of facilities in some regions, particularly for HEFA, which represents ~163 facilities and 6-8% of production.

It may prove economical to develop a hub-and-spoke model, allowing distributed conversion of feedstocks into higher-value intermediary products, which can then be refined at centralized facilities. For example, feedstocks could be converted to alcohols locally, and then transported to centralized AtJ facilities for processing into fuels. Similarly, the development of hydrogen infrastructure may allow distributed production of hydrogen and centralized production for the PtL approach.

How much will this cost?

Building the required facilities will require meaningful investment. ICF's analysis estimates that an investment of 1,080 – 1,450 billion USD will be necessary to build sufficient SAF capacity, equivalent to ~12 USD per gallon capacity (~3,900 $/tonne). This represents ~ 6% of historical annual fossil investments, with the average historical capital expenditure across the global oil and gas industry estimated at ~$770 billion per year[14]. Leaning into the transition, BP and Total have pledged to invest over 15% of their total capital budget for transition investments (including renewables alongside biofuels), and this investment will be bolstered by the considerable additional capital flowing into the emerging producers leveraging niche expertise with biofuel production technologies.

1,080 – 1,450 billion US dollars will be required to build the required infrastructure, which over 29 years is ~ 6% of the historical annual oil and gas capital expenditure

Each of these facilities will produce and monetize fuels and co-products additional to SAF, so revenues from aviation will only support a portion of this investment. The financial profile varies by pathway, with HEFA facilities requiring comparatively lower capital investment but greater feedstock costs, while the FT and AtJ facilities are more complex but use cheaper feedstocks, resulting in a higher capital cost but lower ongoing expenses to acquire feedstock. All pathways will achieve cost reductions as the technologies mature, reducing the investment required for a given unit of capacity.

The opportunity to repurpose obsolete or stranded assets could further reduce the investment required. The collapse in oil demand during the pandemic resulted in a record ~138 bn gpy (420 MT) in spare capacity, compounded by a build-up in excess capacity over prior years. The demand gap, uncertainty in the recovery and growing recognition of the climate emergency have led to announced shutdowns of 55 bn gpy (168 MT), and the IEA forecast[15] that an additional 37 bn gpy (112 MT) will need to close by 2026 for utilization rates to recover. 14% of this capacity is already at various planning stages for conversion to bio-refineries, and conversion of the remaining announced or potential shutdown capacity represents a significant opportunity to reduce the required capital costs. Over the long-term, other industries could be leveraged as their current focus markets contract, such as the 15 bn gpy ethanol industry in the US.

Table 2: Total infrastructure investment required (billion USD)

	Scenario	**Global**	Africa	Asia & Pacific	Europe	Latin America & Caribbean	Middle East	North America
1	Pushing Technology and operations	**1,248**	90	481	259	161	44	212
2	Aggressive SAF deployment	**1,450**	101	554	306	183	55	252
3	Aspirational & aggressive technology perspective	**1,079**	80	421	219	142	36	180

[14] IEA records average upstream spending as $770 bn over 2014-2019 in Oil 2021. Total capital investment extrapolated assuming upstream spending is 70% of total.

[15] https://www.iea.org/reports/oil-2021

This investment will provide benefits beyond decarbonization. Investments in bioenergy are highly effective in creating jobs, with labor required to gather, process and transport feedstock, to design, construct and operate facilities, and to support the wider supply chain. Between 2010-2019, $151 bn was invested in bioenergy and biofuel capacity[16], and in 2020 the sector employed 3.58 million people[17] – suggesting over 23 jobs are created for every $1m invested in capacity. This compares to just 2.7 jobs per $1m invested for solar investments and 1.1 for wind power.

23 people are employed today for every $1m invested in bioenergy over the last decade – 12x greater than wind and solar investments

The distributed nature of this production will also benefit regional energy independence and resilience. The oil and gas industry is concentrated in relatively few countries, with 50% of production capacity in 5 countries and over 90% in just 22 countries. By contrast, SAF production draws on widely distributed feedstocks, enabling many countries to improve their national energy security, independence, and resilience.

The cost premium for airlines is more complex, driven by the cost of production, market impacts and regulation. This analysis estimates the premium as the cost of production, minus the value of the environmental benefits, allowing comparison with fossil fuels on an equivalent basis. The cost of production has been estimated through a detailed cash flow model for each feedstock and pathway, including the facility and feedstock costs, debt payment, equity margin, and the value of the co-products. The environmental benefits have been estimated using the value of the carbon reduction only, with carbon values escalating from $100/tCO$_2$ in 2030 to $200/tCO$_2$ by 2050. This is likely a conservative estimate, with greater carbon reductions possible through increased deployment of CCS during SAF production, potential for higher carbon values, and consideration of the value of the non-CO$_2$ climate benefits of SAF.

Table 3: SAF Premium in 2050 above fossil fuel price, including the value of the carbon reduction (USD/tonne)

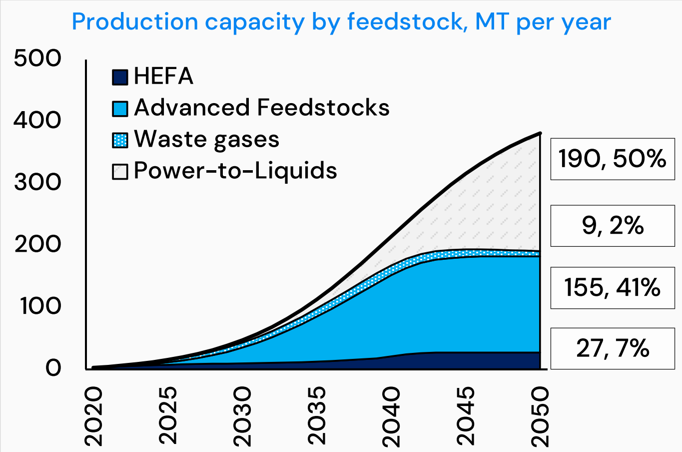
Fossil fuel price	(1) Pushing Technology and operations	(2) Aggressive SAF deployment	(3) Aspirational & aggressive technology perspective
$140 / bbl ($1,106/t)	-256 (-23%)	-206 (-19%)	-346 (-31%)
$65 / bbl ($513/t)	337 (66%)	387 (75%)	247 (48%)

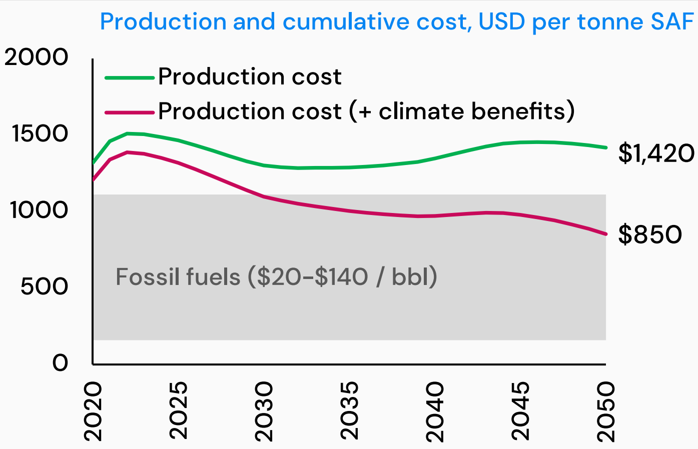
Fossil fuels have peaked above $140 per barrel several times over the past twenty years, and in all scenarios the cost of SAF falls below this high-water mark by 2050. However, there is still a meaningful premium when compared to fossil fuel at a more typical value of $65/bbl. The comparatively high cost of SAF is driven by a high share of PtL production, and a subsequent sensitivity analysis section shows the considerable cost reduction if a higher share of bio-feedstock if available.

[16] https://www.fs-unep-centre.org/global-trends-in-renewable-energy-investment-2020/
[17] https://www.irena.org/-/media/files/IRENA/Agency/Publication/2020/Sep/IRENA_RE_Jobs_2020.pdf

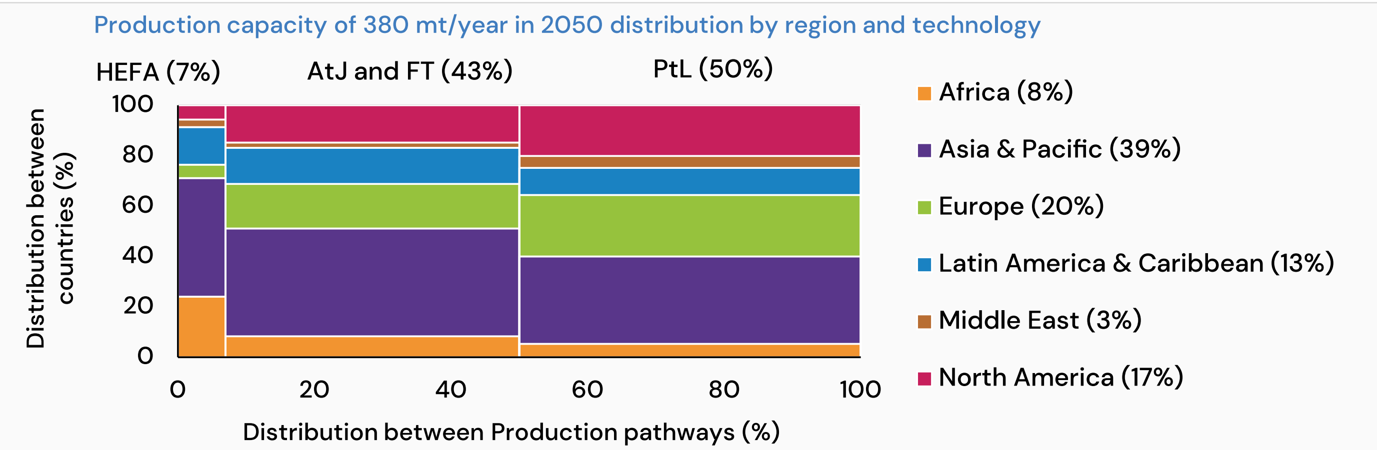
S1: Pushing technology and operations

Significant improvements in technology, operations, and infrastructure drive substantial emission reductions. The shift to hybrid & electric aircraft accelerates from 2035, but full fleet replacement is not achieved by 2050. Replacing 90% of fuel consumption requires 380m tonnes of SAF production per year.





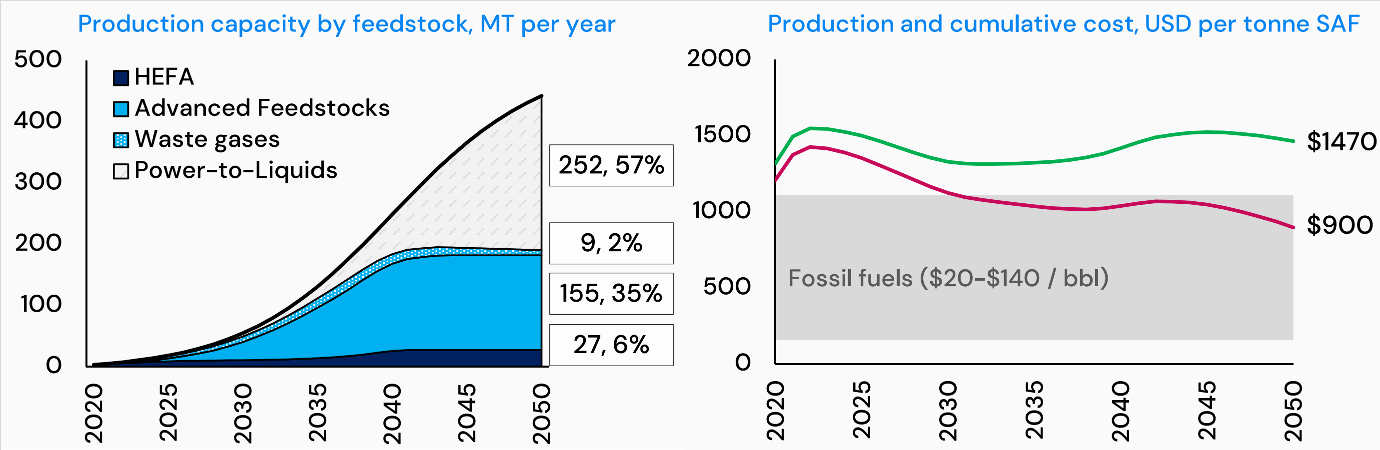
Slightly under half of 2050 capacity is delivered using bio-feedstocks, such as agricultural, forestry and municipal waste. In later years these feedstocks become increasingly constrained, with incremental capacity shifting to PtL. By 2043, greater capacity is added by PtL facilities than bio-feedstocks, and by 2050, 50% of total capacity uses renewable power/PtL as feedstock. The production cost initially increases as first-of-a-kind AtJ and FT facilities come into operation, and then rapidly drops as the technologies mature. As PtL capacity grows in the last decade the average cost increases, before leveling out at $1,420 per tonne SAF capacity. Including a conservative value for the carbon reduction delivered through SAF ($200/t$CO_2$) reduces the cost of SAF to $850 per tonne, which is meaningfully within the typical range of costs for fossil jet fuel.



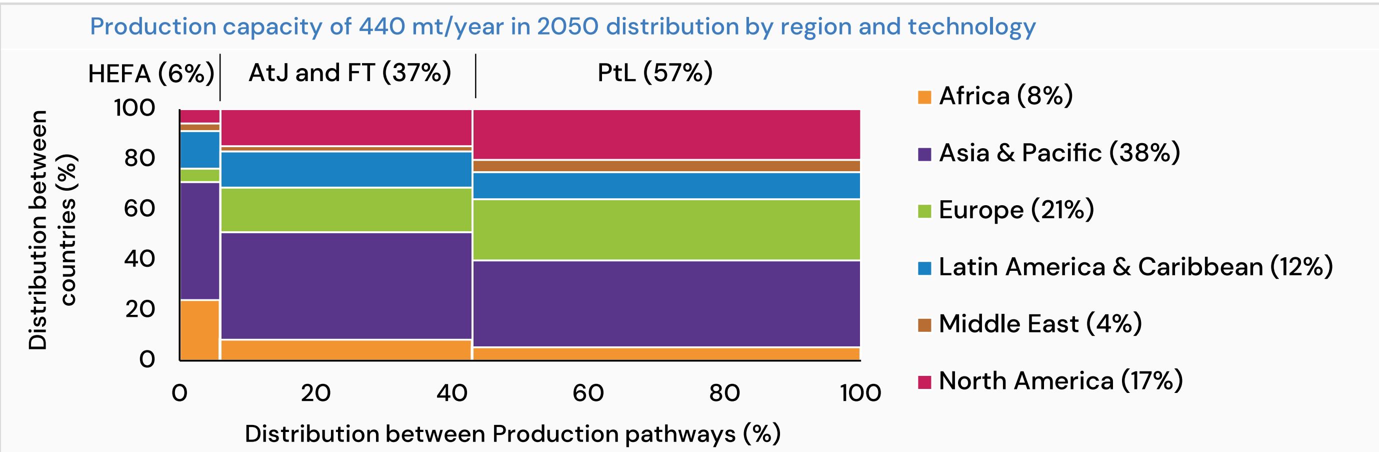
39% of production capacity is located across Asia & Pacific, followed by Europe and North America, drawing on the substantial bio-feedstock availability and considerable renewable energy capacity. Latin America, Africa and the Middle East utilize all bio-feedstock availability by 2050 but deliver limited PtL, as the focus remains on decarbonizing the domestic electrical consumption.

S2: Aggressive Sustainable Fuel development

Technology improvements are ambitious, but there is no significant shift to electric or hydrogen propulsion, and only limited improvements in infrastructure and operations are achieved. The industry focuses on decarbonization through SAF uptake, requiring 440 MT of SAF in 2050.



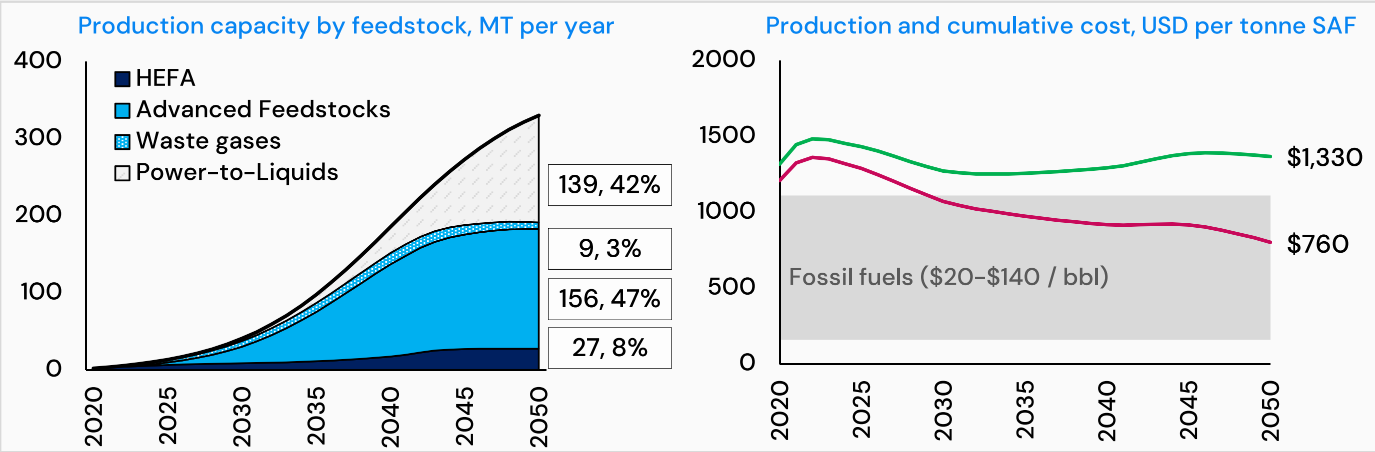
The availability of bio-feedstocks is exhausted by 2040, with a large-scale shift to Power-to-Liquids production using renewable electricity. By 2050, over half of all SAF production capacity uses PtL feedstock, and just 41% from biological feedstocks, with the balance from residual use of waste gases. The production cost increase as first-of-a-kind AtJ and FT facilities come into operation, and then rapidly decreases as the technologies mature. However, the cost of PtL drives up costs in later years, with the average cost of production plateauing at $1,470 per tonne SAF in 2050. Including a conservative value of carbon reductions ($200/t$CO_2$) reduces the cost of SAF to $900 per tonne, at the top of the range for historical fossil fuel costs.



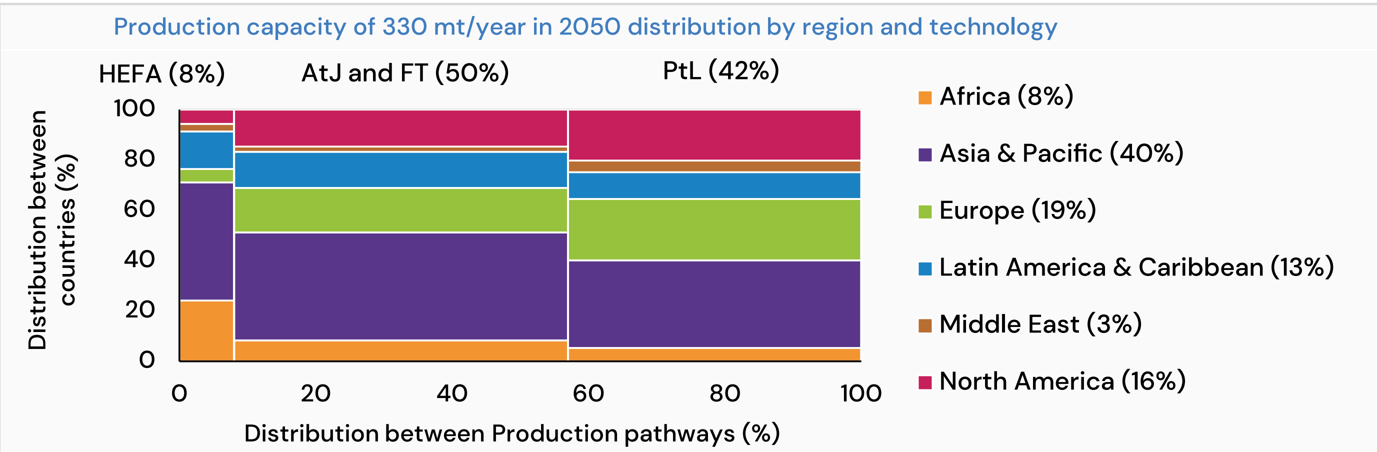
38% of production capacity is located across Asia & Pacific, and the substantial reliance on PtL production drives production capacity in Europe (21%) and North America (17%), drawing on their large renewable energy production capacity. The Middle East delivers a slightly greater portion of capacity, seizing the opportunity for affordable renewables production. Latin America and the Caribbean, and Africa build-out significant capacity for HEFA and other biological feedstocks but deliver slightly a slightly lower percentage of overall capacity due to limited PtL production.

S3: Aspirational & aggressive technology perspective

There is widespread adoption of alternative propulsion, with regional electric aircraft, narrow-body hydrogen aircraft and hybrid-electric propulsion used for larger aircraft. Through aggressive adoption of these technologies and mid-range operational and infrastructure improvements, significant emission reductions are achieved. Replacing 90% of fuel consumption requires 330 million tonnes of SAF production per year.



The availability of bio-feedstocks allows production capacity to increase through 2050, although PtL starts to dominate additional construction from 2045 onward. Over half of SAF production uses biological feedstocks by 2050, with 42% from PtL and the balance from residual use of waste gases. The production cost increases as first-of-a-kind AtJ and FT facilities come into operation, and then rapidly decreases as the technologies mature. As PtL capacity grows in the last decade the average cost increases, before leveling out at $1,330 per tonne SAF capacity. Including the value of carbon reductions reduces the cost of SAF to $760 per tonne, which is well within the historical range of costs for fossil fuels.



The dominance of biological feedstocks results in a higher portion of production capacity in Africa and Latin America and Caribbean, while Asia and the Pacific remains steady at 40% of overall production. With less reliance on renewable electricity, Europe, North America, and the Middle East deliver a slightly lower portion of overall capacity, although the bio-feedstock in all regions is still utilized by 2050.

Deploying capacity: Focus on Scenario 2 dynamics

Building refineries is difficult. Many of the AtJ and FT facilities hoping to commence commercial operations imminently started development work several years ago, and have endured a laborious process of development, planning, and construction. The construction and ramp-up process will reduce with experience but will continue to constrain the speed the industry can scale up production.

ICF's analysis has assessed an ambitious but pragmatic capacity deployment. This following example demonstrates the deployment for scenario 2, which requires the greatest volume of SAF uptake and consequently a comparatively high reliance on the Power-to-Liquids approach.

Initial capacity is dominated by HEFA facilities, many using existing infrastructure. Over the next few years, capacity growth transitions to use the advanced feedstocks and waste gases, driven by the maturing technologies and increasing constraints on the availability of waste lipids for HEFA production. These facilities, using the FT and AtJ pathways and feedstocks such as municipal solid waste, woody biomass and agricultural wastes dominate additional capacity over the next decade.

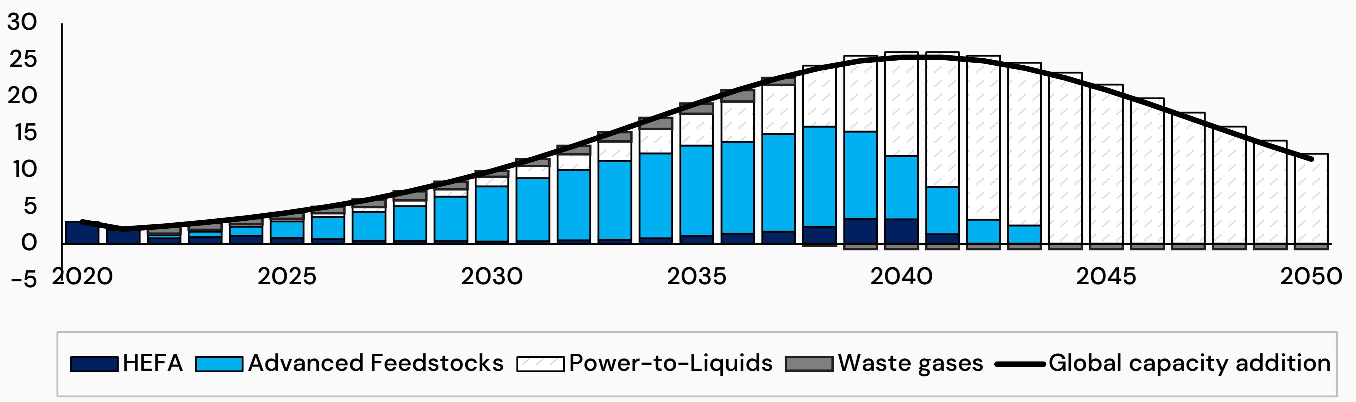
The initial commercial power-to-liquid facilities come online after 2025, providing a small share of additional capacity. While more expensive than other pathways, this early deployment is essential to ensure development of the required technologies and reduce the risk when PtL is demanded in greater quantities in later years. By 2035 the greater availability and lower cost of renewable power allows PtL to begin to be deployed in meaningful volumes.

Around 2035 it becomes economically viable to grow Jatropha on deteriorated land in greater quantities, and the HEFA capacity increases with the additional feedstock. This additional capacity is mostly added in Asia and the Pacific, Africa, and Latin America and the Caribbean due to topological and climate conditions.

By 2040, many other industries are increasingly decarbonizing, with steel mills and other sectors shifting to cleaner approaches. The SAF facilities built to convert their waste gases to SAF transition to the PtL pathway, using carbon captured from the atmosphere and hydrogen from electrolysis. This provides additional capacity for the PtL pathway, although some residual use of waste gases remains by 2050.

Constraints on the availability of biological feedstocks become more prominent over the last decade, as the increasing population limits the land available for feedstock growth and other sectors compete for the same bioenergy. The majority of additional capacity is added through the Power-to-Liquids pathway, and from 2044 essentially all additional capacity uses this approach.

Annual capacity addition by feedstock, Scenario 2, MT

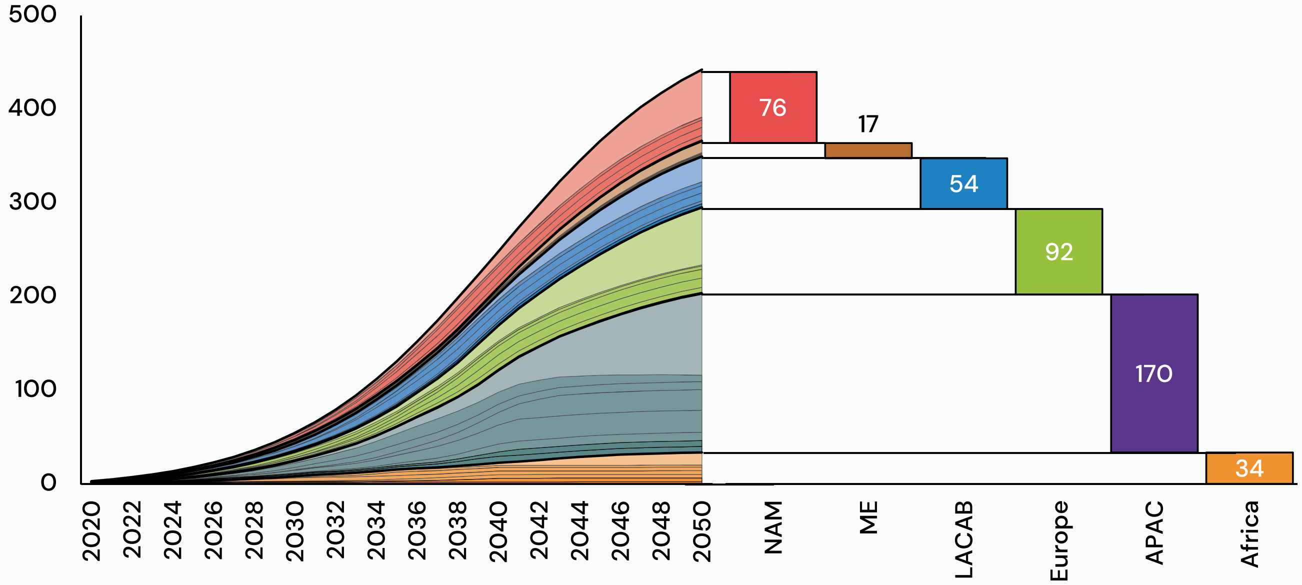


Source: ICF Analysis

The rate of deployment varies by region. The availability of waste lipids for the HEFA pathway is well correlated with population, and consequently distributed across regions. The deployment of advanced feedstocks is driven by the total feedstock availability in each region, with Asia and the Pacific leading with 46% of all feedstock availability. Industrial waste gas availability in Asia and the Pacific, and to a lesser extent in Europe and North America, support the deployment in the middle decade.

The deployment of Power-to-Liquids is driven by both the availability and the price of renewable electricity. In 2020, approximately 40% of renewable capacity is located in Asia and the Pacific, 30% in Europe and 20% in North America, with most of the remainder in Latin America and the Caribbean. As the demand for renewable power for PtL increases, regional distribution is driven by future availability, overlaid with a slight focus on the regions with lower forecast costs of renewable power generation.

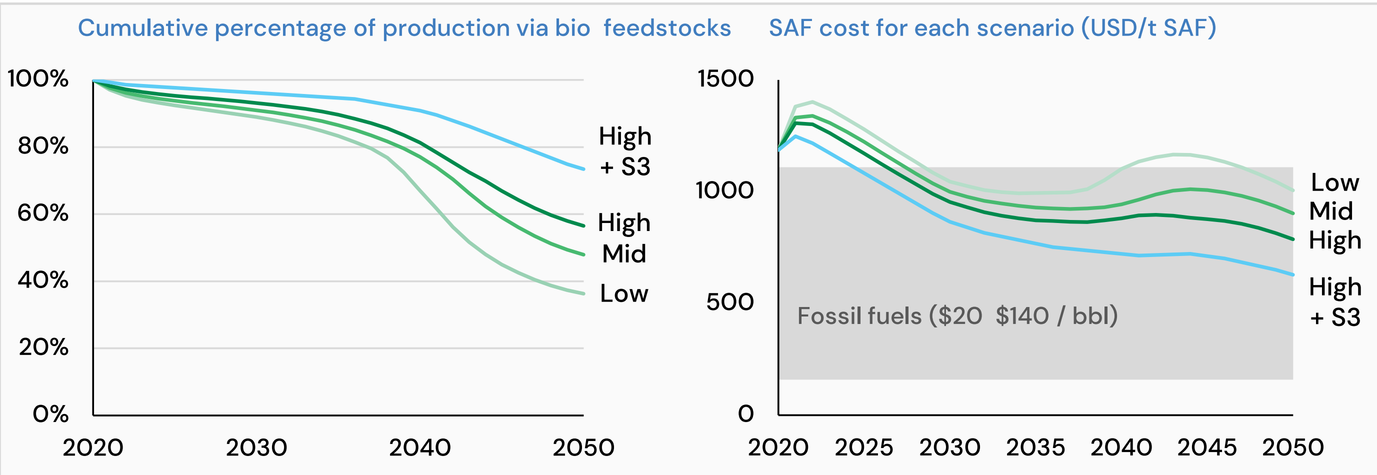
Cumulative SAF production capacity, Scenario 2, (million tonnes pa)



Sensitivity analysis: Biological feedstock availability

The SAF industry is at an early stage of development, and while the environmental benefits are clear the high costs make it extremely challenging for any airline to purchase meaningful quantities of SAF without regulatory support. The regulation today is fragmented, with a patchwork of existing and announced schemes that variously attempt to support SAF production, mandate SAF use, or include the cost of carbon emissions to fossil fuel prices. Historically, regulation has not been sufficient to incentivize SAF production over other sustainable fuels. For example, in 2018 in the US over 300 million gallons of renewable diesel and 32 million gallons of renewable ethanol[18] were produced, while SAF production was just 2 million gallons[19]. With incentives for renewable road fuels and a slightly lower cost of production, this pattern is repeated around the world. While this has built the foundations of the SAF industry by leading the development of renewable fuel technologies, this also diverts most available feedstock to alternative industries, many with far cheaper alternatives to use to decarbonize compared to aviation. Demand for these feedstocks will significantly increase as sectors ranging from shipping and power generation to chemicals and material production also begin to decarbonize. This ICF analysis has been built on the assumption that aviation receives a conservative allocation of bio-feedstock, utilizing renewable electricity through the expensive PtL pathway to make up any shortfall in capacity.

Varying the availability of bio-feedstock to aviation greatly influences the cost. In all three scenarios the decline in production costs as the technologies mature is increasingly offset as the share of PtL increases, resulting in a significant residual premium in 2050. This sensitivity analysis shows the change in the percentage of fuels produced using bio-feedstocks in low, mid, and high bio-feedstock availability scenarios, and the resulting average cost for SAF across the industry, including the value of the CO2 reductions. All three sensitivities have been calculated using S2, representing the highest demand for SAF and therefore the most conservative scenario, although S3 with lower SAF demand has been shown for context.



This shows the crucial impact from feedstock availability to aviation, with SAF costs for S2 ranging from 790-1010 $/t SAF with feedstock availability, and average industry prices well within the range of fossil fuels when lower volumes of SAF are demanded and higher levels of bio-feedstock are available.

[18] D5 & D3/D7 RIN only with (> -50% GHG reduction); D6 ethanol add an additional 14,954 million gallons of ethanol production

[19] US EPA.

How have these results been calculated?

A host of factors drive the decisions made in the market today, including national and international regulations, technologies, local feedstock availabilities, the availability of infrastructure and demand. ICF's modeling distils a complex reality into two key factors that drive the macro trends: the net cost of SAF, and the limitations on the availability of feedstocks.

The cost of SAF is simplified to the feedstock cost, plus the allocated facility expenses, minus the environmental value. Extensive analysis has been conducted to estimate the cost for each feedstock, and a detailed model has been built to calculate the infrastructure capital and operational costs. Regulation drives the market today, and this model simplifies the complex patchwork of policies, mandates, and incentives to a single environmental value for the carbon reduction achieved by the SAF.

Each region has a different set of feedstocks available, imposing a varied set of constraints to the development of the local SAF industry. This report investigates these limitations to show the opportunity for the different feedstocks and technologies in each region. The global availability of feedstocks builds on the excellent work done by the ETC in the report Bioresources within a Net-Zero Emissions Economy: Making a sustainable approach possible, and by the IEA in Net Zero by 2050: A Roadmap for the Global Energy Sector.

SAF demand is an input to this method. The required volumes are based on the extensive Waypoint 2050 report, which analyzes the industry growth, the potential for incremental improvements, novel technologies, and operational improvements to reduce the emissions produced. SAF is used to address the remaining emissions and enable the aviation industry to meet its climate ambitions.

The analysis calculates the cost to produce SAF by each feedstock and pathway, accounts for the carbon value and then uses a merit ranking approach to distribute the incremental capacity. This process is repeated for each year of the analysis, with supporting adjustments to help the model better reflect reality.

The inputs to this analysis were developed through months of research and analysis, building on a variety of public sources, expert input and ICF proprietary tools. This builds on the considerable work by ICF and others in this field, consolidating it into a single analysis and drawing out additional insights.

ICF's report aims to provide an integrated global analysis with internally consistent regional details. The opportunities are different for each region, and it is hoped that this work will support policy makers by providing clarity on the regional advantages and constraints. The regional definitions used in this report are aligned with the Aviation: Benefits Beyond Borders work by ATAG[20], allowing easy comparison.

[20] https://aviationbenefits.org/downloads/aviation-benefits-beyond-borders-2020/

Part 1

How much feedstock is available, and what will it cost?

The environmental attributes, ease of conversion and cost will drive the relative appeal of each feedstock, while environmental limitations and competing demands will constrain the volume of each feedstock that the aviation industry can reasonably expect to use over the long term. The choice of feedstock determines the infrastructure required and can drive up to 85% of the cost of the fuels produced, so understanding the feedstocks is critical to assessing the development of the SAF industry.

Only a single type of feedstock, the lipids used for the HEFA pathway, are in commercial use today. The fuels produced are predominately used for road transport, and the feedstock is typically sourced from Used Cooking Oil (UCO), animal fats such as tallow, and oil-bearing crops. These feedstocks are relatively simple to convert into fuels but are limited in availability, due to both limited volumes that can be sustainably produced and strong competition.

New technologies will broaden the range of feedstocks that can be used. The Fischer-Tropsch (FT) and Alcohol-to-Jet (AtJ) production pathways will be central to the development of the SAF industry over the next few decades, with the first facilities by pioneers such as Fulcrum, RedRock and Velocys (FT) and LanzaJet and Gevo (AtJ) expected to start production over the immediate years. These will allow the conversion of biological feedstocks such as agricultural waste, forestry residues, and some types of municipal waste into SAF. While the feedstocks themselves are typically relatively cheap, the conversion process and consequently the infrastructure required is complex and comparatively expensive. The availability of these feedstocks is fragmented and heavily dependent on local markets, but given the right commercial incentives, significant volumes of these feedstocks could be collected and made available to aviation. However, as the SAF industry grows by several orders of magnitude, the availability of these feedstocks will also become increasingly constrained. When considering the long-term development of the SAF industry these limitations should be considered, but equally they should not be an obstacle to the immediate development of facilities today.

Artificial sources of carbon and hydrogen can also be used to produce SAF. In a process commonly referred to as Power-to-Liquids (PtL), these can be produced using renewable electricity, with the hydrogen created through the electrolysis of water, and the carbon can be captured from point-sources or from the atmosphere. Once obtained, the hydrogen and carbon can be processed and converted using the same technologies as the biological feedstocks, such as FT or AtJ. SAF produced using carbon captured directly from the atmosphere promises significant benefits, such as the production of a very low carbon fuel and far lower land and water requirements than most of the biological feedstocks. However, this approach is extremely expensive today. To be economical, rapid reductions will be required in the cost of direct air capture and green hydrogen production.

Using carbon captured from point sources will allow the development of the required technologies at a fraction of the cost. Point source emissions contain far higher concentrations of carbon than the atmosphere, making the extraction of the carbon easier and cheaper. Some sources such as steel mill emissions are particularly useful, with the waste gases containing both carbon monoxide and hydrogen, which limits the processing and additional hydrogen required. These are inappropriate for long-term use due to challenges with value creation for polluting industries and limits to the maximum emission reduction with the carbon still entering the atmosphere when the SAF is combusted. As other industries decarbonize the availability of these point sources should also decrease, so their use as a feedstock will most importantly be a way to stimulate the development of the industry over the coming decades before tapering to a minimal level near to 2050.

Table 4: Feedstock categories defined in this analysis

Feedstock category			Sub-category	Example feedstocks	Conversion pathway
1	Biological feedstocks	Waste & Residue Lipids		UCO, tallow, tall oil, POME, PFAD	HEFA
2	Biological feedstocks	Non-food crops	Oil Seed crops & trees	Camelina, Jatropha	HEFA
2	Biological feedstocks	Non-food crops	Cellulosic cover crops	Miscanthus, Switchgrass	gas/FT or AtJ
3	Biological feedstocks	Agricultural residues		Corn stover, rice residues, bagasse	gas/FT or AtJ
4	Biological feedstocks	Woody biomass		Forestry coppice, slash, thinnings, offcuts	gas/FT or AtJ
5	Biological feedstocks	Municipal Solid waste		Black bin and industrial solid waste	gas/FT or AtJ
6	Non-biological feedstocks	Renewable fuels of non-biological origin (RFNBO)	Industrial waste gases	Waste carbon gases from industrial plants	gas/FT or AtJ
6	Non-biological feedstocks	Renewable fuels of non-biological origin (RFNBO)	Power-to-Liquids (H2 from electrolysis & CO_2 from DAC)	Renewable electricity	gas/FT or AtJ

The categories shown in Table 4 include many more feedstocks than the examples provided. The diversity is illustrated by the Commercial Aviation Alternative Fuels Institute (CAAFI), which lists over 130 potential feedstocks[21]. These feedstock categories are designed to be a representative selection of all potential feedstocks, and their availability has been benchmarked to industry reports – as described in detail later in this report. These benchmark analyzes consider a wider range of potential feedstocks than this analysis has included, such as algae. In the cases where these benchmark analyzes assume the commercialization of these additional feedstocks, the increased feedstock availability has been pro-rata allocated between the feedstocks this analysis has included.

[21] https://www.caafi.org/focus_areas/docs/CAAFI_Feedstock_List_02_2018.pdf

Biological-based feedstocks

1 Waste and residue lipids

This category covers a range of waste oils, including Used Cooking Oil (UCO), distillers corn oil, tallow (animal fats), fish oil, palm fatty acid distillate (PFAD), palm oil mill effluent (POME) and other smaller waste streams. Used Cooking Oil is generated in the professional sector, including restaurants and food manufacturers, and by individual households. Collection from the professional sector is cheaper and easier than from households as the UCO is available in larger quantities at fewer locations. Consequently, collection networks for the professional sector are relatively developed, and collection rates are generally high. By contrast, the collection rates for households are minimal. Regulation is essential to ensure the UCO is a genuine waste and not splash-blended with virgin oils, which have in some cases have seen prices dip lower than UCO.

Animal Fat includes beef tallow, pork lard and chicken fat obtained from industry rendering waste. Edible fats can be used in food products while inedible fats have uses in pet food, animal food and soap making. Only inedible fats are considered for energy generation. Animal fats are attractive feedstocks as their cost is lower than vegetable oil. However, there are sustainability concerns surrounding the use of animal fat for fuel and it is not accepted in all countries. Germany does not support the use of animal fat in its biofuel mandate due to the risk of indirect emission caused by displacement from existing uses. There is also a concern that increased demand for animal fat in biofuel could result in increased prices and down-classification of high-quality animal fats.

Palm oil was excluded from this analysis, but by-products (PFAD & POME) were considered in the early years and phased out over the analysis duration to represent sustainability constraints becoming more stringent with time. POME is wastewater generated during palm oil milling and is highly polluting. Oil and fat content in POME is 0.5 –1.5% which can be extracted and used as feedstock. PFAD is free fatty acid that is generated during palm oil production and needs to be removed to improve the oil's quality. Apart from their use as biofuel feedstock, these residues are used in making soap, animal feed and oleochemicals.

Other waste streams add to this supply, such as tall oil and distillers corn oil, which are by-products of wood pulp manufacture and ethanol production respectively. These are available in relatively small quantities.

2 Non-food crops

This includes biomass grown on dedicated land, which can include energy crops such as Miscanthus and Switchgrass, short rotation coppice such as Willow or Poplar, and oil-bearing crops such as Jatropha. Estimating the availability of feedstock grown on dedicated land is extremely complex, with estimates of global potential varying from less than 10 EJ to over 1,000 EJ. The availability is limited by multiple constraints, including land use and protections, life cycle carbon footprint, biodiversity implications and the yield potential of the land. Assumptions on the potential crops used, farming practices, logistics and location, processing efficiencies and current land use all influence the expected potential.

3 Agricultural residues

Agricultural residues include wastes such as the stems and leaves left over from harvesting, and wastes created during processing, such as husks, roots, and bagasse.

Today, approximately 10% of these residues are used for commercial applications, such as animal feed or bedding, horticulture, and for heat and power. The remainder is left in-situ and is often burnt, creating air quality issues in many parts of the world. While much of the residues must be left on the land to prevent nutrient loss and erosion – approximately 70% depending on the crop and location – there is a significant remainder that could be collected and used as a feedstock.

4 Woody biomass

Woody biomass includes primary forest residues such as treetops, branches, and stumps from timber harvests as well as secondary forest residues from wood processing industries such as sawdust, bark, and scrap-wood. While the best use of managed forestry is materials production, the left-over residues can provide an important feedstock for biofuel production.

Primary forest residues have traditionally had little commercial value, and the largest managed forest output is low value fuel wood, which is used for heat and power generation. A considerable amount of forestry residue remains unutilized due to a lack of markets that can afford to pay the extraction costs, and a lack of supportive policies and, in some cases, adequate infrastructure. The use of woody biomass must ensure the preservation of the carbon balance by avoiding the conversion of pristine forests and other landscapes with high carbon stocks into managed forests, and by ensuring that the biomass extracted is no more than new growth. Factors such as soil health, erosion and biodiversity must also be considered, and will limit the availability of this feedstock.

Secondary forest residues are produced at industrial facilities such as sawmills and pulp plants. Their centralized nature makes it more affordable to collect these wastes, and most of these residues are currently burned for energy or recycled into other products.

5 Municipal and Industrial waste

Over 2 billion tonnes of municipal solid waste (MSW) are generated annually, equivalent to 0.74 Kg per person, per day. At least a third of this is not managed in an environmentally safe manner, generating an estimated 1.6 billion tonnes of CO_2e in 2016 – substantially more than the aviation sector. As the global population and economy increases, the waste generated is expected to increase by over 60% by 2050, to 3.4 bn tonnes[22].

The EU waste hierarchy[23] provides a useful framework to address this waste. The priority should be prevention, followed by re-use. At the end-of-life, products should be recycled, either mechanically or chemically. The production of SAF from waste should be considered a chemical recycling of the waste, breaking it into feedstock that can be used to produce high-value fuels.

Only where this is not possible should other disposal approaches be considered, such as incineration with energy recovery, which extracts very little energy from the waste and instead primarily serves to reduce the volume for subsequent landfill.

[22] https://datatopics.worldbank.org/what-a-waste/index.html
[23] https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en

The practical availability of MSW for biofuel production should consider the increasing global production, and sharply increased rates of waste avoidance, re-use, and mechanical recycling as the global industry acts to reduce environmental impacts. Effective governance and policies are essential to manage wastes as effectively as possible, including ensuring waste is not diverted from potential re-use or mechanical recycling, and to ensure the energy embodied in waste is well used.

MSW is highly heterogeneous and can be categorized into a biogenic portion (food waste, greens, woods, paper, and card) and a non-biogenic (fossil-fuel) portion such as plastics. Only the biogenic portion offers a reduction to life-cycle emissions when converted into biofuel, but it is often impossible to fully separate the waste streams.

Non-biological-based feedstocks

6a Industrial waste gases

Certain industrial waste gases, such as the carbon-rich flue gases from steel mills, can be used for biofuel production. This process is being commercialized today, with the capture and fermentation of these waste gases into alcohol, which can then be converted to SAF. The waste gases represent an important stepping-stone for the development of the SAF industry and a useful approach to reduce the emissions from heavy industry. However, the emission reduction must not be double counted – the carbon is still released to the atmosphere when the fuel is combusted, and these emissions must be appropriately allocated between the industrial facility and the fuels.

Today, most of these waste gases are either flared or used for on-site energy recovery. Conversion into fuels represents a clear benefit compared to both these approached; flaring produces no benefit, and relatively little energy is captured from the energy recovery, limiting the displacement effect if the gases are instead used for SAF production.

Practical availability of these gases depends on the demand for the industrial products and the technologies used. On one hand, continued growth in demand will likely increase the waste gas availability. On the other hand, ongoing decarbonization efforts in the heavy industry including the increased focus on steel production via Electric Arc Furnaces (EAF, which produce very few emissions) rather than Blast Oxygen Furnaces (BOF, the predominant steel production method today and emits considerably more carbon) may limit waste gases availability over the long-term. Switching costs may also limit the incentive for facilities with on-site energy recovery to consider SAF production.

6b Fuels from renewable electricity

Electricity can be used to produce hydrogen from water through electrolysis, and for direct air capture of carbon from the atmosphere. The hydrogen and carbon are equivalent to syngas and can be used to produce SAF through the approved pathways, such as FT-SPK or AtJ. Fuels produced in this manner are referred to by a variety of names, including Power-to-Liquids (PtL), e-fuels, synthetic fuels, or renewable fuels of non-biological origin (RFONBO). This report will use the term PtL for consistency.

Economic and sustainability considerations will make these fuels increasingly relevant. PtL allows the production of zero carbon fuels, with only the carbon captured during production released during the combustion of the fuel. Production can be more sustainable, with lower requirements for water and land space to produce the required electricity than for biomass growth, and the land that is used can be very poor quality with no need to support life. There are also potentially fewer constraints on the long-term volume of renewable electricity that can be produced than for biomass collection, which may allow considerable volumes of fuel to be sustainably produced through this approach.

SAF produced through PtL is currently expensive. However, the steep learning curve across multiple industries, including renewable electricity generation, electrolyzers for hydrogen production and direct air capture technologies will all rapidly reduce the cost to produce syngas from renewable electricity. As PtL uses the same technologies as biological feedstocks to convert syngas to fuels, this approach will also benefit from cost reductions in other parts of the SAF industry, allowing PtL to be increasingly competitive with SAF derived from other feedstocks.

The limitations on biological feedstocks will be increasingly pronounced in the later years of this analysis, and it will be important to ensure the technologies required for PtL are sufficiently mature to rely on by this point. Initiatives such as the PtL sub-mandate in the EU ReFuel policy and US Earthshot project for Hydrogen will stimulate both the PtL industry and component parts.

Global feedstock availability

The environmental and social integrity of feedstocks is critical, and only feedstocks that contribute to the development of a more sustainable economy should be used for SAF production. There are considerable opportunities across the SAF value chain to lead this development: from reducing carbon emissions to improving waste management and job creation. There are also challenges, with the release of carbon embodied in land reducing the life cycle carbon reduction, and the risks of soil health degradation and biodiversity destruction reducing the long-term potential for feedstock growth.

The integrity of feedstocks is measured and certified today by the Roundtable on Sustainable Biomaterials[24] (RSB) and the International Sustainability and Carbon Certification[25] (ISCC). These ensure that the environmental benefits of feedstocks across the entire value chain are genuine, meaningful, and the feedstock operations respect social, labor and land rights, amongst other criteria.

These considerations are essential to ensure the use of feedstocks is sustainable over a long time period, and the total availability of feedstock must respect these constraints. This analysis considers three key constraints, covering sustainability, fairness, and economic limitations. The sustainability constraint reflects the environmental and social limitations on the feedstock availability, such as the constraints on land that can sustainably be used for energy crop growth, or the fraction of agricultural residues that must be left on the land to maintain the soil quality. The fairness constraint reflects the balance of feedstocks that can be used for SAF production, compared to use by other sectors. Many of these feedstocks are used today for heating, animal bedding or feed, soaps, lubricants, and as raw material for oleochemicals industry. As other industries also decarbonize, there will likely be increasing demand for feedstocks to produce heat and energy, and for material uses such as bioplastics. Aviation is a fraction of global emissions and the decarbonization of aviation must be matched by decarbonization across all sectors, so the demand from other sectors must be considered. The final constraint is the volume of feedstock that can be economically used to produce fuels and enable flights at economically sustainable socially acceptable prices.

Table 5: Feedstock availability must meet three criteria

Feedstock Criteria		
Sustainable (1)	Fair (2)	Economic (3)
It must be possible to sustainably grow, gather or extract the feedstock volume	The feedstock use by aviation must be fair, considering competing demands from other sectors	The feedstock must be affordable and logistically viable

Each of these factors will evolve over the timescale of this analysis, with population increases, economic growth and climate change impacting the availability of feedstocks:

[24] https://rsb.org/
[25] https://www.iscc-system.org/

Population & Economic growth: The UN forecasts the world population to reach 9.7 billion in 2050[26], driving demand for food, water and living space. Meeting this demand will require conversion of land for crops and livestock, reducing the land available for cover crops but increasing the availability of agricultural residues. To a lesser extent, other wastes such as used cooking oil and animal fats may also increase in availability.

Climate change: As the planet warms the suitability of some land for cover crops will degrade, reducing yield and availability. This may be very slightly offset by the CO_2 fertilization effect, which is a slight increase in crop yields as the increase in atmospheric CO_2 concentration enables plants to photosynthesize more efficiently.

The net impact will likely be a reduction in feedstock availability over the analysis timescale. The land converted for agriculture is likely to predominately be the land most suited for dedicated feedstock growth today, and the upside potential from the CO_2 fertilization effect is limited. A report by the WWF on the SAF potential in sub-Saharan Africa estimated that the net impact from the population increase would reduce SAF potential in the region from cover crops by 43% (-3,061 PJ), while the additional feedstock from agricultural residues would only mitigate a fraction of this decrease[27].

Societal decarbonization will also drive competition for these feedstocks. 17 countries have net zero emissions targets achieved, in law or proposed in legislation[28]. Far more have targets under discussion, and in July 2021 over 1,600 companies have committed to science-based emissions reduction targets through the SBTi[29]. Achieving these ambitions will increase demand for many of the same feedstocks the commercial aviation industry is looking to use, ranging from toy companies like LEGO making plant-based bricks from sugarcane[30], to producers like Amyris pivoting from sustainable fuel production to manufacturing sustainable cosmetics[31].

The production of SAF has natural synergies with other industries, as the production slate naturally includes a range of products such as renewable diesel, naphtha, and propane. As production of SAF increases, the production of these co-products will also increase, allowing industries to support mutual decarbonization. The demand from sectors such as militaries[32], maritime[33] and continued road demand must be considered. Aviation is a particularly challenging industry to decarbonize. It is crucial this is recognized in policy developments, and this study takes the stance that due to the significant value added through aviation and the lack of alternatives, commercial aviation should have the priority, but not the exclusivity of these feedstocks.

Each of these limitations will impact the feedstock categories differently. While the availability of some feedstocks such as crops on dedicated land are limited by sustainability factors, other feedstocks such as renewable electricity for PtL production are limited by cost.

26 https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html
27 http://awsassets.wwf.org.za/downloads/sustainable_biofuel_potential_ssaf_summaryreport_finalized_v7_2_digital_pages.pdf
28 https://eciu.net/netzerotracker
29 https://sciencebasedtargets.org/companies-taking-action#table
30 https://www.lego.com/en-gb/aboutus/sustainable-materials
31 https://www.biofuelsdigest.com/bdigest/2018/07/11/amyris-same-as-it-never-was/
32 https://www.gov.uk/government/news/sustainable-fuels-to-power-raf-jets
33 https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12312-CO2-emissions-from-shipping-encouraging-the-use-of-low-carbon-fuels_en

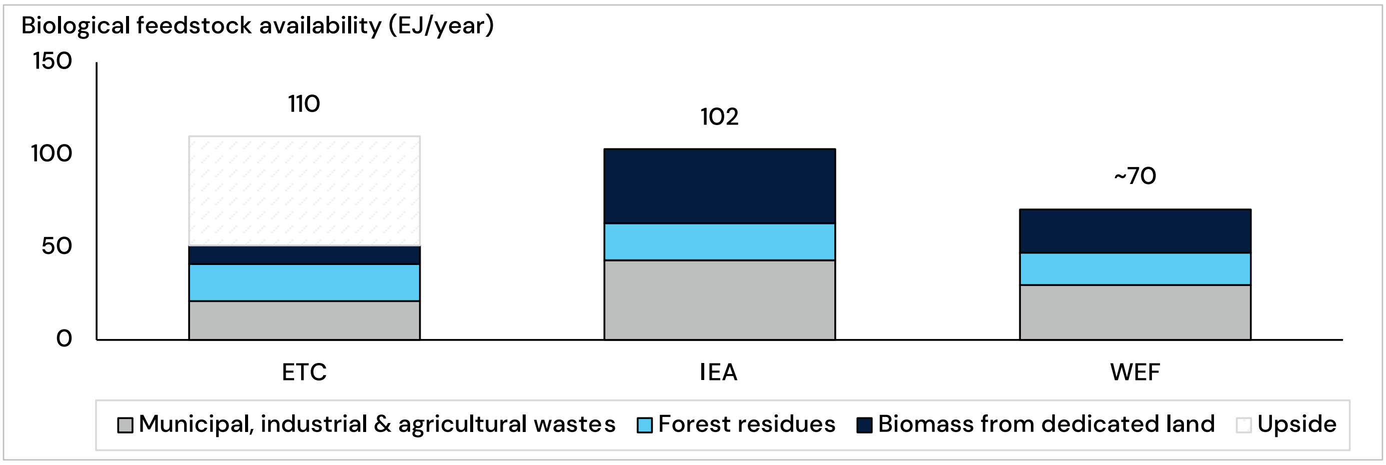
Table 6: Key limitations for each potential feedstock; the more complete the Harvey ball the greater the constraint

		Feedstock category	Technical availability	Environmental limitations	Fairness limitations	Economic limitations
1	Biological feedstocks	Waste & Residue Lipids	●	○	●	●
2a	Biological feedstocks	Oil Seed crops & trees	◔	●	◔	◕
2b	Biological feedstocks	Cellulosic cover crops	◔	●	○	◕
3	Biological feedstocks	Agricultural residues	◑	◕	○	◔
4	Biological feedstocks	Woody biomass	◑	◕	◑	◑
5	Biological feedstocks	Municipal Solid waste	◔	◕	◔	○
6a	Non-biological feedstocks	Industrial waste gases	●	◑	◔	○
6b	Non-biological feedstocks	Renewable electricity	○	○	◑	●

Criterion 1: How much feedstock is sustainably available?

The global availability of bio-feedstocks has been comprehensively analyzed by the Energy Transitions Commission[34], IEA[35], and World Economic Forum[36], and this analysis builds on these results.

Estimates of total bio-feedstock availability vary from 50-110 EJ



Source: "Bioresources within a net zero emissions economy: Making a sustainable approach possible, ETC, July 2021. "Net Zero by 2050: A Roadmap for the Global Energy Sector", IEA, Revised June 2021, "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", WEF, 2020

[34] https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-emissions-economy/
[35] https://www.iea.org/reports/net-zero-by-2050
[36] https://www.weforum.org/reports/a356c865-311e-45ca-845d-efe5f762a820

The ETC estimate is the most conservative on total feedstock available, with a prudent range estimate of 30–50 EJ. This estimate is based on:

- 5–10 EJ/year from non-food crops grown on dedicated land
- 10–20 EJ/year from forest residues, excluding material uses (e.g., timber)
- 5–12 EJ/year from agricultural residues
- 6–9 EJ/year from municipal and industrial wastes
- 0–1 EJ/year from aquatic sources (macro & micro algae)

The ETC also calculates a maximum potential of 110 EJ, based on three potential developments:

- An increase in land available for biomass feedstock production, which may result if there are major societal or technological changes, such as reduced meat consumption or increased substitution of synthetic meats, that reduce the land required for food.
- Improvements to waste management, increasing the municipal and industrial waste availability.
- Development of macroalgae for energy, potentially increasing supply by 10 EJ/year.

The IEA estimate of 102 EJ is similar to the ETC high-case estimate. The municipal, industrial, and agricultural residues are significantly higher, at 43 EJ/year compared to the ETC maximum potential estimate of 26 EJ/year. The IEAs estimate of biomass supply from dedicated land, including food crops, non-food crops and forestry plantings is 40 EJ/year, is also significantly above the ETCs prudent estimate of 5-10 EJ/year, and close to the ETC's maximum potential estimate of 55 EJ/year, which includes the major societal and technology changes mentioned above.

The estimate by the World Economic Forum has been converted from a feedstock tonnage availability to energy availability based on assumed energy density values for each feedstock to allow comparison to the ETC and IEA. The WEF estimate lies just above the mid-point of the ETC prudent estimate and the IEA estimate. Compared to the ETC prudent case of 50 EJ/year, the WEF estimates an additional 13 EJ/year (+133%) of available biomass from dedicated land, and an additional 9 EJ/year (+40%) from municipal, industrial, and agricultural wastes.

Criterion 2: How much of the total bio-feedstock can aviation use?

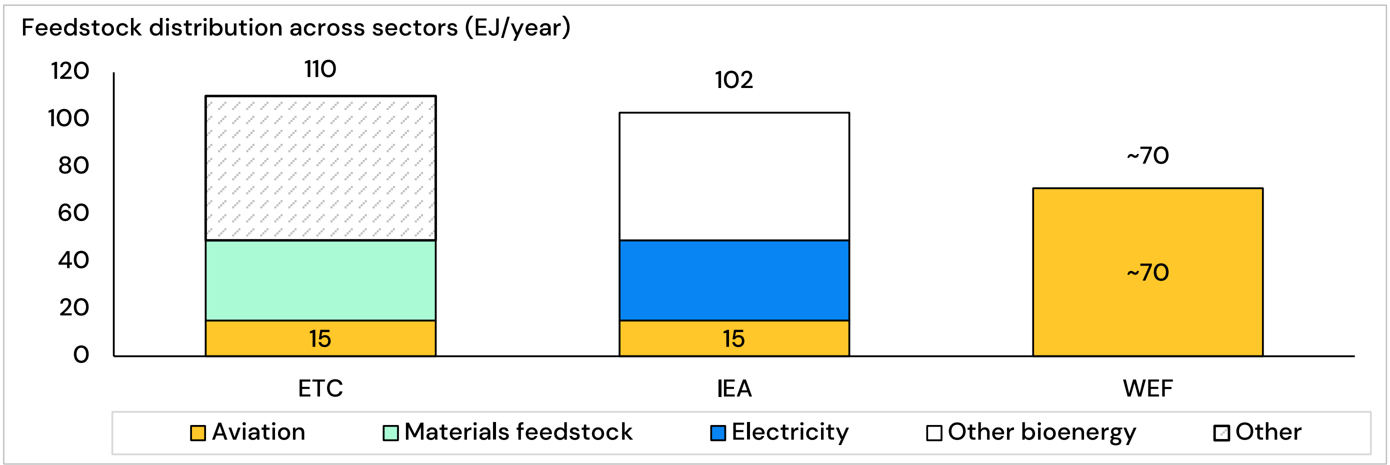
A multitude of sectors are increasingly looking to use biomass as a raw material or a feedstock for material production, and as a source of sustainable energy. Example material uses are timber for construction and furnishings, paper production and textiles. As a feedstock for material production, biomass can be used for plastics, solvents, paints, and many other products. When used for energy production, biomass can be directly combusted, or converted into fuels using thermochemical or biological conversion.

The combined forecast demand from these applications greatly exceeds the sustainable biomass availability. The ETC estimates that potential demand could be as high as 650 EJ/year, over ten times greater than their prudent estimate of availability. It is essential that the assumed share by aviation is considered in context of these competing demands.

Both the ETC and the IEA prioritize SAF as a high priority sector for biomass use, allocating 15 EJ/year. However, the other sectors' priorities vary considerably between the studies. The ETC prioritizes the use of biomass as a material or feedstock, with aviation as the only non-material priority due to the lack of cost-effective alternatives until PtL production can scale sufficiently. Since the additional feedstock available in the ETC maximum potential case is not guaranteed, this feedstock is assumed to be allocated to lower priority sectors, or to support the global transition in other ways, such as re-wilding to create carbon sinks and improve biodiversity. By contrast, the IEA prioritizes energy uses, and does not consider material uses.

The global WEF report calculates feedstock availability net of existing uses, such as animal feed and bedding, but does not consider other energy or material uses, although subsequent studies provide additional detail at the regional level such as for India[37] and Europe[38].

Several sectors will compete for bio-feedstock. Both the ETC and IEA prioritize aviation as a hard-to-abate sector.



Source: "Bioresources within a net zero emissions economy: Making a sustainable approach possible, ETC, July 2021. "Net Zero by 2050: A Roadmap for the Global Energy Sector", IEA, Revised June 2021, "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", WEF, 2020

Conclusion: Global feedstock availability for aviation

This analysis represents an ambitious decarbonization of the aviation sector. Reflecting this, three bio-feedstock availability scenarios have been defined:

Prudent case: This case is benchmarked to the global availability of 15 EJ/year calculated by the Energy Transition Commission in their report Bioresources within a net-zero emissions economy, which also aligns to the 15 EJ/year allocation to aviation estimated by the IEA. This analysis considers that this estimate represents the lower range of potential feedstock availability, with all other feedstock allocated to materials uses, and any residual availability allocated to lower-value applications.

Mid bio-feedstock case: This scenario assumes that 20 EJ of bio-feedstock is available for aviation. This includes the base 15 EJ of availability, plus an additional 5 EJ of additional bio-feedstock. This case is therefore based on two key assumptions:

1. The major social and technology transformations fundamental to the ETCs maximum potential scenario take place, including a meaningful reduction in land used for livestock, reduced food waste, and commercialization of algae.
2. Aviation is prioritized for a small portion of this incremental availability, reducing the feedstock availability for power, heat, and the availability of land for uses such as rewilding.

[37] https://www.weforum.org/reports/deploying-sustainable-aviation-fuels-at-scale-in-india-a-clean-skies-for-tomorrow-publication
[38] http://www3.weforum.org/docs/WEF_CST_EU_Policy_2021.pdf

While ambitious, this assumption is based on the principle that the aggressive decarbonization of aviation is reflected in a global transition, with other sectors also experiencing significant technical developments.

High Case: This assumes that an additional 15 EJ of bio-feedstock is available above the prudent case, giving 30 EJ/year. This represents aviation accessing approximately a quarter of the incremental feedstock availability in the ETCs maximum potential scenario. It relies on the same assumptions described in the mid case, but to a somewhat more aggressive degree. With 30 EJ of dedicated sustainable biomass, this would make aviation the largest single sectoral consumer, with plastics feedstocks second at 21 EJ/year.

In all cases, the bio-feedstock availability is complemented by non-biological feedstocks, including industrial waste gases and renewable energy. The industrial waste gases can be processed into the equivalent of syngas, which can then use the same infrastructure as the biological feedstocks for conversion into fuels. Renewable electricity can be used to electrolyze water to provide hydrogen, and for direct air capture (DAC) technologies to extract carbon from the atmosphere. The carbon and hydrogen can similarly be processed into a syngas and converted into fuels.

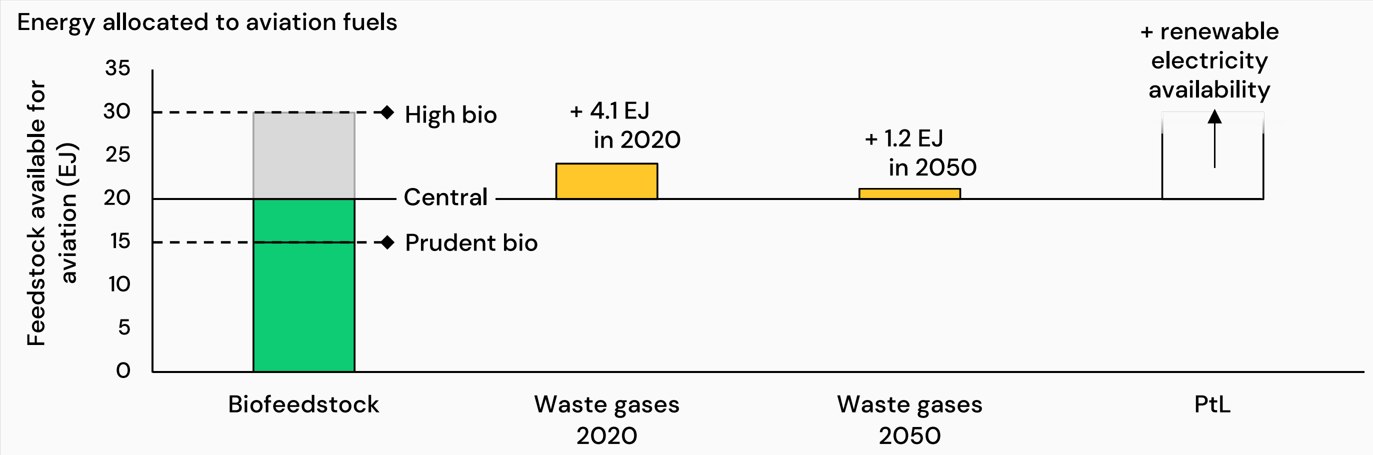
The industrial waste gases provide point-sources of concentrated carbon, greatly reducing the cost for collection. Specific industries emit waste gases with greater value as feedstocks, particularly steel mills, which emit a potent combination with 24% carbon monoxide by weight[39] and energy equivalent to 6 GJ per tonne of steel produced. Compared to concentrated CO_2, this greatly reduces the effort and cost to prepare the gases into a syngas equivalent.

The availability of waste gases will reduce as all industries decarbonize, so this feedstock is particularly useful as a bridging feedstock. The waste gases are low-cost, reducing the cost of production and stimulating the build-out of infrastructure. Over the longer-term, the infrastructure can then be retrofitted to avoid stranded assets.

The IEA estimates under the Sustainable Development Scenario that the volume of steel mill waste gases will decrease by 40% by 2050[40], with increased steel production offset by an increased share of electric arc furnaces (which emit far less) and other mitigation approaches. Much of this gas is in use today for on-site heat and power generation, and there may be increased demand from other sectors, with companies such as Carbon4PUR trialing conversion of these gases into polyurethane plastics[41] and FReSMe into methanol for shipping[42]. This analysis assumes that up to half the waste gases emitted in 2020 may be available for SAF production, with the remainder either emitted by unsuitable factories (perhaps too small or too remote) or where it would be uneconomical for the facilities to transition away from the use of the gases for co-located power and heat generation. The available waste gases for aviation are reduced over the analysis timescale, due to the reduction in total waste gases created and increasing competition from other industries. This analysis concluded that just over 4 EJ of waste gas energy are available in 2020, tapering to 1.2 EJ by 2050, representing additional energy equivalent to 27% and 8% of the bio-feedstocks in the respective years.

[39] https://cefic.org/app/uploads/2019/01/Low-carbon-energy-and-feedstock-for-the-chemical-industry-DECHEMA_Report-energy_climate.pdf
[40] https://www.iea.org/reports/iron-and-steel-technology-roadmap
[41] https://www.carbon4pur.eu/
[42] http://www.fresme.eu/

In the central scenario, bio-feedstocks provide 20 EJ, with additional energy from waste gases and renewable electricity



Source: ICF Analysis, Waste gas availability estimated using the IEA Iron and Steel technology Roadmap

The base feedstock for the Power-to-Liquids process is renewable electricity. This is both used for the electrolysis of hydrogen, and for the direct air capture of carbon. The constraints on renewable electricity availability are expected to be more fluid than other feedstocks, with feedback loops between the demand for power and the infrastructure build-out. However, the availability is not inexhaustible.

In 2019, renewables (solar, wind[43]) generated 10% of global electricity, with a further 16% from hydropower and 10% from nuclear; the remaining 64% of electricity was generated by oil, natural gas, and coal[44]. At 97 EJ in 2019, total electricity consumption is just 17% of primary energy use (581 EJ). The construction of renewable capacity is therefore in a ferocious race to decarbonize the existing demand for electricity, while the demand for electrify itself accelerates as other primary consumers of carbon-intensive primary energy (such as gasoline in cars) aim to electrify. Renewable generation has grown at a remarkable rate of 15.3% over the last decade, but there is still a displacement risk on the use of renewable electricity for SAF production with ongoing competition for the limited renewable generation. This limitation has been considered with both a constraint on the growth rate for renewable energy consumption, and a detailed geographic analysis to ensure the demand from aviation does not dominate renewable energy capacity in any region.

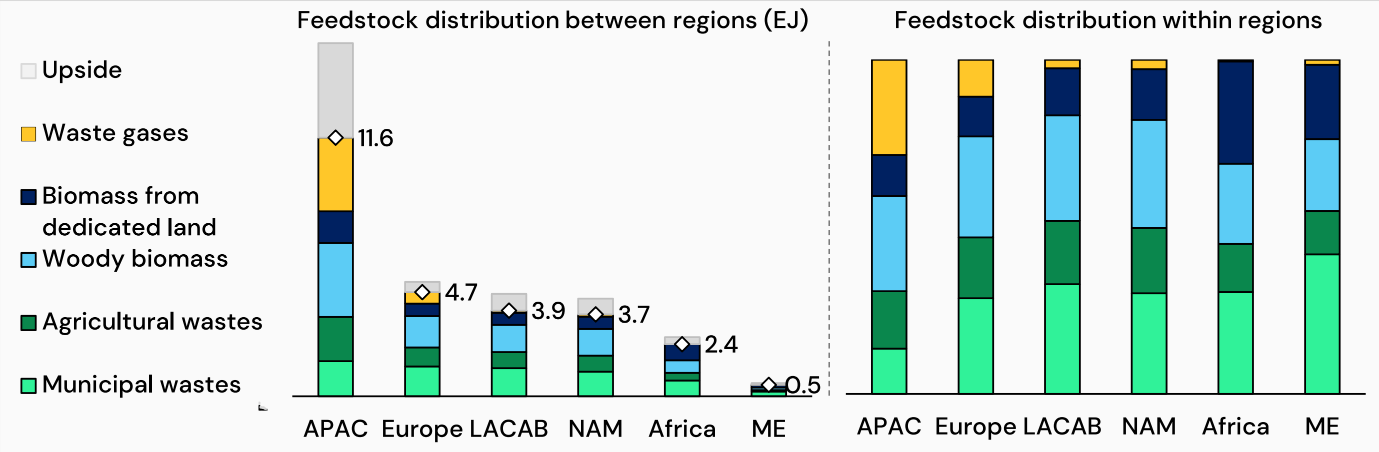
What is the regional distribution of this feedstock?

While some feedstocks (such as UCO) are sufficiently valuable for a given weight to justify transporting long distances, most potential feedstocks (such as forestry residues) are only economical when the transport costs are minimized by refining into higher value intermediaries or finished products close to the point of collection. Therefore, the local availability of feedstocks will determine the infrastructure required in each region.

[43] And other smaller sources, such as geothermal
[44] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

The geographic, climatic, and societal differences in each country provide each region with a different opportunity set. Through detailed analysis of each feedstock, the distribution between each region has been calculated and is illustrated below.

APAC leads feedstock supply; remainder spread across all regions



Sources: ICF Analysis

This shows the different magnitude and mix of feedstocks in each region. The difference in size, population and wealth of the regions challenges direct comparison, but initial implications can be made by comparing the share of feedstock to the share of passenger traffic in 2019, as calculated in the ATAG Aviation: Benefits Beyond Borders report[45].

Table 7: Ratio of 2050 passenger traffic (RPKs) to feedstock availability in each region

	APAC	Europe	LACAB	NAM	Africa	ME
Share of RPKs (2019)	36%	25%	6%	26%	3%	4%
Share of RPKs (2050)[46]	42%	21%	5%	23%	3%	5%
Share of feedstock[47]	46%	17%	14%	13%	8%	2%
Ratio of feedstock to RPKs (2050)	**1.1**	**0.8**	**2.8**	**0.6**	**2.7**	**0.4**

Source: Share of Revenue Passenger Kilometers (RPK) (IATA Forecast), Share of feedstock (ICF analysis)

Almost half of all feedstocks, and approximately a third of the bio-feedstock, is distributed across the Asia Pacific region, which includes India, China, South-East Asia, Indonesia, and Oceania, amongst others. This significant geographic spread also offers a range of feedstock types, with considerable municipal wastes (which includes both municipal solid waste and waste lipids) complemented by a high availability of forestry residues and potential for biomass from dedicated land. The concentrated heavy industries across Asia Pacific generate significant waste gases that will be crucial to utilize over the next decades, and there is also significant potential to extend the bio-feedstock availability through reduced land use for. Effective utilization of the significant feedstocks available in Asia Pacific will be essential for aviation to decarbonize.

[45] https://aviationbenefits.org/
[46] Revenue Passenger Kilometers (RPKs) will not directly link to SAF demand, with traffic types and lengths creating differences in fleet mix and opportunities for hydrogen or electric aircraft, and different growth rates distorting the relative shares of traffic, but this comparison may be useful for a sense of magnitude
[47] Including bio-feedstocks and waste gases; not including renewable power

Europe, which includes western and eastern Europe and Russia, contains a quarter of total available feedstock. Municipal waste production is strongly correlated with population and wealth, and while only ~10% of the global population resides in Europe, the region generates over 30% of the global GDP and consequently produces a significant volume of municipal waste. While this is somewhat tempered by high recycling rates, the unrecyclable and post-recycled components provide a high availability of municipal waste that can be used for SAF production. There are also relatively high woody residues, primarily produced through the managed forestry in the Nordics, Russia, and some of the Eastern European countries. The large aviation industry in Europe results in a particularly low ratio of feedstock to aviation activity, suggesting that the region may need to utilize feedstocks and fuels internationally to decarbonize.

Latin America and the Caribbean includes South America through to Central America and Mexico, and the Caribbean Islands. While a relatively small portion of energy, the biomass from dedicated land has a high percentage of oils from Jatropha, which can produce a high yield of biofuels and presents a particular opportunity for this region. While this region has the highest forestry area of any region, the high carbon stock and biodiversity limits their use for managed forestry. LACAB offers comparatively high feedstock availability for the level of aviation activity in the region.

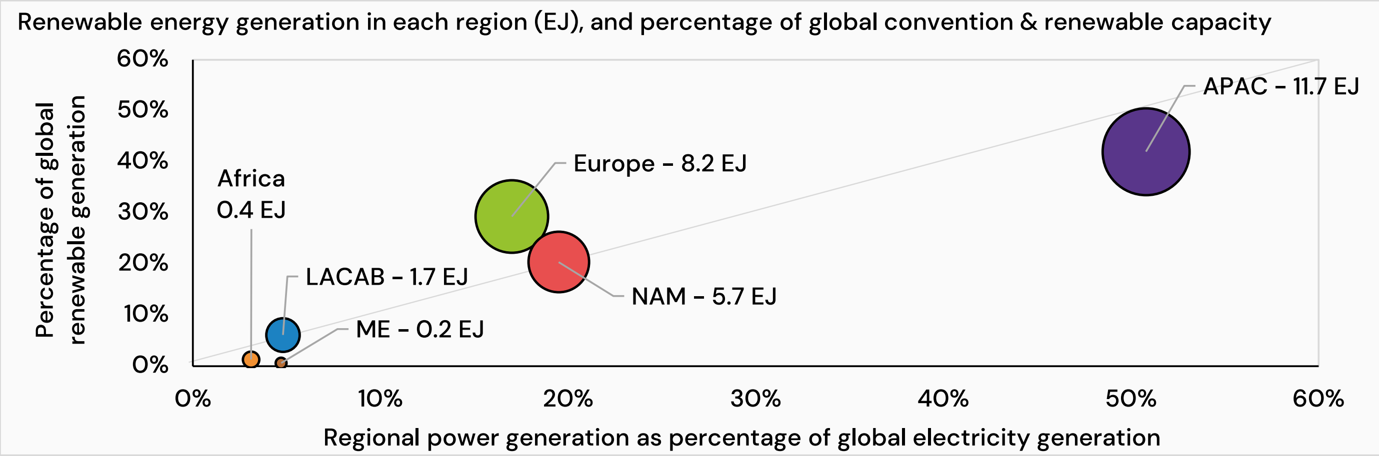
North America includes the US and Canada, and has an even distribution of feedstocks, with the managed forests in the eastern states and Canada providing forests residues, the central states producing agricultural residues and large cities producing municipal wastes. At just 3%, this region has the smallest population, but generates a fifth of global GDP and has a high propensity to fly. This drives the one of the lowest ratios of feedstock availability to aviation activity in any region.

Africa has a particularly high availability of bio-feedstock from dedicated land, including opportunities for both cellulosic and oil-bearing feedstocks. This land availability may be even higher in the short term, with much of the potential land reserved to accommodate the substantial population growth, from 17% of global population in 2020 to 25% in 2050. The comparatively small aviation activity in Africa result in an exceptional ratio of feedstocks to aviation activity, and while this may reduce with rapid growth in the industry, there is a clear opportunity for Africa to lead the development of a sizeable SAF industry.

The Middle East is the smallest region geographically and equally has the lowest availability of bio-feedstocks. Municipal waste is a particularly high percentage of the feedstock that is available, and the lipid fraction of this may align with the regional opportunity to retrofit fossil fuel infrastructure. The large connecting airlines in the Middle East drive significant traffic within the region, and the limited local feedstock availability may require the use of alternative feedstocks, such as the plentiful sunlight and suitable land for the non-biological feedstock pathways.

Each region offers different opportunities for SAF production through renewable power. Almost half of all electricity, and just over 40% of renewable electricity was generated in the Asia Pacific region in 2019. Europe and North America both generate slightly under 20% of global electricity, but Europe is somewhat ahead with 8.2 EJ of renewables compared to 5.7 EJ in North America. Latin America and the Caribbean generates a significant percentage of domestic energy through hydropower, with 1.7 EJ of renewables. Africa and the Middle East each generate ~5% of global electricity but have limited renewable generation.

~28 EJ of renewable electricity was generated in 2019, with just under half in APAC and most of the remainder in Europe and North America



Source: BP Statistical Review of World Energy, 2020. EJ values shown are input equivalent.

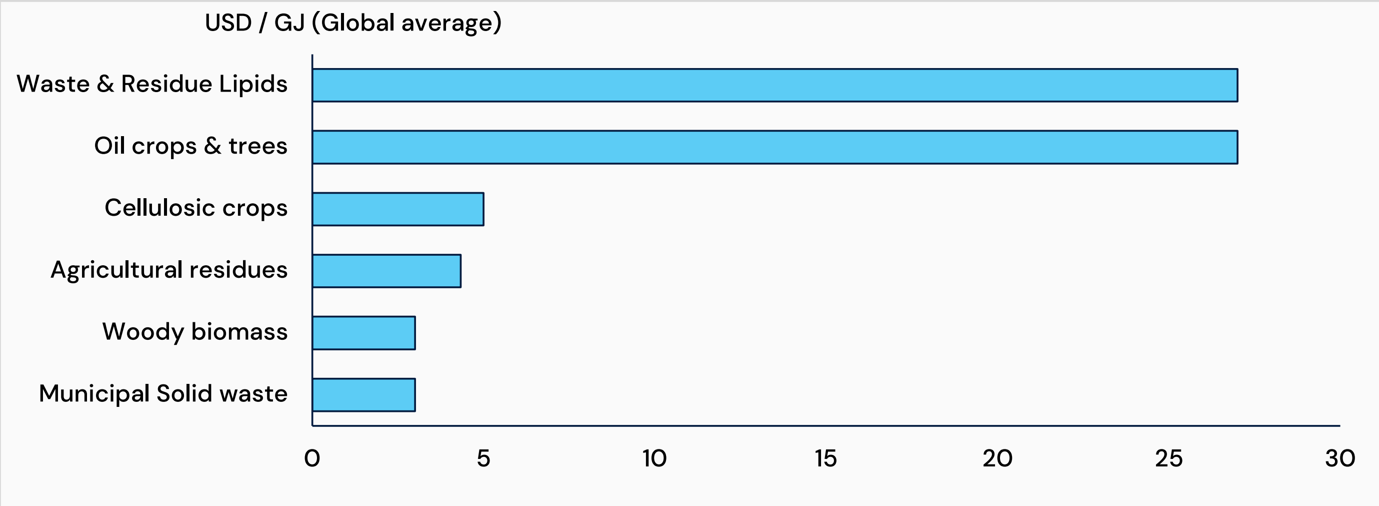
The distribution of renewables will rapidly shift as regions increasingly exploit the renewable natural resources. Renewable capacity in the Middle East grew by 45% over the past decade, although from a low base, and plentiful sunlight and strong winds hold the promise of a highly competitive renewable industry. Africa and Asia Pacific both grew their renewable industries at over 20% per year, which is particularly impressive considering Asia Pacific's high base. Renewable power generation in Latin America and the Caribbean grew at 16% over the past decade, while Europe and North America grew a little slower at just over 10% each year.

How much will feedstocks cost?

A high uptake of SAF will be unachievable if the fuel costs far more than conventional fuels. The feedstock cost can be a considerable part of the total SAF production costs, so understanding the current and potential cost for each feedstock is critical.

The cost for each feedstock is driven by the cost of production and the demand for the feedstock. As demand increases, the cost of production for many of the feedstocks will increase, for example as the remaining land for feedstock growth is of lower quality, or the agricultural residues are more distributed. These feedback effects of increased cost with increased demand are captured in the following analysis. High demand has disconnected the price of some feedstocks, particularly the waste lipids, from the cost of production. The market for these lipids is global, complex, and driven by both demand and supply side factors. As an example, the price of soy (used for renewable diesel production) has increased to a six year high by mid-2021, driven by poor harvests in some countries and additional demand from fuels and livestock feed in others. To model these effects, this study considers base prices and multipliers for some feedstocks. The base price is the best estimate of the cost of each feedstock today. For the feedstocks that are actively traded, this is set to the market value. For those that are not traded or only thinly traded, the value is set to the estimated cost of production plus an appropriate premium. For some, such as the oil and cellulosic crops, the cost of production is expected to increase with demand, and this impact has been analyzed and included.

Waste Lipids are most expensive, with other feedstock below $5/GJ



Source: ICF analysis. Values shown are global averages, some difference between regions. Waste & residue lipid costs based onreported market values in 2021 and oil crops and trees assumed to achieve same market value. Cellulosic crops and agriculturalresidues based on aggregated estimates of refinery gate costs. Woody biomass based on 2021 market values. Municipal SolidWaste cost represents sorting expense, underlying feedstock assumed to be zero cost. Gate fees for MSW included separately.

Waste & Residue Lipids

Waste lipids are actively traded, allowing accurate spot prices to be used. Recent UCO prices have set record highs[48], with continued demand accentuated by limited supply due to restaurant and bar closures during the pandemic. UCO is traded internationally, and currently over half of UCO used in the EU for biofuel production is imported, principally originating in Asia. The challenging logistics of pandemic operations have disrupted this market, further increasing the price, and driving considerable volatility.

To avoid distorting this analysis by using a value recorded during these exceptional circumstances, a value of $1,150 per tonne UCO has been used, which represents future expectations for UCO[49] and approximates the pricing seen in 2019 and the pre-pandemic months of 2020.

Other sources of useable lipids are marginally cheaper but typically require greater processing. PFAD and POME typically follow the trajectory of crude palm oil and trade at a slight discount with prices reaching $740-$770 per tonne in December 2020[50]. The EU reports typically animal fat prices of $350-500 per tonne[51], which is corroborated by the USDA tracking, with a 5-year average of ~ $500 per tonne (25 $/cwt)[52]. For simplicity, an average value of $1,150 per tonne waste lipid feedstock has been used in every region. This study used regional values for feedstock availability and implicitly assumes feedstocks are converted into fuels by local refineries, so parity in each region reflects an assumption of local supply and consumption. Continued international trade may result in higher costs in regions where demand far exceeds supply (as it does today in the EU) and increases in demand for sustainable feedstocks may further increase costs, suggesting that while a value of $1,150 per tonne is relatively aggressive in historical terms, it may be conservative for the next few decades.

48 https://www.argusmedia.com/en/news/2183456-recordhigh-uco-prices-squeeze-eu-ucome-margins
49 Source: Argus Media
50 https://www.argusmedia.com/en/news/2172467-viewpoint-asian-biodiesel-resurgence-limited-by-costs
51 https://ec.europa.eu/energy/sites/ener/files/documents/Annex%20II%20Case%20study%202.pdf
52 https://mymarketnews.ams.usda.gov/filerepo/

Non-food crops, including oil crops & trees and cellulosic crops

Non-food crops for biofuel feedstock are currently grown in relatively small volumes. This analysis considers these crops in two categories; crops or trees to produce oils that can be converted to fuels via the HEFA pathway, and cellulosic crops that can be fermented or gasified for subsequent conversion into SAF.

The cost for both the oils and cellulosic crops is driven by the cost of production and will increase with demand. Many of the production costs are fixed for a given harvest, such as the machinery, labor and consumables required, while the yield will depend on the quality and suitability of the land. The initial demand can be met with crops grown on high-quality land, offering high yields and low prices. As demand increases the crops will progressively be grown on land of decreasing quality, offering lower yields but requiring the same fixed costs, driving up marginal prices.

The environmental benefit from use of low-quality land is also reduced. This analysis assumes that the land used for these dedicated crops is currently unutilized to avoid the displacement impact from using existing cropland. Conversion of unutilized land for agricultural use incurs a carbon debt as an estimated 20-50% of soil carbon is released when native vegetation is converted[53]. If land has a particularly high carbon stock or low expected yields, this paydown period will become infeasibly long and result in zero or negative carbon benefits from the use of the land. To illustrate, the estimated carbon payback period from the conversion of peatland or tropical rainforest for palm oil or soybean production can be nearly 700 years[54] – with additional negative impacts to biodiversity. The economic and environmental limitations therefore provide a lower limit to potential yields, with poor quality land producing feedstock that is both costly and represents a minimal carbon benefit.

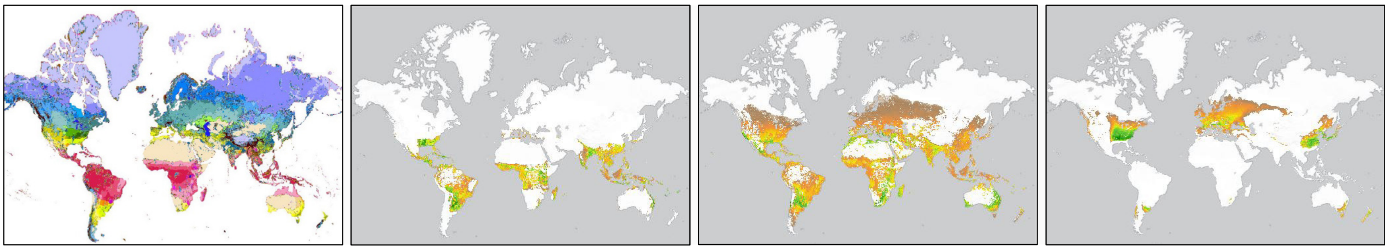
The initial price for the cellulosic cover crops was set to the cost of bioenergy grasses as tracked by the USDA. Assuming a 15% moisture content and energy content of 18.5 MJ/dry Kg, this gives 4.8 USD/GJ (88 USD/ dry tonne). The initial cost for the oil harvest from oil crops and trees is set to equal the market price for the waste and residue lipids. It was assumed that increases in production cost can be passed through to the consumer.

The key factor in the increase in production cost is the availability of suitable land in each region. As land suitability depends on the crops, three different crops were analyzed: Miscanthus, Switchgrass and Jatropha. The first two provide cellulosic feedstock while Jatropha yields oil-bearing seeds. All three of these crops can be grown on poor quality land, reducing the competition with food crops, and each is suitable for different climates, ensuring the potential in each region is accurately captured.

The FAO Global Agro-Ecological Zones database[55] was used to assess the suitability for each crop, using their requirements for specific climate and land (edaphic) conditions. The underlying Agro-Ecological Zones (AEZ) classification is illustrated on the left-hand side of Figure 14 and can be compared to the suitability for each of the selected crops in the remaining panels. As shown, Jatropha is particularly suited to the tropical latitudes, and while Switchgrass is well suited to specific temperate climates, Miscanthus is broadly suitable for a wide range of conditions.

[53] Scharlemann et al. (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. https://www.tandfonline.com/doi/full/10.4155/cmt.13.77
[54] https://econpapers.repec.org/article/eeerensus/v_3a70_3ay_3a2017_3ai_3ac_3ap_3a161-184.htm
[55] https://gaez.fao.org/

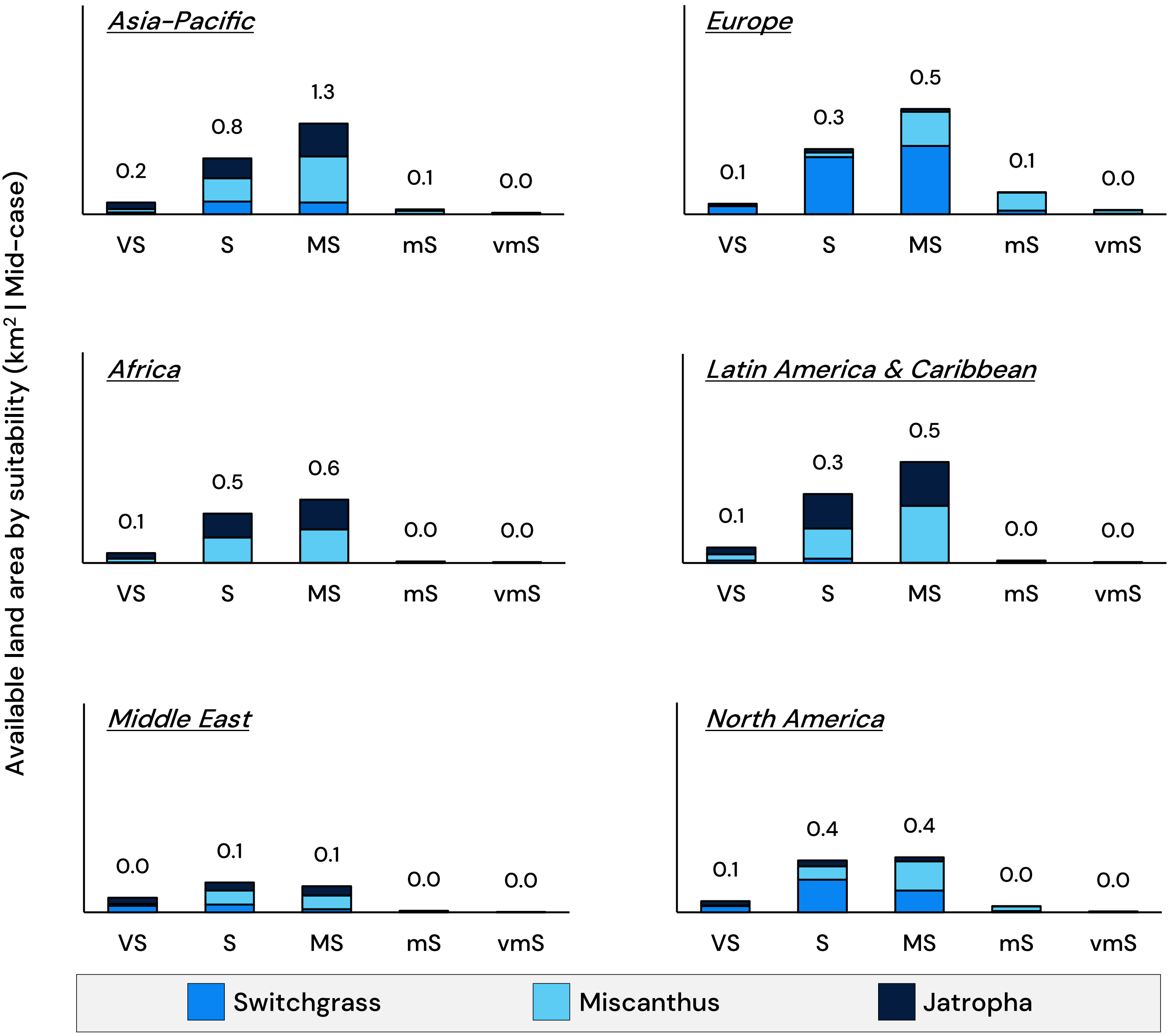
From left: Current land use in the GAEZ model, suitability for Jatropha, Miscanthus and Switchgrass



Source: FAO GAEZ, ICF Analysis

The land unsuitable for feedstock growth was removed from the analysis, including land required for food crops and livestock rearing & feed, forests, land with high embodied carbon, protected regions, built-up areas, and land offering uneconomical yields. The distribution of land suitable for each crop in each region has been illustrated in the following figure, using the GAEZ definitions: VS = Very Suitable, S=Suitable, MS = Moderately suitable, mS= Marginally suitable and vmS = very marginally suitable.

Suitability of available land in each region



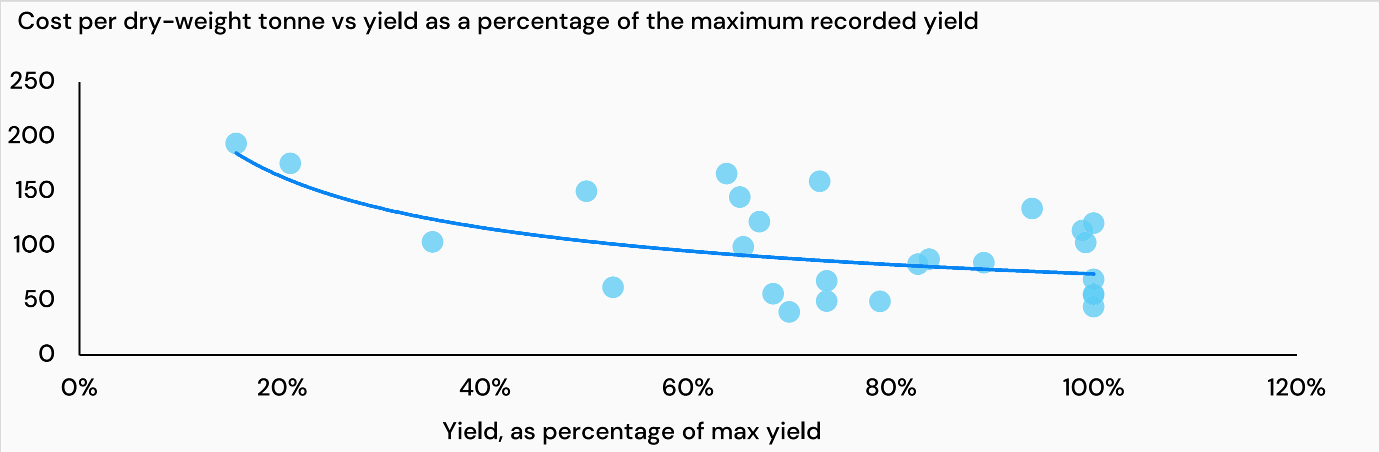
Source: ICF analysis

Globally, half the land is Moderately Suitable, just over a third is Suitable, ten percent is Very Suitable, with the residual in the lower categories. North America and the Middle East stand out with over half of available land Very Suitable or Suitable for the selected crops, while Europe has the lowest potential yield from the available land.

Africa and Latin America have the greatest land suitable for oil crops with Jatropha, with 46% and 48% respectively, followed by 37% in Asia and the Pacific. In the other regions the cellulosic crops dominate, with Jatropha more suitable than the cellulosic crops for 12% of land in North America and just 4% in Europe.

A great deal of research has already been published on the potential yield for all three of the selected crops. This research was aggregated and used to calculate a series of yield-curves, with as shown in the following example for cellulosic crops. The impact of yield on cost is clearly shown, with the cost per dry tonne of feedstock varying from less than 50 USD on the highest-yielding land, up to 200 USD on marginal land. The noise in the data illustrates the considerable uncertainty, driven by different assumptions for financial parameters such as land rent, and the more nuanced factors, such as the perennial nature of the crops resulting in a gradual increase in yields over time.

The cost of energy crops on dedicated land varies from 50-200 USD/t depending on the yield of the available land

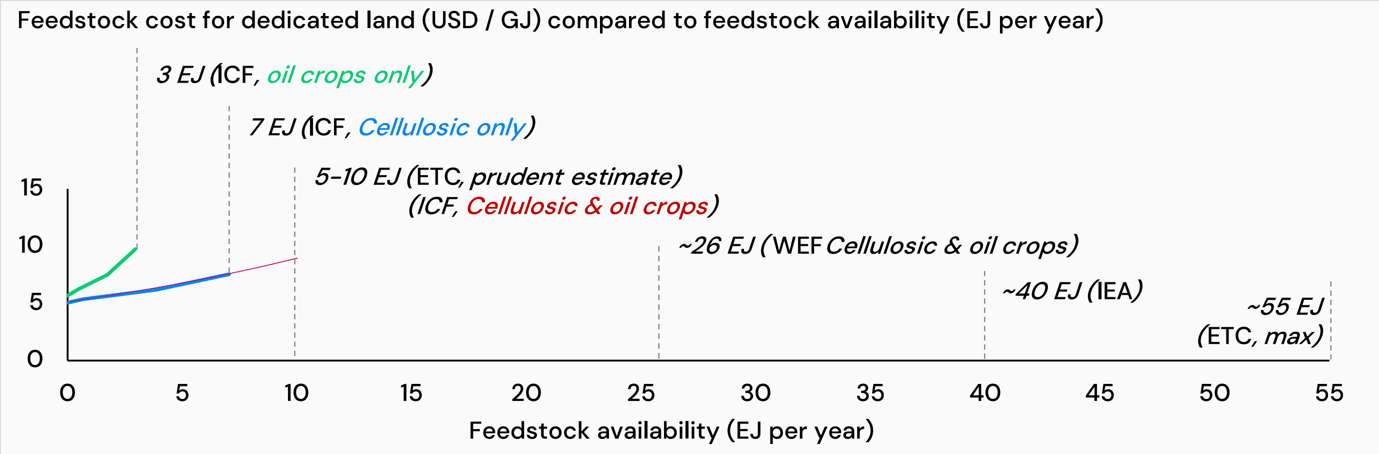


Source: "An integrated biogeochemical and economic analysis of bioenergy crops in the midwestern United Stated", Jain et al, "U.S. Billion-Ton Update", US DoE, "Costs and Profitability of Crops for bioeconomy in the EU", Panoutsou et Al. "Economic and greenhouse gas costs of Miscanthus supply chains in the United Kingdom", Wang et al, "Spatiotemporal assessment of farm-gate production costs and economic potential of Miscanthus × giganteus, Panicum virgatum L., and Jatropha grown on marginal land in China", Zhang et al.

The realistic potential for each of these crops is still to be proven. Disappointing practical results have limited the use of Jatropha, with recorded crop yields of 0.5 – 2 tonnes per hectare in India, Belgium, South Africa, and Tanzania falling far short of the estimated break-even yield of 4-5 tonnes per hectare[56]. Typically, no seeds can be harvested for the first 3-5 years after planting, limiting the industry growth rate and increasing the payback period for farmers. These may improve as the industry scales, with a greater understanding of the plant, improved seed strains, and better processing of the seeds.

[56] https://www.intechopen.com/books/frontiers-in-bioenergy-and-biofuels/jatropha-biofuel-industry-the-challenges

The cost of feedstocks from dedicated land increases with demand, as production is increasingly driven to land offering lower yield



Source: ICF Analysis, using FAO GAEZ dataset, reports including "Bioresources within a net zero emissions economy: Making a sustainable approach possible, ETC, July 2021. "Net Zero by 2050: A Roadmap for the Global Energy Sector", IEA, Revised June 2021, "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", WEF, 2020

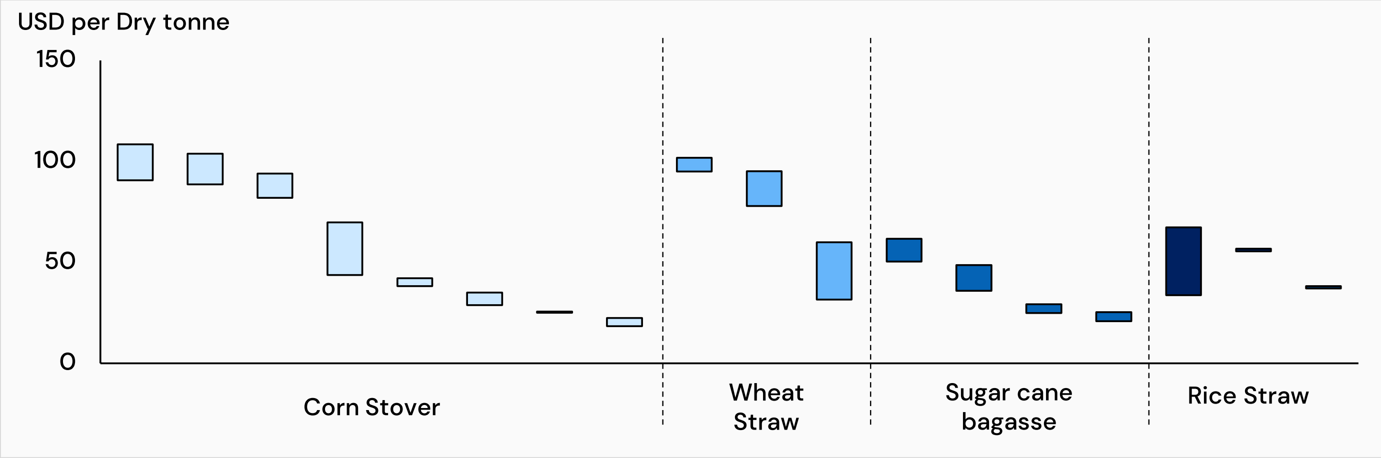
The consolidated results show relatively sharp increases in feedstock cost at greater levels of demand and provides perspective to the assumptions on total feedstock availability from dedicated land from the ETC analysis. The qualities illustrated are for all industries, and the quality of land and hence yield has been prorated between industries and in the high and low cases considered.

Agricultural residues

Each crop type provides a different Crop-to-Residue-Ratio (CRR), which alongside the local growth characteristics, determines the volume of residues created. To limit soil erosion and carbon and nutrient loss, the majority must be left in-situ. The remaining residues can be gathered, and alongside any processing wastes, can be used as feedstock.

The cost to gather these feedstocks is dominated by economic factors such as machinery and labor cost, which vary with crop type. This cost was assessed through a comprehensive literature review to provide the cost for each crop type, which was then weighted by the crop distribution in each region to develop separate estimates. Corn, maize, sugar cane and rice were investigated, and the results were adjusted for inflation and moisture content to ensure consistency.

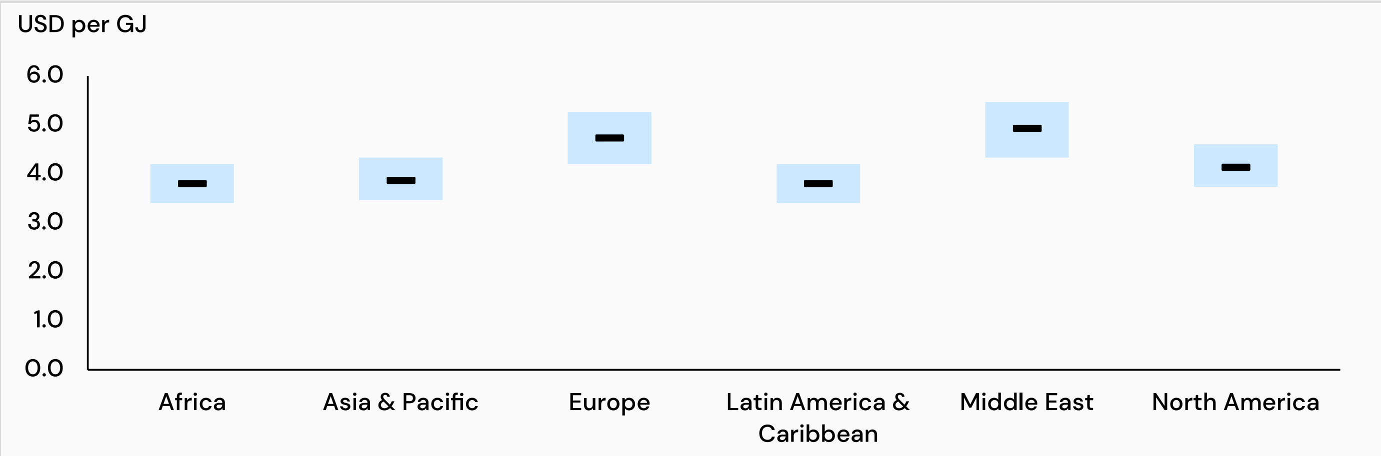
Agricultural residue collection costs vary by crop, driven by residue ratios and assumed labour & equipment expenses



Source: "Biofuel Costs, technologies and Economics in APEC Economies", APEC Energy Working Group, "Biomass power generation. Sugar cane bagasse and trash", Hassuani et al, 2005, "Rice Straw and Wheat Straw: Potential feedstocks for the biobased Economy", Bakker et al, 2013. "Supply and social cost estimates for biomass from crop residues in the United States", Gallagher et al, 2003.

The average, high and low range for each crop was calculated and combined with the distribution of crops in each region to provide the average cost and associated range in each region. The highest costs are expected in Europe, driven by the high cost and share of wheat in the crop mix. Africa and Asia Pacific are likely to have the lowest costs due to the low cost for rice straw and other wastes such as sugar cane bagasse.

The differences in crops grown in each region and labour expenses result in small variations in the residue collection cost



Source: ICF Analysis. Calculated by combining the residue collection cost for each crop with the distribution of crops grown in each region. Crop distribution from FAOSTAT.

Woody biomass

Woody biomass refers to forest residues such as treetops, branches, and stumps from timber harvests as well as residues from wood processing industries such as sawdust, bark, and scrap-wood. These residues are used for low value applications such as heat and power generation or pulpwood, but a considerable amount remains unutilized due to a lack of existing high-value applications, policy or market incentives, extraction costs and in some cases, infrastructure.

The cost as a feedstock consists of harvesting, processing, storage, and transportation. On-site processing, such as grinding or chipping, is typically required to improve transportation efficiency. Conventional harvesting systems can be expensive due to high machine costs and low machine utilization rates. Cost analyzes in North America estimate the refinery gate cost per dry tonne at $30-$60[57], while similar studies for Europe estimate $35-$95, matching the low end but suggesting a higher range[58]. These studies are corroborated by the costs seen in the market today.

Municipal solid waste

Municipal solid waste is a heterogenous feedstock, composed of multiple streams of waste (food, greens, plastics, paper, card, and others), with diverse approaches to collection and management. The cost for feedstock use is driven by the existing collection and disposal infrastructure and sorting costs, and potentially reduced by disposal incentives such as gate fees.

Collection rates vary substantially by region. North America, Europe, and Central Asia report collection rates close to 100%, while South Asia and sub-Saharan Africa report rates of 44%. Other regions fall towards the higher end of this range. These collection rates are expected to rapidly increase as countries look to build-out the required infrastructure, reduce pollution and improve health.

Once collected, the waste management approaches vary substantially. At a global level, only 19% is recycled or composted. Over 60% is disposed in open dumps and various types of landfill, and the remainder is incinerated. Without progress, the World Bank forecasts global waste emissions will rise to 2.6 bn tonnes of CO_2e by 2050, from 1.6 bn tonnes in 2016 (5% of global emissions)[59]. The situation at the country level is more nuanced with substantial variations across collection, recycling, composing, landfills (managed & unmanaged), open dumping and incineration (with and without power recovery). Economic and regulatory factors drive this, with up to 20% of municipal budgets spent on waste management and the cost for recycling or composing varying from $5 - $90 per tonne.

As we move to a more sustainable world, the priority should be reducing the waste produced, followed by re-use and recycling. Where this is not possible, for example with waste that is too mixed, degraded or unsuited for recycling, biofuel production offers a route to use the waste to produce a high-value product while reducing pollution and emissions. The benefits are particularly stark for biogenic wastes; when landfilled these degrade to produce methane, and with a global warming potential 28-34 times that of the CO_2[60], even slight fugitive emissions have a steeply negative impact. Similarly, incineration yields very little energy from the waste and is primarily useful only to reduce volume to make landfill easier[61].

The cost as a feedstock is a consequence of these factors. In some countries, high gate fees will allow SAF producers to claim the financial benefits of avoided landfill and provide a negative cost for the feedstock. Many other countries allow use of the waste for free, benefiting indirectly through the reduced pollution. Once received, the waste must be sorted and processed, which typically costs ~$40 per tonne of waste.

[57] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-BIOMASS.pdf

[58] https://www.bioboost.eu/uploads/files/bioboost_d1.1-syncom_feedstock_cost-vers_1.0-final.pdf

[59] https://openknowledge.worldbank.org/handle/10986/30317

[60] https://unece.org/challenge#:~:text=Methane%20is%20a%20powerful%20greenhouses,are%20due%20to%20human%20activities.

[61] https://e360.yale.edu/features/as-china-pushes-waste-to-energy-incinerators-protests-are-mounting

This assessment assumed that gate fees range from $60 per tonne to $0 and combined this with the sorting costs to give a feedstock range from -$20 to $40 per tonne. It is assumed that initial facilities will be constructed in regions where they can benefit from favorable regulation, so this range was integrated as an increasing cost for MSW feedstock with demand. The first factories receive feedstock at -$20 per tonne, while facilities constructed when feedstock demand is close to 100% incur the full sorting costs.

Affordability of non-biological feedstocks

Industrial waste gases

The cost to use industrial waste gases for SAF production is driven by three elements: the value of the energy, a transition premium, and the cost for additional hydrogen to achieve the optimum CO:H2 ratio for synthesis. To estimate the energy value the cost for equivalent renewable electricity was calculated, assuming the refineries would transition to grid-based renewable power if the waste gas was not available. The premium was added to represent the transition costs and to incentivize steel mills to work with the SAF producers. The hydrogen is useful to adjust the ratio of carbon monoxide to hydrogen in the waste gases to realize the highest yield of ethanol and the cost was calculated using the stoichiometric demand and expected hydrogen costs.

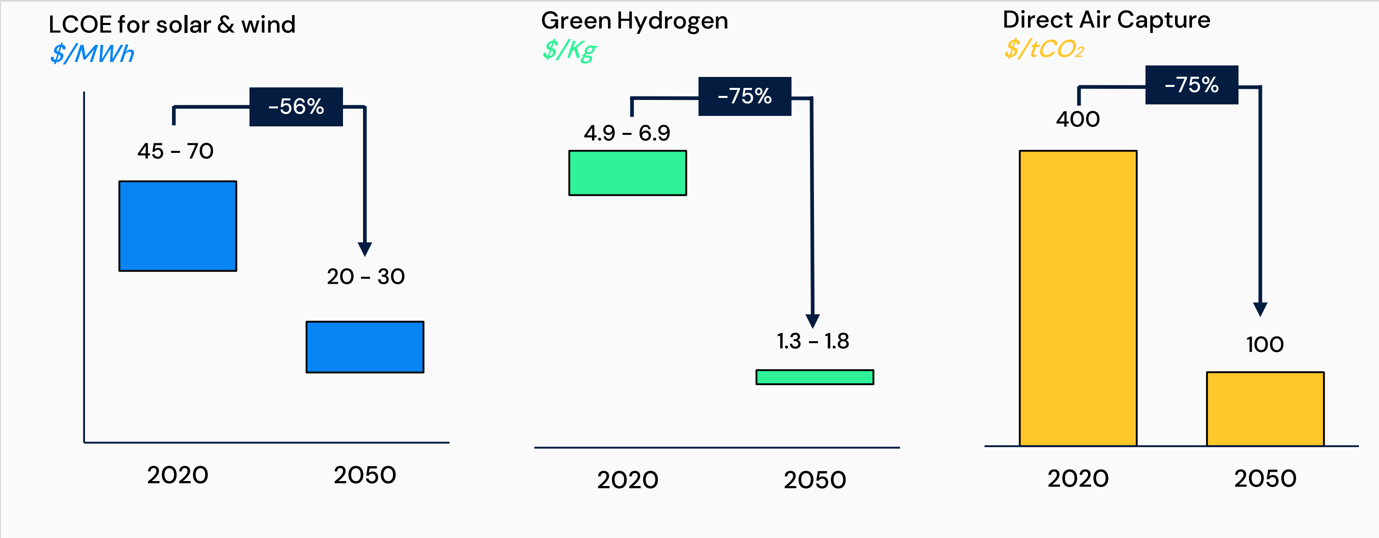
Syngas production through Power-to-Liquids

SAF can be produced using renewable energy, water, and air. In this process, renewable electricity is used to electrolyze water to produce hydrogen and for Direct Air Capture (DAC) of CO_2 from the atmosphere. The CO_2 can be converted to Carbon Monoxide, and when combined with hydrogen becomes equivalent to syngas, which can then be used as the input for either the FT or AtJ pathways.

The production of SAF in this manner has many appealing characteristics, including no requirement for physical feedstocks (beyond water and air) and the potential for fuel with high emission reduction factors. However, this pathway requires a significant amount of electrical energy, and to ensure a net reduction in carbon emissions, this energy must be generated using renewable stations, such as wind turbines and solar panels.

There are four main cost drivers for this pathway: the cost of renewable electricity, the electrolysis expense, the cost for direct air capture of the carbon, and the cost to convert the resulting syngas into fuels. This section investigates the first three costs, which together produce syngas. While electricity is the primary feedstock, the syngas is the main feedstock for the fuel conversion pathways

Renewable energy, hydrogen and carbon capture costs



Source: ICF analysis. Values show industry averages, some exceptional projects will be outside these ranges. LCOE based on ICF analysis using IEA, IRENA, US NREL datasets. Hydrogen production costs use LCOE input and estimated electrolysis infrastructure cost, assuming evolving mix of Alkaline, PEM and SOEC technologies. DAC costs assume commercial scale facilities, using cost estimates from expert interviews.

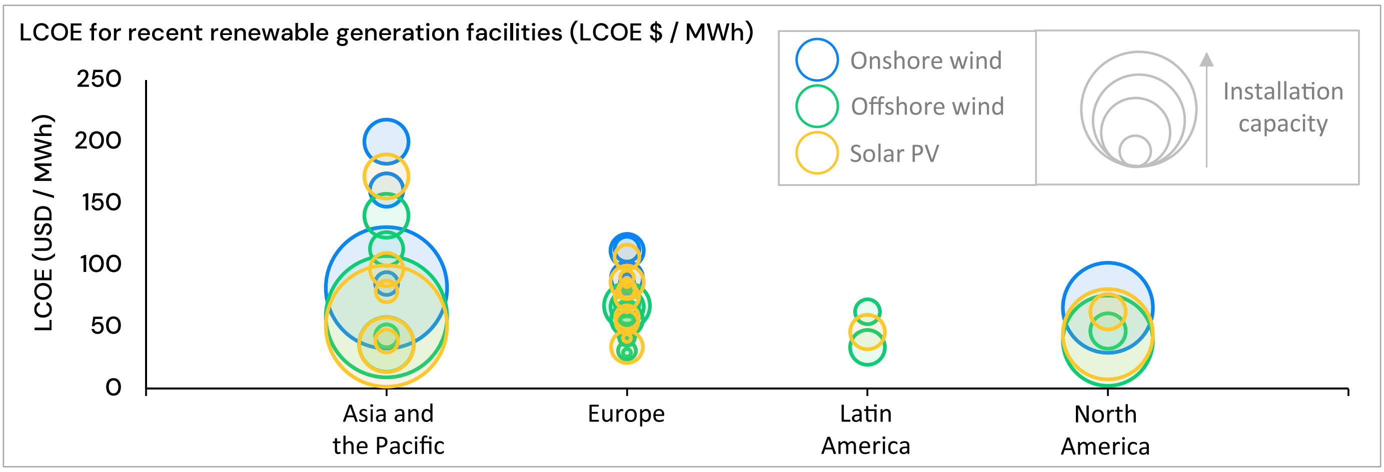
Renewable electricity costs

Renewable electricity is required for both the production of green hydrogen and the extraction of carbon from the atmosphere. Renewable energy costs were calculated as the Levelized Cost of Electricity (LCOE), which is used as a proxy for the cost required to incentivize renewable energy development for sustainable aviation fuels. Historical data on LCOE by country and region has been merged with projections on LCOE by technology type. Projections for renewable energy deployment were used to weight each renewable energy technology LCOE, and countries were weighted by their demand for electrical energy to develop a consolidated value across each region. The analysis incorporates historical information from a variety of sources, including the International Energy Agency, the International Renewable Energy Agency, and the US National Renewable Energy Laboratory.

The LCOE for renewables has been rapidly decreasing; five years ago, the global median renewable LCOE exceeded USD 150/MWh and has plummeted to well below USD 100/MWh[62] and is expected to continue falling over the next decades. Significant variations remain between countries and projects, driven by the ease of construction, value of land, and suitability for renewable power generation, such as strong winds or reliable sunshine.

[62] https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

Renewable LCOE varies significantly between installations



Source: IEA, IRENA, US NREL, ICF Analysis

There is significant variation in the LCOE between facilities, as illustrated – recent tenders have been seen as low as $10/MWh, while others can be over $200/MWh. The PtL production in this analysis achieves considerable scale, and while some early facilities may be co-located with facilities offering power at the low end of this range, the scale of production will drive PtL towards the industry average LCOE. Consequently, the average LCOE for renewable facilities has been used as the baseline to ensure the analysis is internally consistent. In addition, production will be a trade-off between using electricity when there is excess (e.g., curtailed power) and ensuring a high utilization of the infrastructure for electrolysis. This analysis has applied a small discount to the LCOE to represent this trade off.

Hydrogen production

Hydrogen can be produced in several ways, including from fossil fuels (gray hydrogen), from fossil fuels with carbon capture (blue hydrogen) and through electrolysis using renewable electricity (green hydrogen). The main pathways for hydrogen production today are fossil fuel based. Natural gas is the largest source of hydrogen production through steam methane reforming (SMR), representing three-quarters of the 70Mt of annual hydrogen produced and emitting 10 tonnes of CO_2 per tonne of hydrogen. It is followed by coal, generating just below a quarter of total hydrogen, and emitting 19 tonnes of CO_2 per tonne of hydrogen[63]. Hydrogen produced in this manner generates considerable life cycle emissions and cannot be used for SAF production.

According to the IEA, applying carbon capture utilization and storage (CCUS) solution to SMR plants could reduce carbon emissions by up to 90%. This 'blue hydrogen' improves the environmental attributes, but significant fugitive emissions remain, reducing the life-cycle emissions reduction of the SAF produced. While hydrogen produced in this manner is currently cheaper than green hydrogen, research by ICF has estimated that green hydrogen could achieve cost-parity with blue hydrogen by 2050[64], which suggests a steep advantage for green hydrogen once the environmental attributes are also considered.

63 https://www.iea.org/reports/the-future-of-hydrogen

64 https://www.icf.com/insights/energy/economics-hydrogen-energy#

This analysis has focused on green hydrogen for SAF production, and all costs and environmental attributes have been calculated on this basis. Very little hydrogen is produced through electrolysis as of 2020, representing less than 0.1% of total dedicated hydrogen production. However, the focus on green hydrogen has greatly increased recently, with Europe publishing a roadmap for production of at least 10m tonnes of renewable hydrogen in the EU[65] by 2030, Japan publishing a roadmap for annual production of 300,000 t/ H2 by 2030 and up to 5-10 mt in the long-term[66], and the US setting a target through the Earthshot initiative to produce renewable hydrogen at $1/Kg within a decade[67]. These initiatives will likely stimulate the industry and achieve significant reductions across the supply chain.

The cost of green hydrogen is influenced by the technology of electrolyzer used, the infrastructure utilization, lifetime, efficiency, and the cost of renewable energy. The cost of renewable energy has been calculated as the average LCOE for each region. Four types of electrolyzer have been considered, including Alkaline (AEC), Proton Exchange Membrane (PEM), Solid Oxide Electrolysis Cells (SOEC) and Anion Exchange Membrane (AEM). Each technology is at a different stage of maturity, and the technical development and the cumulative capacity for each has been assessed and combined to estimate the infrastructure cost and conversion efficiency for hydrogen production.

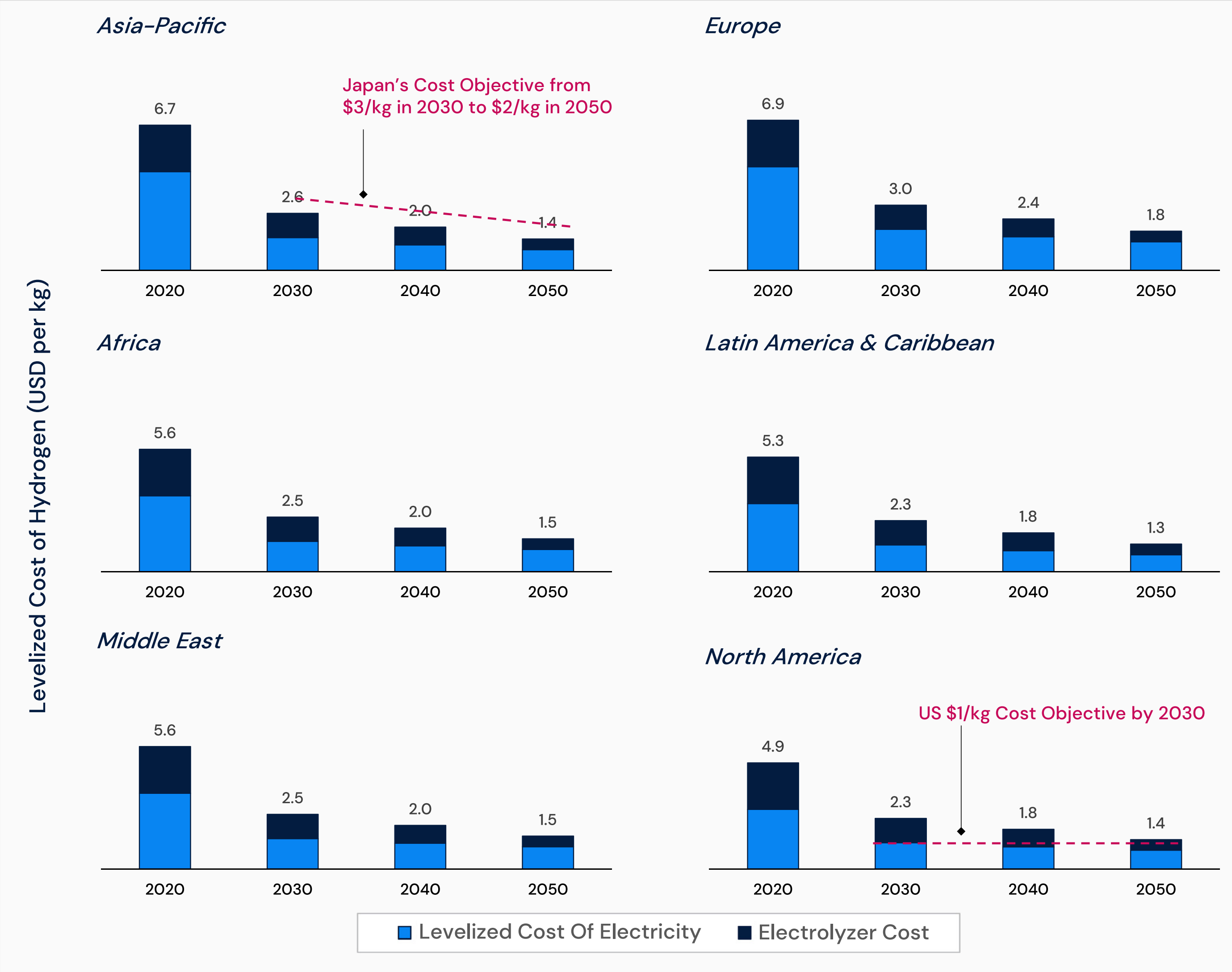
The cost of other inputs for hydrogen production, such as water, have been included, although these add little expense. There may be interesting synergies across the industry to further reduce costs; for example, the electrolysis also produces oxygen, which is frequently vented. This could be a valuable input for the gasification segment of SAF facilities, suggesting benefit to co-locating infrastructure.

[65] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

[66] https://www.meti.go.jp/english/press/2017/pdf/1226_003a.pdf

[67] https://www.energy.gov/eere/fuelcells/hydrogen-shot

Projections of the Levelized Cost of Hydrogen by region



Source ICF analysis

Carbon capture costs

Jet fuel is ~81% carbon by weight, and the carbon for this must be extracted from the atmosphere via Direct Air Capture (DAC). This yields carbon dioxide, which is ~27% carbon by weight, so a minimum of 3 tonnes of CO_2 must be captured per tonne of SAF produced – and more, if there are any losses during conversion. Once captured, the CO_2 must be converted into Carbon Monoxide for use as a syngas, which can be done using the Reverse Water Gas Shift (RWGS) process. This combines hydrogen (supplementary to the hydrogen required for the syngas) with the CO_2 to produce carbon monoxide and water.

Several approaches can be used to capture carbon, differing in the source and approach. When used for industrial waste gases, the carbon is highly concentrated and is relatively affordable to capture. While some degree of re-use of industrial waste gases, particularly those containing carbon monoxide has been included, this has only been included on a limited scale. Point capture of CO_2 may represent a considerable bridging feedstock for PtL production, although the net carbon reduction would be significantly reduced due to low rates of carbon capture (50% and 94%[68]) and only the factory or airline can claim the emissions reduction to avoid double counting. The use of point-captured CO_2 represents an upside to this analysis.

In the atmosphere, Carbon Dioxide represents 412 parts per million, equivalent to 0.04%. Due to this low concentration, significant volumes of air must be processed to extract meaningful volumes of Carbon.

There are currently two main technologies to achieve this[69]:

1. **High temperature (HT) aqueous solutions:** the carbon dioxide from ambient air is brought into contact with a solvent to form a solution of sodium carbonate. It is then heated to 900°C to release the CO_2 and regenerate the solvent, and therefore also requires electricity, RNG or another source of high-grade heat.
2. **Low temperature (LT) solid sorbent:** ambient air goes through the system either naturally or with the help of fans and the CO_2 binds to the solid sorbent material through a chemical reaction. When the sorbent is fully saturated with CO_2, the system is closed, and CO_2 is released with lower levels of heating (80°C to 100°C depending on the sorbent) and the sorbent is regenerated.

Several companies are commercializing each approach. Carbon Engineering[70] is leading the development of the high-temperature route, with an operational pilot plant and commercial scale facilities under construction in the Permian Basin, U.S., and in North-East Scotland. Climeworks is pioneering the LT approach, with several pilot plants and a commercial plant nearing operation in Iceland[71]. Multiple additional companies are also rapidly developing these technologies.

The cost seen today are high, but only small-scale pilot plants are in operation. As large, commercial plants begin operations, the cost will rapidly decrease. This study assumes an initial cost of $400/tonne CO_2, which rapidly drops as the industry scales and the technology matures, with this analysis using a cost of $100/ tonne CO_2 in 2050. This may prove too conservative if the technology develops better than expectations, particularly if other industries use considerable carbon removals, allowing the industry to scale and further reduce costs. For context, a detailed technical analysis by Carbon Engineering estimated costs of an N^{th} of-a-kind 1 Mt-CO_2/year plant to be $94-$232/tCO_2[72].

Other requirements

Electrolyzers require clean water to perform the chemical separation into hydrogen and oxygen. Recycled water from RWGS can be feed back into the electrolyzer, supplemented by fresh or desalinated water. Desalination costs are marginal, below $0.01 per kg$H_2$, and this cost has been included. The water required for PtL is certainly less that that required for bio-feedstock production.

PtL facilities may also benefit from batteries to store renewable electricity, and hydrogen storage to ensure the FT of AtJ facility can be run at full capacity, while the electrolyzer use is optimized to match renewable electricity costs.

[68] Leeson et al., 2017. International Journal of Greenhouse Gas Control, 61 (2017), pp. 71-84: A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources
[69] Fasihi et al., 2019. Journal of Cleaner Production, 224 (2019), pp.957-980: Techno-economic assessment of CO_2 direct air capture plants
[70] https://carbonengineering.com/
[71] https://climeworks.com/
[72] https://www.cell.com/joule/pdf/S2542-4351(18)30225-3.pdf

Part 2

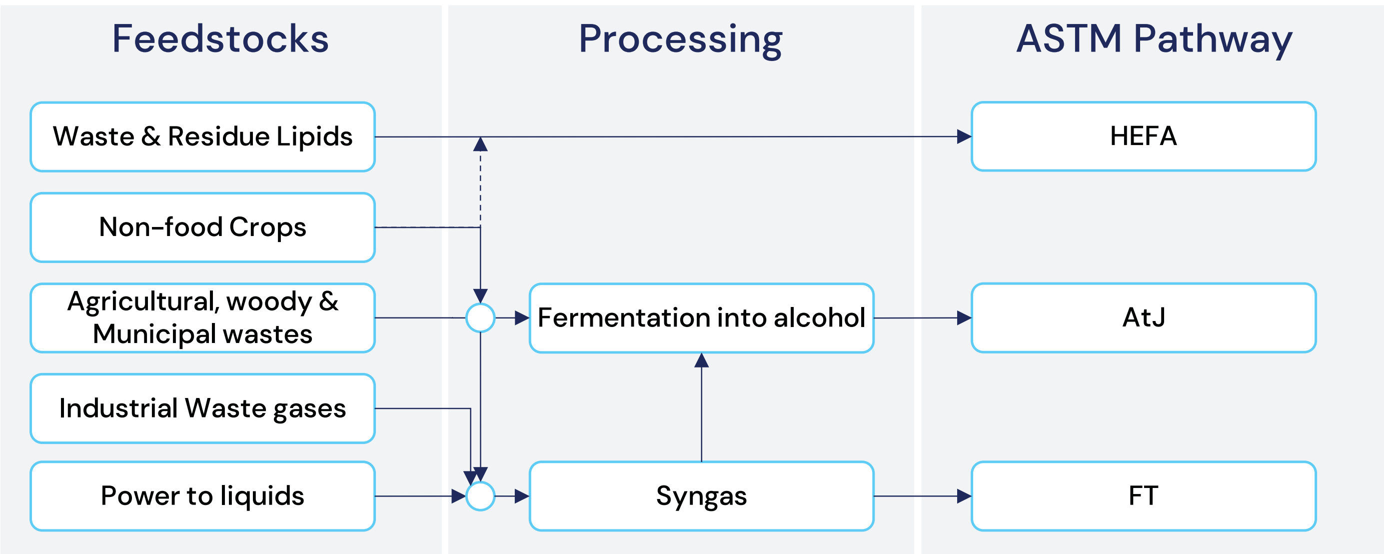
How much will it cost to produce SAF?

Several technologies can be used to convert feedstocks into fuels, each utilizing a different conversion process and requiring different infrastructure. Many feedstocks can be converted into fuel using a choice of pathways, allowing the industry to tailor the infrastructure to specific requirements.

The technical certification of these pathways is regulated by the American Society of Testing and Materials (ASTM) standard D7566, which specifies the technologies and specifications that can be used to produce SAF[73]. Once produced to the set criteria, the neat SAF must be blended to a specified ratio and will then meet the D1655 specifications, allowing safe use as a drop-in fuel for commercial aviation. Seven technology pathways are currently certified to produce sustainable aviation fuels, with several more approaches under consideration.

It is likely that the future development of the SAF industry will use all these pathways, with facilities built to produce fuels using both the existing pathways and those that will be certified over the coming decades. This report is not designed to choose a winner from these pathways or inform investments or research efforts. Instead, three of these pathways have been selected to illustrate the potential development of the industry, each representing a different set of benefits and trade-offs.

The three pathways selected for consideration are hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (AtJ) and gasification with Fischer-Tropsch (gas/FT). Each of these pathways is either in active use or advanced stages of development; World Energy and Neste operate facilities using HEFA, LanzaJet and Gevo are developing AtJ facilities, and Fulcrum, RedRock and Velocys are pioneering the gas/FT pathway – with many other companies and facilitates in various stages of development and construction.



These pathways each require different inputs. For the HEFA pathway, waste lipids can be used with relatively limited processing beyond cleaning and filtering. Oil-bearing crops much be pressed to yield oils and can then be used in a similar manner. The alcohol to jet (AtJ) pathway requires an alcohol as the input, which can be either isobutanol or ethanol. These can be made by direct fermentation of feedstocks, or through fermentation of syngas. The Fischer-Tropsch (FT) pathway uses syngas directly as a feedstock. In both cases, the syngas can be made through gasification of feedstocks, use of industrial waste gases, or

[73] https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf

manufacture using renewable electricity (PtL), and for the latter two an intermediary process is required to convert carbon dioxide to carbon monoxide. The following section describes each production process in more detail.

Hydrogenated esters and fatty acids (HEFA)

HEFA is the only pathway in commercial use today. The HEFA pathway can convert oils and fats to SAF, with potential feedstocks including UCO, waste animal and plants fats and oils, distillers corn oil, tall oil, and several others. The HEFA feedstocks are often high value for a given weight, facilitating the development of an active international market, and allowing facilities to be built with very large capacities by drawing on large feedstock catchment areas.

Feedstock costs are critical for HEFA production and typically drive significantly over three quarters of the price for the SAF produced. The facility costs are comparatively low, making this pathway suitable for investors seeking low initial investments and are comfortable with exposure to the commodity volatility. The technology is well proven in operation and the SAF produced is cheaper than most other pathways, although still significantly more expensive than conventional fuels. There are growing limitations to the feedstocks available, and in this analysis the HEFA pathway is expected to dominate the early years but subsequently contribute a smaller portion of the overall production mix as feedstock limitations are met.

As with all sustainable fuel technologies, the HEFA pathway produces a slate of products, including SAF, renewable diesel, naphtha, and light ends. Most HEFA production today is used to produce renewable diesel, however as ground vehicles increasingly decarbonize more HEFA capacity is expected to sell into the aviation market. The product slate can produce a maximum of 50-60% SAF, although as this percentage increases there may be some yield losses that make it more economical to optimize for a lower percentage of SAF production.

The carbon reduction from HEFA facilities is driven by the feedstock used, with the CORSIA default carbon reduction values[74] varying from 84% for used cooking oil to 47% for rapeseed oil, both compared to conventional jet fuel. This carbon reduction may be increased through operational improvements such as the use of green hydrogen and renewable electricity during the production process, and through Carbon Capture and Sequestration (CCS) of the facility waste gases.

Alcohol-to-Jet (AtJ)

Several companies are developing AtJ technologies with the first commercial facilities are expected to begin production from 2022. This pathway requires two distinct production phases; firstly, the feedstocks must be converted into alcohol, which can then use the AtJ process to produce SAF. There are several possible routes covered by this pathway, with direct fermentation of the feedstocks or conversion into syngas, which is then fermented, and either ethanol or butanol can be used as the alcohol intermediary. This flexibility allows the AtJ pathway to use a range of feedstocks, from cellulosic and MSW wastes to syngas produced through the power-to-liquid approach.

The feedstocks are relatively low value, resulting in a more even split of production costs between the feedstock and infrastructure. The technology to produce ethanol is well proven with a global ethanol industry

[74] https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

producing ethanol for use in road vehicles. This reduces the technical risk for part of the approach and may allow the SAF industry to use the ethanol already produced or re-fit the existing infrastructure, further reducing costs. There are few limitations on feedstock availability, and the industry is unlikely to encounter feedstock constraints over the next decades. In the longer-term, the use of Power-to-Liquids to produce synthetic syngas will allow the AtJ pathway to produce SAF from renewable electricity, and the use of industrial waste gases may provide a useful bridging feedstock for these facilities.

The AtJ pathway has a high specificity, allowing the product slate to produce a high percentage of SAF and up to 90% in some cases. The carbon reduction through this technology depends on the feedstock, with the baseline CORSIA values varying from 73% with forestry residues to 56% with corn grain, and these values can be further reduced through use of renewables and CCS.

Gasification/Fischer-Tropsch (gas/FT)

This pathway gasifies the feedstocks to produce syngas, which is then converted to fuels using the Fischer-Tropsch reactions. Similar to the AtJ pathway, a wide variety of feedstocks can be used, including biological feedstocks and syngas produced through the PtL approach.

The gas/FT pathway is relatively capital intensive, with sophisticated infrastructure required for the process, but typically low feedstocks costs. However, the feedstocks typically have a low energy and value density, increasing transport costs. Together with the technology characteristics, this is likely to result is relatively small facilities of a few tens of million-gallon annual capacity. There are some operating gasifies used for other industries, so the key part of this technology are the FT reactors. As the technology matures the capital costs are expected to rapidly decrease, although from a high starting point.

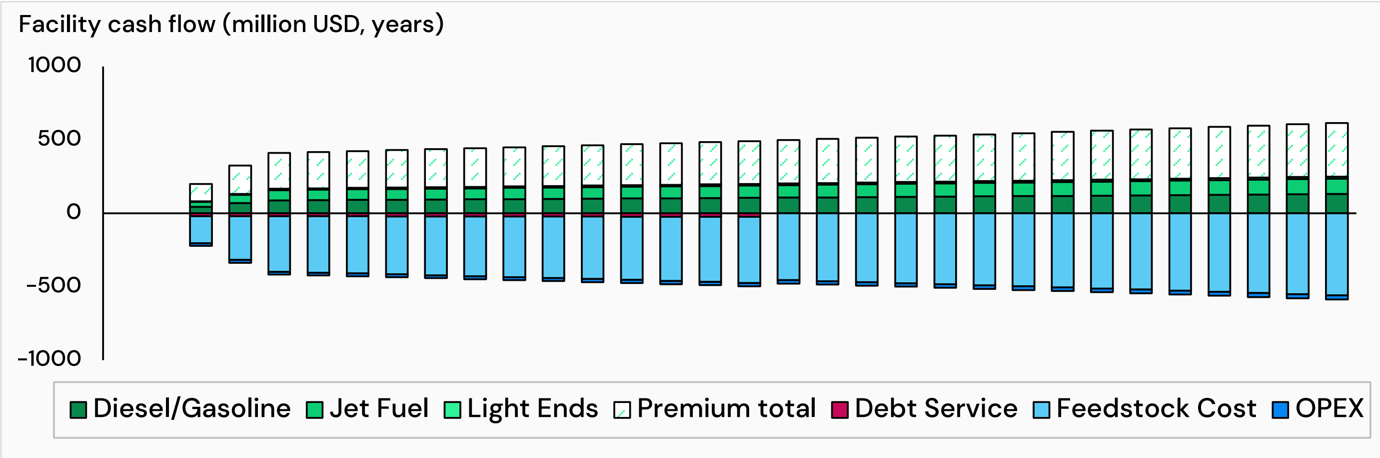
The gas/FT pathway has a similar product slate to the HEFA pathway, delivering up to 60% SAF. The carbon reduction is particularly high at approximately 90% for feedstocks such as agricultural and forestry residues. Municipal Solid Waste is likely to be a key feedstock for the gas/FT pathway, and the carbon reduction is driven by the biogenic component of the waste used, with a very high reduction for the biogenic portion which rapidly decreases as the non-biogenic portion grows.

The financial profile varies for each feedstock and pathway

Each feedstock and pathway selection will be suited to a different set of requirements and local conditions. For example, the HEFA profile requires lower initial costs for infrastructure but higher ongoing costs for feedstock, while the FT pathway requires considerable infrastructure but very low feedstock costs. Each pathway also offers different technical and delivery risks, and local conditions, such as the availability of feedstocks, logistics facilities and potential to re-purpose infrastructure, will influence the selection.

This analysis calculates the costs for each feedstock and pathway using a detailed production cash flow model, considering the feedstocks costs, maintenance and operating costs, financial costs, and revenues for SAF and co-products. The costs (debt payments, feedstock, and other operational costs) and revenues are balanced with a premium on the revenues. This premium is added above the market price for each of the products (jet, diesel, and light ends) and is set to ensure the equity IRR equals 15%. This premium is then allocated to each of the products, with the jet fuel market price plus the premium giving the net cost of production for SAF.

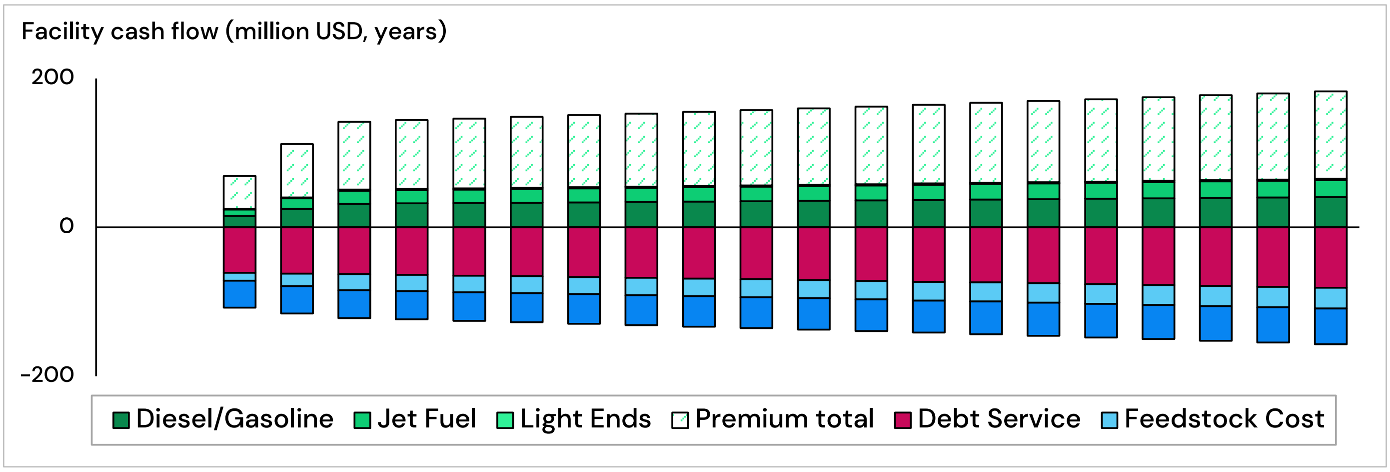
Illustration of production cost model: HEFA, 2025



Source ICF Analysis

This illustrates many of the factors considered in the analysis, including the start-up period, production ramp-up, facility lifetime and inflation over the lifetime, and the split of costs and revenues. Some costs are aggregated, such as the feedstock and cost for hydrogen in the HEFA pathway. This also provides a visual comparison of the different financial profile for each pathway, as shown with the dominance of the debt payments for the gas/FT pathway compared to the HEFA pathway.

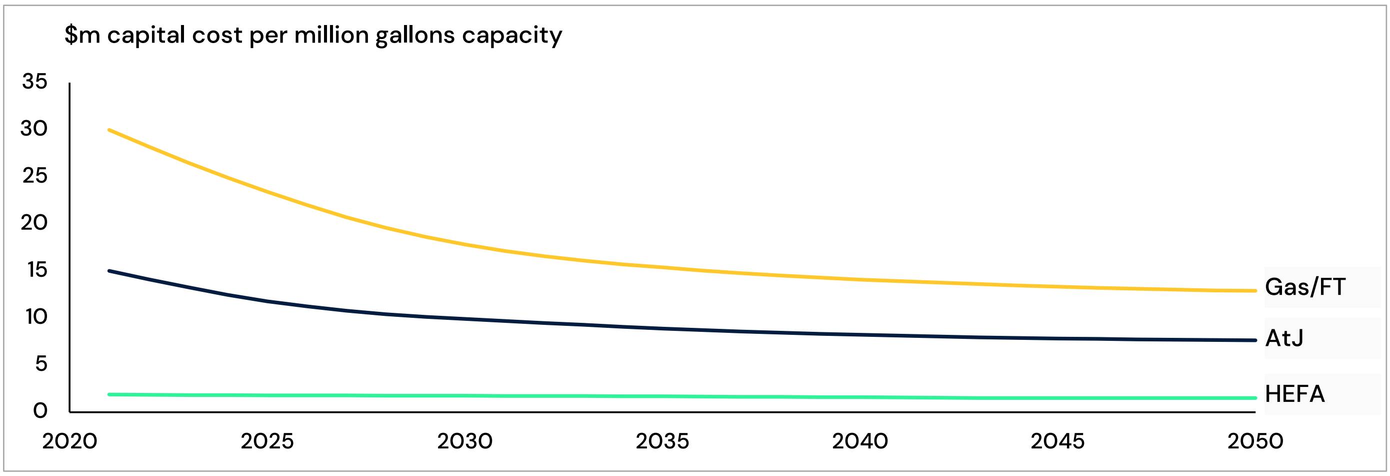
Illustration of production cost model: Gasification & FT, 2025



Source ICF Analysis

The financial profile for each facility will evolve as the facility, feedstock and logistic costs reduce as the technologies are deployed at scale. The most notable change is likely to be the reduction in capital costs for the AtJ and FT pathways, with the high costs for the first-of-a-kind facilitates seen today rapidly decreasing as the lessons learned from these projects are incorporated into future facilities. While the HEFA infrastructure costs will decrease, the decrease will be less as the technology is already more mature, and the smaller contribution of capital costs to overall production costs will result in a smaller impact. The operational costs are also expected to experience a similar decrease.

Reduction in capital costs as SAF production scales



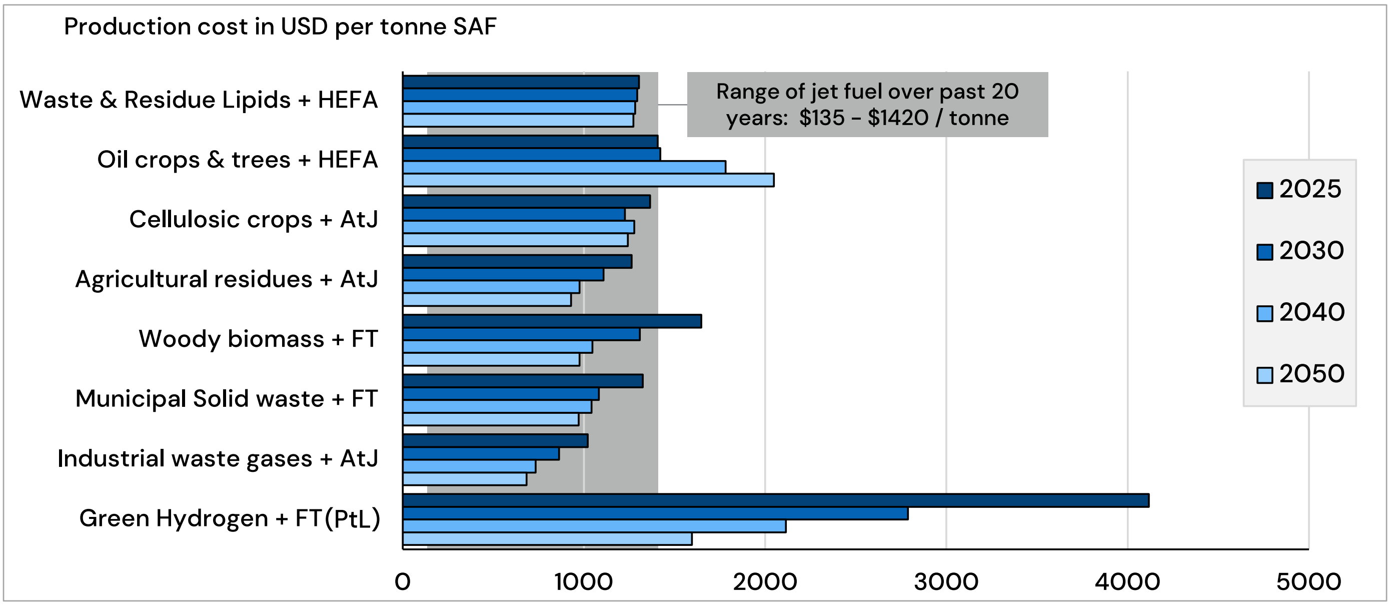
Source ICF Analysis

The evolution of feedstock costs will be driven by both the cost of production and the supply-demand dynamics. The development of more efficient methods to collect feedstocks and improvements to supply chains should reduce the cost of production. The increased demand is likely to increase prices, although this is uncertain and will likely be strongly influenced by regulations and incentives, both on the supply of feedstocks and on the value of resulting products. This analysis assumes steady bio-feedstock costs, except for feedstocks where the cost of production is likely to significantly increase with increased demand, particularly for feedstocks grown on dedicated land.

The cost of production for PtL is expected to rapidly decrease, although from a high initial cost. This will be driven by the decreasing cost of renewable energy, in turn reducing the cost for hydrogen production and direct air capture of carbon. This reduction will be compounded by the reduction in infrastructure costs for electrolysis, DAC, and the AtJ or FT facilities to convert the syngas to fuel.

These calculations have been based on central estimates for feedstock and production costs, but considerable variation is expected across the market. The cost of waste lipids for HEFA has increased significantly over recent months, and the estimated cost of production is heavily dependent on the expected future costs. This analysis has assumed these high costs represent the new normal with increased demand from multiple sectors. Individual producers may acquire feedstocks at lower cost through vertical integration and carefully arranged offtake contracts. The increased cost seen for oil crops and trees is driven by the increased marginal cost of feedstock production, as the producers are driven to use land with lower yields. This is seen to a lower extend for cellulosic, with the increased feedstock cost offset to a greater degree by reductions in production costs. The costs for production using industrial waste gases are low due to the limited feedstock cost, although these will heavily depend on the expense of integrating with the infrastructure producing the waste gases. The cost for PtL feedstock will vary with the cost of renewable electricity. This analysis has used average values to represent the cost seen as the industry scales and is unable to exclusively use cheap generation or curtailed power; therefore, some estimates are considerably lower, but may not scale to the degree required by this analysis. The infrastructure costs are averaged but will vary by facility depending on if the project is a greenfield, expansion, retrofit or re-use of decommissioned infrastructure.

Change in production costs for selected pathways as technologies mature



Source: ICF Analysis, not all production possibilities are shown

Several factors additional to production costs influence the choice of feedstock and pathway. The technology risk is low for the mature HEFA technology but higher for the developing AtJ and FT pathways. The high value to weight of HEFA feedstock facilitates the construction of large, centralized production capacity, often close to the source of demand. The lower value to weight of other feedstocks results in smaller facilities, typically closer to the source of feedstock. The environmental benefits are key, and the production costs must be considered in context of the environmental benefits each pathway can provide.

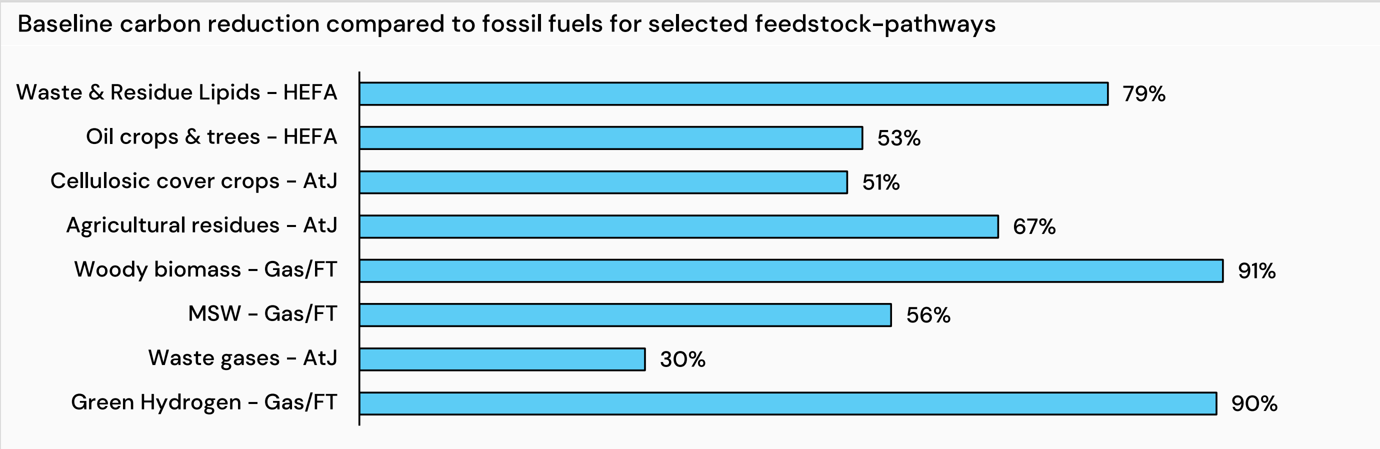
What environmental benefit do the fuels provide and what financial value does this offer?

Sustainable Aviation fuels provide a far greater array of value compared to conventional fuels, including environmental benefits, economic benefits, social value, and increased potential for energy security. The environmental benefits are typically measured across the life cycle of each fuel and the carbon value is given as the grams of carbon equivalent emitted per unit of energy (gCO_2e/MJ). These can then be compared to the baseline emissions for fossil jet fuel of 89 gCO_2e/MJ.

The measurement of carbon reductions through life cycle assessments is complex and each feedstock, and fuel offers different baseline benefits; each consignment of fuel will also vary from the baseline depending on nuanced factors, such the origin of the feedstock and the carbon intensity of the electricity used during refining. Producers therefore have a suite of options to influence the emission reduction from the fuel, ranging from careful selection of feedstock and use of renewables, to the use of carbon capture and sequestration of the refinery waste gases produced during manufacture.

This analysis uses the agreed default LCA values from CORSIA[75], which builds on extensive analyzes using the GREET, E3, and E3db models. The agreed carbon reduction values compared to fossil fuels are illustrated in the following panel and shows the considerable variety between feedstocks and pathways. The indirect land use change (ILUC) is considered when calculating these values, which represents the substitution impact from growing feedstocks leading to the conversion of additional land for agricultural use. In general, the carbon reduction is lower for the fuels with less ILUC impact, such as waste and residue lipids, while the feedstocks grown on dedicated land, such as the oil crops and trees and cellulosic cover crops, result in a lower carbon reduction.

The carbon reduction achieved by a selection of feedstocks and pathways



Source: CORSIA Eligible Fuels – Life Cycle Assessment Methodology, some values have been averaged

Each category represents a number of specific feedstocks, so the values for individual feedstocks do vary. For example, the waste & residue lipids have been calculated as the average LCA for UCO, tallow and PFAD; different blends or inclusion of corn, soybean, rapeseed, or palm oil would further change this value. The properties of individual feedstocks also vary, for example, the LCA for MSW depends on the biogenic portion of the waste – in this analysis a biogenic portion of 80% has been assumed, but this will depend on the waste received and the ease of separating the different waste streams. The emission reduction for waste gases has been estimated based on values seen in the current market, although this is driven by the counterfactual use of the waste gases; for example, if they are flared on-site or used for heat and power generation. The emissions from green hydrogen in the PtL pathway are equally complex, depending on the emissions from the energy used. While the use of renewables and green heat/power does offer a very significant emission reduction, it is unlikely to achieve a complete reduction.

These values are expected to increase as producers seek greater value from the fuels. The use of carbon capture and sequestration (CCS) can significantly increase the carbon reduction achieved, and this is already under investigation by some producers today. This involves CCS of the concentrated carbon emitted during the manufacture of the fuels, and therefore adds some infrastructure and operating costs in exchange for a significant increase in the carbon reduction. This analysis has assumed fuels can achieve net zero emissions, with additional costs incurred for the CCS portion. This is significant, but still perhaps conservative given some proposals seen in the market today. The restraint is due to the lack of sequestration resources in some geographies, and the lack of incentives in some policies suggested, such as mandates which drive volume but do not always incentivize producers to incur the additional expense required to increase the carbon reduction achieved.

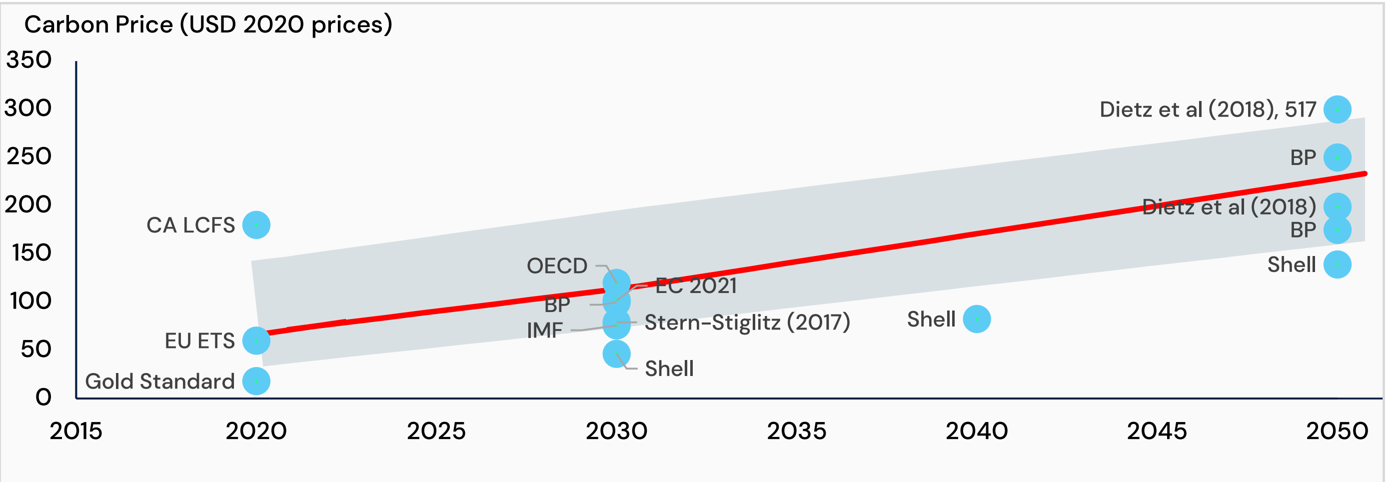
[75] https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

The financial value associated with the carbon reduction is driven by regulation. The regulatory landscape is complex, with international, national, and regional schemes. The EU, UK, Australia, South Korea, South Africa, parts of China and California already have active carbon markets, and policies specific to sustainable fuels are also developing, such as the blenders tax credit in the US, RED II in the EU and the RTFO in the UK. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) provides an international mechanism for carbon offsetting in aviation. This analysis distills the combined impact from these schemes into a single value for the carbon emission reductions.

Carbon prices are expected to rise in the future, however there is a wide variation between estimates. A key factor is the industry considered; while a low carbon price may be sufficient to incentivize an industry with low marginal costs to decarbonize, some industries are much more difficult and expensive to decarbonize. Aviation is particularly difficult, and this is recognized by some schemes today: for example, the Californian LCFS schemes values carbon reduction by the transport sector at ~$180 per tonne CO_2. This is significantly more than the voluntary markets, which are typically closer to $2-$20.

This analysis investigated a range of studies to develop an estimate for the global carbon reduction value included in the assessment, and selected values of $100 /t$CO_2$ in 2030, $150 /t$CO_2$ in 2040 and $200 /t$CO_2$ in 2050. In the early years this is somewhat higher than the large-scale markets and assumes that schemes that recognize the unique value from reducing aviation emissions, such as the LCFS, become more commonplace. In the later years this estimate falls in the middle of the estimates, and as these represent a broad range of industries and developed and emerging economies, this indicates the estimate is potentially conservative.

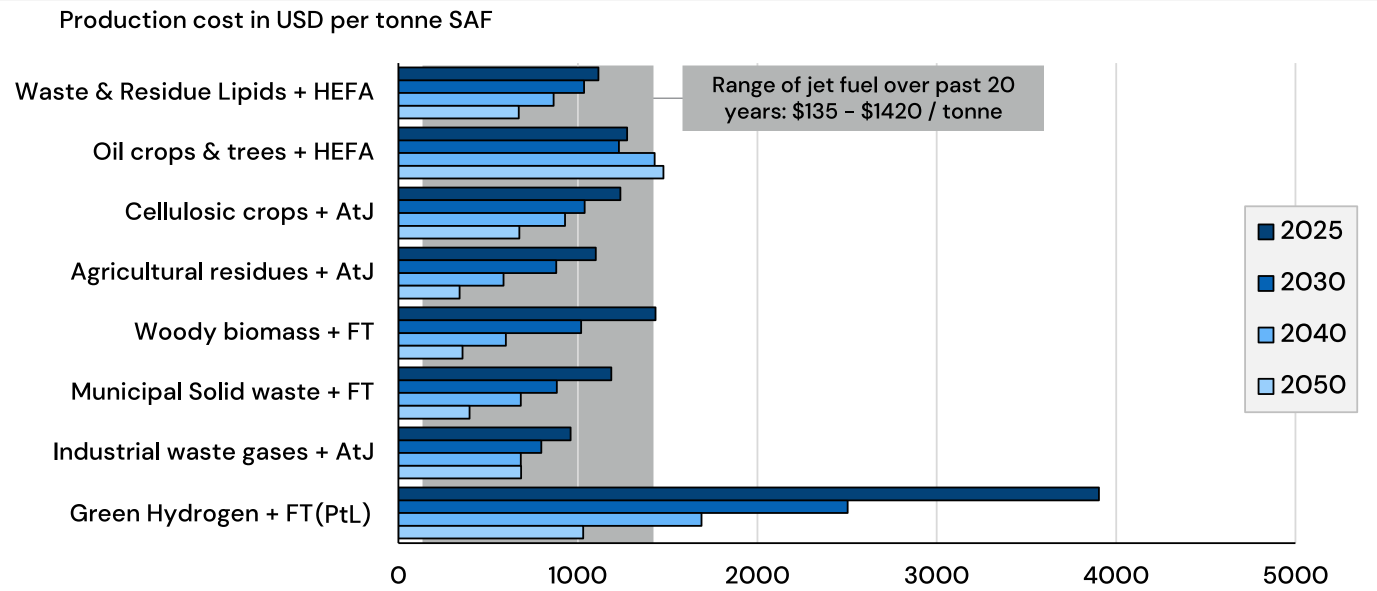
Carbon reduction value forecasts



Source: European Commission, Proposal (14 July 2021), Gold Standard, California Air Resources Board, LCFS, Shell Scenarios, Sky Scenario (2018), Dietz et al (2018) "The economics of 1.5c climate change, London School of Economics and Imperial University Grantham's Institute", Stern, Nicholas, and Joseph Stiglitz (2017) "Report of the HighLevel Commission on Carbon Pricing." IMF (Fiscal Monitor, October 2019), bp (Energy Outlook, 2020) IEA, Net Zero by 2050 (July 2021, 3rd revision)

When the environmental benefits, calculated as the carbon reduction multiplied by the value of carbon reduced, are combined with the production cost, the cost of production can be compared to fossil fuels on a level basis.

Including environmental benefits, costs for several pathways drop below $400 per tonne SAF by 2050



Source: ICF Analysis, not all production possibilities are shown

This analysis forecasts that many of the bio-feedstocks achieve net prices of $360-$700 by 2050, equivalent to just $45-$90 per barrel jet fuel. However, the average industry costs are higher in most scenarios due to the considerable share of PtL, with a net cost of just under $1,100 per tonne SAF by 2050.

SAF offers considerable environmental value in addition to the carbon reduction, with a recognized reduction of non-CO_2 emissions including sulfur oxides, soot, and contrail formation. Research[76] estimates that the warming effect from CO_2 is approximately a third of the aviation total, with the remaining two thirds from contrails and NOx. Consequently, reducing the non-CO_2 impacts from jet fuel will be critical and the financial value of SAF could considerably increase if regulations increasingly recognize the value of the reductions SAF can offer. This potential has not been included in the analysis and presents a potential upside to the cost comparisons given here.

SAF provides additional social and energy security benefits. The production of SAF requires an extensive value chain, with a spectrum of jobs created in the refining and to gather and process the feedstocks. Initial evidence suggests that investment in SAF production yields a high return in jobs created. Many of these fuels provides further value, for example the collection and processing of MSW reduces litter and pollution, and the use of agricultural residues greatly reduces air pollution compared to the currently common practice of burning residues in the field.

This analysis has shown the opportunity for infrastructure based on local feedstock availability. The availability of the feedstocks is well distributed, with different opportunities in each region and country. Consequently, SAF can also provide additional energy independence for many countries by producing high-value fuels from the common, low-value feedstocks discussed.

[76] D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L.J. Wilcox, The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018, Atmospheric Environment, Volume 244, 2021, 117834, ISSN 1352-2310,

Appendix

Technical references

Glossary

TERM	DEFINITION
Anthropogenic	Resulting from or produced by human activities.
American Society of Testing and Materials (ASTM)	An international standards organization that sets requirements for criteria such as composition, volatility, fluidity, combustion, corrosion, thermal stability, contaminants, and additives, among others to ensure that the fuel is compatible when blended. The standard regulating the technical certification of SAF is ASTM D7566. This evaluates which technologies, under specific circumstances and characteristics, can be used for producing on specification neat SAF.
Aviation Emissions	Aviation emissions include only the emissions from aircraft (both from domestic and international operations) including all phases of flight and APU use.
CAPITAL EXPENDITURE	Funds used to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment.
CCs (Carbon Capture and Sequestration)	The process of capturing and storing carbon dioxide (CO_2) before it is released into the atmosphere.
CCUS (Carbon Capture UtiliZation and Storage)	Emissions reduction technologies that involve the capture CO_2 from fuel combustion or industrial processes, the transport this CO_2 via ship or pipeline, and either its use as a resource to create valuable products or services or its permanent storage deep underground in geological formations.
CARBON DIOXIDE (CO_2)	A colorless, odorless and non-poisonous gas formed by combustion of carbon and is considered a greenhouse gas.
Carbon Neutral	Reduce scope 1 and scope 2 CO_2e emissions and compensate the remaining CO_2e emissions through the purchase of certified emission reduction units or carbon offset credits.
Carbon Removal or GHG Removals	Activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products.
CORSIA	Carbon offsetting and Reduction Scheme for International Aviation is an emission mitigation approach for the global airline industry, developed by the International Civil Aviation Organization (ICAO) and adopted in October 2016. Measures include primarily offsets and 'alternative' fuels.
CROP TO RESIDUE RATIO (crr)	The quantity of crop residues created per specific quantity of crop harvested.

Decarbonization	The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.
DIRECT AIR CAPTURE	A technology to capture CO_2 from the atmosphere. The CO_2 can be permanently stored in deep geological formations or used in the production of fuels, chemicals, building materials and other products containing CO_2.
EU ETS	The European Union Emissions Trading System, launched in 2005 to fight global warming, was the first large greenhouse gas emissions trading scheme in the world and is a major pillar of EU energy policy. Under the 'cap and trade' principle, a maximum (cap) is set on the total amount of GHG that can be emitted by all participating installations. EU Allowances for emissions are then auctioned off or allocated for free and can subsequently be traded. Installations must monitor and report their CO_2 emissions, ensuring they hand in enough allowances to the authorities to cover their emissions. If emission exceeds what is permitted by its allowances, an installation must purchase allowances from others.
FISCHER-TROPSCH	A catalytic chemical reaction in which the carbon monoxide (CO) and hydrogen (H2) in the syngas are converted into hydrocarbons.
Greenhouse Gas Emissions (GHG)	Gases in the atmosphere that absorb and emit radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect and increases in anthropogenic GHG have been linked to increases in global average temperatures since the mid-20th century, known as climate change. The most significant GHG associated with an airport is carbon dioxide (CO_2). Other GHGs included in the Kyoto Protocol are methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF6). Airports can also be sources of emissions that affect climate, such as oxides of nitrogen (NOx) and ozone (O3). Water vapor (H2O) is also a GHG but not one addressed by airport operators.
HEFA	Hydroprocessed Esters and Fatty Acids. HEFA refines vegetable oils, waste oils, or fats into SAF through a process that uses hydrogen (hydrogenation). In the first step of the process, the oxygen is removed by hydrodeoxygenation. Next, the straight paraffinic molecules are cracked and isomerized to jet fuel chain length. The process is similar to that used for Hydrotreated Renewable Diesel production, only with more severe cracking of the longer chain carbon molecules. The maximum blend ratio is 50%.
LCOE (Levelized Cost of ELECTRICITY / ENERGY)	Also referred to as the levelized cost of electricity or the levelized energy cost (LEC), this is a measurement used to assess and compare alternative methods of energy production. The LCOE of an energy-generating asset can be thought of as the average total cost of building and operating the asset, per unit of total electricity generated over an assumed lifetime
LCFS	The Low Carbon Fuel Standard is a market-based program that focuses specifically on reducing carbon intensity of fuels used within California. It was created in 2011 by the California Air Resources Board (CARB) as part of several measures to reduce GHG emissions throughout the state by 20% by 2030 and 80% by 2050. The LCFS program provides several credit generation opportunities to incentivize production and use of low carbon fuels.

LIFE CYCLE ASSESSMENT	A set of procedures that examine inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product throughout its life cycle.
Net Zero Carbon	*According to the Intergovernmental Panel on Climate Change (IPCC), Net Zero Carbon Emissions are achieved "when anthropogenic CO_2 emissions are balanced globally by anthropogenic CO_2-removals over a specific period"*[77]. It requires that the maximum feasible reductions of CO_2e emissions are first made and any residual emissions are balanced by an equal volume of carbon removals. Carbon removal mechanisms must result in a carbon negative contribution to achieve net-zero carbon. First, planned absolute reductions from efficiency savings and asset replacement must be compliant with a regularly reviewed pathway to limit global heating to 1.5°C by achieving as close as possible to 'absolute zero' carbon emissions. Second, residual emissions are balanced by Greenhouse Gas Removals (GGR). Carbon removal mechanisms used to remove residual emissions must result in a carbon negative contribution to achieve net-zero carbon.
NITROGEN OXIDES	NOx is the generic term for a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts (such as nitric oxide (NO) and nitrogen dioxide (NO2)).
Offsetting	Offsetting is to 'cancel out' or 'neutralize' emissions of CO_2 (and other GHG emissions) by financing projects that reduce CO_2 emissions and that would not have otherwise been implemented. Airport operators can achieve this by purchasing properly certified offset credits.
Paris Agreement	The Paris Agreement under the UNFCCC was adopted on December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is *'Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels',* recognizing that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change. The Paris Agreement is intended to become fully effective in 2020.
1.5 pathway	A pathway of emissions of greenhouse gases and other climate forcers that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of global warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot.
PFAD	Palm Fatty Acid Distillate is a cheap and valuable byproduct of edible oil processing industries (e.g. a waste from the conversion of crude palm oil (CPO) into cooking oil). The PFAD is a feedstock for SAF.

[77] Net-zero carbon FAQ, ACI

POME	Palm Oil Mill Effluent is an oily wastewater/sludge generated from palm oil milling arising at a palm oil mill during the palm oil production process. The small oil contained in the wastewater (POME oil) settles on top of the POME pond and can be extracted (skimmed off) and used as feedstock for biofuel production.
POWER TO LIQUID (PtL)	A synthetically produced liquid hydrocarbon. Renewable electricity is the key energy source, and water and carbon dioxide (CO_2) are the main inputs. PtL production comprises three main steps: first, renewable energy powers electrolyzers to produce green hydrogen. Second, climate-neutral CO_2 (e.g. captured via DAC) is converted into carbon feedstock. Third, carbon monoxide and green hydrogen ('syngas') are synthesized (e.g. via FT) to generate liquid hydrocarbons, which are further refined into SAF.
PTC	The US production tax credit (PTC), a per-kWh credit for electricity generated by eligible renewable sources, was first enacted in 1992 and has been extended over a dozen times, most recently in connection with the Consolidated Appropriations Act, the second relief bill aimed at providing economic relief from COVID-19 disruptions.
RED	The EU RED Directive, developed in 2009, was designed to help EU countries reach renewable energy targets. It aims to ensure that biofuels used in the EU are "produced in a sustainable and environmentally friendly manner". A number of clear criteria were set out defining the scope of this sustainability ambition.
RED II	The RED II defines a series of sustainability and GHG emission criteria that bioliquids used in transport must comply with to be counted towards the overall 14% target and to be eligible for financial support by public authorities. Some of these criteria are the same as in the original RED, while others are new or reformulated.
RFNBO	Renewable Fuels of Non-biological Origin are renewable liquid or gaseous transport fuels for which none of the energy content of the fuel comes from biological sources. These fuels are considered renewable where the energy content of the fuel comes from renewable energy sources, such as using electricity and/or heat and/or cold from wind, solar, aerothermal, geothermal or water.
RFS	The Renewable Fuel Standard (RFS) is an American federal program that requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels. It originated with the Energy Policy Act of 2005 and was expanded and extended by the Energy Independence and Security Act of 2007. The RFS requires renewable fuel to be blended into transportation fuel in increasing amounts each year, escalating to 36 billion gallons by 2022. Each renewable fuel category in the RFS must emit lower levels of greenhouse gases relative to the petroleum fuel it replaces.
RTFC	Renewable Transport Fuel Certificates. Suppliers of sustainable biofuel can apply for RTFCs under the RTFO. Biofuel must meet specified sustainability criteria in order to be entitled to the benefit of RTFCs. One RTFC is issued per liter/kg of liquid biofuel derived from crop-based feedstocks. Biofuels produced from wastes, non-agricultural residues, non-food cellulosic material, and lignocellulosic material are issued twice the number of RTFCs per liter/kg to reflect the lower risk that these materials will cause undesirable impacts such as indirect land use change (ILUC).

RTFO	The Renewable Transport Fuel Obligation is one of the UK Government's main policies for reducing greenhouse gas emissions from fuel supplied for use in road vehicles and non-road mobile machinery, tractors, and recreational craft. From 15 April 2018, renewable fuel used in aviation in the UK is also eligible for reward under the RTFO.
RWGS	Reverse Water Gas Shift is a process that converts carbon dioxide and hydrogen into carbon monoxide and water
Scope 1 emissions	GHG emissions from sources that are owned or controlled by the reporting organization. For example, at an airport, these could include emissions from combustion in boilers, airport power generation facilities and airport fleet vehicles. These are the most significant emissions for airlines, with direct combustion emissions falling into this category.
Scope 2 emissions	GHG emissions from the off-site generation of electricity (and heating or cooling), purchased by the organization.
Scope 3 emissions	GHG emissions from related activities from sources not owned or controlled by the reporting entity. Examples include emissions from third party ground handling services, employee commutes, codeshare partners (for airlines) and tenant emissions (for airports).
SAF (Sustainable aviation fuel)	A nonconventional (fossil derived) aviation fuel, which is derived from a range of feedstocks, converted through certified pathways as a synthetic equivalent to kerosene, blended with fossil fuels and are operationally identical to Jet-A1.
Uco (used cooking oil)	An oil feedstock that can be used for the production of SAF via the HEFA technology process.

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Alastair leads the sustainable aviation team at ICF, supporting companies and governments across the global industry to reduce the environmental impact from aviation. This includes development and implementation of decarbonization strategies, working with airlines to understand, identify and contract for sustainable fuels, and supporting organizations across the aviation value chain to measure, mitigate and report on ESG factors.

In recent projects, Alastair has worked with several airlines in the US and Europe to accelerate their use of SAF, supported ACI world to establish a net zero carbon target for their ~2,000 airport membership by 2050, and delivered sustainable aviation policy analyses for the UK government and the EU's DG CLIMA.

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