twelve | a world made from air

Know Your SAF

The Power-to-Liquid Advantage

executive summary

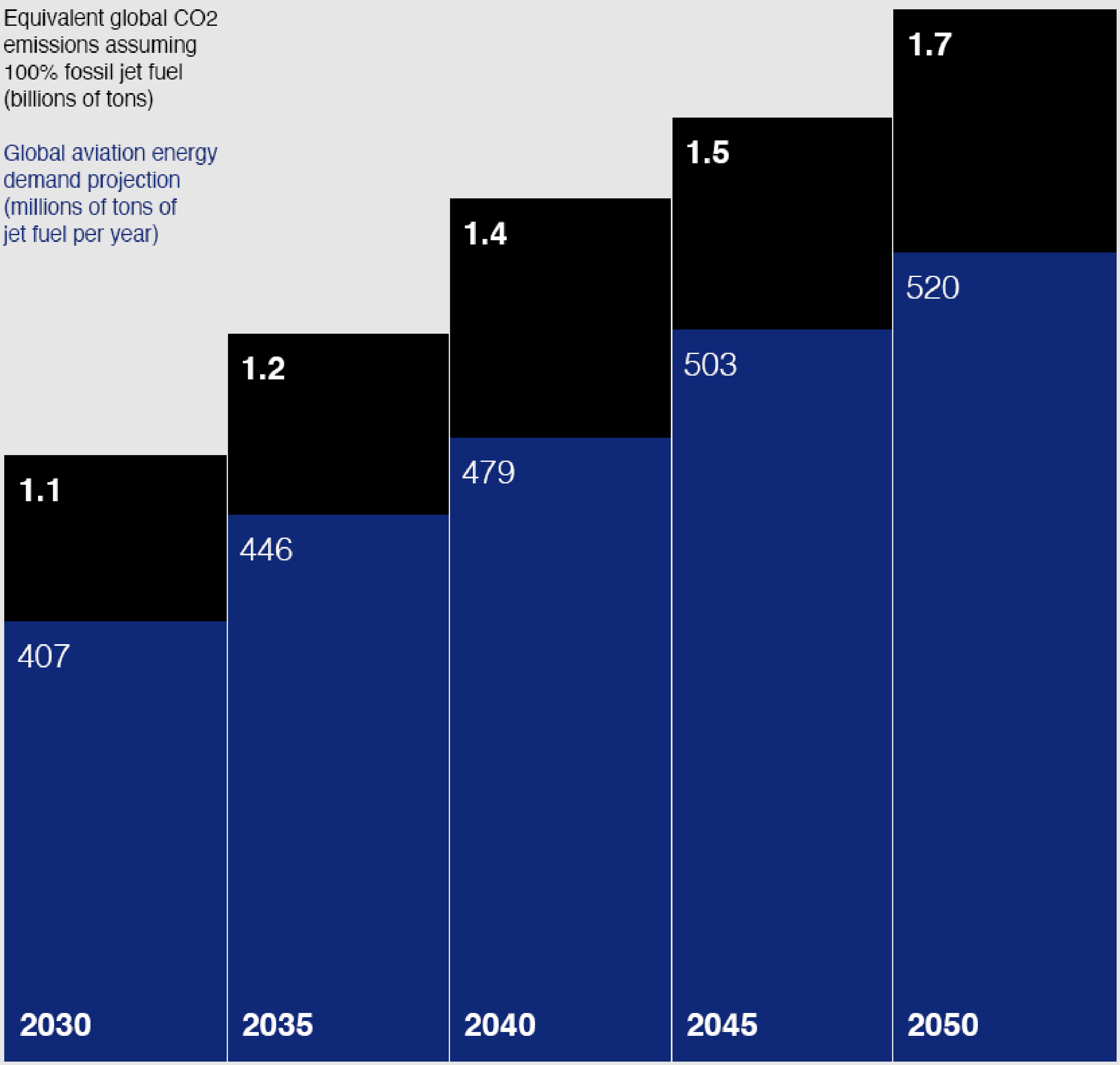
At Twelve, we are optimistic about the future of aviation and believe that there is a solution to the industry's emissions problem. While the aviation sector is responsible for a significant share of global CO_2 emissions (2-3%), we believe that Sustainable Aviation Fuel (SAF) provides a key alternative to conventional, petroleum-based jet fuel. Today the industry consumes approximately 100B gallons of conventional, petroleum-based jet fuel annually, a figure that is expected to increase to ~150B gallons by 2050.

The sector is inexorably linked to fossil fuel extraction. A world in which we reach our climate targets will need to decouple itself from this dependence. Non-fossil-derived Sustainable Aviation Fuel (SAF) provides an alternative without sacrificing access to the air travel that makes up a key pillar of our modern transport networks for goods and people.

We acknowledge that there are multiple pathways to low-emission, fossil-free aviation, but not all fuel options are created equal. It is important for decision-makers in the industry, from airline and corporate executives to customers buying plane tickets, to be armed with the information to evaluate the quality of each gallon of SAF. We believe that the tradeoff between SAF options should be clear, with a focus on the most efficient and sustainable options.

Most of all, we believe Power-to-Liquid fuels ("the air way") represent the most promising SAF pathway. These fuels have industry-leading emissions reduction potential of >90% while using 3-30X less land and 1,000X less water over alternatives. We believe in the power of this fuel for the long haul, because good for now is not good enough.

Projected Jet Fuel Demand & Resulting CO2 Emissions



SAF is best positioned to decarbonize the aviation industry

Low or zero-emission flight will be a notoriously difficult challenge. Flight requires a huge amount of energy to enable lift-off and keep a plane moving forward at 30,000 feet, but there is limited space and weight tolerance on board for energy storage. Fossil fuels are a remarkably low-cost, energy-dense fuel option that makes this miracle possible. Unfortunately, burning these fuels releases ancient CO2 and other greenhouse gases, thus contributing to climate change.

The industry is exploring multiple alternative technologies such as electric planes and hydrogen, but only drop-in ready Sustainable Aviation Fuels can address most aviation use cases. As molecularly near identical to fossil-derived jet fuel, SAF works in existing aircraft but can offer significantly lower emissions. However, there are many ways to create SAF, and not all SAF gallons are created equal.

100

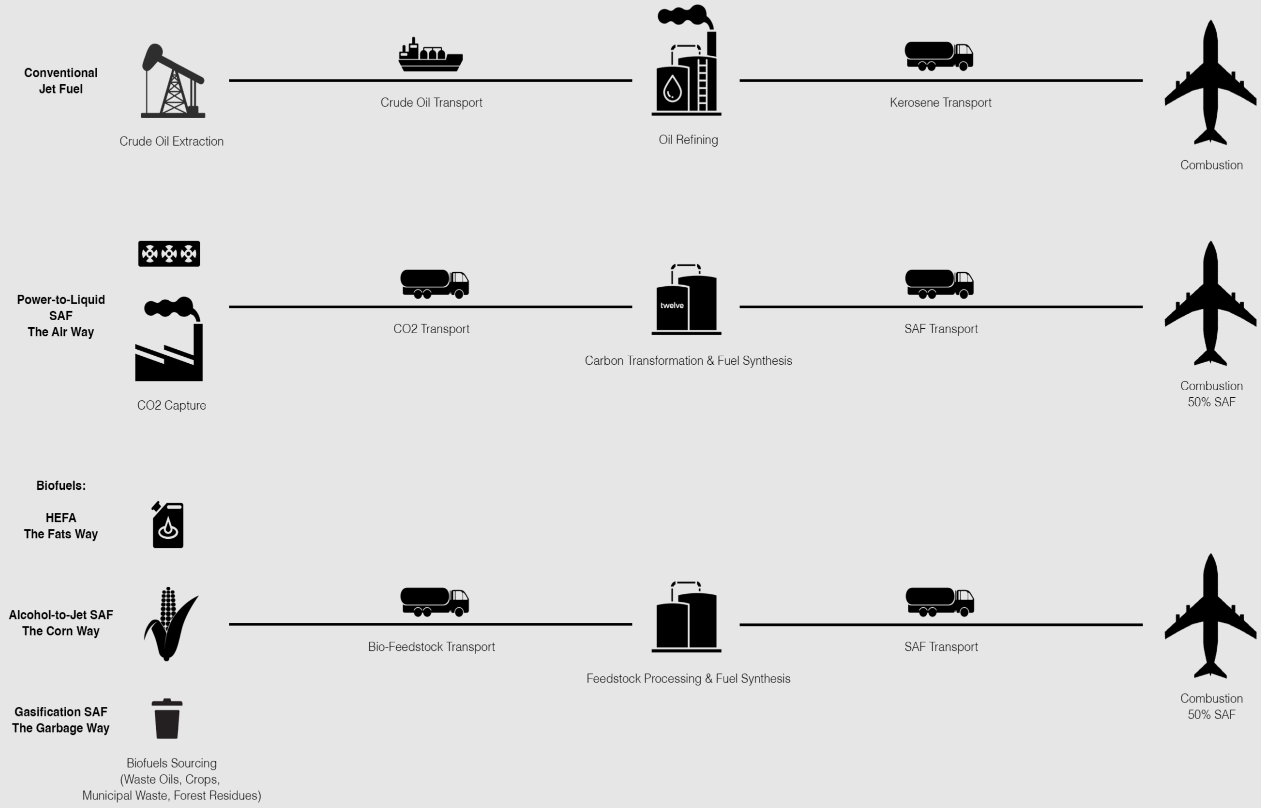
BILLION GALLONS

Annual aviation fuel usage

The Pathways to SAF

All pathways to make SAF take non-crude oil feedstocks and turn them into the same thing we use today for aviation fuel: kerosene. Kerosene-based jet fuel, simply put, is made up of chains of carbons and hydrogens (hydrocarbons), specifically chains containing between 8 and 16 carbons. Players in the industry today are looking at 4 main pathways to create these 8-16 carbon kerosene / hydrocarbon chains.

An Overview of SAF and Conventional Jet Fuel Production



Four pathways to meet global SAF demand

Not all SAF is created equal

All pathways to make SAF take non-crude oil feedstocks and turn them into the same thing we use today for aviation fuel: kerosene. Kerosene-based jet fuel, simply put, is made up of chains of carbons and hydrogens (hydrocarbons), specifically chains containing between 8 and 16 carbons. Players in the industry today are looking at 4 main pathways to create these hydrocarbon chains.

The Air Way: Power-to-Liquid

The Power-to-Liquid (PtL) pathway, also sometimes called synthetic fuels, E-Fuels, or Power-to-X, does not use direct organic compounds as feedstocks like other pathways, and is therefore not a biofuel. Instead, this pathway uses direct CO2, renewable electricity, and clean hydrogen as feedstocks.

Water Use: **Low**
Land Use: **Low**
Scaleability of Feedstock: **High**

The Fats Way: HEFA Biofuels

HEFA is the primary option in use today due to its maturity and inexpensive cost. However, the available supply of waste feedstocks puts a cap on how much HEFA fuel can be made using low-emissions waste materials.

Water Use: **High**
Land Use: **High**
Scaleability of Feedstock: **Low**

The Corn Way: Alcohol-to-Jet

Alcohol-to-Jet derived fuels are dedicated corn feedstocks, but there is increasing interest in using bio-waste products such as agricultural residues. There are only enough of these waste feedstocks globally to supply ~50B gallons of SAF assuming all these feedstocks were solely dedicated to SAF production. Beyond this, dedicated feedstocks would be required.

Water Use: **High**
Land Use: **High**
Scaleability of Feedstock: **Medium**

The Garbage Way: Gasification

Gasification is a process that converts any carbon-based raw material into synthetic gas (syngas) and then to fuel via the Fischer-Tropsch process. There are only enough of these waste feedstocks globally to supply ~50B gallons of SAF assuming all of these feedstocks were solely dedicated to SAF production.

Water Use: **High**
Land Use: **Medium**
Scaleability of Feedstock: **Medium**

Biofuels use organic feedstocks to derive fuels through a variety of technologies

HEFA - The Fats Way

HEFA fuel is a biofuel made with feedstocks such as:

- Vegetable oils (e.g. canola, soy, and palm oils)
- Waste oils (e.g. used cooking oil from restaurants
- Tall oil – a byproduct from paper manufacturing
- Fatty acid distillates (e.g. waste oils from sewage sludge etc.)
- Animal waste fat (tallow)

Producers bombard these fats and oils with hydrogen to remove their oxygens through a well-developed process called hydrodeoxygenation. What's left are hydrocarbon chains that aren't the right length. To achieve the magic C8-C16 range, they go through the cracking and isomerization stage. These fuels can then be shipped and blended for use as jet fuel.

HEFA is the primary option in use today due to its maturity and inexpensive cost. However, the available supply of waste feedstocks puts a cap on how much HEFA fuel can be made using low-emissions waste materials. There simply isn't enough used cooking oil and animal fat to produce more than ~5B gallons or 5% of aviation fuel demand.[1] of all jet fuel with these feedstocks. Beyond this volume, dedicated crops to produce vegetable oil would be necessary.

1. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

Alcohol-to-Jet (AtJ) - The Corn Way

Alcohol-to-Jet fuels are biofuels that derive ethanol or isobutanol from agricultural feedstocks such as:

- Corn
- Sugarcane
- Switchgrass
- Other energy crops or their residues (including agricultural and gas residues)

Once the alcohol via ethanol or isobutanol arrives at the fuel production facility, it undergoes 4 steps: dehydration (to remove the oxygen), oligomerization (to combine the smaller molecules to create longer hydrocarbon chains), hydrogenation (the addition of hydrogen), and fractionation (to filter out the magic C8-C16 range).

Alcohol-to-Jet derived fuels are just now becoming commercially available today but are quickly ramping up production within the next one to two years. Most feedstocks used today are dedicated corn feedstocks, but there is increasing interest in using bio-waste products such as agricultural residues (e.g. the waste stalks, stems, or leaves remaining after harvesting), forestry residues, or other wastes, which have lower emissions, land, and water impact associated. While using waste products typically adds processing steps and therefore costs, the improved sustainability of these feedstocks is driving interest. However, there are only enough of these waste feedstocks globally to supply ~50B[2] gallons of SAF assuming all these feedstocks were solely dedicated to SAF production. Beyond this, dedicated feedstocks would be required.

2. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

Gasification - The Garbage Way

Gasification converts waste into synthetic gas and then to fuel. It uses waste from sources such as:

- Municipal Solid Waste (MSW)
- Forestry and agricultural residues
- Some non-waste products such as short rotation forestry products

These feedstocks are gasified (burned) in a high-pressure vessel with air and steam, and the resulting gas is collected and cleaned to contain only hydrogen and carbon monoxide (CO), otherwise known as syngas. Solid by-products called ash or slag are also produced and disposed of. The syngas is then put through a conversion step, such as Fischer-Tropsch, methanol synthesis, or gas fermentation to produce liquid products that can then be upgraded to the appropriate C8-C16 hydrocarbon chain lengths to make SAF.

Gasification derived fuels are not commercially available today, but production is expected to ramp up in the coming years. Gasification is one of the lowest emissions pathways, as the feedstocks for this pathway are almost entirely composed of waste products. However, there are only enough of these waste feedstocks globally to supply ~50B[3] gallons of SAF assuming all of these feedstocks were solely dedicated to SAF production.

3. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

Power-to-Liquid fuels directly transform CO_2 into SAF

Power-to-Liquid - The Air Way

Power-to-Liquid fuels convert CO_2 directly into SAF. Sources of CO_2 include:

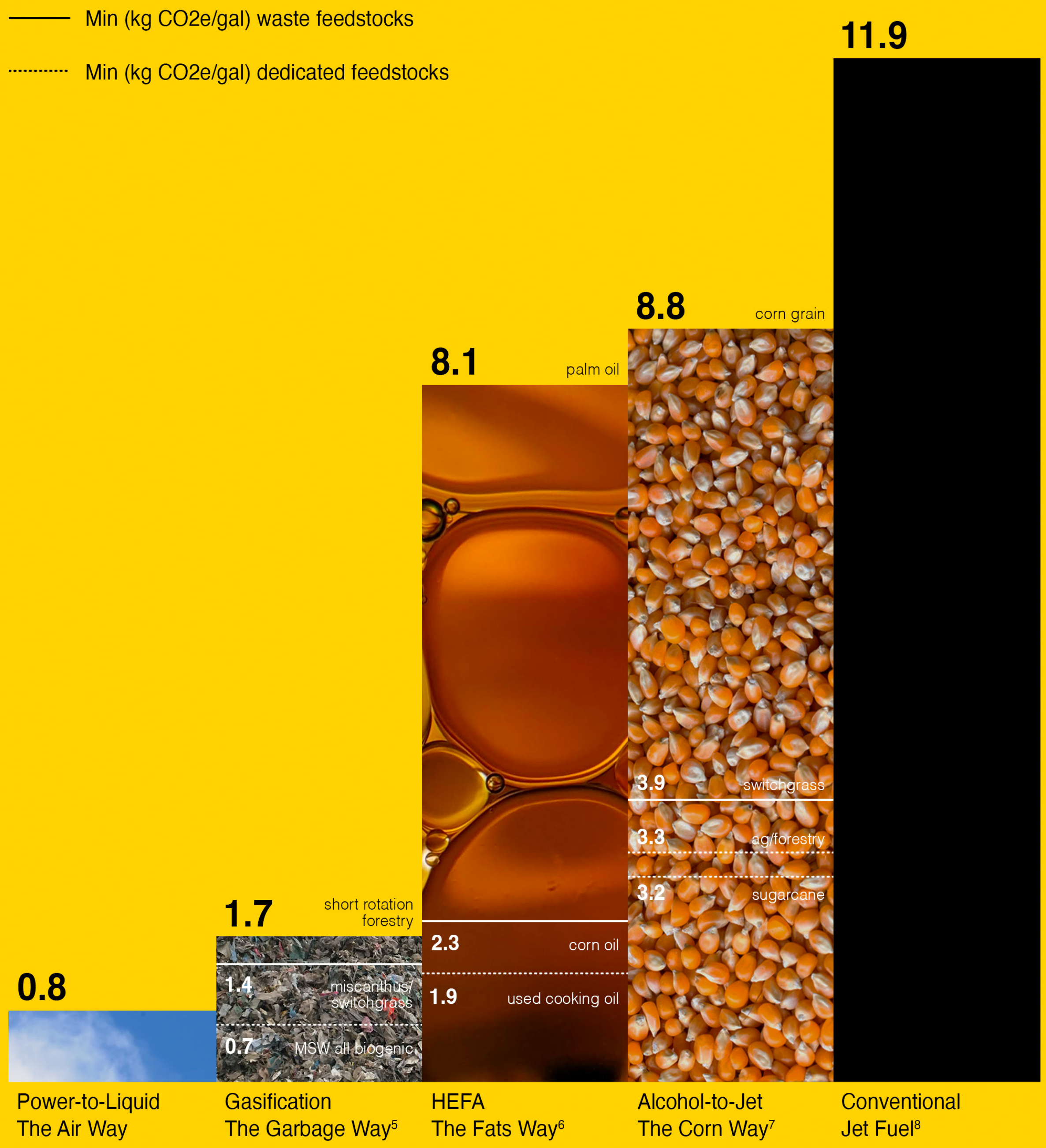
- Biogenic industrial sources
- Direct Air Capture
- Captured industrial emissions

The Power-to-Liquid (PtL) pathway, also sometimes called synthetic fuels, E-Fuels, or Power-to-X, does not use direct organic compounds as feedstocks like other pathways, and is therefore not a biofuel. Instead, this pathway uses direct CO_2, renewable electricity, and clean hydrogen as feedstocks. These feedstocks combine to create syngas, a mixture of hydrogen and carbon monoxide (CO)[4]. The syngas is then put through a conversion step, such as Fischer-Tropsch, methanol synthesis, or gas fermentation to produce liquid products that can then be upgraded to the appropriate C8-C16 hydrocarbon chain lengths to make SAF.

PtL technologies are the newest to enter the market, having limited production for the next few years. They are correspondingly more expensive than the other pathways already discussed but are seen as the next generation of fuels that will likely make up a significant portion of the SAF production in the coming decades. Today CO_2 feedstocks are waste gases from biogenic (living carbon-based) industrial sources such as ethanol production, but could also come straight from the atmosphere through Direct Air Capture (DAC). Once DAC comes down the cost curve, CO_2 feedstocks, and therefore PtL fuels, could be virtually unlimited.

4. Applies to most, not all, PtL processes.

LCA Emissions by Pathway
Max kg CO2e/gal



5. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf
6, 7, 8. ICAO document 06 - Default Life Cycle Emissions - June 2022.pdf

Tons not gallons: all gallons are not created equal

Because the inputs and processes differ for each SAF pathway, the total emissions associated with the production of each gallon of SAF, calculated via a Life Cycle Assessment, differ. What this means in practice is that measuring SAF in terms of the tons of GHG emissions reduced will go a lot further than simply the gallons consumed.

For Alcohol-to-Jet processing is one of the most emissions-intensive of all SAF pathways. Given the emissions intensity of processing, the most AtJ fuels can reduce emissions over fossil jet fuel is ~70%.

With HEFA, the emissions associated with the fuel processing including the use of fossil-derived hydrogen, limit HEFA's reduction potential over fossil jet fuel in the best-case scenario to ~84%.

Both gasification and PtL typically synthesize fuels through the low-emissions Fischer-Tropsch process. Depending on feedstocks, gallons produced through these pathways can achieve >90% emissions reduction, making them the lowest emissions SAFs.

When it comes to biofuels, there is a limited supply of waste feedstocks

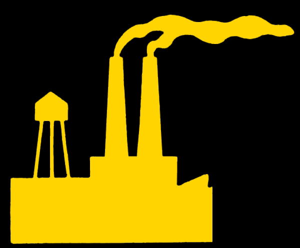
Biofuels all require an initial organic feedstock, which could be dedicated products produced specifically for SAF, or they can be collected waste products from other processes. Cultivating, harvesting, and processing dedicated crops is emissions intensive. As is the case with all biofuels, typically the higher the concentration of waste products versus dedicated feedstock, the lower the emissions contribution from feedstocks.

For example, while all-used cooking oil HEFA fuel would have a reduction potential over fossil jet fuel of >80%[9] , an all-palm oil HEFA fuel would only see a 30% reduction (not including land use change). Meeting the 2050 demand of ~150B gallons would exhaust the supply of waste products after ~5B gallons, meaning the remaining ~145B gallons of fuel would have only between 30-80% reduction potential.[10]

While an entirely agricultural waste-based feedstock AtJ fuel can reduce emissions ~70%, an entirely dedicated corn feedstock AtJ fuel would only reduce emissions ~25%. Meeting 2050 demand of ~150B gallons would exhaust the supply of waste products after ~50B gallons[11] , meaning the remaining ~100B gallons of fuel would have only between 25-70% emissions reduction potential.

Gasification fuels suffer the least from this dynamic. While a waste-based MSW derived fuel can achieve >90% emissions reduction, even using dedicated short rotation forestry feedstocks, gasification can still achieve >85% emissions reduction.

9. ICAO
10., 11. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf



2400

GIGATONS

CO_2 emitted by human activity since 1850

Power-to-Liquid fuels have a virtually unlimited waste feedstock

PtL fuels are not biofuels, and are therefore not bound to the same dynamic of waste versus dedicated feedstock. PtL fuels use captured CO_2 that is either a waste product from industrial processes or directly out of the air and therefore has few emissions and a virtually unlimited supply. Instead, the source of process electricity drives the carbon intensity of PtL fuels. Fuel production that relies on electricity as a main feedstock is as clean as the electricity source used. As long as clean electricity is used with biogenic/DAC CO_2 PtL fuels can have >90% emissions reduction over fossil fuels.

CO_2 emissions reduced if we supplied all gallons of SAF per pathway

Pathway	Max (kg CO2e/gal) waste feedstocks	Max (kg CO2e/gal) dedicated feedstocks	Min impact (% CO2e reduction)
HEFA **The Fats Way**	**84%** used cooking oil	**80%** corn oil	**32%** palm oil
Alcohol-to-Jet **The Corn Way**	**73%** ag/forestry residues	**67%** switchgrass	**26%** corn grain
Gasification **The Garbage Way**	**94%** MSW - all biogenic	**88%** miscanthus/switchgrass	**86%** short rotation forestry
Power-to-Liquid **The Air Way**	**92%** Twelve fuel @ 100% clean	N/A	as clean as the electricity that produces the fuel

Why biofuels alone can't meet long-term jet fuel demand

Today ~40 million square miles of land are habitable[12] of which approximately half is already used for agriculture. If we are to replace aviation fuels with lower emissions alternatives, we will need to do this without adding additional pressure on land availability, diverting resources to produce food, or destroying existing wild ecosystems. Biofuels producers not using waste feedstocks, will require dedicated land from this limited supply. Once again, the differentiation between waste and dedicated feedstocks is the key driver of associated land use for biofuels SAF pathways.

Gallons of jet fuel yield per square mile of land[13]

Pathway	Min yield (gals/mi2)	Max yield - dedicated feedstocks (gals/mi2)	Max yield - waste only (gals/mi2)
HEFA **The Fats Way**	**29,000** jatropha oil	**340,000** palm oil	**1 million+** up to ~5-10B gallons
Alcohol-to-Jet **The Corn Way**	**162,000** corn	**290,000** sugar beet	**1 million+** up to ~50B gallons
Gasification **The Garbage Way**	**87,000** short rotation forestry	**320,000** short rotation forestry	**1 million+** up to ~50B gallons
Power-to-Liquid **The Air Way**	**900,000** onshore wind	N/A	**9 million** offshore / wind / nuclear

12. www.ourworldindata.org/land-use
13. German Environment Agency. Power-to-Liquids: Potentials and Perspectives. (2016).

There are not enough waste feedstocks for biofuels to meet aviation demand

While HEFA fuels today are largely waste products of food production, if HEFA fuels replace >5-10% of jet fuel supply, producers will need land dedicated solely to the production of HEFA feedstocks. Dedicated feedstocks for their oil content can have some of the highest land use impacts of any SAF pathway. With dedicated feedstocks, replacing 100B gallons with HEFA fuels would require between 0.3-3M mi^2, an area of land ranging from larger than Texas to the entire continental United States.

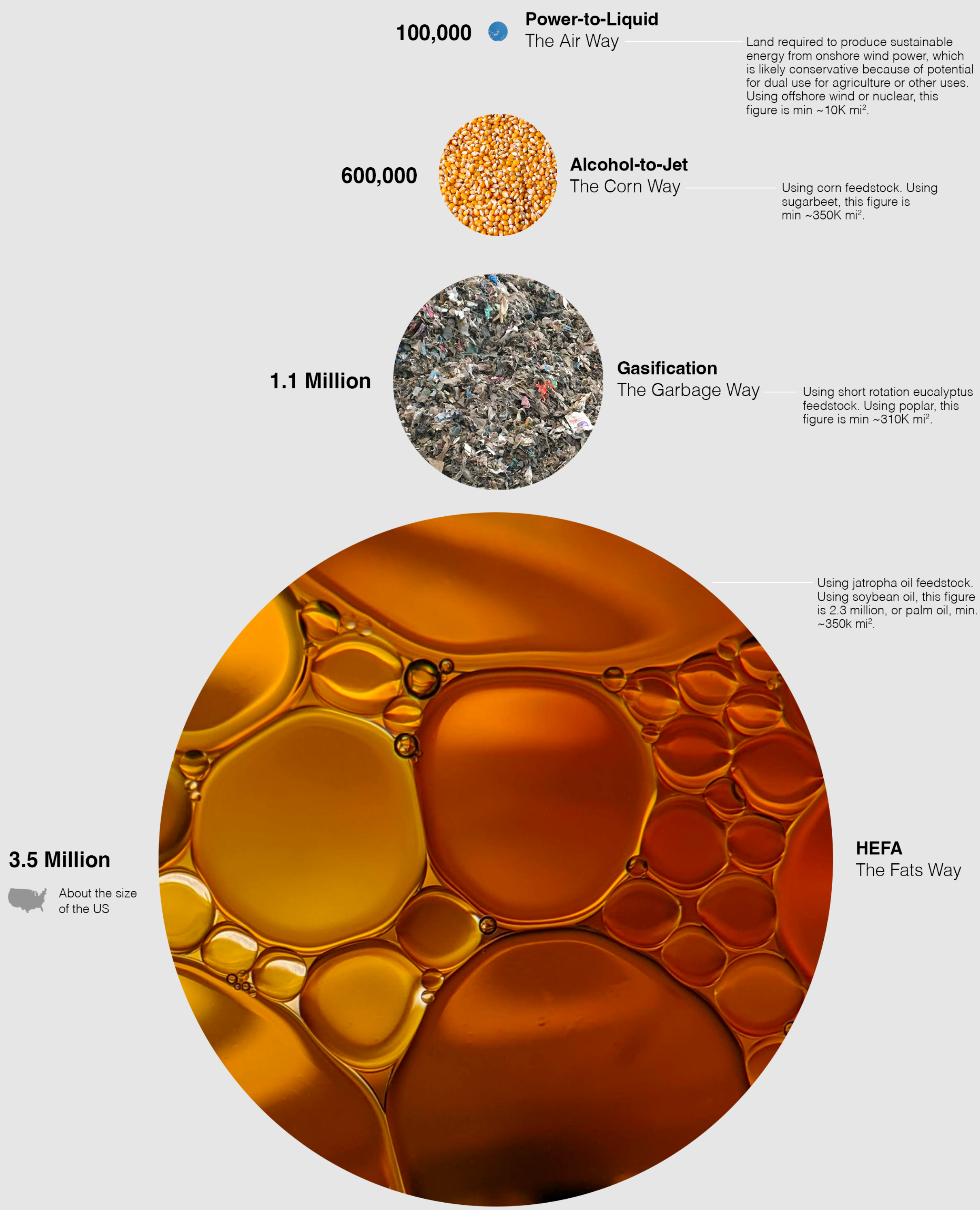
Dedicated corn, sugar beets, or sugar cane used to produce ethanol in Alcohol-to-Jet fuels are estimated to yield ~600-1100 gallons of fuel per acre each year. There are only enough waste feedstocks to cover ~50B gallons of demand, by 2050 100B gallons would still need to come from dedicated feedstocks. Scaled up to replace all 100B gallons of today's jet fuel demand, corn, sugar beets, or sugar cane would cover 350-600k square miles of land, enough to cover the UK 4-7 times.

The initial gallons of gasification fuels using waste products do not require significant dedicated land, but beyond ~50B gallons[13] of SAF dedicated feedstocks would be required. Assuming dedicated short rotation forestry feedstock gasification fuels would require 300k-1.1M square miles to replace 100B gallons, enough to blanket the UK in cultivated forests 3-12 times.

PtL fuels require 3-30X less land than even best-case dedicated feedstock biofuels

As the captured CO2 required for PtL fuels is either a waste product from other industrial processes or captured from the air through Direct Air Capture there is very little land use associated with the feedstocks for PtL fuels. Most land use is instead associated with the clean power required to produce the fuel, with solar PV and onshore wind requiring the most land and offshore wind and nuclear requiring the least. Replacing all jet fuel consumption with PtL fuels would require between 10k-100k mi^2 of land; an area equivalent to the country of Wales up to the whole of the UK.

Land use required to supply 100B gallons of SAF
(~100% of today's demand or 66% of 2050 demand)
Max mi² with dedicated feedstocks



PtL fuels require up to **30x** less land, and up to **1,000x** less water than biofuels

Water is finite: we must ensure we use it responsibly

Humans use over 1 quadrillion gallons (15 0's) of water every year, which is expected to rise with the increase in human population. As humans use this water primarily for agriculture, industry, and for personal use such as bathing and drinking, it is diverted from freshwater sources such as groundwater, lakes, and rivers. The 1 quadrillion gallons we use is the approximate equivalent of draining Lake Michigan every year. With moderate use, these sources will replenish themselves, but not indefinitely. As the human population rises we will need increased access to clean drinking water, therefore diverting ever more water for other uses (farming, industry, etc.). As the world replaces fossil-derived jet fuel with lower emissions SAFs, it is vital we ensure responsible water use in their production to minimize the impact on water usage and safeguard global access to clean drinking water.

Gallons of water required to make one gallon of jet fuel[15, 16]

Pathway	Max water (gal H2O / gal jet fuel)	Min water (gal H2O / gal jet fuel) dedicated feedstock	Min water (gal H2O / gal jet fuel) waste only
HEFA **The Fats Way**	**19,900** jatropha oil	**5,200** palm oil	**< 5,200** up to ~5-10B gallons
Alcohol-to-Jet **The Corn Way**	**3,500** corn	**1,400** sugar beet	**< 1,400** up to ~50B gallons
Gasification **The Garbage Way**	**3,900** short rotation forestry	N/A	< N/A up to ~50B gallons
Power-to-Liquid **The Air Way**	**< 3** onshore wind	N/A	**< 3** offshore / wind / nuclear

15. Schmidt, P., Batteiger, V., Roth, A., Weindorf, W. & Raksha, T. Power-to-Liquids as Renewable Fuel Option for Aviation: A Review. Chemie Ingenieur Technik 90, 127–140 (2018)
16. German Environment Agency. Power-to-Liquids: Potentials and Perspectives. (2016)

< 3
GALLONS

Water used by PtL pathway to make one gallon of SAF

Biofuels with dedicated living feedstocks use between 1,000-10,000 gallons of water per gallon of SAF

The necessary dedicated feedstock HEFA fuels to replace ~100B gallons can have an enormous water impact ranging from 500-2,000 trillion gallons of water, depending on feedstock type. This equates to 50-200% of current total annual water usage for humans across all uses.

If instead all 100B gallons of aviation fuel were replaced with dedicated feedstock Alcohol-to-Jet fuels, it would require between 140-350 trillion gallons of water: approximately all of the water in Lake Erie or Lake Ontario. While significantly less than HEFA fuel water usage, this still represents 10-30% of total annual human water usage.

The same 100B gallons of dedicated feedstock Gasification fuels would require up to 400 trillion gallons, or 40% of total annual human water usage.

PtL fuels use less than 3 gallons of water per gallon of SAF

For PtL fuels, some water is required in the production of hydrogen, an intermediate step in the production of E-Fuels. However, this process is highly efficient and results in ~1 gallon of water becoming 1 gallon of jet fuel, rather than 1,000s of gallons of water required per gallon of jet fuel. The water required to replace a year of jet fuel with PtL fuels (100-200B gallons) is equivalent to the water required to run US thermoelectric power plants for only 1 day.

Gallons of water required to replace 100B gallons of jet fuel

Pathway	Max water (gal H2O)	Min water (gal H2O) dedicated feedstock
HEFA **The Fats Way**	**520 trillion** palm oil	**1,991 trillion** jatropha oil
Alcohol-to-Jet **The Corn Way**	**142 trillion** sugar beet	**353 trillion** corn
Gasification **The Garbage Way**	N/A	**353 trillion** short rotation forestry
Power-to-Liquid **The Air Way**	**138 billion**	**138 billion**

in summary

1 Measure impact in tons of CO2e reduced, not gallons of fuel purchased

If they give the latter, ask for the former. Doing this will ensure that SAF dollars spent are efficiently addressing the intended purpose – reducing aviation emissions.

2 PtL fuel maximizes emissions reductions and minimizes resource use

PtL fuels have some of the highest emissions reduction potential of all fossil alternatives, while having the lowest land and water requirements. Almost universally, experts forecast PtL fuels as either the largest or one of the largest alternatives to fossil aviation by 2050.

3 When it comes to biofuels, waste feedstocks are limited

With biofuels, prioritizing SAF made in this way (and using rule #1) will go a long way.

- HEFA fuels can be waste-based up to 5B gallons or 5% of fuel demand. These fuels can achieve up to 84% emissions reduction.
- Alcohol-to-Jet fuels do not consistently prioritize waste products today but could in the future, though only up to 50B gallons.[17] These fuels could achieve up to a 70% emissions reduction.
- Gasification fuels use waste products as fuel today and can up to 50B gallons.[18] These fuels can achieve >90% emissions reduction.

4 It takes everybody – we will need all solutions to address aviation emissions

>13B gallons of SAF offtake agreements (including multi-year agreements) have been publicly announced to date, with purchases across all pathways. These announced purchases today are only a small fraction of the commitments required to eliminate emissions and reduce dependency from >100B gallon / year of fossil-derived jet fuel. However, with the passage of the 2022 Inflation Reduction Act in the US and the recent ReFuelEU in Europe, these commitments are expected to increase rapidly over the next few years. As airlines, corporations, and passengers raise the bar for lower emissions, it will become increasingly important to ensure replacement fuels are transparent in their emissions reduction potential and resource consumption, empowering all stakeholders to make informed choices about how and with whom they fly. Know, and trust, your SAF.

17., 18. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf

the future is fossil free

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