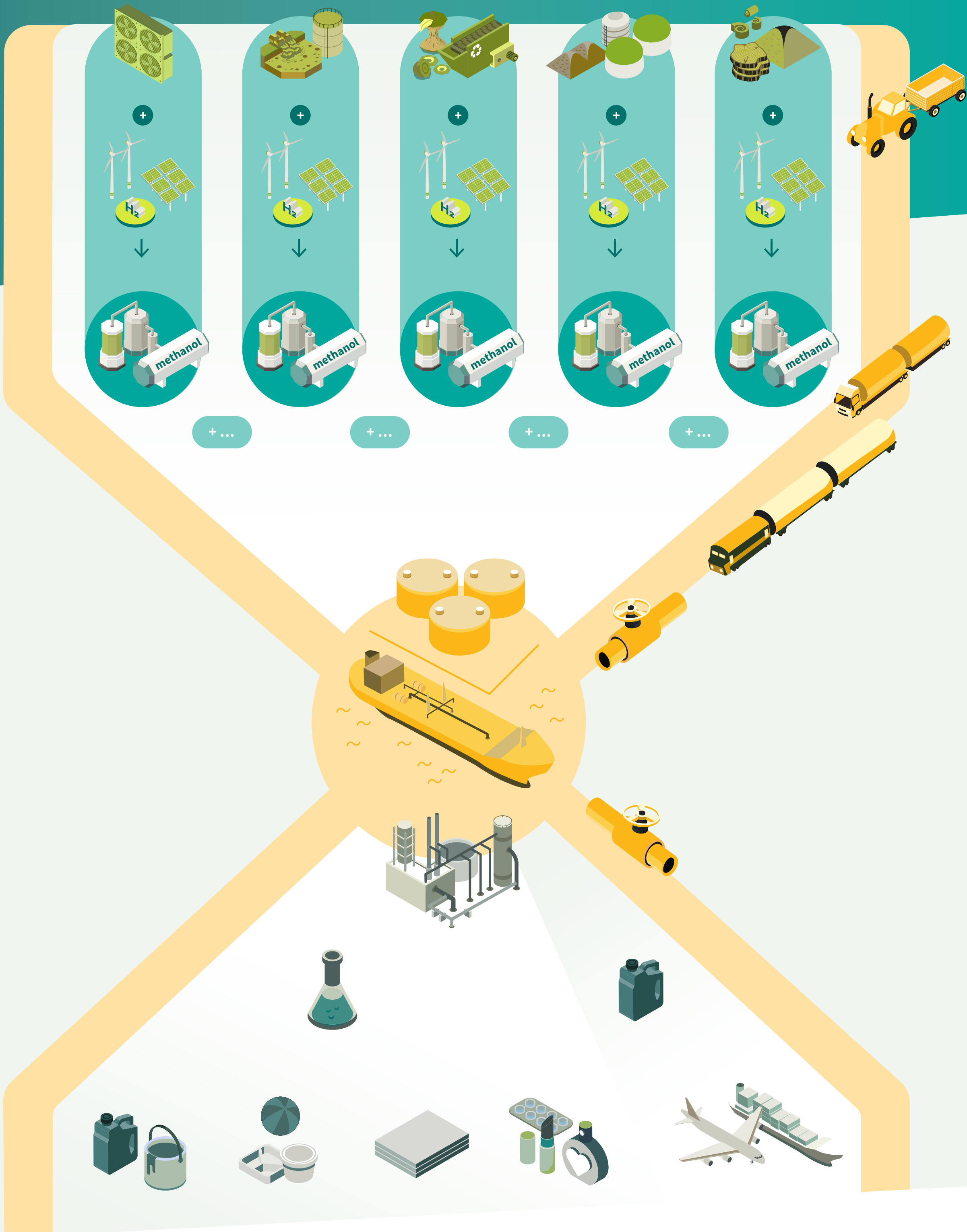
Preparing for e-SAF at scale

Introducing the PtX.CarbonRun



International PtX Hub

On behalf of:
Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

IKI INTERNATIONAL CLIMATE INITIATIVE

Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Berlin, Germany
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Executive Summary

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The aviation sector has largely answered the question of whether Sustainable Aviation Fuels (SAF) are necessary with a strong yes. Battery-electric aircrafts are being tested for short- haul routes, and purely hydrogen-powered ones for both short- and medium-haul. But for long-haul operations and the long time to market for these alternatives, hydrocarbon fuels are crucial. The question is if their non-fossil versions can be scaled fast enough. Global aviation currently consumes more than 300 million tonnes of jet fuel annually, with demand rising, while SAF production currently only supplies less than one percent of demand. The challenge is no longer to prove that SAF works technically, but to build a system that builds new supply chains capable of replacing fossil aviation fuels at global scale.

This impulse paper proposes the PtX.CarbonRun as a system to establish these new resilient supply chains. Rather than discussing the potentials of different fuel production technologies or feedstocks, the PtX.CarbonRun starts from a different observation: the future of sustainable aviation depends on mobilising vast quantities of renewable carbon from diversified and sustainable sources. Agricultural residues, forestry residues, biogas, sewage sludge, municipal waste, black liquor, other industrial biogenic carbon streams and, with sufficient economic viability, Direct Air Capture (DAC), i.e. carbon dioxide captured from the atmosphere, will all have a role to play. No single feedstock will be sufficient to satisfy the rising global demand for aviation fuels. Successful scaling of production therefore depends on creating a value chain capable of integrating many feedstocks into one common system.

The concept builds on three fundamental ideas:

First, the transition towards large-scale Power-to-Liquid (PtL) aviation fuels might not begin with billion-euro mega-projects. Biomass-to-Liquids (BtL) and Power-and-Biomass-to-Liquids (PBtL) production, using carbon from biogenic residues, can produce renewable fuels today at reasonable costs, while simultaneously creating the industrial capabilities required for future PtL deployment. Every project contributes fuel volumes, operational experience and expansion of supply chains, certification systems, logistics infrastructure and investment confidence. The real value of these projects therefore lies, beyond the produced SAF itself, in creating PtL readiness.

Second, the renewable carbon that is one key ingredient of all Sustainable Aviation Fuels must be transformed into a common, globally tradable intermediate product. The PtX.CarbonRun proposes methanol as the most suitable collection medium. Methanol is a liquid under ambient conditions, a globally traded commodity and a carrier of both renewable carbon and renewable energy. Unlike other intermediates, it can be produced economically at relatively small scale at the locations where the biogenic residues occur and then be transported efficiently using existing infrastructure. Methanol allows renewable carbon collection and final fuel production to be geographically separated, which is a game changer for both robustness and economics of sustainable aviation fuel production.

Third, with methanol as the intermediate product, aviation does not have to build these supply chains alone. Renewable methanol is already sought after by the chemical industry, the maritime sector and industrial applications. These off-takers can absorb significant methanol volumes long before Methanol-to-Jet facilities reach full-scale demand, creating early business cases, attracting investment and accelerating cost reductions and technology learning. Following ASTM‘s approval of methanol as a feedstock for Alcohol-to-Jet production in June 2026[1] , these new renewable methanol value chains can now directly supply future SAF production. Aviation becomes part of a

1 ASTM International. (n.d.). Work item WK96698: Revision of D7566-24d standard specification for aviation turbine fuel containing synthesized hydrocarbons. Retrieved July 16, 2026, from **https://www.astm.org/membership-participation/technical-committees/workitems/workitem-wk96698**

much larger renewable carbon economy that serves other industries and maritime transport as well, rather than carrying the entire burden of scale-up of production on its own.

The PtX.CarbonRun creates a new setup of value chains. Renewable carbon and hydrogen are converted into methanol wherever resources are available. Methanol is then aggregated, transported and traded globally. Downstream, Methanol-to-Jet modules can be integrated into existing refineries, allowing SAF production to benefit from decades of industrial experience. Furthermore, in the form of methanol, both renewable carbon and renewable energy are imported to refineries. Therefore, unlike a hydrogen economy, this setup already contains all ingredients for downstream production and is easier to implement.

Because such a system involves thousands of producers, transfer points and transactions, trust becomes as important as the molecules themselves. The ecosystem to be built should therefore be digital-by-design. Every methanol batch is accompanied by a digital product passport containing quality parameters, sustainability attributes and logistics information. Chain-of-custody systems, Monitoring, Reporting and Verification (MRV) procedures and digital traceability ensure that sustainability claims, regulatory compliance and future book-and-claim systems can operate at industrial scale. At the same time, these data streams become a strategic asset in themselves, which enable future optimisation through artificial intelligence and advanced analytics.

Many of the technological capabilities, industrial experience and renewable carbon resources required to implement the PtX.CarbonRun already exist. However, these are distributed across countries, sectors and value chains, which have rarely been considered as part of one common system. The challenge lies in connecting these existing competencies to create the basic architecture for a non-fossil economy. Building such a system clearly requires technological innovation, industrial investment and supportive regulation. However, the process of defossilisation is not as far-fetched as one might think, especially if international cooperation based on trust, shared values and long-term partnerships is utilised to its full potential.

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Aviation's path to net zero depends on seriously scaling Sustainable Aviation Fuels

From SAF deployment to SAF at scale

The question of whether Sustainable Aviation Fuels (SAF) are needed to defossilise aviation has largely been answered. Across industry, policy, and research, there is broad consensus that aviation will continue to rely on liquid hydrocarbon fuels for decades to come. Aircrafts entering service today are expected to remain operational well beyond 2060, while battery-electric and hydrogen-powered aircrafts are unlikely to replace a significant share of global long-haul aviation within the required timeframe in line with the Paris Agreement. As a result, the transition to climate-friendly aviation will depend on replacing fossil carbon in jet fuel rather than replacing hydrocarbon fuels altogether.

Technological feasibility of SAF production and use has been proven. Multiple SAF pathways have been certified by ASTM in recent years, commercial plants are operating, and regulatory frameworks are emerging worldwide. Yet despite this progress, global SAF production in 2025 amounted to only around 1.9 million tonnes against a jet fuel demand of approximately 310 million tonnes. The decisive question has become whether SAF can scale fast enough to enable the targeted emissions reductions.

This next phase of aviation's defossilisation must focus on building supply systems capable of delivering hundreds of millions of tonnes of non-fossil aviation fuel.

Defossilisation requires a different perspective

Much of the current SAF discussion remains centred on the potentials of individual production pathways and their respective feedstocks. Questions such as whether a particular fuel originates from used cooking oil, municipal waste, forestry residues, ethanol, renewable hydrogen, or captured carbon dioxide continue to dominate policy debates.

These discussions are important. However, when viewed from the perspective of complete defossilisation, they address only part of the challenge.

Aviation ultimately requires a supply system that can replace virtually all fossil carbon in current fuel supply. This shifts attention away from individual projects and towards the broader question of resource mobilisation. Instead of asking which feedstock can supply the next SAF plant, the more relevant question becomes how to funnel abundant but geographically dispersed biogenic carbon into a common fuel system.

The scale of the transition suggests that no single feedstock will be sufficient on its own. Oils and fats, agricultural residues, forestry by-products, biogenic waste streams, industrial biogenic carbon, and eventually atmospheric carbon will all have roles to play. Defossilisation therefore depends on creating value chains capable of integrating many feedstocks.

Why feedstock-agnostic pathways matter

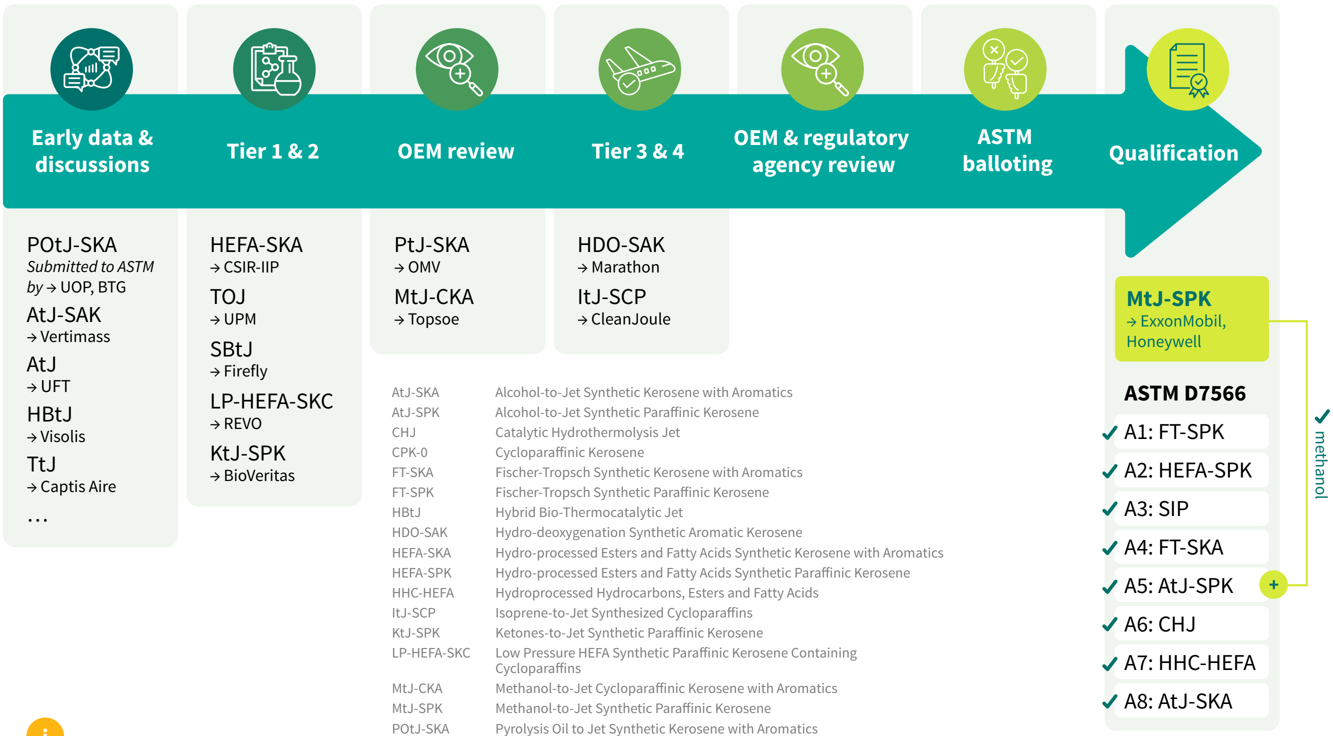
This perspective changes how SAF pathways are evaluated. Feedstock-specific pathways have played a critical role in establishing the SAF market. For example, the HEFA market provides early volumes, operational experience, and investor confidence. However, their growth potential is constrained by the availability of the specific feedstocks.

For the long-term transition, the SAF pathways that can accommodate a widening range of renewable carbon sources become increasingly important. Syngas-based pathways, such as Methanol-to-Jet and Fischer-Tropsch, are agnostic to where the carbon and hydrogen come from. Their strategic value extends beyond the fuel they produce to their ability to absorb any new feedstocks to transform anything to e.g. methanol, as technology, sustainability frameworks, and carbon sourcing opportunities evolve.

The distinction between feedstock-specific and feedstock-agnostic pathways is strategic. It determines whether SAF remains a niche fuel supplied from limited resource pools like used cooking oil or ethanol or develops into a system based on a globally scalable commodity like methanol capable of supporting the complete defossilisation of aviation.

From this perspective, the future success of SAF should be measured by more than production costs or conversion efficiencies. Rather, the ability of a pathway to connect diverse renewable carbon sources to large-scale fuel production turns into a major factor.

ASTM D4054 Pipeline



AtJ-SKA	Alcohol-to-Jet Synthetic Kerosene with Aromatics
AtJ-SPK	Alcohol-to-Jet Synthetic Paraffinic Kerosene
CHJ	Catalytic Hydrothermolysis Jet
CPK-0	Cycloparaffinic Kerosene
FT-SKA	Fischer-Tropsch Synthetic Kerosene with Aromatics
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
HBtJ	Hybrid Bio-Thermocatalytic Jet
HDO-SAK	Hydro-deoxygenation Synthetic Aromatic Kerosene
HEFA-SKA	Hydro-processed Esters and Fatty Acids Synthetic Kerosene with Aromatics
HEFA-SPK	Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene
HHC-HEFA	Hydroprocessed Hydrocarbons, Esters and Fatty Acids
ItJ-SCP	Isoprene-to-Jet Synthesized Cycloparaffins
KtJ-SPK	Ketones-to-Jet Synthetic Paraffinic Kerosene
LP-HEFA-SKC	Low Pressure HEFA Synthetic Paraffinic Kerosene Containing Cycloparaffins
MtJ-CKA	Methanol-to-Jet Cycloparaffinic Kerosene with Aromatics
MtJ-SPK	Methanol-to-Jet Synthetic Paraffinic Kerosene
POtJ-SKA	Pyrolysis Oil to Jet Synthetic Kerosene with Aromatics
PtJ-SKA	Plastics-to-Jet Synthetic Kerosene with Aromatics
SATF	Synthetic Aviation Turbine Fuel
SBC	Synthetic Blending Component
SBtJ	Sewage Biosolids to Jet
SIP	Synthetic Iso-paraffins
TOJ-SKA	Tall Oil Jet Synthetic Kerosene with Aromatics
TtJ	Terpenes-to-Jet

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The graph shows the current state of existing SAF production pathways, as well as where new SAF pathways candidates are in the certification process (ASTM D4054).

Source: courtesy of Gurhan Andac, GE Aerospace, ASTM D02.J06 Chair

How Biomass-to-Liquid and Power-and-Biomass-to-Liquid can accelerate the learning curve and help to become Power-to-Liquid ready today

2

e-SAF and PtL are not yet cost-competitive

Most aviation transition scenarios assume that electricity-based Sustainable Aviation Fuels (e-SAF or Power-to-Liquid/PtL) will ultimately provide the largest share of future jet fuel demand and are the only currently available solution to reach full defossilisation of the sector. Yet the direct transition from today's fossil-based aviation fuel production to large-scale PtL production faces substantial economic and practical barriers.

The main challenge is the simultaneous need to scale renewable electricity generation, hydrogen production, carbon sourcing, fuel synthesis, logistics infrastructure, certification systems, financing structures and industrial know-how. Attempting to build all elements at full scale from the outset creates considerable cost and investment risks, possibly prohibitively high.

Scaling SAF must allow learning curves and cost reductions first

While meeting the majority of jet fuel demand with e-SAF by 2050 remains the long-term objective, a direct transition is neither economically viable nor supported by present policies and infrastructure. While it's necessary to stay committed to this goal, the transition to achieving it must factor in the necessary learning curves by building the value chains step by step. Virtually every successful energy transition technology has gone through a learning curve including rapid costs reductions before reaching large-scale deployment. Wind turbines, solar modules, batteries and electrolysers all benefited from years of operational experience before becoming competitive at scale. The same trajectory applies to Sustainable Aviation Fuels.

Biomass-to-Liquid and Power-and-Biomass-to-Liquid as PtL enablers

Biomass-to-Liquids (BtL) and Power-and-Biomass-to-Liquids (PBtL) can make today's SAF market "PtL ready". Both technologies start with renewable carbon in form of residue streams that are vastly available today: biogas, agricultural residues, forestry residues, sewage sludge, municipal waste streams, black liquor, and other industrial biogenic carbon sources can all serve as feedstocks.

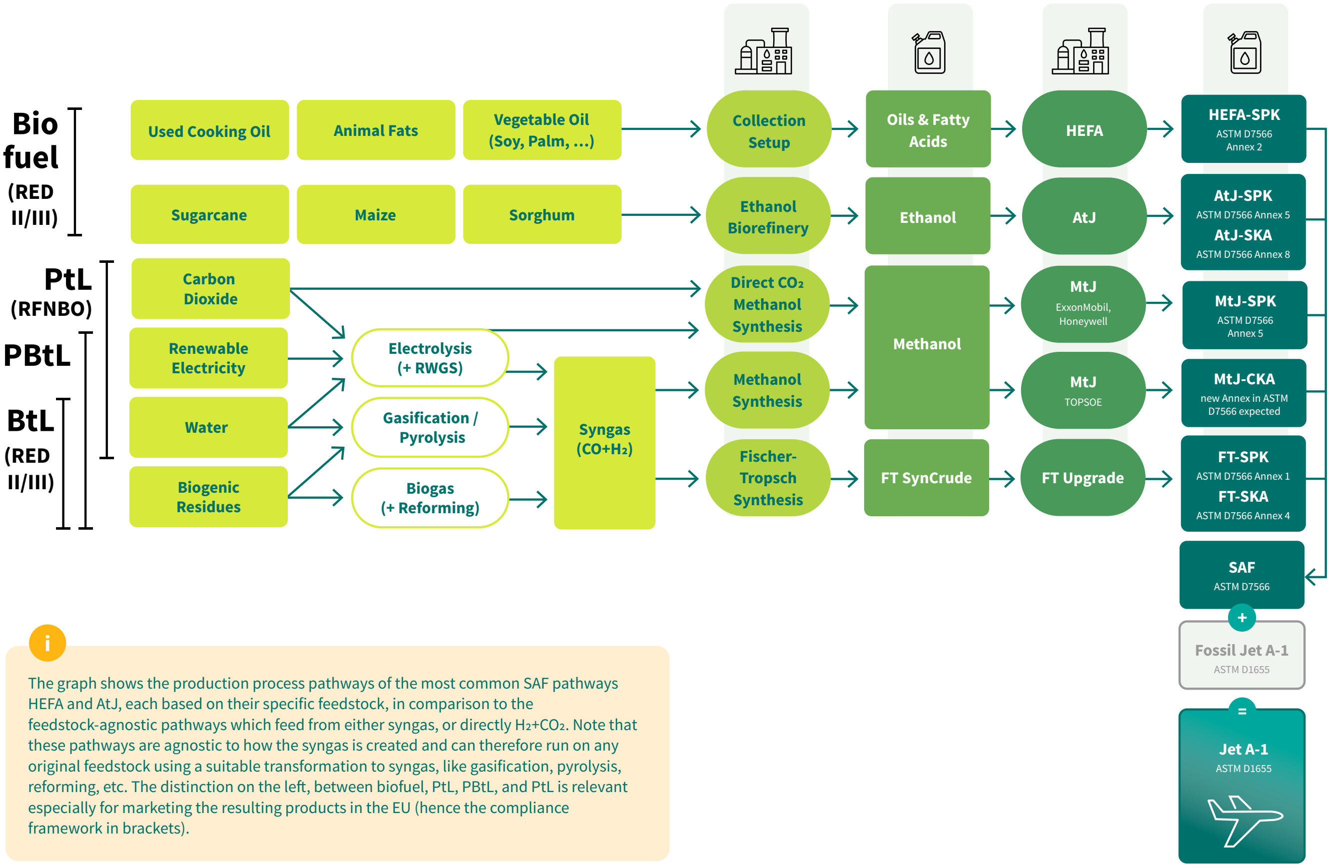
In BtL, both building blocks for either Fischer-Tropsch or methanol production are created from the biomass itself: hydrogen and carbon monoxide. The biomass needs to come with a sufficiently high energy content to make this possible. Suitable feedstocks are biogas or wood residues. But there is a downside: drawing energy from the original feedstock means losing valuable energy and carbon.

In PBtL, a certain amount of green hydrogen is added, with its useful high energy content. This increases carbon utilisation in the chemical process. Therefore, PBtL already introduces green hydrogen production from renewable electricity and water at site.

The strategic value of BtL and PBtL extends beyond the fuel volumes they produce. Every successful project contributes to the development of industrial capabilities that remain relevant in a future PtL economy. Fuel upgrading facilities, logistics systems, storage infrastructure, quality assurance procedures, certification processes, digital traceability systems and commercial offtake structures can all be developed long before fully synthetic fuels (PtL/e-SAF), made from green hydrogen and sustainable CO_2, are traded in larger volumes.

Thus, instead of viewing biomass-based and electricity-based fuels as competing alternatives, they can be interpreted as overlapping stages along a common industrial learning curve, as long as they feed into the same process steps eventually required for PtL. In this sense, while with every PBtL plant the physical output of SAF increases, something more valuable grows: PtL readiness.

Relevant SAF pathways



The graph shows the production process pathways of the most common SAF pathways HEFA and AtJ, each based on their specific feedstock, in comparison to the feedstock-agnostic pathways which feed from either syngas, or directly H_2+CO_2. Note that these pathways are agnostic to how the syngas is created and can therefore run on any original feedstock using a suitable transformation to syngas, like gasification, pyrolysis, reforming, etc. The distinction on the left, between biofuel, PtL, PBtL, and PtL is relevant especially for marketing the resulting products in the EU (hence the compliance framework in brackets).

Smart Renewable Carbon Sourcing is Key to Achieve the Necessary Volumes

3

Renewable carbon comes in many forms

The renewable carbon sources mentioned above have one important characteristic in common: they are fundamentally different from one another. Biogas occurs as a gaseous carbon source rich in methane. Agricultural and forestry residues are solid lignocellulosic materials. Black liquor is a liquid process stream from the pulp and paper industry. Sewage sludge, municipal waste and industrial residues each come with their own physical and chemical properties. Carbon dioxide from biogenic sources or Direct Air Capture contains carbon in its most oxidised low-energy form.

In this sense, different classes of feedstock require different technological approaches. Biogas may be reformed, lignocellulosic residues gasified, wet biomass processed hydrothermally, and carbon dioxide combined with renewable hydrogen through dedicated synthesis routes. The PtX.CarbonRun will therefore rely – but only upstream – on a portfolio of conversion technologies.

Carbon quality matters

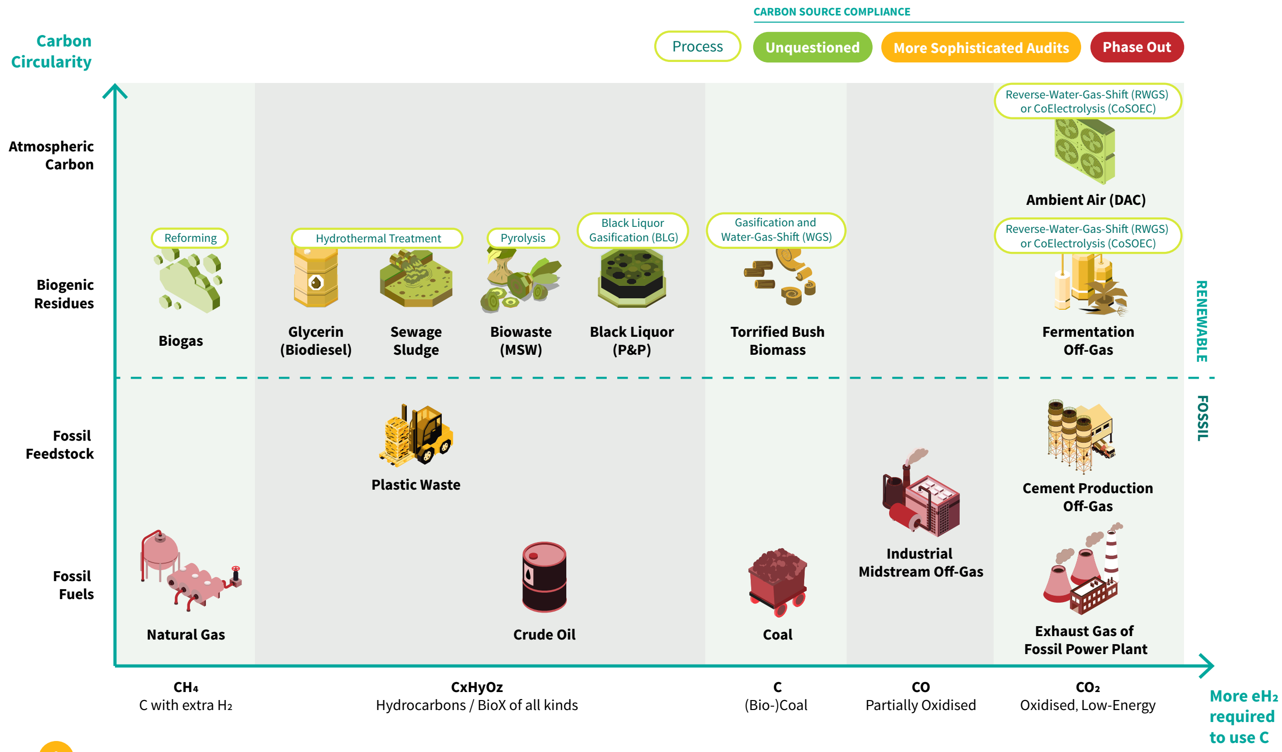
The effort required to transform renewable carbon into aviation fuel depends on its chemical state. Carbon sources that already contain hydrogen are easier to convert into liquid hydrocarbons, energetically speaking. Methane is the most obvious example. Its carbon atom is already fully surrounded by hydrogen atoms, meaning comparatively little additional hydrogen is required during fuel synthesis.

At the opposite end sits carbon dioxide. Here, carbon is already fully oxidised and therefore low in energy. Before it can become a hydrocarbon fuel again, significant amounts of hydrogen must be added.

Most renewable carbon sources fall somewhere between these two extremes. Biomass, biogenic residues, black liquor and other organic feedstocks contain varying proportions of carbon, hydrogen and oxygen, resulting in different volumes of hydrogen required to convert the carbon source into a liquid hydrocarbon.

Infographic on the next page ↓

Carbon Sourcing
Feedstock Variety



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The graph shows examples of carbon sources, classifying them between fossil and non-fossil on the vertical axis, and the form of occurrance on the horizontal axis. In red are the sources which ideally won't exist in a non-fossil future economy, in yellow the ones which will remain but are not really perfectly sustainable. In green the ones which are unquestioned and compliant even if regulation tightens. To make the C usable for BtL, PBtL or PtL, some transformation needs to occur. As rule of thumb, we can state that the more O is attached to the C in its form of occurrance, the more H is needed to make it usable. In other words: more energy is necessary for CO_2 than for C, and CH_4 even comes with excess energy.

From this perspective, the transition from BtL to PBtL and eventually PtL can also be understood as a gradual shift along a carbon spectrum: from hydrogen-rich renewable carbon sources as a starter towards increasingly oxidised carbon sources that require larger quantities of renewable hydrogen but ultimately offer greater scalability since CO_2 as a carbon source is abundant, even before Direct Air Capture eventually becomes cost-effective.

The role of hydrogen

While the different forms of biogenic residues provide the carbon required for future fuels, renewable hydrogen acts as the essential ingredient that turns these carbon sources into liquid hydrocarbons.

Unlike carbon, however, hydrogen does not need to be sourced from different natural resource streams. It can be produced with renewable electricity and water at site. Water is often already contained in the carbon source itself, since most residues need to be dried first anyway. And as renewable electricity deployment continues to become cheaper and accelerate globally, hydrogen availability can grow alongside.

Methanol as the Collection Medium

4

A common language for renewable carbon

The previous chapters established that renewable carbon would originate from a wide variety of sources. While the pathways differ substantially at the feedstock and first processing level, they ultimately face a common requirement: their output must become part of a scalable global supply chain. For such a supply chain to emerge, renewable carbon requires a common language. Methanol provides exactly that.

Methanol is a single chemical compound, well-defined in several industrial norms. Regardless of its original carbon and hydrogen feedstock, the resulting product remains chemically identical: CH_3OH.

Economies of scale without upstream mega-projects

Many industrial processes only become economically viable at very large scales. Renewable carbon sourcing via methanol follows a different logic. Since the most crucial feedstock renewable carbon is dispersed across many locations and may only be available in moderate quantities, methanol synthesis is particularly attractive because it can operate efficiently across a broad range of plant sizes. This allows for a modular approach: production facilities can be standardised, even serial produced and certified via a type-specific procedure rather than a time-consuming and expensive site-specific licensing. Ideally, a biogas producer could order a biogas-to-methanol upgrade plant, which comes in a few standard size containers, each stamped with its CE or TÜV certificate from a company that produces these plants in series, just as cars are produced today.

And for the product methanol: as a liquid at room temperature, it can be stored in smaller tanks onsite, then transported by truck, rail, barge or ship. It can be handled using proven infrastructure and handling procedures that are in place almost everywhere in the world. From a systemic perspective, methanol represents the bridge between distributed carbon sources upstream and industrial-scale refineries downstream, which then serve the traditional offtake market with now renewable end products.

A mature global commodity

Hardly any other energy carrier benefits from the level of industrial experience that exists globally with methanol. Global methanol production, most of it fossil currently, exceeds one hundred million tonnes per year. International specifications, safety standards, storage procedures, shipping regulations and trading mechanisms are well established. Decades of operational experience exist across the chemical, energy and maritime sectors.

This maturity reduces investment risk considerably. Instead of creating an entirely new commodity from scratch, renewable methanol can build upon existing infrastructure, existing regulations and existing market mechanisms.

The transition from grey to green becomes an evolution of an already mature commodity market with changes upstream that are gradual but have the potential to grow exponentially.

The downsides of methanol

Methanol is not a perfect molecule. Its most important disadvantage is toxicity. Methanol can cause severe poisoning if ingested and may lead to blindness or even death. Exposure can also occur through inhalation or prolonged skin contact. Another notable characteristic is that methanol burns without a visible flame. Strict handling procedures are therefore essential throughout the supply chain, as is the case with gasoline, naphtha, or other flammable hydrocarbons.

Fortunately, methanol‘s hazards are well understood. The chemical industry has handled large volumes of methanol safely for decades, supported by comprehensive international regulations, established training procedures and mature safety standards.

More of an economic concern is the fact that the production procedures generate water alongside methanol. If this water is transported unnecessarily, logistics costs increase while no additional value is created. For this reason, a first distillation step should generally occur at the production site. The objective is straightforward: transport carbon and embedded energy, not water.

Neither of these challenges fundamentally limits methanol‘s suitability as a collection medium. They simply reinforce the need for good engineering practice and established industrial procedures.

The centre of the PtX.CarbonRun

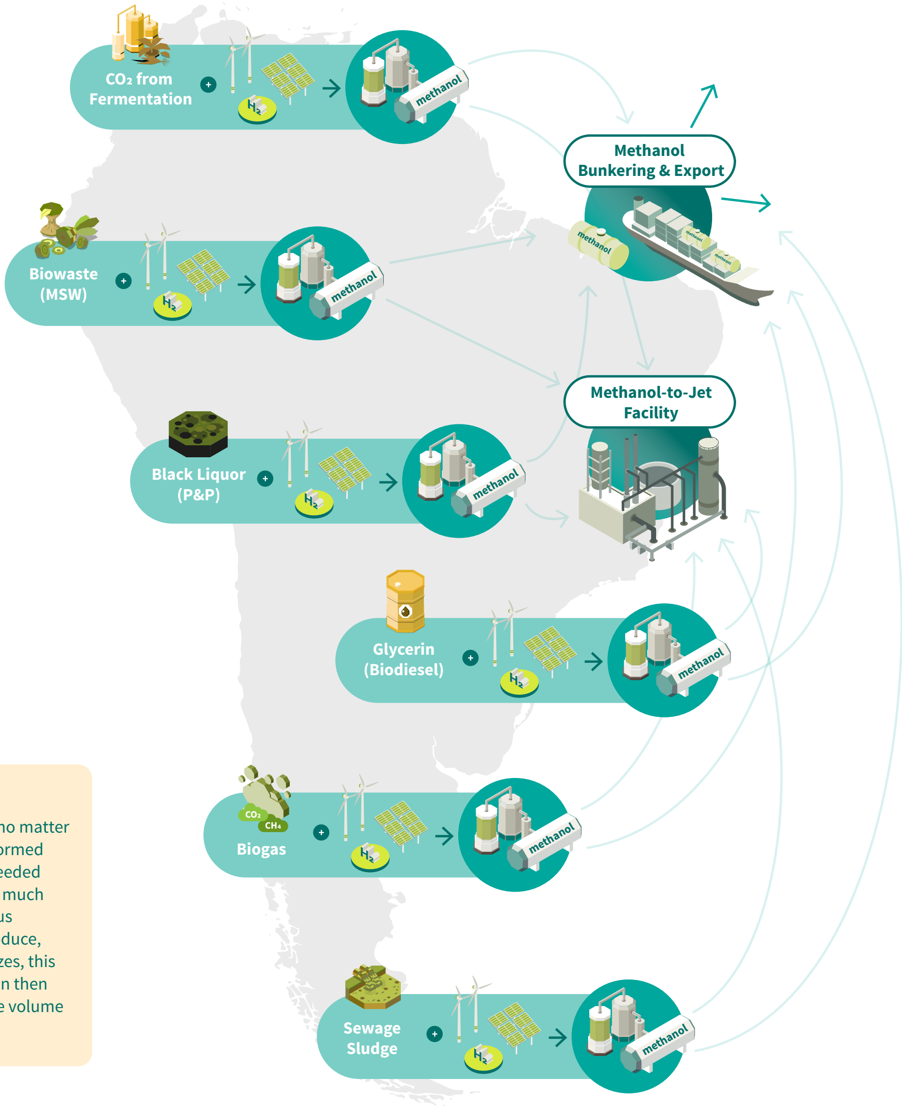
Taken together, these characteristics make methanol uniquely suited to connect distributed renewable carbon resources and green hydrogen with global markets.

As a standardised molecule, liquid commodity, carrier of both carbon and embedded renewable energy, compatible with decentralised production and supported by decades of industrial experience, methanol is not just an intermediate product, but the pivot point of the PtX.CarbonRun.

Infographic on the next page ↓

Carbon Sourcing

Decentralised production of renewable methanol



The graph illustrates the upstream part of the PtX.CarbonRun. Any carbon containing residue, no matter where and in which form it occurs, can be transformed into methanol at site. More or less hydrogen is needed depending on the form of occurrence, or on how much oxygen is tied to the carbon (see graph of previous chapter). Since methanol is relatively easy to produce, and economically viable even at smaller plant sizes, this decentralised setup is possible. The methanol can then be transported like any other fuel to agglomerate volume at ports or refineries.

Aviation does not have to build its Supply Chain alone

5

Scaling starts where demand already exists

One of the most common assumptions in discussions about Sustainable Aviation Fuels is that dedicated value chains must be built specifically for aviation fuels. We would like to suggest otherwise. Technologies can scale by serving multiple markets simultaneously, allowing production volumes, operational experience and investor confidence to grow long before a dominant application emerges.

Local demand creates the first business case

For many future producers of renewable methanol, the first customer may not be a fuel trader or a refinery, but a local industrial facility. Often the price these companies currently pay for fossil methanol is much higher than world market price, due to transport costs. The renewable methanol produced next door not needing to be transported far might be able to compete with the price of fossil methanol.

The importance of these early markets should not be underestimated. They allow production facilities to generate revenues, build operational experience and improve process performance while broader international markets continue to develop.

Defossilising existing industrial value chains

One large opportunity lies in the chemical industry as first off-takers for green methanol. Methanol serves as a feedstock for numerous products including plastics, solvents, paints, adhesives and synthetic materials. With renewable methanol all these products can be defossilised immediately in all cases where methanol is the current feedstock.

For the long-term transition, existing industrial sites currently dependent on crude oil derivatives and naphtha-based feedstocks can progressively integrate green methanol into their processes while maintaining much of their existing infrastructure, workforce and industrial know-how. Although this requires retrofitting, it presents a powerful pathway for industrial defossilisation and counteracts deindustrialisation.

Shipping can accelerate market growth

Among emerging sectors, shipping stands out as one of the most promising demand drivers for renewable methanol. The maritime sector faces a challenge similar to aviation: large vessels require energy-dense fuels that can be safely stored onboard and transported globally. Methanol has therefore emerged as one of the leading candidates as the e-fuel to enable maritime defossilisation. A rapidly growing fleet of methanol-capable vessels speaks for itself.

For renewable methanol producers, shipping fuel provides an attractive market. The sector can absorb large volumes, does not require much upgrading of the methanol itself, and can create demand long before the aviation sector reaches comparable scale. So, rather than competing with aviation, shipping can help establish the production base upon which future aviation fuel supply will build upon.

Aviation as the next scale destination

A decisive milestone was reached in June 2026 when methanol was accepted as a feedstock under the Alcohol-to-Jet Synthetic Paraffinic Kerosene (AtJ-SPK) pathway of ASTM D7566 Annex A5. Another methanol-based SAF is also advancing in the certification process and will likely result in a dedicated annex to ASTM D7566: Methanol-to-Jet Cycloparaffinic Kerosene with Aromatics (MtJ-CKA)[1]. With this, methanol becomes a recognised building block of the future SAF fuel supply and allows for the PtX.CarbonRun for aviation.

Rather than constructing complete SAF production chains close to the renewable carbon and energy source, the value chains build up to "just" green methanol at these disperse locations. The methanol is then transported to existing refining and fuel production centres, where dedicated MtJ modules are integrated into established facilities. Refineries already possess storage facilities, utilities, logistics connections, product handling systems, fuel qualification laboratories, and direct access to jet fuel markets. Adding a Methanol-to-Jet conversion unit therefore becomes considerably simpler than building up the entire SAF production chain at every feedstock location.

The result is a newly configurated value chain. Upstream regions collect renewable carbon and produce methanol, without the need of sophisticated SAF qualification procedures. Downstream industrial hubs upgrade methanol all the way to certified Jet A-1 fuel. Between them emerges a global renewable methanol market that connects both approaches.

Systemically speaking, this Methanol-to-Jet SAF architecture allows renewable carbon collection and aviation fuel production to develop independently while remaining connected through the common intermediate methanol.

From demand diversification to market resilience

Aviation may ultimately become one of the largest consumers of renewable methanol-derived products. Yet the transition becomes significantly more robust when growth is supported by multiple offtake sectors rather than a single market: diversified demand creates diversified revenue streams. Diversified revenue streams attract investment. Investment drives scale. And scale is precisely what the defossilisation of the growing aviation sector requires.

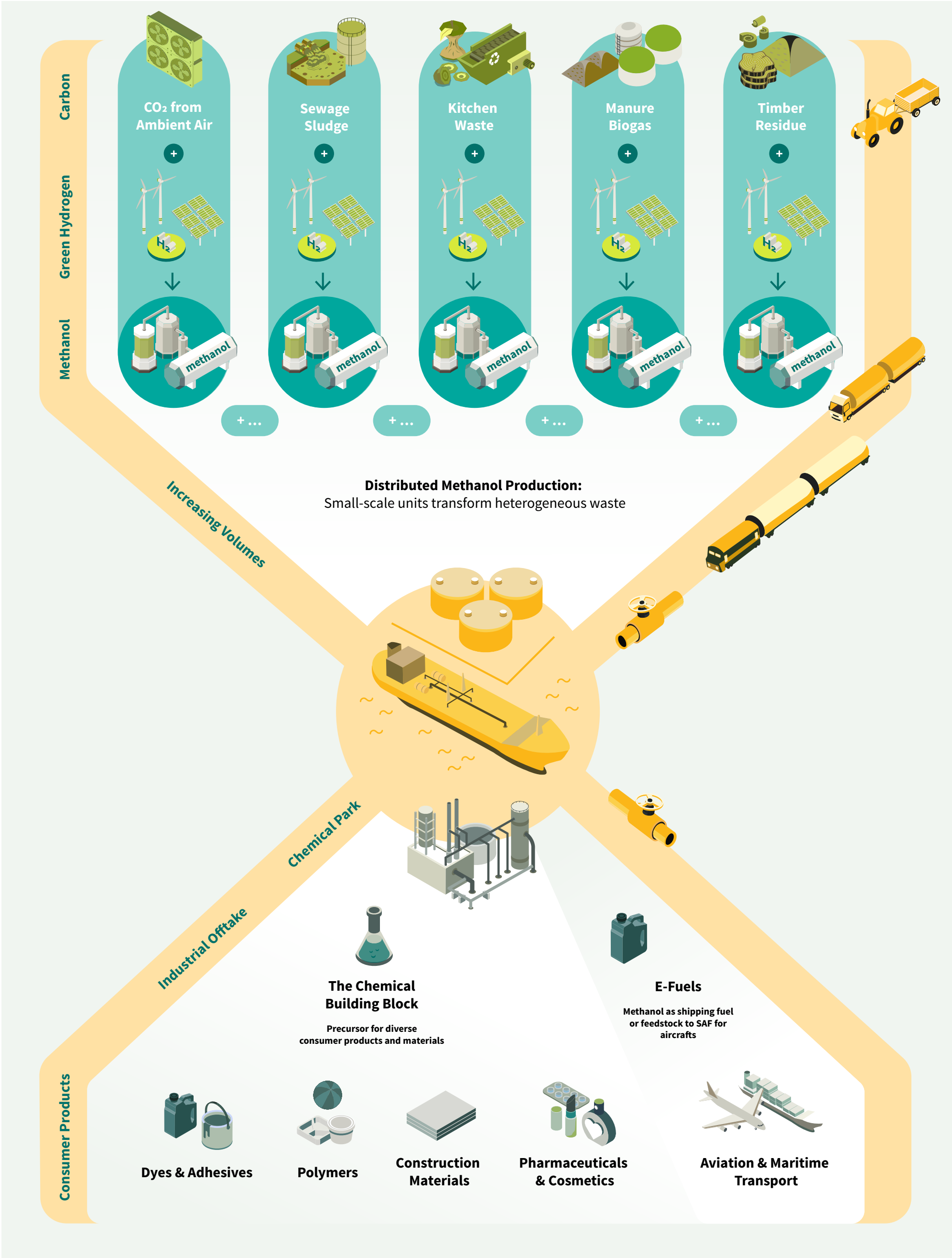
The PtX.CarbonRun is not an aviation-only concept but proposes a renewable carbon ecosystem in which aviation acts as both pioneer and one of several off-takers within a much broader industrial transition.

Infographic on the next page ↓

1 Methanol Institute. (2026, January). Methanol-to-Jet SAF: Policy, Technoeconomic and Commercial Outlook. **https://methanol.org/wp-content/uploads/2026/01/MTJ-Report-1-20-26_V13.pdf**

The PtX.CarbonRun

Scaling decentralised renewable carbon to supply industries globally



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The graph illustrates the PtX.CarbonRun as a whole. The upper part recapitulates the previous chapters on carbon sourcing and the transformation to methanol. The pivot point of the hour glass represents the methanol ecosystem already in place, with its storage facilities, terminals, pipelines, the associated norms, certificates, and trading system. Below this pivot point the diverse landscape of offtake sectors take over the methanol, fossil today, renewable in the future, but always the same substance, no technical changes necessary.

Digital by Design: Trust as an Asset

6

Trust becomes the critical resource

The PtX.CarbonRun envisions a future in which methanol is produced and collected from thousands of locations, aggregated through international supply chains and ultimately transformed into certified products such as Sustainable Aviation Fuel. Such a system can only function if each methanol batch is trusted to be as renewable as it is claimed to be.

Traditional fossil supply chains rely on relatively few producers, established infrastructure and decades of operational experience. Renewable carbon supply chains are fundamentally different. They involve a much larger number of participants, a wider variety of feedstocks and highly branched value chains.

In this scenario, trust in the product's characteristics becomes more crucial. While physically molecules are moved, information must be gathered along the way and at the utmost granularity.

Every batch has its individual properties

The value of renewable methanol is determined by more than its chemical composition. Two physically identical methanol molecules may carry entirely different sustainability attributes depending on how they were produced:

- Which carbon source was used?
- How was the hydrogen supplied?
- Which electricity source powered the process?
- Which environmental safeguards were applied?
- Were social and labour standards respected?

To answer these questions reliably, every batch of renewable methanol should be accompanied by a digital product passport, which contains granular information on quality specifications, sustainability performance, regulatory compliance, logistics history, and ownership transfers throughout the value chain.

Chain of custody at industrial scale

The decentralisation inherent to the PtX.CarbonRun only works if this traceability is secured. The PtX.CarbonRun therefore incorporates chain-of-custody systems from the outset. At every transfer point, information travels alongside the product itself. Production data, measured/probed quality parameters, sustainability attributes and logistics information are continuously updated at a centralised registry, and are verified immediately.

Telemetric monitoring systems, digital reporting tools and automated MRV (Monitoring, Reporting and Verification) procedures create a transparent record of the product‘s journey. When methanol from multiple producers is aggregated, the associated digital records can be consolidated while preserving provenance information and sustainability attributes. This capability becomes increasingly important as sustainability reporting requirements tighten.

Compliance as a stepping stone

The first applications of such systems will naturally focus on certification and regulatory compliance. Frameworks such as ICAO CORSIA, EU RED III, ReFuelEU Aviation and future international sustainability schemes require increasing levels of transparency and verification. Digital product passports and chain-of-custody systems can substantially reduce administrative complexity while improving confidence in reported sustainability performance.

However, compliance represents only the first layer of value. Once reliable data flows exist, they can also be used to improve operational performance.

Data as a strategic asset

Every transaction, every shipment and every production batch generate data. Over time, these data streams become one of the most valuable outputs of the PtX.CarbonRun themselves: production data can reveal potential process improvements. Logistics data can identify bottlenecks and inefficiencies. Market data can improve forecasting and investment decisions. Environmental data can support continuous sustainability improvements.

As artificial intelligence systems become increasingly capable, the value of these datasets is likely to increase further. Machine learning models can optimise production processes, improve maintenance schedules, identify operational anomalies, support the qualification of produced batches, and certification of products across different markets.

Building tomorrow‘s renewable carbon economy today

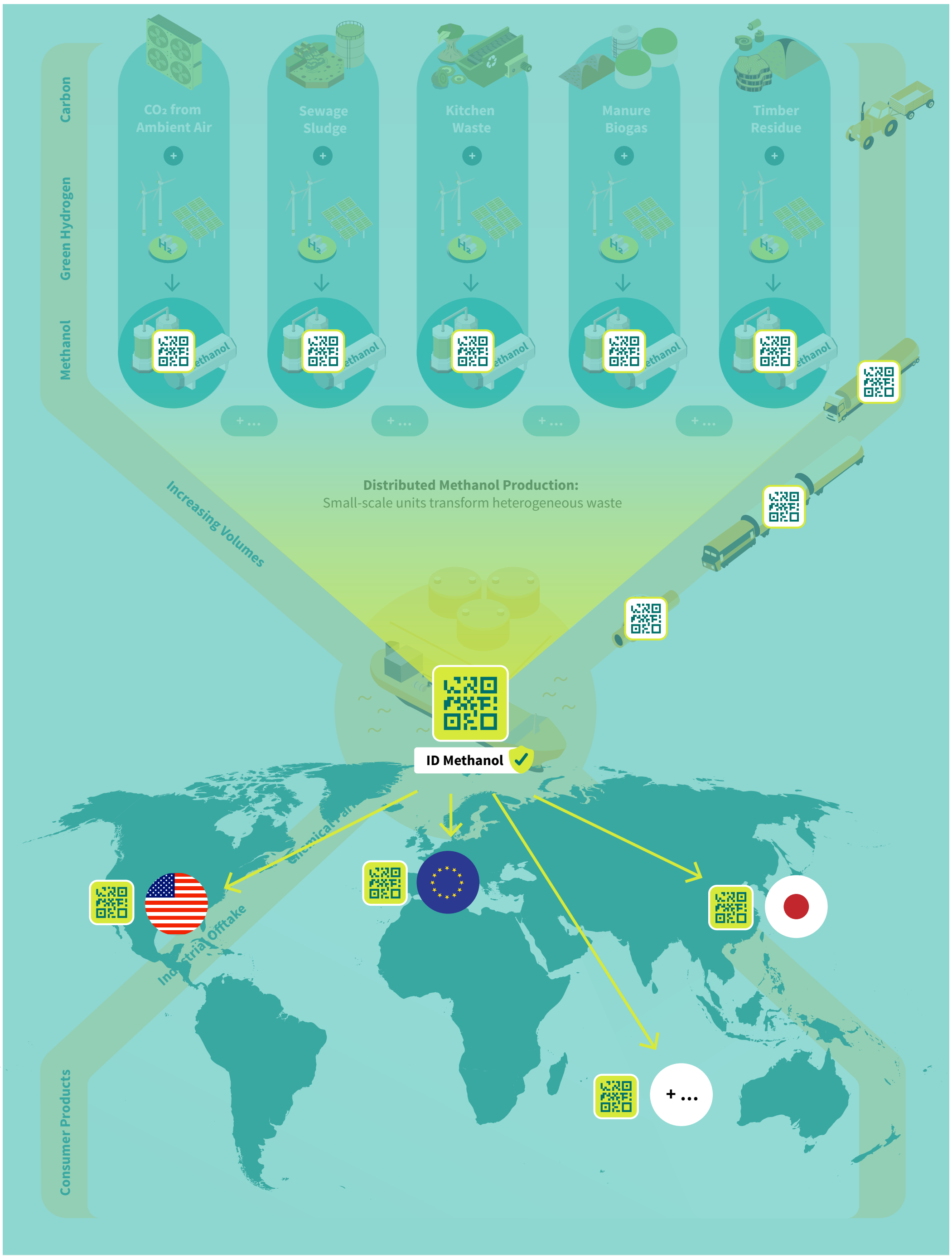
Since the renewable carbon economy is still emerging, digital infrastructure can be incorporated from the beginning and as part of the frameworks regulating agencies and policy makers are developing and implementing today. This has the potential to rapidly create an innovative, transparent, compliant, and adaptable system.

New sustainability criteria, emerging market mechanisms, book-and-claim systems, AI-driven optimisation tools, and future regulatory requirements can all be integrated more easily when high-quality data already exists. In this sense, digitalisation means future-proofing the entire PtX.CarbonRun.

Infographic on the next page ↓

Chain-of-Custody

Digital by design



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The graph illustrates how a digital chain-of-custody chain could look like. Any batch of methanol produced anywhere gets its digital fingerprint at the production site, the data being fed into a global registry. The volumes and quality control data is constantly fed into the system using the batch's QR code. Agglomeration generates a new entry, combining the previous data. Eventually, a trustworthy product arrives at the offtaker's terminal or a border control point.

Bullet-Proofing the PtX.CarbonRun

7

A promising concept is not enough

The previous chapters described how renewable carbon can be collected, upgraded into methanol, connected to multiple offtake sectors and ultimately serve as the intermediate to produce Sustainable Aviation Fuel at scale. The remaining question is whether such a system can scale in the real world.

Even though technological feasibility is given, a successful industrial transition such as this must also be investable, financeable, operable and resilient under changing market conditions. The PtX.CarbonRun should therefore be assessed both from a technological perspective and from the perspective of risk and robustness.

Eliminating risk entirely is not possible, but it can be distributed and managed across many market participants, locations and stages of the value chain.

Reducing market risk through diversified demand

One of the largest uncertainties facing many e-SAF projects is demand development. High future SAF demand appears likely, driven by regulatory frameworks such as ReFuelEU Aviation and international decarbonisation commitments. Yet investors remain confronted with a market in which long-term offtake agreements remain the exception rather than the rule.

The PtX.CarbonRun addresses this challenge through positioning methanol as a tradeable commodity with multiple offtake sectors. Unlike SAF itself, methanol is already a globally traded commodity with multiple established end-uses. Chemical industries producing pharmaceuticals, solvents, paints, adhesives and many other commodities already consume substantial volumes today. As a result, early projects do not depend exclusively on demand from the aviation sector. Methanol producers can access existing markets, while the SAF demand continues to increase.

Institutionalising aggregation and market coordination

A further challenge of the PtX.CarbonRun concerns market organisation rather than technology. While decentralised methanol production increases resilience and enables the mobilisation of diverse renewable carbon sources, it also creates transaction complexity. Large industrial off-takers, shipping companies, and refineries are unlikely to engage in contractual relationships with hundreds or thousands of individual methanol producers. Equally, the aggregation, certification, storage and logistics coordination of renewable methanol across numerous upstream locations cannot be expected to emerge spontaneously through market forces alone.

The PtX.CarbonRun may therefore require dedicated coordinating institutions acting as aggregators and market facilitators. Such entities could organise upstream logistics, manage contract pooling, operate digital traceability systems and ensure reliable delivery to downstream markets. To avoid introducing additional profit margins into an already cost-sensitive value chain, this role may be best performed by non-profit organisations, cooperative structures or public-interest institutions operating as neutral intermediaries within the renewable carbon ecosystem.

Building on proven technologies

A second source of uncertainty concerns technology. Many SAF pathways are still at an early stage of commercial deployment. Financial institutions often struggle to assess performance risks where little operational track record exists.

The PtX.CarbonRun deliberately starts with technologies that produce the intermediate methanol and for which significant industrial experience already exists. Biogas production and reforming are mature technologies, while several other syngas production routes continue to advance. Methanol synthesis from syngas is well established. Direct methanol synthesis from carbon dioxide and hydrogen is increasingly commercialised.

The PtX.CarbonRun starts today with easily available carbon sources and proven conversion technologies. Operational experience gained in these projects then supports the gradual introduction of additional feedstocks and conversion routes.

Learning before scaling

Large industrial projects often promise impressive economies of scale. They also concentrate risk. The prevailing assumption in many SAF discussions is that only very large facilities can become economically viable. Such projects may require billions of euros of capital expenditure, lengthy permitting processes and complex financing structures. Any delay or performance shortfall affects the entire investment.

The PtX.CarbonRun separates this capital intensive and rather innovative SAF production from building the logistics structure to collect renewable carbon. SAF and jet fuel are produced further downstream in existing refineries and industrial parks by actors with proven track record and thus more favourable financing conditions.

For the many methanol production facilities at smaller scale and close to the respective renewable carbon sources, less investment is required. The technology set up allowing a modular approach enables incremental learning and the operators to gain practical experience before scaling further by unit number.

This approach does not eliminate risk, but it prevents risk from becoming concentrated in a small number of mega-projects.

Creating resilience through feedstock diversity

No single renewable carbon source can satisfy the global SAF demand in the long-term. The PtX.CarbonRun therefore relies on diversity of carbon sources from the outset. Biogas, black liquor, sewage sludge, municipal waste, agricultural residues, forestry residues and carbon dioxide based pathways can all contribute to the system through feedstock-specific conversion technologies that are funnelled into the feedstock-agnostic intermediate methanol.

This diversity creates resilience. If one feedstock pathway develops more slowly than expected, others can continue to contribute and scale up. As additional conversion technologies mature, they can be integrated into the same methanol-centred value chain without fundamentally changing downstream infrastructure.

A bridge towards future PtL systems

The finite availability of biogenic resources is often cited as a limitation of biomass-based pathways. This observation is correct. The PtX.CarbonRun does not seek to replace future e-SAF pathways with biomass. Instead, bioresidue derived carbon streams are used to accelerate learning curves and establish industrial capabilities while renewable hydrogen and carbon dioxide pathways are scaled up.

As described in Chapter 2, BtL and PBtL should therefore be viewed as instruments for building PtL-readiness. The destination remains large-scale PtL. The difference is that the journey begins with cost efficient feedstocks and technologies available today.

Resilience through decentralisation

Modern supply chains often depend on a small number of critical assets. A single refinery outage, pipeline interruption or geopolitical disruption can affect large portions of the supply chain.

The PtX.CarbonRun promotes resilience through its descentralised sourcing from many locations. The suggested system is inherently distributed. Individual facilities remain important, but no single site determines the success of the entire value chain. The resulting architecture resembles a network rather than a chain, the failure of one node can be absorbed by other nodes within the system. Eventually, that principle might also turn into an interesting option for some downstream processing.

A system designed to evolve

Viewed as a whole, the PtX.CarbonRun is undeniably complex. It connects carbon sources, hydrogen production, methanol synthesis, logistics systems, digital infrastructure, commodity markets and fuel production facilities across multiple regions and sectors.

Yet complexity does not automatically imply fragility. When built around standardised interfaces, diversified supply sources, proven technologies and transparent information flows, complexity can become a source of resilience rather than weakness.

The PtX.CarbonRun is no fixed blueprint, but more of a framework designed to evolve. New feedstocks can enter the system. Additional conversion technologies can be integrated. Regulatory requirements can change. Digital tools can improve. However, the core architecture of connecting decentralised systems upstream and centralised setups downstream remains unchanged.

Where to start with the PtX.CarbonRun

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The renewable carbon economy already exists in fragments

Many of the technological capabilities, industrial experience and renewable carbon resources required to implement the PtX.CarbonRun already exist. They are distributed across countries, sectors and value chains that have rarely been considered as part of a common system.

The challenge is to connect existing competencies into a new architecture for a non-fossil economy. This observation is particularly relevant for many countries of the Global South. While discussions on Sustainable Aviation Fuels often focus on future industrial investments, numerous countries already possess precisely the types of industrial ecosystems, renewable resources and practical experience that could enable the first stages of the PtX.CarbonRun.

Building on existing strengths

Brazil provides a particularly compelling example. Decades of experience with biofuels have created industrial capabilities that closely resemble the requirements of future renewable methanol production. Distributed biomass supply chains, agricultural logistics, fuel certification systems, industrial process integration and operation of medium-scale fuel production facilities have all been developed over several decades. Renewable methanol production can become a natural extension of these established capabilities.

India offers another example. The country has accumulated significant experience in the gasification of agricultural residues and organic by-products from food production. Many of these feedstocks remain underutilised despite containing valuable renewable carbon. Converting such distributed resources into standardised intermediates such as methanol could transform local waste management challenges into opportunities for industrial development and participation in global renewable carbon markets.

South Africa contributes another essential element. Few countries possess comparable industrial experience in syngas-based production processes. Decades of expertise in gasification, synthesis technologies and large-scale industrial operations provide valuable capabilities that could support the transition towards renewable carbon-based fuel production systems.

In Kenya and many other emerging economies, renewable methanol production may initially find its first customers not in international commodity markets, but locally. Industrial consumers often pay substantial premiums for imported fossil methanol due to transport costs and volumes too low to negotiate bulk discounts. Locally produced renewable methanol may therefore establish commercially viable business cases long before international renewable fuel markets fully mature.

From supply chains to partnerships

Traditional fossil energy systems evolved around the extraction and transportation of concentrated natural resources. The renewable carbon economy follows the different logic presented above.

As any transition, this creates opportunities to build something new and greater than before, and that on a global scale. Countries rich in underused renewable carbon residues, renewable electricity potential or industrial expertise can become active participants in creating value rather than merely supplying raw materials. Technology development, industrial deployment, workforce development and value creation can emerge simultaneously across multiple regions.

A call for value-based partnerships

The PtX.CarbonRun outlines a possible framework for organising the transition towards a non-fossil global economy. Building such a system requires technological innovation, industrial investment and supportive regulation. Equally important, however, is the willingness to create new forms of international cooperation based on trust, shared values and long-term partnerships.

The technologies largely exist. The renewable carbon resources exist. The industrial experience exists. The market demand is emerging. The opportunity now lies in connecting these elements into a common system: a resilient renewable carbon economy built on diversified supply chains, shared prosperity and value-based international partnerships.