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May 2025

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### Managing Editor

Rachel Storry  
rachel.storry@emap.com  
tel +44 (0)7786 136440

### Consulting Editor

Robin Nelson  
robin.nelson@  
decarbonisationtechnology.com

### Editorial Assistant

Lisa Harrison  
lisa.harrison@emap.com

### Graphics

Peter Harper

### Business Development Director

Paul Mason  
info@decarbonisationtechnology.com  
tel +44 844 5888 771

### Managing Director

Richard Watts  
richard.watts@emap.com

EMAP, 10th Floor  
Southern House  
Wellesley Grove,  
Croydon CR0 1XG



**Cover Story** Mura's Wilton Advanced Plastic Recycling Facility.  
Courtesy: Mura Technology

The Energy Institute Statistical Review of World Energy 2024 shows that carbon emissions reached a new record in 2023. Although renewables are growing, so is the global energy demand. Consumption of coal continues to increase in the Asia Pacific region, accounting for 80% of global output, whereas coal consumption in both Europe and North America fell. Coal accounted for 35% of electricity production, with gas at 23% and renewables rising to 30%.

These figures reflect slow progress with the energy transition, but in part this is due to the scale needed. As often stated in my forewords for *Decarbonisation Technology* magazine and elsewhere, investments in developing the technologies required for the transition indicate that we have the necessary technologies; now, we need to deploy them at scale. As such, I found the theme of the Baker Hughes annual meeting held earlier this year, 'Progress at Scale', to be spot on. We now need to see exponential growth in the deployment of available technologies and solutions.

Flaring is one of the biggest sources of emissions from oil and gas operations. Carbon dioxide emissions from flaring increased by 7% in 2023, while methane emissions from pipelines and industrial processes also increased (the reported increase may, in part, be because monitoring and reporting of such emissions has also improved). Most gas production companies have pledged zero methane emissions by 2030. The technologies and know-how to reduce flaring and manage pipeline leaks are critical in meeting this challenge.

Carbon capture, utilisation and storage is critical for the oil and gas industry and other energy-intensive industries. The evolution of industrial clusters can de-risk investment in developing carbon dioxide transport and storage solutions. In the EU, the ReFuelEU regulation will drive the utilisation of captured carbon dioxide for the production of e-fuels, which will go some way to restoring a healthy carbon cycle. As one of the articles in this edition illustrates, integrating the production of e-fuels with existing refinery processes can be financially attractive.

Building capacity for low carbon intensity hydrogen necessitates the deployment of a range of technologies, including electrolysis, reforming with carbon capture, and methane pyrolysis. We have to maximise our chances of achieving the scale needed and should not be technology prescriptive.

Progress with the energy transition depends heavily on the US, both as one of the largest sources of emissions and on leadership from US universities and companies in developing technology solutions and delivering engineering expertise. We must make 'progress at scale'.

**Dr Robin Nelson**



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# Securing sustainability claims: certification and credit transfers

The role of certification in promoting the credibility of SAF and alternative marine fuels, with a special focus on the ISCC Credit Transfer System

Laura Günther  
International Sustainability & Carbon Certification

The global push for decarbonisation has placed significant pressure on 'hard-to-abate' sectors and major contributors to greenhouse gas (GHG) emissions, such as aviation and maritime transport. International and national climate goals targeting net-zero emissions by 2050 and voluntary programmes such as the Science Based Targets initiative (SBTi) are intensifying the need for drastic reductions in carbon footprints. Given that direct electrification poses challenges within these sectors, sustainable aviation fuels (SAF) and alternative marine fuels (AMF) present essential and non-negotiable options for achieving ambitious climate targets.

SAF is a renewable, non-fossil-derived fuel

from biomass, waste oils, and fats, or e-fuel generated using renewable electricity, which can reduce emissions by up to 80% compared to conventional jet fuel (The University of Manchester, 2023). SAF's chemical and physical properties are nearly identical to those of traditional jet fuel. This compatibility allows SAF to be mixed with conventional fuels in varying proportions, utilise the same supply infrastructure, and require no modifications to aircraft or engines, making it a 'drop-in' fuel technology. To ensure technical and safety standards, SAF must be produced according to one of the ASTM-approved methods (ASTM, 2023), the most widely used of which is hydroprocessed esters and fatty acids (HEFA),

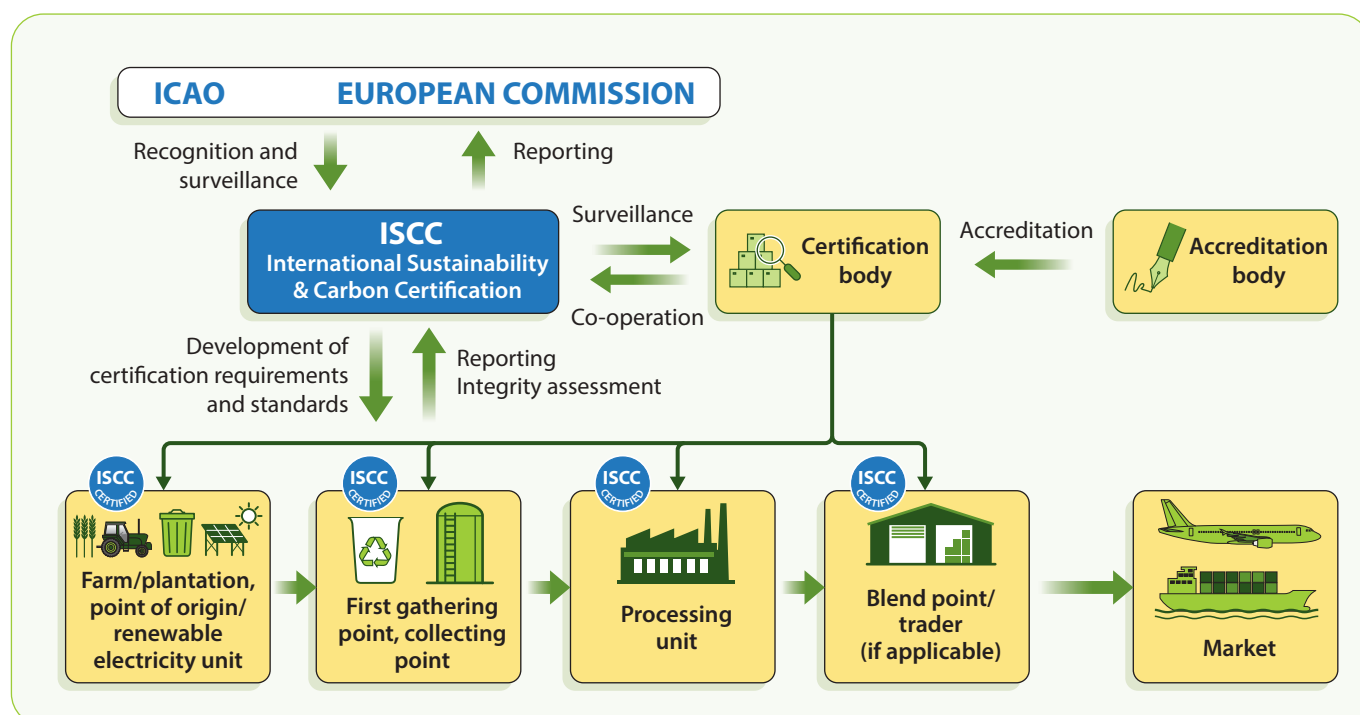
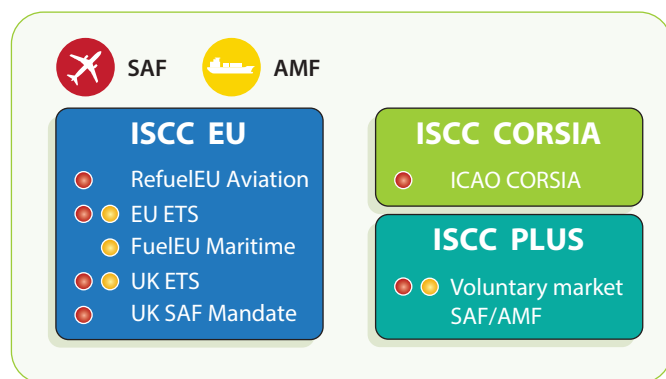


Figure 1 Interplay between regulation, accreditation, certification standard, and certification body





**Figure 2** ISCC Certification schemes under which SAF and AMF can be certified (as of May 2025)

converting waste oils and fats into SAF. Another rising process is alcohol-to-jet (AtJ), where alcohols such as ethanol and isobutanol are transformed into SAF. Drop-in AMFs include biofuels, e-fuels, and liquefied biogas (Bio-LNG). In contrast with SAF, non-drop-in AMFs, such as methanol, ammonia, and hydrogen, also play a crucial role in the sector. While these non-drop-in fuels offer greater long-term sustainability benefits, they involve significant investment in new technologies.

Policies require both the adoption of alternative fuels and evidence that these fuels produce measurable sustainability outcomes. At the same time, market participants – ranging from producers to end consumers – increasingly seek transparency, accountability, and verified carbon footprint reductions throughout the supply chain. Rigorous certification systems like the International Sustainability & Carbon Certification (ISCC) confirm these standards are met. This article explores the role of certification in promoting the credibility of SAF and AMF, with a special focus on the ISCC Credit Transfer System (CTS), its structure, impact, and significance for stakeholders. The CTS enables the tracking and trading of SAF credits for verified carbon reductions within the voluntary market.

### From EU RED to CORSIA: policy-driven pathways to net-zero transport

The aviation and maritime industries are considered among the most difficult to decarbonise due to their current heavy reliance on fossil fuels, each accounting for approximately 2-2.5% of global CO<sub>2</sub> emissions (IEA, 2025) (IEA, 2023). Reducing emissions from these sectors requires developing,

producing, and scaling alternative low-carbon fuels and adopting these solutions throughout global supply chains and policies.

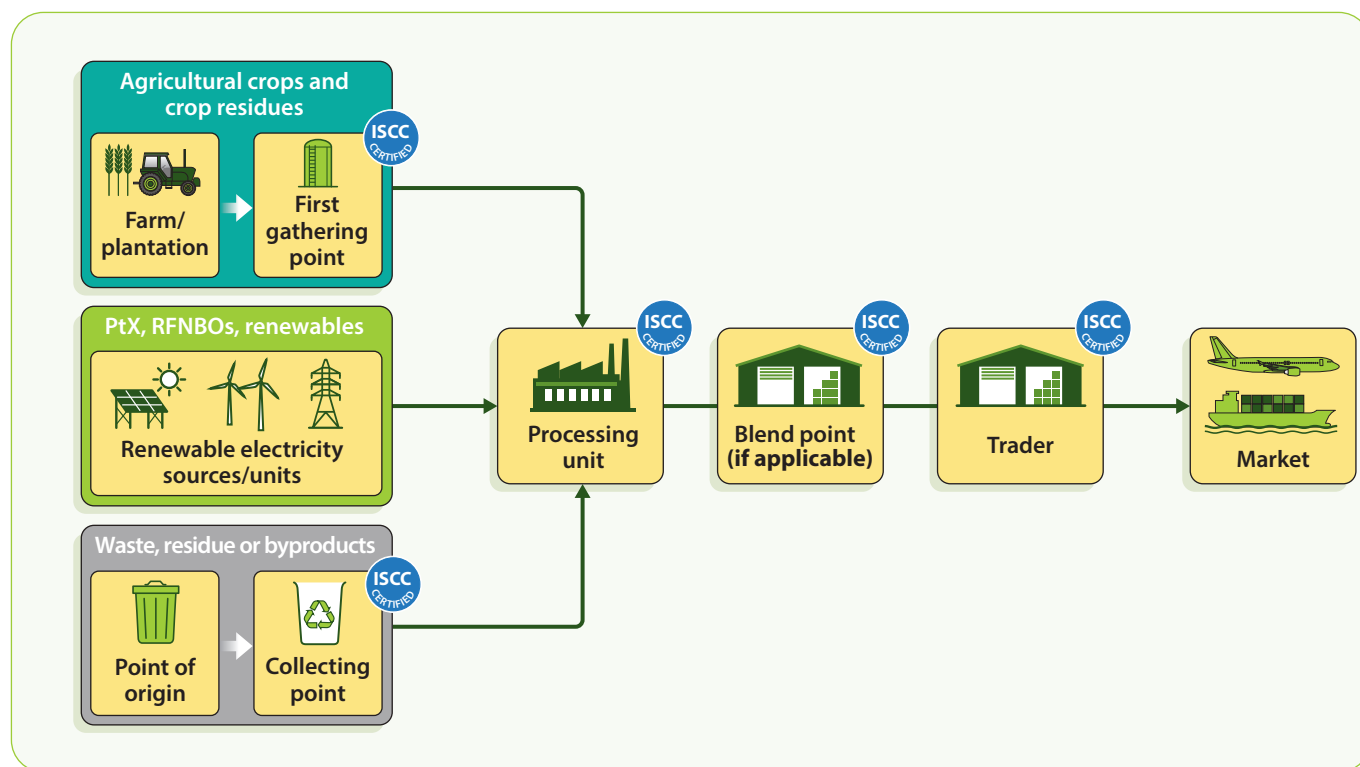
As part of the European Union's (EU) Renewable Energy Directive (RED), which sets targets for the EU's renewable energy use and GHG reductions, the ReFuelEU Aviation Regulation focuses on reducing aviation's carbon footprint and accelerating the transition to sustainable aviation practices, including blending targets for SAF. Beginning in 2025, at least 2% of all aviation fuel used within the EU must be SAF, gradually increasing to a minimum of 70% SAF in all EU airports by 2050 (EUR-Lex, 2023).

Additionally, the regulation sets specific sub-targets for the utilisation of synthetic aviation fuels derived from renewable hydrogen or captured carbon. Similarly, the FuelEU Maritime Regulation aims to promote renewable, low-carbon fuels and clean energy technologies for ships to reduce GHG intensity. This regulation stipulates that the GHG intensity limit should decrease by 2% starting in 2025, with more ambitious reductions planned for subsequent years, ultimately achieving an 80% reduction by 2050 (EUR-Lex, 2023).

From the global perspective, the International Civil Aviation Organization (ICAO) established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming to stabilise net CO<sub>2</sub> emissions from international aviation at 2020 levels. To achieve this, the framework sets rules for monitoring, reporting, and verifying emissions, with a system to offset emissions via the use of credits, CORSIA Eligible Units, or the usage of SAF, neutralising the environmental impact of international aviation growth. The International Maritime Organization (IMO) has established the IMO GHG Strategy, which aims to achieve net-zero GHG emissions from international shipping by 2050. According to projections from the Fourth IMO GHG Study, approximately 64% of the total CO<sub>2</sub> reduction in the shipping sector by 2050 is expected to come from the use of alternative low- or zero-carbon marine fuels (IMO, 2020).

### Certification as a cornerstone for sustainable fuel production and traceability

Sustainable fuels are defined by strict criteria that ensure their production is environmentally



**Figure 3** Simplified SAF/AMF supply chains

responsible. Key factors include the selection of raw materials, life cycle emissions, land use impact, and traceability. Certification mandated by the EU RED and ICAO CORSIA demonstrates compliance with these requirements and documents traceability throughout the supply chain, covering feedstock identity, production processes, and chain of custody options. It increases transparency for governments, regulators, and consumers and provides clear and accessible information on the environmental impact of the fuel, the reduction of greenhouse gases, and the integrity of the supply chain.

ISCC is the leading certification system for the EU renewable energy market, regulated by the RED. The system applies globally and encompasses all agricultural and forest biomass, biogenic waste and residues, non-biological renewable materials, and recycled carbon-based materials. Certification under ISCC can be utilised throughout the entire supply chain and is relevant to a wide array of sectors and markets. For this purpose, ISCC operates distinct certification systems, including ISCC EU, ISCC PLUS, and ISCC CORSIA, with the latter also being the leading certification system under the ICAO CORSIA framework. Accredited third-party Certification Bodies

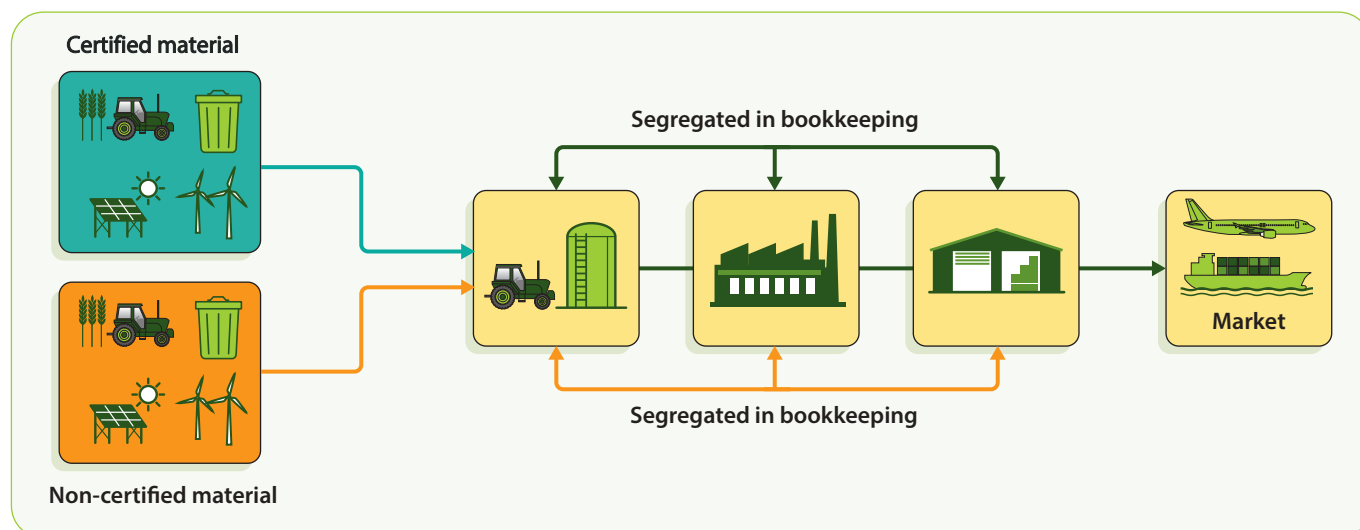
(CBs) verify compliance with the certification requirements and issue certificates following successful auditing.

Since 2011, ISCC EU has demonstrated compliance with the legal requirements for sustainability and GHG emissions savings criteria established by the RED. As of February 2025, it boasts 7,536 valid certificates (ISCC, 2025), making it the largest of the three schemes.

The ISCC PLUS certification was developed for voluntary markets such as food, feed, chemicals, plastics, packaging, and renewable energy sources outside the scope of the RED. With 5,545 valid certificates (ISCC, 2025), it is the second-largest scheme. ISCC CORSIA, specifically designed to comply with the ICAO framework for SAF, has been recognised since 2020. Currently, it is the fastest-growing scheme, with a remarkable growth rate of 326% generated in 2024, when the number of certificates surged from 95 to 405 (ISCC, 2025). This highlights SAF's growing importance and interest among regulators, producers, airlines, and passengers.

### Verifying every step: supply chain certification and mass balance

Certification ensures that every step in the SAF and AMF supply chains complies with robust



**Figure 4** Mass balance approach in certified supply chains

sustainability and traceability standards. SAF can be certified under all three ISCC schemes, while AMF certification occurs under both ISCC EU and ISCC PLUS. Each actor in the supply chain handling the alternative material – whether involved in production, collection, processing, storage, or trading – must hold valid ISCC certification.

The supply chain for SAF and AMF begins at the source and may vary depending on the feedstock type. For bio-based feedstocks, the journey starts at a farm or plantation. In the case of bio-circular materials from waste or residues of biological origin, as well as circular materials from fossil-based waste or residues, the supply chain starts at the point of origin.

The chain for renewable feedstocks begins at the renewable electricity unit. For each actor in the supply chain to handle these materials, a valid ISCC certification issued by a CB is required, and verifiable documentation that sustainability criteria are being met at every stage must be available. Evidence of such is passed along using a Sustainability Declaration (SD), often referred to as a Proof of Sustainability (PoS), which is a delivery document containing information about the certified material and must be issued by the supplier for every delivery. Such a system safeguards sustainability claims are transparent, traceable, and verifiable, creating a robust framework for compliance and trust within the certified supply chain.

Often, in aviation and maritime transport, alternative drop-in fuels are stored and distributed via a shared infrastructure, making

it impossible to segregate certified fuels from conventional fossil fuels physically. Therefore, SAF and AMF supply chains regularly utilise mass balance – a chain of custody option that accurately captures sustainability characteristics while allowing logistical flexibility. This approach tracks the quantity and sustainability characteristics of bio-based, circular, or renewable energy-derived materials in the value chain and attributes them based on verifiable bookkeeping.

### Importance of certification for market integrity and credibility

Certification plays a critical role in ensuring market integrity and credibility in the aviation and shipping industries, which are under increasing pressure to decarbonise and comply with stringent environmental regulations. As governments and investors increasingly prioritise net-zero commitments, certified SAF and AMF will be essential to future-proof organisations in the industry. With the transition to lower carbon fuels and sustainable operations well underway, certification provides a verifiable and transparent framework that reassures airlines, shipping companies, regulators, and consumers that sustainability claims are credible and measurable. Such frameworks not only support airlines and shipping companies in their compliance with regulatory requirements but also assist access to financial incentives, as certification encourages innovation by stimulating investment in advanced fuel production technologies, sustainable supply



chains, and carbon reduction strategies. This gives certified companies a competitive advantage in a rapidly evolving industry. Concurrently, certification promotes systematic change through the resulting ripple effect to not only foster, but strengthen a global culture of sustainability in the industry.

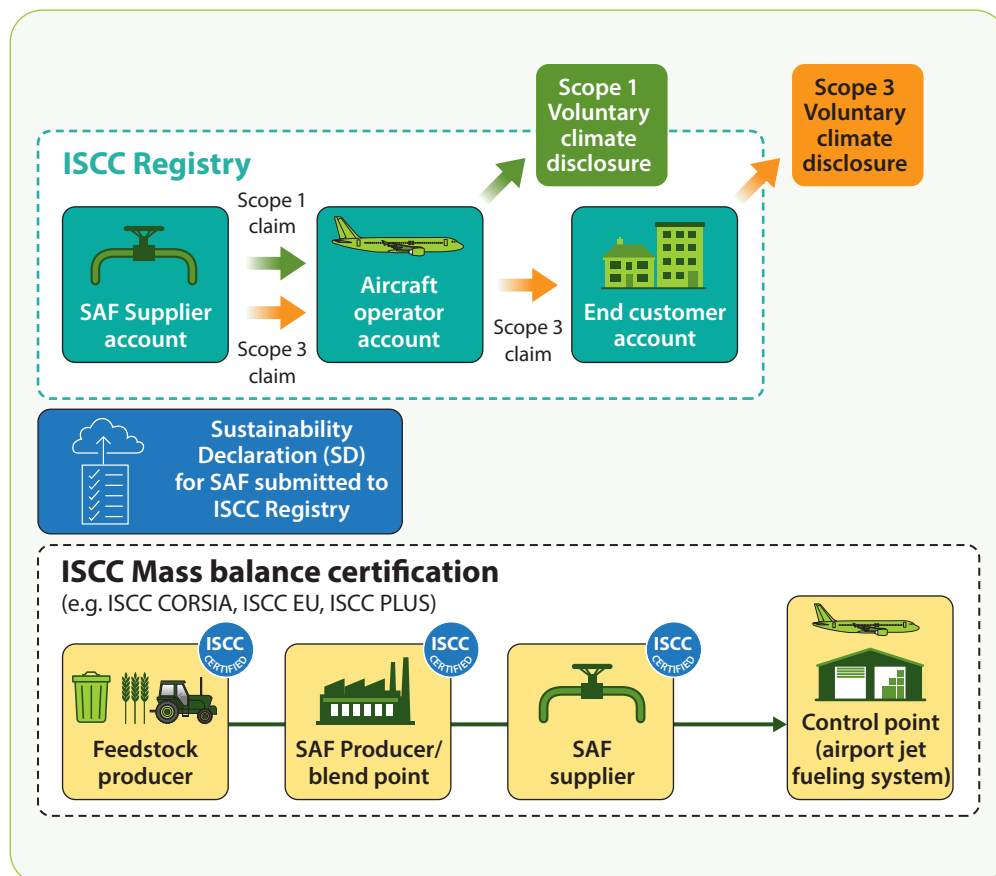
### ISCC credit transfer system for SAF

Traditionally, sustainability certification verifies SAF's environmental credentials along the supply chain, but it typically concludes at airport delivery or earlier, leaving limited mechanisms to track SAF claims following uplift. As airlines, logistics providers, and corporate end-customers increasingly seek to report emissions reductions from their SAF purchases credibly, ISCC responded by launching the ISCC CTS in April 2024.

SAF credits provide a mechanism to ensure that emission reductions are achieved and correctly accounted for. They serve as evidence of the environmental benefits of SAF and allow organisations to use SAF credits for voluntary emissions reductions for corporate sustainability reporting, increasing the credibility of companies' decarbonisation efforts. In addition, the credits facilitate the financial transactions needed to incentivise the production and subsequent uptake of sustainable fuels, enabling a market-based approach to emissions reduction.

### A digital solution for traceable and verifiable SAF claims

The ISCC CTS is a digital registry-based system that facilitates the secure transfer of SAF sustainability claims – in the form of Scope 1



**Figure 5** Sample transaction flow within the ISCC Credit Transfer System, complementing traditional supply chain certification

and Scope 3 credits – between SAF suppliers, airlines, logistics providers, and end users. This system ensures that credits are generated, transferred, and retired transparently, preventing double counting and reducing the risk of misleading sustainability claims.

Through the ISCC CTS, traceability goes beyond supply chain certification as often occurs under mandates, and enables tracking SAF claims after delivery, ensuring that emission reductions are accurately reported. Transparency is achieved through the ISCC Registry, a secure, open-access database where SAF credits are tracked and managed. Furthermore, the ISCC CTS ensures participants adhere to criteria to validate that claims made represent additional emissions reductions that go beyond what may be considered under regulatory mandates.

To qualify for registration of SAF volumes within the system, SAF suppliers must hold valid certification under either ISCC PLUS or a recognised certification under ICAO CORSIA or EU RED. Furthermore, suppliers need to undergo the ISCC CTS audit procedures to

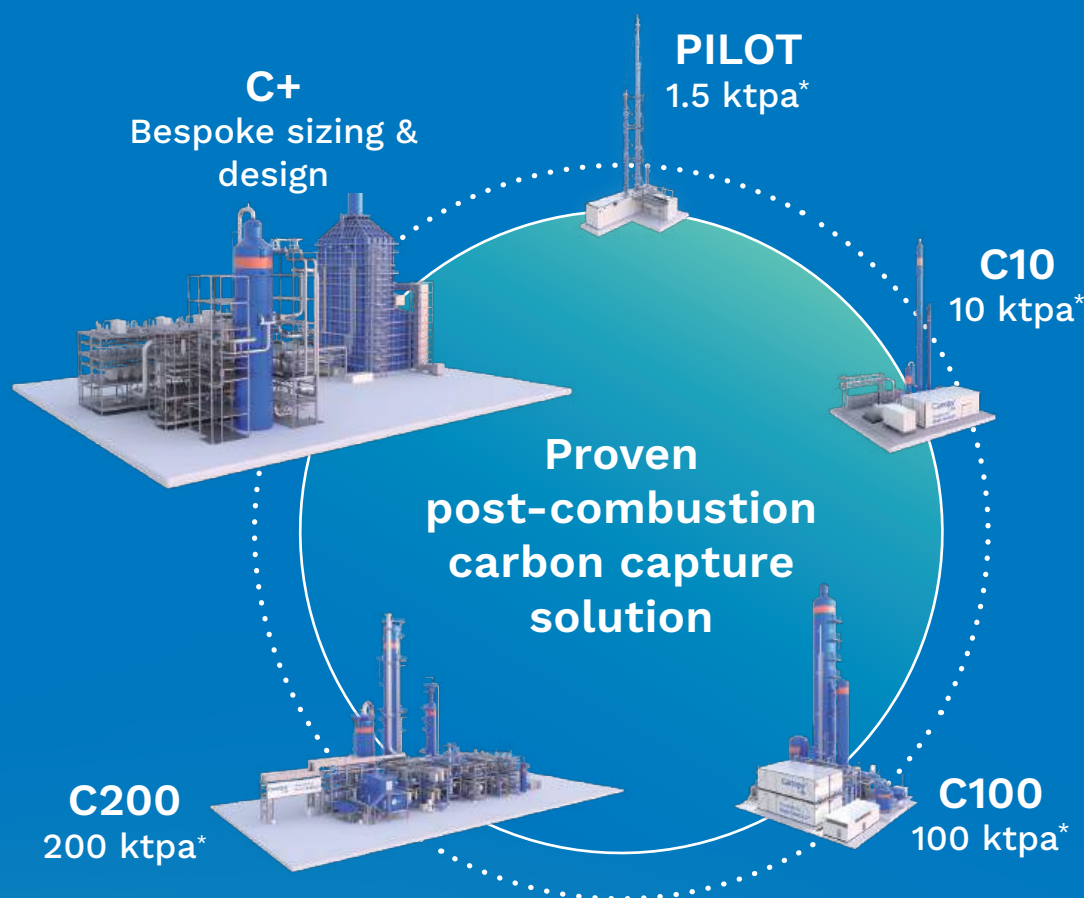
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ensure they meet the requirements and manage transactions according to the rules set forth. When complete, certified SAF suppliers register SAF volumes and generate credits for verified SAF batches delivered to an airport in the ISCC Registry.

Following verification, each metric ton of neat SAF generates a Scope 1 and Scope 3 credit in the supplier's account, which can then be transferred to, or managed for, other stakeholders. Leaning on principles defined by the GHG Protocol (GHGP, 2004) and SBTi (SBTi, 2021), Scope 1 credits are transferred to the aircraft operator that physically uplifts the SAF, which corresponds to a direct emission reduction from SAF combustion, and Scope 3 credits are passed down the supply chain for downstream utilisation. Therefore, Scope 3 credits to offset emissions associated with air transport or business travel may only be transferred downstream in the value chain; for example, from the SAF supplier to the aircraft operator to the end customer or from the SAF supplier directly to the end customer.

Upstream transfer (for example, from the end customer back to the aircraft operator) or across value chains (for example, from aircraft operator to aircraft operator) is not possible. Organisations with credits available in their accounts then retire these credits and automatically receive a retirement declaration. This declaration includes information that allows the organisation to claim sustainability characteristics, such as the GHG emissions reductions associated with the retired credits in their voluntary climate disclosures.

### Driving market confidence and investment in sustainable fuels

For alternative fuel suppliers, certification and credits offer a competitive advantage in the market by demonstrating the environmental credentials of their products. For airlines, logistic providers, and corporate end customers, the ability to purchase certified SAF and the associated sustainability benefits via a crediting mechanism provides a clear path to achieve credible emissions reduction targets and the ability to reliably communicate such claims. As a market-orientated mechanism for tracking

and verifying emissions reductions, the ISCC CTS encourages investment in SAF production, accelerating the aviation sector's transition to net-zero emissions.

Several industry leaders, such as United Airlines, DHL Express, Neste, Cosmo Oil, OMV, and Microsoft, have recognised this and have already adopted the CTS in their sustainability strategies. DHL Express, for example, is integrating ISCC credits into its GoGreen Plus programme, which allows customers to offset air freight emissions. Another case is Neste Impact, a solution that enables companies to reduce the carbon footprint of their air and transport activities by using SAF tracked through the ISCC CTS.

### Expanding credit transfers: supporting aviation, shipping, and beyond

The future of the ISCC CTS is promising, as it has the potential for broader application in a wide array of varying sectors, such as AMF within shipping markets. The system will likely expand further as industries increasingly adopt alternative fuels and set emission reduction targets. As the market evolves, ISCC remains committed to improving the CTS through continued collaboration and engagement with stakeholders to support the industry in scaling such fuels efficiently and transparently to achieve the quantifiable emissions savings required to meet net-zero targets.

The introduction of sustainably certified fuels is more than an opportunity – it is a responsibility for stakeholders within the aviation and maritime markets. By leveraging certification and voluntary credit transfers, organisations have the potential to drive the transition to a low-carbon future while ensuring credibility and transparency in their climate commitments.

Collaboration, innovation, and accountability will define the next era of sustainable transport – those who lead today will shape the industry for generations to come.

### VIEW REFERENCES



Laura Günther  
guenther@iscc-system.org



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**TOPSOE**  
Making Energy Transition

# Finance, technology, and policy for green investment

By harnessing the power of policy, technology, and finance, we can unlock the potential of green investment and quicken the transition to a low-carbon economy

Valentina Dedi  
KBR

**T**he global community finds itself at a pivotal moment in the battle against climate change. As the urgency to transition from a fossil fuel-dominated energy system, heavily reliant on oil and gas, to one driven by greener sources intensifies, governments and investors alike are managing the challenges and opportunities presented by this shift. This article explores how the right mix of supportive policies, financial mechanisms, and technological innovation can de-risk investments in carbon capture, utilisation and storage (CCUS) and maximise the potential for green investment amid uncertain times while also addressing the role of the oil and gas industry in the transition.

Governments around the world have acknowledged the urgency of accelerating the energy transition and have prioritised capital allocation in their national energy policies. The Paris Agreement sets ambitious targets for reducing greenhouse gas emissions with the goal of limiting global temperature rise to well below 2°C above pre-industrial levels. Meeting these targets requires an unprecedented level of investment in clean energy technologies and infrastructure.

S&P Global Platts estimates it will require more than \$5 trillion in investment each year from now through to 2050 to meet the targets agreed by the world's major economies under the Paris Agreement by 2050 (S&P Global, 2023). To put this into perspective, this is equivalent to investing the entire economy of Germany today, every year for the next two and a half decades. This scale of investment is well beyond what government budgets can afford

alone. Large-scale private sector engagement will be critical, too, including from the oil and gas industry.

In recent years, significant capital has been directed towards energy transition projects. However, these investments have been largely constrained to commercially viable projects, primarily favouring renewable power generation, such as wind and solar. These technologies have matured and are now market-ready thanks to a continuous decline in technology costs and the advances in efficiency over the past decade. While they are crucial to the energy transition, they alone cannot address



Industry is facing an urgency to accelerate the energy transition

### Industrial clusters

Industrial clusters or 'decarbonisation hubs' are gaining traction as one way of reducing uncertainty and de-risking investments in decarbonisation. The World Economic Forum reports that, to date, more than 33 industrial clusters across 16 different countries have joined their global Transitioning Industrial Clusters (TIC) initiative (WEF, 2025).

Industrial clusters are eminently suitable for energy-intensive industries considering investments in carbon capture, transport, and storage. Government involvement through funding or public-private partnerships is a common feature in such

clusters. Knowledge sharing is also considered to be a critical success factor. In many of the clusters, the oil and gas industry brings its experience in gas pipelines for the supply of hydrogen as well as expertise in carbon capture, transport, and suitable locations for permanent storage, for example in depleted oil and gas fields.

The cooperation between the governments of the UK and Brazil is another good example of knowledge sharing to progress industrial decarbonisation. The aims of this cooperation include knowledge sharing and support in identifying and accessing international climate finance (UK Gov, 2024).

the full scope of the challenge, especially in decarbonising the hard-to-abate sectors.

### Decarbonisation potential of CCUS projects

CCUS has the scope to play a pivotal role in the latter sectors. It can be readily deployed at fossil fuel power plants and industrial facilities such as cement, iron and steel, and chemicals, where carbon dioxide (CO<sub>2</sub>) can be captured and stored or used to create products such as fuels and chemicals (carbon capture and utilisation or CCU). CCUS can also provide a low-cost pathway for low-carbon hydrogen

**“CCS is not a new technology, but the challenge lies in its economically large-scale deployment as investors face several uncertainties and risks”**

production, which can further contribute to the decarbonisation of the industry and transportation sector, or it can enable the removal of CO<sub>2</sub>, which is unavoidable or technically difficult to abate, directly from the atmosphere through direct air capture with storage (DACS) or bioenergy with CCS (BECCS). This technology is particularly relevant for the oil and gas industry, as it can help mitigate emissions from its operations and products.

Although the adoption of CCS has lagged behind initial projections, there has been a substantial increase in activity and interest

in recent years. Across the globe, novel technologies are being piloted with the goal of driving down the cost of carbon capture for both the power generation and industrial sectors. In addition to chemical absorption and physical separation, which are currently the two most advanced capture technologies, other separation technologies are in development, including membranes and looping cycles.

To meet net-zero targets, CCUS deployment must increase by several orders of magnitude within the next two to three decades. In the case of the US, it would mean a scale-up to as much as 100 times today's levels, according to the US Department of Energy's Office of Clean Energy Demonstrations (OCED) (US Dept. of Energy, 2023). While an ever-increasing number of projects across the entire value chain are being announced, only a fraction of them can take a final investment decision.

CCS is not a new technology, but the challenge lies in its economically large-scale deployment as investors face several uncertainties and risks. These risks can entail technology failures, cost overruns, extended timeframes, and high capital costs, among others. Another significant risk factor is the lack of clarity with respect to the demand outlook, which makes it challenging for investors to understand the scale of opportunity and, thus, for projects to reach a financial investment decision. Scaling up the infrastructure needed to transport and store captured carbon dioxide also requires the development of new

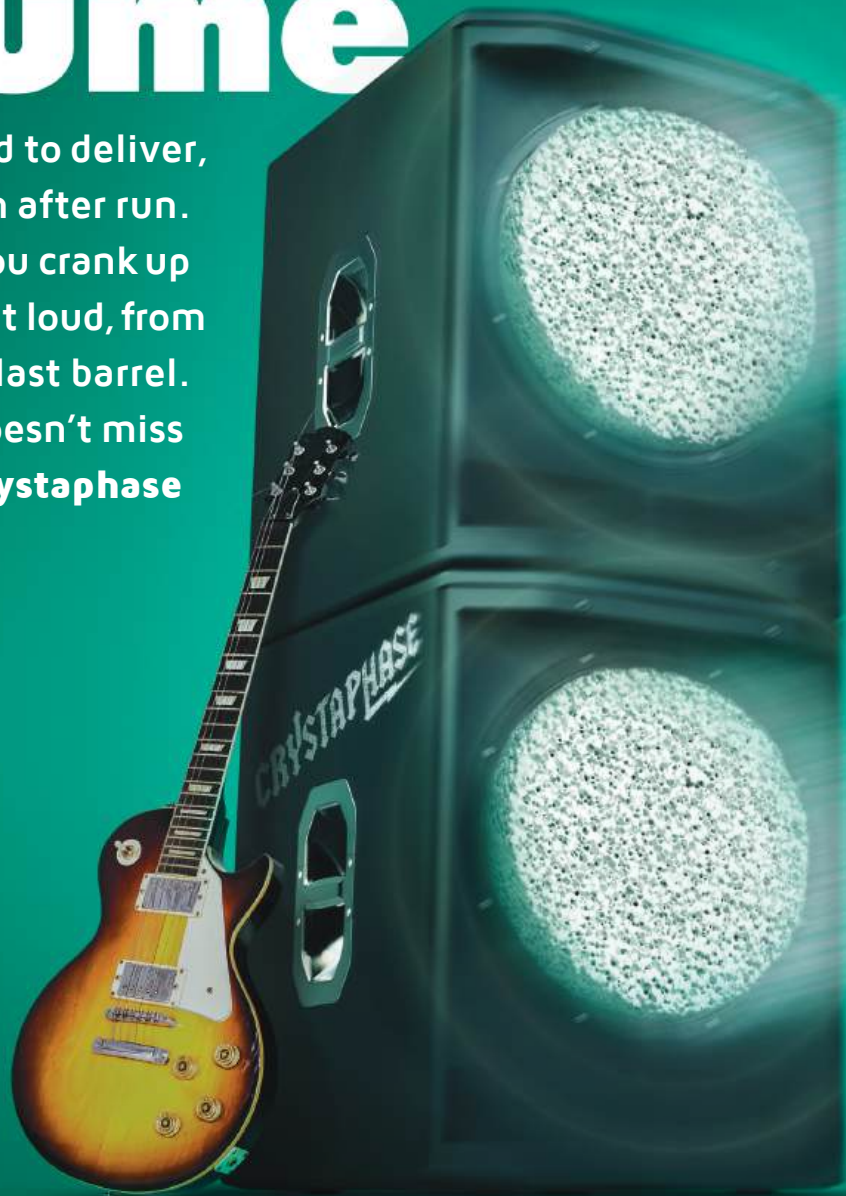




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The oil and gas industry can play a key role in developing business models to scale up infrastructure

business models which secure the required revenue streams, as well as partnerships between emitters, technology providers, and storage operators. The oil and gas industry, with its expertise in managing large-scale infrastructure projects and subsurface storage, can play a key role here.

Industrial clusters, in which different energy-intensive industries work collaboratively to invest in the infrastructure for transport and storage of captured carbon dioxide, are proving to be an effective de-risking approach. Such clusters can create the scale needed to justify investment in pipelines for the transport of carbon dioxide to sites for permanent storage.

### Importance of policy and regulation

Realising the full potential of the CCUS technology, especially at these early stages, will require continued policy support and collaboration between governments, industry, and investors. Coming up with the right policy framework and financing and incentive mechanisms will be critical. Governments and policymakers must establish an environment that creates stability and revenue predictability to attract the required investment and support the acceleration of the technology.

Thus, setting clear targets and priorities over the short, medium, and long term, including legally binding policy and regulatory frameworks, will be crucial to minimise policy uncertainty. At the same time, policy efforts should centre around the introduction of de-risking mechanisms and incentives that support green growth and foster green investment. This is especially pertinent for technologies and infrastructure, such as CCUS, which stand at a risky point in their deployment curve. This can be achieved through a wide range of instruments and approaches, including innovation funding, carbon pricing instruments, carbon credits, tax incentives, guarantees, and low-interest loans, among others.

Recent policy developments in the US, such as the Inflation Reduction Act and the Infrastructure Investment and Jobs Act, have started driving investment in clean energy technologies. The Inflation Reduction Act, in particular, is expected to be a game-changer for the CCS industry as it provides significant tax incentives for capturing and storing carbon dioxide. At the same time, as the UK envisions becoming a global technology leader for CCUS, the government announced a funding of £20 billion to support the initial deployment of projects, aiming to unlock



further investment from the private sector as it provides the much-needed certainty to investors. Previously, in the UK, a lack of agreement on government budgeting and capital allocation, in tandem with a lack of understanding of the commercial risks, had led to CCUS project cancellations in 2011 and 2015.

### Path forwards

Mobilising the capital needed to achieve the ambitious targets will require careful design of policies, financing mechanisms and incentives, and innovation funding. These measures must work together to de-risk investments, boost capital availability, and ultimately make clean energy technologies economically sustainable. The oil and gas industry has a critical role to play in this transition by leveraging its expertise, infrastructure, and financial resources to support the deployment of CCUS and other low-carbon technologies.

The path to a sustainable energy future is complex and challenging but also filled with opportunity. By harnessing the power of policy, technology, and finance, we can unlock the vast

potential of green investment and accelerate the transition to a low-carbon economy. Governments must continue to lead the way. At the same time, the private sector must step up and embrace its role as a catalyst for change, channelling capital towards innovative

**“The private sector must step up and embrace its role as a catalyst for change, channelling capital towards innovative technologies and approaches”**

technologies and approaches. Recent policy developments in the US and Europe are a promising sign of the growing momentum behind the energy transition. However, much more needs to be done.

### VIEW REFERENCES



Valentina Dedi

**Announcement:** OGT and Hovyu are hosting a 3-day **Carbon Capture Masterclass** in April 2025. For more information, scan the QR code or contact [simon.weiland@ogtrt.com](mailto:simon.weiland@ogtrt.com) or [info@hovyu.com](mailto:info@hovyu.com)



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# Can advanced adsorbents make direct air capture scalable?

With continued progress in sorbents, energy integration, and policy frameworks, DAC can help transform CO<sub>2</sub> into a manageable resource

Vahide Nuran Mutlu  
SOCAR Türkiye Research & Development and Innovation

**T**he concentration of carbon dioxide (CO<sub>2</sub>) in the atmosphere has increased by more than 50% since the Industrial Revolution. This invisible gas is the primary driver of global warming, and now, with every breath we take, we inhale 420 ppm of CO<sub>2</sub>. But what if we could extract the CO<sub>2</sub> out of the air? Direct air capture (DAC) offers the possibility of actively removing excess carbon from the ambient air (see **Figure 1**) and is emerging as one of the boldest solutions for tackling the climate crisis. This capability is essential for offsetting residual emissions from sectors where decarbonisation is difficult, such as aviation and shipping, while also addressing historical emissions that have led to the increased atmospheric concentration (Lebling, Leslie-Bole, Byrum, Bridgwater, 2022).

The International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) both consider DAC to be an essential technology. In the IEA's Net Zero by 2050 Scenario, DAC must scale from today's 0.01 MtCO<sub>2</sub>/year to 85 MtCO<sub>2</sub>/year by 2030, building to nearly 1 GtCO<sub>2</sub>/year by 2050. Yet DAC faces significant technical and economic barriers related to high energy consumption, material durability, and cost-effectiveness. Current capture costs range from \$250 to \$600/t CO<sub>2</sub>, although advancements in adsorbent materials and process efficiency are expected to reduce these costs to below \$100 per tonne by 2030 (IEA, 2021).

## Science behind direct air capture

The idea of pulling CO<sub>2</sub> directly from the air, grabbing invisible molecules floating around

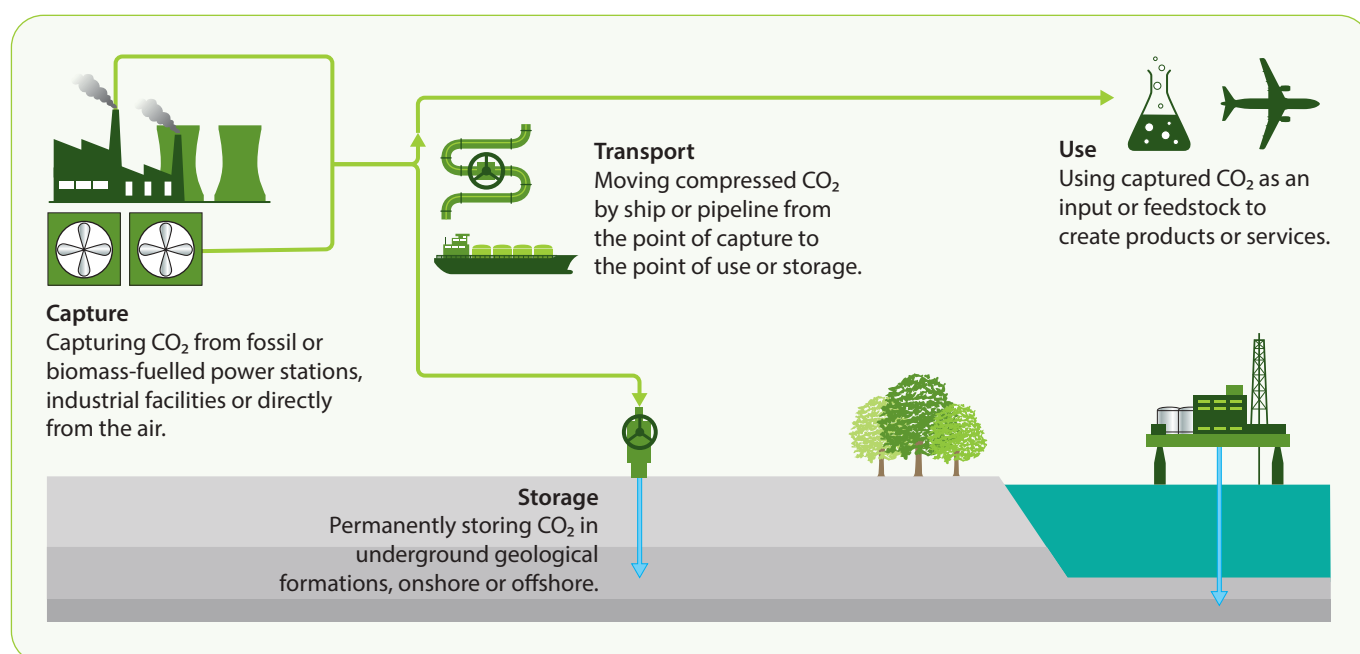


Figure 1 Carbon capture and storage infographic

Credit: iea.org

us and storing them sounds almost futuristic. However, DAC is already a proven technology, operating at a small scale. The challenge is to expand the capacity to deliver a meaningful difference.

Unlike traditional carbon capture methods that extract CO<sub>2</sub> from concentrated industrial emissions, DAC works with an immense disadvantage: the gas it seeks to capture is incredibly diluted. At just 0.04%, atmospheric CO<sub>2</sub> is far more dilute than that in flue gas streams, where concentrations can reach 10-15%. This makes DAC an uphill battle in terms of efficiency and energy demand, requiring highly selective materials that can take CO<sub>2</sub> out of the air without excessive energy use.

Currently, two main approaches are used to achieve this: liquid solvent-based DAC (L-DAC) and solid sorbent-based DAC (S-DAC), each with distinct mechanisms, energy requirements, and scalability potential.

**“Despite the high energy demand, L-DAC systems can operate at scale, with some commercial plants capturing 1 MtCO<sub>2</sub> per year”**

L-DAC relies on two closed chemical loops to extract CO<sub>2</sub> from the atmosphere. In the first loop, air is brought into contact with an aqueous basic solution (such as potassium hydroxide), where CO<sub>2</sub> reacts to form a stable carbonate. In the second loop, the captured CO<sub>2</sub> is released through high-temperature processing in a series of units operating between 300°C and 900°C, which makes this approach highly energy-intensive. Traditionally, this heat is sourced from natural gas or concentrated solar power, increasing operational costs and, unless they are fully powered by renewables, emissions.

Despite the high energy demand, L-DAC systems can operate at scale, with some commercial plants capturing 1 MtCO<sub>2</sub> per year. A downside is the water consumption, as a L-DAC plant may require 4.7 tonnes of water per tonne of captured CO<sub>2</sub>, particularly in regions with low humidity and high temperatures.

S-DAC uses solid adsorbents, such as amine-functionalised materials, metal-organic

frameworks (MOFs), and mixed metal oxides (MMOs), to selectively bind CO<sub>2</sub> molecules to their surface. These materials operate through an adsorption/desorption cycling process, where CO<sub>2</sub> is first captured at ambient temperature and pressure, then released through a temperature-vacuum swing process at a much lower temperature than for L-DAC, typically 80-120°C. This significantly reduces energy consumption and allows integration with waste heat and renewable electricity (Jialiang Sun, 2023).

While S-DAC systems are generally more energy-efficient, they still face challenges related to long-term stability, sensitivity to moisture, and degradation over multiple capture-release cycles. However, they offer a modular design, meaning plants can be scaled by adding more adsorption/desorption units. At present, a single S-DAC module has a capture capacity of up to 50 tCO<sub>2</sub>/year and, in some cases, can simultaneously extract water from the air, with early prototypes removing 1 tonne of water per tonne of captured CO<sub>2</sub>.

The largest currently operating S-DAC plant captures 4,000 tonnes of CO<sub>2</sub> per year, so it is much smaller in scale compared to large L-DAC plants. Further material improvements and cost reductions will be needed for S-DAC to play a critical role in decentralised and renewable-powered DAC applications.

**Energy dilemma: can DAC be scaled without a carbon footprint?**

While DAC offers an effective means of removing atmospheric CO<sub>2</sub>, its energy demand presents a major challenge: can it be scaled without leaving a carbon footprint? Today's DAC systems require between 5.5 and 9.5 GJ of energy per ton of CO<sub>2</sub> captured, depending on the technology used. The critical question is where does this energy come from? If DAC plants rely on fossil fuels, they risk undermining their own climate benefit. The ideal scenario is to power them with waste heat, geothermal energy, nuclear, or surplus renewables, but availability and cost remain barriers to large-scale deployment.

The energy demand for DAC varies significantly depending on the technology and whether the captured CO<sub>2</sub> is stored or used.

Liquid-DAC with storage (L-DACS) requires a large amount of high-temperature heat, whereas solid-DAC with storage (S-DACS) primarily relies on low-temperature heat and electricity. Additionally, CO<sub>2</sub> compression energy is only relevant for storage cases, as shown in **Figure 2**.

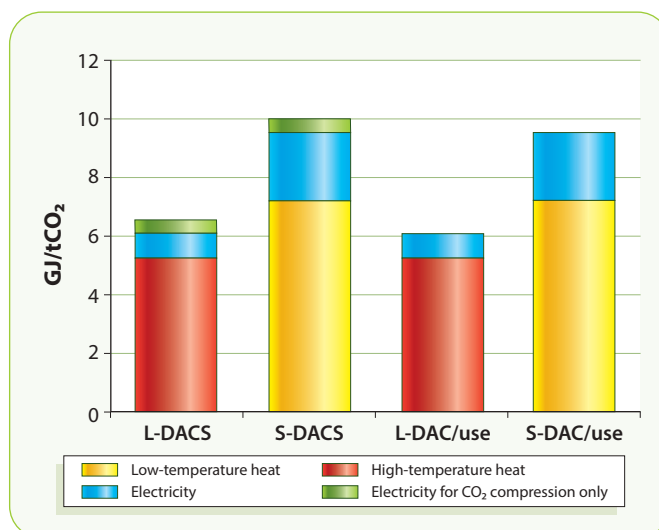
### Search for the perfect material

At the heart of every DAC system lies a specially designed material: the sorbent that captures the CO<sub>2</sub>. The ideal material is highly selective for CO<sub>2</sub>, capturing as much as possible per cycle and requiring minimal energy for regeneration. It must also be durable, enduring thousands of cycles without degrading, and, perhaps most critically, it needs to be cheap enough for large-scale deployment.

Currently, researchers are focusing on some major material classes, each offering its own advantages and trade-offs (see **Figure 3**).

### Amine-functionalised adsorbents: the current industry standard

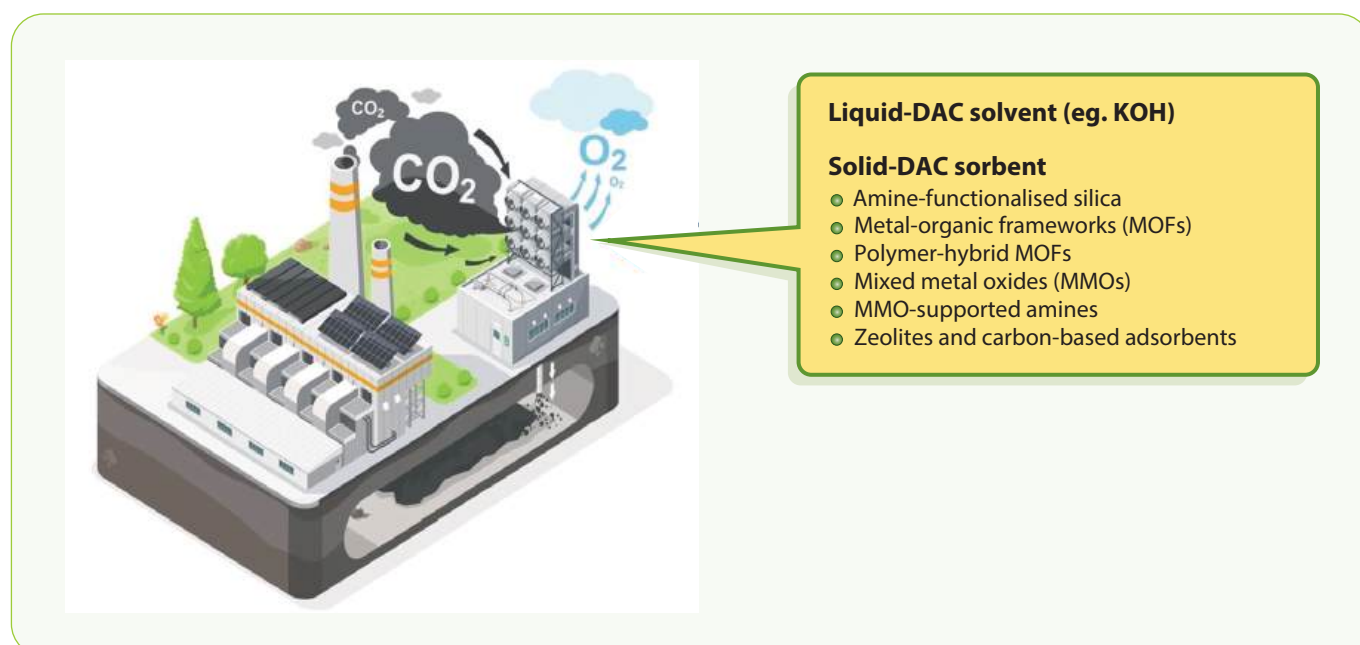
Currently, amine-functionalised materials such as polyethylenimine (PEI) or tetraethylenepentamine (TEPA) are the most widely used DAC systems due to their strong CO<sub>2</sub> binding capabilities. These materials are typically supported on mesoporous silica (SBA-15),  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, or other oxide supports, which provide a high surface area for CO<sub>2</sub> adsorption.



**Figure 2** Energy needs of DACS and DAC with CO<sub>2</sub> use by technology  
Credit: IEA

Amine-based adsorbents dominate the market because they operate at low regeneration temperatures (80-120°C), making them compatible with waste heat. Their strong chemical affinity for CO<sub>2</sub> allows for efficient capture, even at atmospheric concentrations of 400 ppm. Additionally, their widespread study and use make them easier to commercialise.

Despite their advantages, amine-functionalised adsorbents face several challenges. They are prone to oxidative degradation over time, reducing their capture efficiency due to prolonged exposure to oxygen. They are also sensitive to moisture; while some amine-based materials benefit from humidity,



**Figure 3** Sorbents for DAC

excessive water can lead to amine leaching and performance loss. Moreover, their durability is limited, as many amine-based adsorbents suffer from gradual efficiency loss over multiple capture-release cycles. To overcome these issues, researchers are developing stabilised amine formulations using additives and structural modifications to prevent oxidation and extend the material's lifetime. New formulations based on pore-expanded mesoporous silica (PME) have demonstrated significantly higher CO<sub>2</sub> uptake and stability.

### **Metal-organic frameworks (MOFs): the high-tech CO<sub>2</sub> sponges**

Metal-organic frameworks (MOFs) have emerged as promising next-generation DAC materials due to their tunable structures and massive surface areas. Some MOFs, such as MIL-101(Cr) and Mg<sub>2</sub>-based frameworks, can store large amounts of CO<sub>2</sub> per gram of material. They also exhibit cooperative chemisorption, allowing for faster and more efficient adsorption cycles. MOFs stand out because of their unmatched CO<sub>2</sub> uptake, with some exhibiting adsorption capacities exceeding 6.8 mmol/g, significantly higher than conventional amine sorbents. Their highly tunable properties enable modifications in pore size and surface chemistry to optimise CO<sub>2</sub> selectivity. Additionally, certain MOFs require only mild temperature swings to release CO<sub>2</sub>, making them energy efficient.

However, MOFs also have limitations. Many are highly sensitive to moisture and degrade in humid environments, making them impractical for real-world DAC applications. Their production costs remain high due to complex synthesis processes, limiting their large-scale deployment. To address these issues, researchers are developing polymer-hybrid MOFs, which encapsulate MOFs in protective polymer coatings. This approach improves stability and moisture resistance while maintaining high CO<sub>2</sub> capture efficiency.

### **Mixed metal oxides (MMOs): a durable alternative**

Mixed metal oxides (MMOs), such as MgO-based adsorbents, are gaining attention for their durability and scalability. Unlike amine-based materials and MOFs, MMOs do not

suffer from oxidative degradation and can withstand extreme environmental conditions. Their advantages include high durability, allowing them to function in harsh conditions without performance loss. They are also more moisture-tolerant than MOFs and some amines, making them suitable for humid environments. Furthermore, they are cost-effective to produce, making them attractive for large-scale deployment.

Despite these benefits, MMOs have drawbacks. Most MMO-based sorbents require regeneration temperatures above 300°C to release CO<sub>2</sub>, making them more energy-intensive than amine-based adsorbents. Additionally, their CO<sub>2</sub> selectivity is lower compared to functionalised amines despite their excellent stability. Current research is focused on hybrid MMO materials that integrate amine functionalities, combining the durability of MMOs with the selectivity of amines.

### **Zeolites and carbon-based adsorbents: the low-cost workhorses**

Zeolites and carbon-based adsorbents, such as activated carbons, are among the most cost-effective and stable DAC materials. These materials rely on physisorption, meaning they trap CO<sub>2</sub> through weak van der Waals interactions rather than forming chemical bonds. Their primary advantages include low cost and widespread availability, as they are already produced on a scale for various industrial applications. They also exhibit high thermal stability, allowing them to withstand elevated temperatures without degradation. Additionally, they require extremely low energy for regeneration, making them highly energy-efficient compared to chemisorption-based materials.

However, zeolites and carbon-based adsorbents have limitations. Their CO<sub>2</sub> selectivity is relatively low at atmospheric concentrations, making them more effective in environments with concentrated CO<sub>2</sub> rather than in DAC applications. Many zeolites also suffer from high moisture sensitivity, which can significantly reduce their performance in humid conditions. To improve their viability for DAC, researchers are exploring hydrophobic



Adsorbent type	Support material	Capture mechanism	CO <sub>2</sub> capture capacity (mmol/g)	Energy efficiency	Advantages	Limitations	Lifetime and stability	Durability
Amine-functionalised silica (PEI/TEPA on SBA-15)	Mesoporous silica	Chemisorption (carbamate & bicarbonate)	2.0 – 4.5	Moderate	High capacity, low regeneration energy, good recyclability	Oxidative degradation at high temperatures	Moderate, degradation over cycles	Moderate
PEI on PME (Pore-expanded mesoporous silica)	Extra-large pore silica	Chemisorption (amine-CO <sub>2</sub> interaction)	3.5 – 7.3	High	Enhanced amine dispersion, high uptake under humid conditions	Complex synthesis, higher cost	High, stable under multiple cycles	High
TEPA on $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	$\gamma$ -Al <sub>2</sub> O <sub>3</sub>	Strong chemisorption (carbamate)	1.5 – 3.8	Moderate	High CO <sub>2</sub> affinity, stable adsorption at ambient temperature	Lower adsorption under humid conditions	Moderate, good oxidation resistance	Moderate
MOF-based adsorbents (MIL-101(Cr)-TEPA)	MOF (MIL-101(Cr))	Weak chemisorption (carbamic acid)	1.2 – 3.5	Moderate	Lower energy regeneration, good moisture tolerance	Lower capacity compared to $\gamma$ -Al <sub>2</sub> O <sub>3</sub>	Moderate, sensitive to high humidity	Moderate
Mg <sub>2</sub> (dobpdc) functionalised with amine	MOF (Mg <sub>2</sub> (dobpdc))	Cooperative chemisorption	4.0 – 6.8	Moderate to high	High selectivity, tunable adsorption, excellent CO <sub>2</sub> uptake	Moisture sensitivity, high regeneration energy required	Moderate, dependent on humidity	Moderate
UiO-66-NH <sub>2</sub>	MOF (UiO-66)	Chemisorption & physisorption	2.1 – 4.2	Moderate	High surface area, good thermal stability	Low CO <sub>2</sub> uptake, competitive water adsorption	High, stable under humid conditions	High
ZIF-8 functionalised with amine	MOF (ZIF-8)	Physisorption and weak chemisorption	1.5 – 3.0	High	Good moisture tolerance, Recyclability	Low CO <sub>2</sub> selectivity	Moderate	Moderate
Polymer-hybrid MOFs	MOF/polymer composites	Chemisorption & physisorption	3.0 – 5.5	High	Enhanced stability, tunable porosity, improved CO <sub>2</sub> uptake	Potential complexity in synthesis, moisture sensitivity	High, dependent on polymer type	High
MMO-supported amines	Mixed metal oxides (MMOs)	Chemisorption	3.0 – 6.0	High	High capacity, regenerability, scalable	Cost of material synthesis	High	High
Zeolites and carbon-based adsorbents	Zeolites, activated carbons	Physisorption	0.5 – 2.0	Very high	Low-cost materials, stable structure	Low selectivity, sensitive to moisture	High for zeolites, lower for carbon	Moderate

**Table 1** Comparison of DAC adsorbents

modifications that enhance their resistance to moisture and maintain their adsorption efficiency.

Looking ahead, the real breakthrough in DAC will likely come from better hybrid materials as sorbents that can be cheaply produced, highly durable, and ultra-efficient in CO<sub>2</sub> capture. Research is advancing rapidly, and what seems like an obstacle today could be solved within the next decade. Some of the most exciting developments include:

- Combining amines with MMOs to improve stability while maintaining low-temperature regeneration.
- Encapsulating MOFs with hydrophobic

polymers to make them moisture-resistant and more durable.

- Exploring biomimetic materials that mimic natural carbon-fixing mechanisms, such as enzyme-based adsorption systems.

The next challenge? Scaling up. DAC materials are only half the equation – turning lab-scale success into gigaton-scale carbon removal will require massive infrastructure investment, smart policy incentives, and an energy system that can power DAC without undoing its benefits.

### Challenges and future directions

DAC has come a long way from conceptual technology to a real-world climate solution with

commercial-scale plants under development. But as promising as DAC is, it still faces significant hurdles before it can truly operate at the gigaton scale required to impact the global atmospheric concentration of CO<sub>2</sub>. The fundamental question remains: Can we make DAC affordable, energy-efficient, and scalable in time to meet climate goals?

The challenges are not just technical. They span cost, energy requirements, infrastructure, policy, and public perception. Without addressing these barriers, DAC risks being a breakthrough that never breaks through.

### Can DAC compete economically?

One of the most pressing challenges is cost. Current DAC systems operate at a price of \$250-\$600 per ton of CO<sub>2</sub> removed, making it one of the most expensive carbon removal technologies available. In comparison, nature-based solutions like afforestation cost less than \$50 per ton. For DAC to be viable, costs need to drop below \$100 per ton – a price point considered feasible but only with significant technological improvements, economies of scale, and policy incentives. The main cost drivers are:

- **Adsorbent material costs:** High-performance materials like MOFs and polymer-hybrid adsorbents are expensive to produce, limiting large-scale deployment.
- **Energy demand:** The need for heat and electricity, especially in solvent-based DAC, makes operating costs high.
- **Infrastructure and deployment:** DAC requires piping, storage, and integration with CO<sub>2</sub> sequestration or utilisation facilities, adding to costs.

There is reason for optimism, though. Learning curves from solar and battery technologies suggest that, with scaling, costs could fall rapidly. Government incentives, like the US 45Q tax credit, are already pushing prices down, and industry-backed purchasing programmes are helping to create early demand for captured CO<sub>2</sub>.

### A carbon-neutral solution needs carbon-free power

DAC is only effective if it removes more CO<sub>2</sub> than it emits, which means energy sources

matter. The two dominant DAC approaches have vastly different energy footprints:

- **Liquid DAC** (for example, Carbon Engineering) requires extreme heat (900°C+) to release CO<sub>2</sub>, making it heavily reliant on natural gas with carbon capture or concentrated solar power.
- **Solid DAC** (for example, Climeworks and Global Thermostat) requires significantly lower temperatures (80-120°C), making it easier to integrate with waste heat, nuclear power, or renewable electricity.

One of the most promising developments is the integration of DAC with low-carbon energy sources. Future DAC plants could be powered by geothermal energy, as demonstrated by Climeworks, surplus renewable energy, or nuclear energy.

### Where does the captured CO<sub>2</sub> go?

Capturing CO<sub>2</sub> is one thing; what to do with it is another challenge entirely. There are two main pathways:

- **Permanent sequestration:** Injecting CO<sub>2</sub> into underground rock formations (such as basalt or depleted oil fields) for permanent storage. This is the only way to guarantee long-term carbon removal.
- **CO<sub>2</sub> utilisation:** Using captured CO<sub>2</sub> to produce synthetic fuels, concrete, carbon fibre, or chemicals. However, many of these applications re-release CO<sub>2</sub> into the atmosphere, making them less impactful for long-term removal.

Current infrastructure for CO<sub>2</sub> transport and storage is limited, meaning large-scale DAC will require billions in new investment. Governments are already funding DAC hubs and storage projects, with the US committing \$3.5 billion towards regional DAC facilities.

### Can DAC avoid the 'moral hazard' debate?

One of the biggest non-technical challenges DAC faces is public perception. Critics argue that DAC could be used as an excuse to delay emissions reductions, allowing industries to continue polluting under the assumption that CO<sub>2</sub> can simply be 'cleaned up' later. This is sometimes called the 'moral hazard' of carbon removal.

To counter this concern, policymakers and scientists stress that DAC should complement,

not replace, emissions reductions. The key message is:

- Emissions reduction must always come first. DAC is not an excuse to delay decarbonisation.
- DAC is essential for addressing historical emissions. Even if the world reaches net zero, DAC will still be needed to remove CO<sub>2</sub> already in the atmosphere.
- Transparency and accountability are crucial. Companies investing in DAC must show that they are cutting emissions first and not using DAC as a cover for inaction.

Public engagement and clear communication will be critical to ensuring DAC is seen as part of a responsible climate strategy.

### DAC at a crossroads

Once seen as an impractical vision, DAC is now essential in the fight against climate change. With growing climate commitments and breakthroughs in adsorbent materials, the challenge is no longer proving DAC works – it is scaling it quickly and affordably.

The key lies in advanced sorbents – materials that efficiently capture CO<sub>2</sub>, endure thousands of cycles, and regenerate with minimal energy.

While amine-functionalised adsorbents dominate today, MOFs, mixed metal oxides (MMOs), and polymer-hybrid materials are expanding the possibilities.

Yet materials alone will not be enough. DAC must become cheaper, more energy-efficient, and fully integrated with CO<sub>2</sub> storage and utilisation, backed by strong policy incentives and carbon markets. The world needs gigaton-scale carbon removal by mid-century, yet today's capacity remains in the kiloton range. Bridging this gap demands scientific innovation, industrial investment, and bold policy action.

The challenge is immense, but so is the opportunity. With continued progress in sorbents, energy integration, and policy frameworks, DAC can transition from an expensive experiment to a scalable pillar of carbon removal, helping transform CO<sub>2</sub> from a crisis into a resource we can manage.

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Dr Vahide Nuran Mutlu  
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# Solid-state adsorbent technology for carbon capture

A pathway to low-cost carbon capture from a wide range of sources using an energy-efficient process

Nigel Campbell and Shane Telfer  
**Captivate Technology**

Carbon capture adoption is recognised by the United Nations Intergovernmental Panel on Climate Change (IPCC) as vital for mitigating harmful carbon dioxide (CO<sub>2</sub>) and other greenhouse gas emissions to achieve net-zero goals, particularly in sectors like power generation, cement, steel, and biogas upgrading. Capturing CO<sub>2</sub> not only eliminates emissions from these processes; it also reduces the need for fossil fuel extraction, with fuels and products increasingly being manufactured from CO<sub>2</sub> as a raw material.

Despite the growth of renewable energy, hydrocarbons will continue to be used for the foreseeable future. Hydrocarbons remain necessary for our daily lives and the growing needs of developing countries. Carbon capture plays a key role in mitigating the damaging effects of hydrocarbon combustion and can reduce the need for fossil-sourced hydrocarbons. Increasingly, refineries and petrochemical plants are able to secure carbon feedstock from non-fossil sources.

CO<sub>2</sub> separation is a necessary part of many hydrocarbon processes but has historically had high capital and operating costs. Methods using chemical absorption of CO<sub>2</sub> with solvents have been used for more than a century and involve significant chemical process equipment (such as large processing towers) and massive amounts of heat (commonly fuelled by further fossil fuel combustion and emissions) for CO<sub>2</sub> recovery from the solvent. Naturally occurring CO<sub>2</sub> in fossil gas and CO<sub>2</sub> produced in hydrogen manufacture must be separated, and costs flow through to be included the price of the product.

With the fairly recent adoption of CO<sub>2</sub> separation to reduce the emissions in power generation or product manufacture, chemical absorption methods using solvents have proven to be costly in both economic and environmental terms. This is due to the nature of working with solvents. They are prone to side reactions, are volatile, are difficult to handle, and have environmental concerns. In response, and driven by industry and government commitments to net zero, there is a surge of interest, technology development, and investment in lower-cost methods for CO<sub>2</sub> separation.

One such method used by Captivate Technology employs a solid-state adsorbent that provides a low-cost process for CO<sub>2</sub> separation. Adsorption of CO<sub>2</sub> in Captivate's process occurs at ambient temperature and pressure, eliminating the need to use energy to compress the entire emissions stream at the start of the process. The emissions stream may only contain in the order of 10% CO<sub>2</sub>, depending on the source. In the adsorption process used by Captivate, energy use is significantly less than solvent absorption because energy is only used

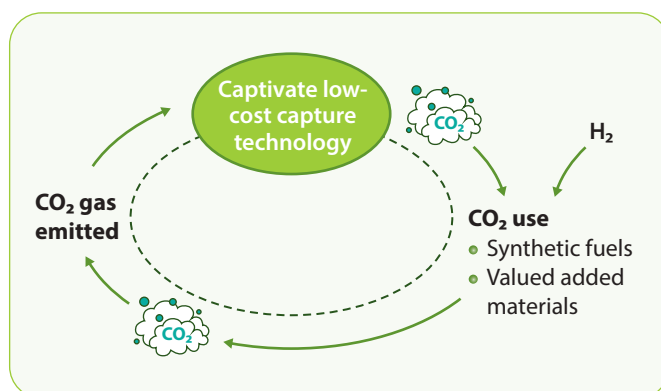
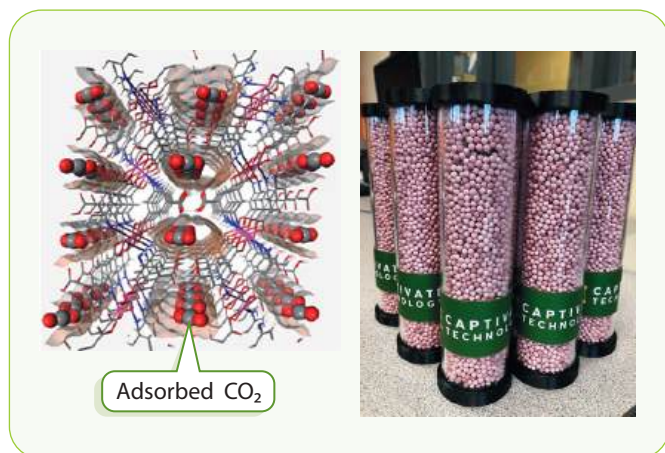


Figure 1 Circularity of CO<sub>2</sub>



**Figure 2** MUF-16 crystalline structure and pellets

for the CO<sub>2</sub> fraction of the emissions stream and thermal energy is not used to regenerate the adsorbent.

Such low-cost methods are not just achieving emission reductions; they are spurring a completely new CO<sub>2</sub> feedstock utilisation opportunity as low-cost CO<sub>2</sub> is produced at scale. From being a harmful waste greenhouse gas, new opportunities for harnessing CO<sub>2</sub> are rapidly emerging, and as a consequence an emerging market for CO<sub>2</sub> use is also rapidly growing, for example, in the manufacture of liquid fuels or polymers.

Captivate is an integral part of the emerging circular economy for carbon that obviates the need for the introduction of extra carbon into the biosphere from fossil fuel extraction. CO<sub>2</sub> is captured in waste emission streams and transformed into useful products using established and emerging process technologies, for example, with the addition of hydrogen produced from renewable electricity. As shown in **Figure 1**, once combusted or used, the CO<sub>2</sub> is captured and transformed again into a useful product, allowing the circular use of CO<sub>2</sub>.

Captivate Technology has built a carbon capture capability by developing a porous, solid-state material that is a sponge for CO<sub>2</sub>. This novel material, a type of metal-organic framework (MOF), selectively sieves CO<sub>2</sub> from gas streams. The process is continuous and recyclable, generating a steady stream of gaseous CO<sub>2</sub> to be stored or used. The company is rapidly moving to demonstration scale in collaboration with industrial partners and end users.

MOFs are porous, crystalline materials built

using metal ions and organic ligands. Certain MOFs have other advantageous properties for carbon capture applications, including high thermal and chemical stabilities, tuneable selectivity, low energy of desorption, and recyclability. MOF-based carbon capture has the potential to deliver significant advantages over incumbent technologies, including increased energy efficiency, lower process complexity, and smaller operating footprints.

**Figure 2** shows MUF-16 (MUF = Massey University Framework), a MOF discovered at Massey University, New Zealand, in 2018. The conclusions from de-risking work and a survey of the commercial landscape indicated that the adsorbent is at the forefront of CO<sub>2</sub> capture from various gas emission streams. Captivate Technology was subsequently launched as a start-up in 2023.

MUF-16 is made inexpensively and easily in large quantities using a straightforward process and readily available raw materials. It is then pelletised and deployed in adsorbent columns. Industrial flue gases or biogas are separated into CO<sub>2</sub>-rich and CO<sub>2</sub>-light streams using vacuum pressure swing adsorption (VPSA).

Its network of pores traps CO<sub>2</sub> via weak interactions, and CO<sub>2</sub> is easily removed once the MUF-16 bed reaches saturation capacity. This regenerates MUF-16 for another round of carbon capture, a process that can be repeated many thousands of times. The rate of CO<sub>2</sub> adsorption is high for the adsorbent which means there are no kinetic limitations on its performance.

Captivate Technology has developed the use of MUF-16 for separating CO<sub>2</sub>, determining its performance in real-world scenarios, and scaling up to pilot demonstration at industrial sites across New Zealand. De-risking showed that the combination of selectivity, capacity, tolerance to water and impurities, ease of manufacture, and cost make it an ideal adsorbent for CO<sub>2</sub> capture from flue gas streams. The US Department of Energy targets for purity (95%) and recovery (90%) can be exceeded using a simple step VPSA process, with high productivity and low energy consumption.

Solid-state adsorbent technology for carbon capture requires one-quarter to one-

third of the energy needed to capture one tonne of CO<sub>2</sub> using chemical absorption, the incumbent process employed to separate CO<sub>2</sub> from a mixture of gases (Hong, 2022). The combination of MUF-16 in a VPSA process provides very low Capex and Opex costs for industrial users, as demonstrated by the commercial costs of analogous modular carbon capture systems. This opens up carbon capture beyond large-scale applications that require economies of scale, significant Capex, and government support. Captivate Technology provides a pathway for modular carbon capture that can be applied economically on a small or large scale.

In addition, the adsorbent has a low affinity for nitrogen, methane, and other gases, which translates into a high purity for the captured CO<sub>2</sub>. Its durability and longevity stem from its tolerance of impurities, such as water vapour, steam, H<sub>2</sub>S, NO<sub>x</sub>, and SO<sub>x</sub>. It is compatible with well-established engineering processes, such as pressure swing adsorption (PSA).

MUF-16 maintains its performance over multiple adsorption and desorption cycles with real-world flue gases. An investigation into its lifecycle assessment has also been conducted. This includes experimental work that has shown it can be easily restored to pristine condition at the end of its life (expected after several years of continuous use), avoiding landfill or incineration.

The combination of MUF-16 and VPSA provides a process technology for point-source CO<sub>2</sub> capture from a wide variety of waste emissions sources. This includes post-combustion emissions from industry (such as power generation), commercial, residential, and transportation sectors, cement and steel industries, biogas upgrading, geothermal power generation, and others.

Captivate Technology has also rapidly grown its capability in the optimisation of the adsorption and desorption process through multi-objective computational simulations. This enables process optimisation under any given industrial scenario and further reduces the cost of capture.

Results

Captivate Technology has worked with several emitters in New Zealand to demonstrate the capabilities of MUF-16 in a VPSA process at industrial sites, as shown in **Table 1**. The adsorbent has been tested at six different industrial locations between 2023 and 2024. Testing has occurred on a demonstration scale with a simple, two-column VPSA unit, each holding one kilogram of MUF-16. The unit receives a small slipstream of emissions from the flue stack.

The mobile demonstration unit is shown in **Figure 3**. Straightforward gas pre-conditioning (cooling, dehumidification, and particulate removal) occurs before the emission stream enters the VPSA columns containing MUF-16.

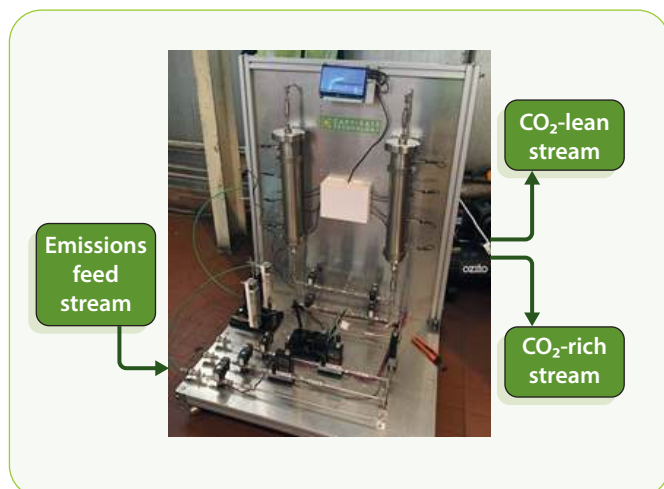
Notably, the adsorbent was proven to withstand contaminants such as NO<sub>x</sub>, SO<sub>x</sub>, and H<sub>2</sub>S, which do not impede the carbon capture process. Results consistently demonstrated a clean emissions stream, free of CO<sub>2</sub> with no adverse effects on MUF-16 and no change in the effectiveness of CO<sub>2</sub> separation over the test period. This is a very promising set of results and is a springboard for scale-up to demonstration and commercial scale units. The field tests have proven that MUF-16 is a highly effective and robust adsorbent for carbon capture.

The following sectors and applications are suitable for MUF-16 and Captivate Technology:

- **Biogas upgrading:** VPSA systems for biogas upgrading to renewable natural gas (RNG) are commercially available. Captivate has conducted process calculations and used its bespoke

Industrial site and emission source	CO <sub>2</sub> %	Impurities in emissions stream
Geothermal power station		
non-condensable gases	25	N <sub>2</sub> , O <sub>2</sub> , H <sub>2</sub> S, Hg
Fossil fuel power station steam turbine	8	N <sub>2</sub> , O <sub>2</sub> , NO <sub>x</sub>
Sawmill wood waste biomass boiler	10	N <sub>2</sub> , O <sub>2</sub> , NO <sub>x</sub>
Peaker plant natural gas turbine	4	N <sub>2</sub> , O <sub>2</sub> , NO <sub>x</sub> , CO
Food and beverage industry hot water gas fired boiler	8	N <sub>2</sub> , O <sub>2</sub> , NO <sub>x</sub> , CO
Cement plant	25	N <sub>2</sub> , O <sub>2</sub> , NO <sub>x</sub> , SO <sub>x</sub>

**Table 1** MUF-16 demonstration sites and emissions source



**Figure 3** Captivate Technology's mobile demonstration unit

software to identify processes that deliver optimal purity, recovery, productivity, and lowest energy consumption when using MUF-16. For example, a simple four-step process can deliver methane with up to 99% recovery and up to 99% purity from raw biogas.

Analysis has also been conducted to capture methane from post-membrane tail gas, which has a  $\text{CH}_4/\text{CO}_2$  ratio = 6/94. A two-step VPSA process can recover high-quality methane from this tail gas.

- **Cement process emissions capture:** The cement industry accounts for approximately 8% of global  $\text{CO}_2$  emissions. Emissions occur in the manufacture of clinker, which is an initial step in making cement.  $\text{CO}_2$  emissions occur from the kiln combustion of fuel and limestone ( $\text{CaCO}_3$ ), which liberates  $\text{CO}_2$ . The  $\text{CO}_2$  stream to be captured is, therefore, at a relatively high concentration (>20%), which provides favourable conditions for the use of MUF-16 on cement sites. The adsorbent has been tested at a cement plant in an early-stage duration test, and results showed it to be a very suitable for removing  $\text{CO}_2$  from cement emissions.

- **Natural gas post-combustion capture:** Natural gas engines, boilers, and turbines are abundant in industry for power and electricity generation and process heat. MUF-16, as shown in Table 1, has been demonstrated to be effective in capturing  $\text{CO}_2$  from these emissions. The  $\text{CO}_2$  concentration in the emission stream can vary from 3% in gas turbines to close to 10% in boilers. With its favourable properties, the adsorbent can be used for economic

projects at small to medium scale (individual engine capture) and at low concentration.

- **Biomass combustion capture:** Biomass boilers burning wood waste are commonly found at commercial greenhouse complexes and sawmills. Waste  $\text{CO}_2$  can be captured using a Captivate carbon capture unit, with  $\text{CO}_2$  used, for example, to enhance growth in greenhouses.

- **Geothermal applications:** Some geothermal electricity generation plants emit non-condensable gases containing  $\text{CO}_2$ . MUF-16 has been demonstrated to successfully capture  $\text{CO}_2$  among a mix of gases that even contain  $\text{H}_2\text{S}$  and mercury vapour. This challenging gas mixture has provided significant confidence about the longevity of the adsorbent under operational conditions.

- **Syngas:**  $\text{CO}_2$  is found in raw syngas produced by the steam reformation of methane (SMR). As such, there is a significant opportunity for the inclusion of economic carbon capture units in syngas operations. Air Products SMR process in Port Arthur, USA, uses a PVSA process and a solid-state sorbent to capture  $\text{CO}_2$  at a rate of 60,000  $\text{m}^3/\text{hr}$ . MUF-16 would be a suitable alternative adsorbent in this process and presents an exciting future business opportunity. The superior performance of MUF-16 lowers total costs in comparison to standard sorbents.

### Financial analysis

Discounted cashflow economics using capital costs and energy consumption from commercially available small and medium-scale PSA carbon capture systems has been conducted. Low energy requirements lead to low operating costs and attractive internal rates of return, even at small scale and low concentration carbon capture. While not essential for compelling business cases, where available, tax credits, carbon taxes, and emission trading schemes can contribute to the revenue side of the equation.

### Future plans

Captivate is now scaling up to design and construct pre-commercial demonstration units that have a capture capacity of approximately 1 tonne  $\text{CO}_2$  per day, to provide the technical de-risking required to springboard into full commercial-scale operations. The small footprint



and flexible engineering of MUF-16 capture units make the process ideal for both brownfield applications and greenfield sites. By stacking modular units, the capacity can be increased to meet the emissions reduction requirements of any industrial emitter or biogas operation of any size. Once captured and separated, the CO<sub>2</sub> can be stored or utilised.

Captivate's business model is to sell or licence MUF-16 and provide CO<sub>2</sub> capture equipment as a turnkey solution or as a service. The company can tailor the process to the ultimate end use of CO<sub>2</sub>, whether that be underground sequestration or the manufacture of synthetic fuels or materials. Local markets, geography, and the strategic goals of emitters will have significant influence on the destination of the captured CO<sub>2</sub>.

## Conclusions

With its next-generation adsorbent, Captivate Technology provides a pathway to carbon capture that can produce CO<sub>2</sub> at low cost and from sources previously thought to be impractical or uneconomic. Carbon capture processes have historically used chemical absorption by solvents such as amines, a process that has many drawbacks. Solid-state carbon capture technology using MUF-16 in a VPSA processes expedites the roll out of carbon capture by providing a cheaper, more flexible, and lower energy option that is attractive for emitters and project developers. This opens up a broad market for carbon capture across all scales.

## Acknowledgements

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**Nigel Campbell**  
nigel@captivatetechnology.com



**Shane Telfer**  
shane@captivatetechnology.com

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# SAF production via the HEFA route: chemistry and catalysis

The crucial role of the catalyst system in producing sustainable aviation fuel from waste and residue oils and fats via the HEFA route

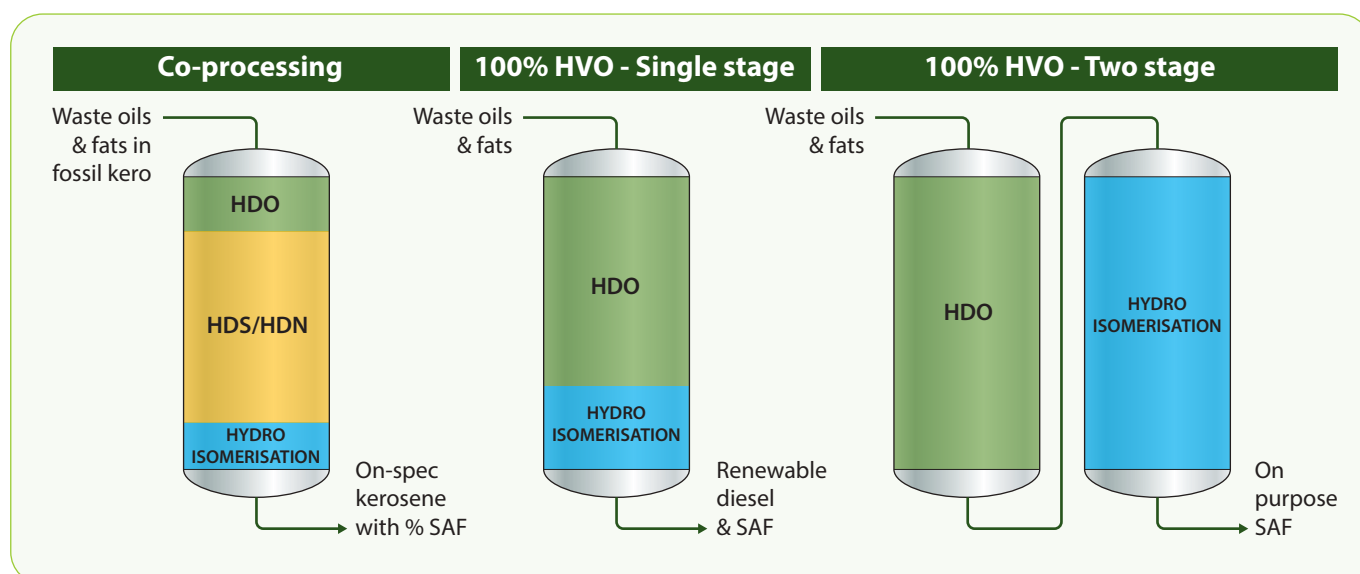
Jaap Bergwerff  
Ketjen

**G**lobal mandates and incentives are driving efforts to increase the production of sustainable aviation fuel (SAF). Although alternative methods, such as alcohol-to-jet processes and the production of e-fuels, are being developed, hydrotreated esters and fatty acids (HEFA) are expected to remain the primary feedstock for commercial-scale SAF production in the coming years (S&P Global, 2025). Operators of HEFA units are increasingly inclined to switch production from renewable diesel to SAF.

Several approaches can be employed to convert oils and fat streams into products that meet the specifications for the SAF component, which can be blended with conventional kerosene. These approaches are illustrated in the schematic process schemes in **Figure 1**. One approach involves mixing the renewable feedstock with a conventional kerosene fraction

to be co-processed in an existing kerosene hydrotreater, producing aviation fuel with a certain renewable content that meets JET A-1 specifications. This approach requires (i) hydroprocessing of the kerosene fraction to remove nitrogen and sulphur compounds, (ii) hydrodeoxygenation (HDO) of the triglycerides, and (iii) dewaxing to reduce the freezing point of the final product, all within a single reactor under the same operating conditions. This constraint typically limits the amount of renewable feedstock that can be co-processed to no more than a few per cent.

Alternatively, standalone processes can be used to convert oils and fats into a SAF stream that can be blended with conventional kerosene. In any case, HDO and subsequent hydroisomerisation (HI) of the n-paraffins generated are required. Two types of processes can be distinguished to produce 100%



**Figure 1** Schematic representation of different processes for the production of SAF via the HEFA route



Property	Typical HDO product (mixture of linear paraffins)	ASTM D7566 A2 (requirements for SAF component)	Aviation jet fuel JET A-1 (final spec)
Density (kg/m <sup>3</sup> )	770-790	730-772	775-840
Freezing point (°C)	20-30	Max. -40	Max. -47
Flash point (°C)	>50	Min. 38	Min. 38
Distillation 10 vol-% (°C)	275-290	Max. 205	Max. 205
Distillation FBP (°C)	310-325	Max. 300	Max. 300

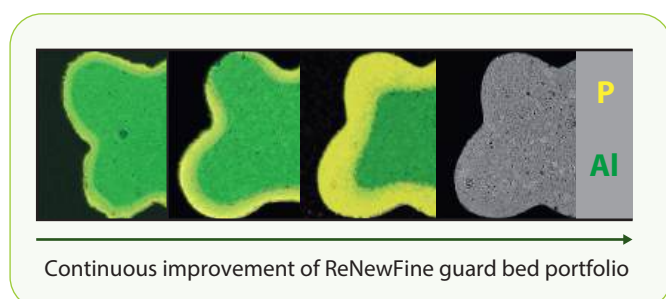
**Table 1** Typical properties of a hydrogenated HEFA-feed and specifications for SAF product

hydrogenated vegetable oils (HVO) based on the composition of the gas stream in the HI reactor. In sour mode or single-stage operation, the conversion of triglycerides to linear paraffins and their isomerisation are carried out without intermediate gas purification. Alternatively, in sweet mode or two-stage operation, HI is essentially carried out in the absence of NH<sub>3</sub> and H<sub>2</sub>S in a separate reactor,

**“With waste oil and fat streams replacing relatively pure vegetable oils as feedstock for the HEFA process, the management of heteroatoms during the HDO step has become increasingly important”**

allowing the use of highly selective and active noble metal catalysts. This configuration enables a high degree of isomerisation, making it ideally suited for on-purpose SAF production with high SAF yields.

Regardless of the process used, the challenge of producing SAF from waste fat and oil streams remains the same, as illustrated



**Figure 2** Development of improved ReNewFine 100 series guard bed catalysts illustrated by SEM images of spent catalysts showing the P-deposition profile (in yellow) across spent catalyst extrudates

in **Table 1**. This table compares the typical properties of a hydrogenated triglyceride stream produced after the HDO step with the specifications for SAF as a blending component and the final aviation fuel. It is evident that a significant shift in both boiling point and freezing point must be achieved in the HI step to produce in-spec SAF.

### Hydrodeoxygenation

With waste oil and fat streams, such as used cooking oil and animal fats, replacing relatively pure vegetable oils as feedstock for the HEFA process, the management of heteroatoms during the HDO step has become increasingly important. Regardless of the mode of operation, inorganic impurities, such as phosphorus (P) and metals, which can be present in significant concentrations in waste feedstocks, can severely deactivate the HDO catalysts, resulting in unstable operation and short cycles. Therefore, it is critical that these components are effectively removed. Dedicated guard catalysts provide the delicate balance between (i) activity to decompose the organic compounds containing P and metals, and (ii) accessibility and pore volume to allow for optimal uptake capacity for these contaminants throughout the cycle.

**Figure 2** illustrates the evolution of the ReNewFine catalyst portfolio for P-trapping guard-bed catalysts. As shown by the P-profile over the catalyst extrudates obtained via scanning electron microscopy (SEM), each generation of guard bed catalysts has effectively utilised a larger fraction of the extrudate for trapping P, thereby drastically improving P-uptake capacity. Currently, ReNewFine 102 represents Ketjen’s latest generation of guard catalysts especially developed for HEFA

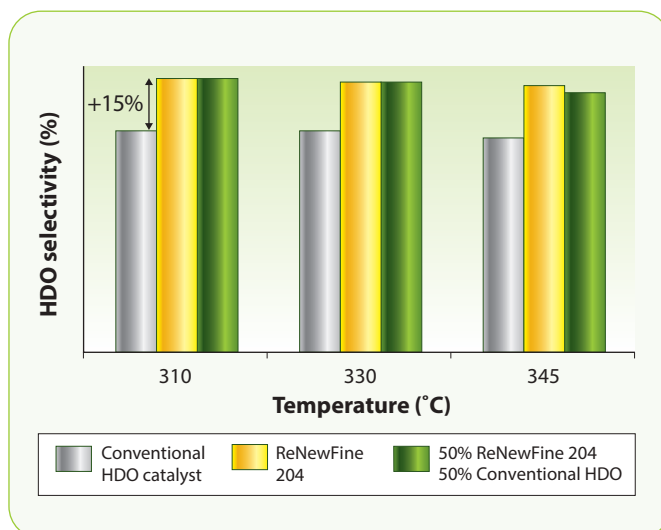


applications. Notably, the core of the catalyst extrudate, where only a low concentration of P is deposited, represents just 24% of the catalyst volume, indicating that the effective use of the catalyst is nearly 76%.

Another important aspect of an HDO catalyst is its ability to selectively remove oxygen via the hydrodeoxygenation pathway, splitting off oxygen as H<sub>2</sub>O instead of CO or CO<sub>2</sub> during the HDO step. Besides reaction conditions, such as temperature (T) and pressure (P), the HDO selectivity is determined by the catalyst applied. The use of a selective HDO catalyst minimises the formation of CO, which can cause issues in off-gas handling and results in maximum carbon yield as valuable products. This HDO selectivity can be derived from the ratio of C<sub>17</sub> and C<sub>18</sub> n-paraffins in the HDO product since fatty acid chains with an uneven C-number do not naturally occur in biogenic triglycerides.

Ketjen's ReNewFine 204 catalyst was designed to deliver optimal HDO selectivity. As illustrated in **Figure 3**, compared to previous-generation HDO catalysts, a 15% higher selectivity can be achieved using ReNewFine 204 over a broad temperature range, which translates to almost 1% higher carbon yield in the final product. This catalyst provides supreme stability towards the deposition of phosphorus (P), ensuring that the high HDO selectivity can be maintained throughout the HDO cycle. By targeting the use of this catalyst grade in the reactor zone where triglycerides are converted, a small layer of this catalyst is required to improve the HDO selectivity of the entire reactor loading.

N-compounds, such as fatty amines and amides, form another class of heteroatom compounds that require special attention in the HDO reactor. If N-compounds are not effectively removed by the HDO catalyst system, this may significantly lower the performance of the downstream HI catalyst. This is particularly critical when the goal is to produce SAF, which requires deep isomerisation. N-slip from the HDO reactor can lead to sub-optimal performance. While deep hydrodenitrogenation (HDN) is important, care must be taken to prevent the oligomerisation of n-paraffins in the final zone of the HDO



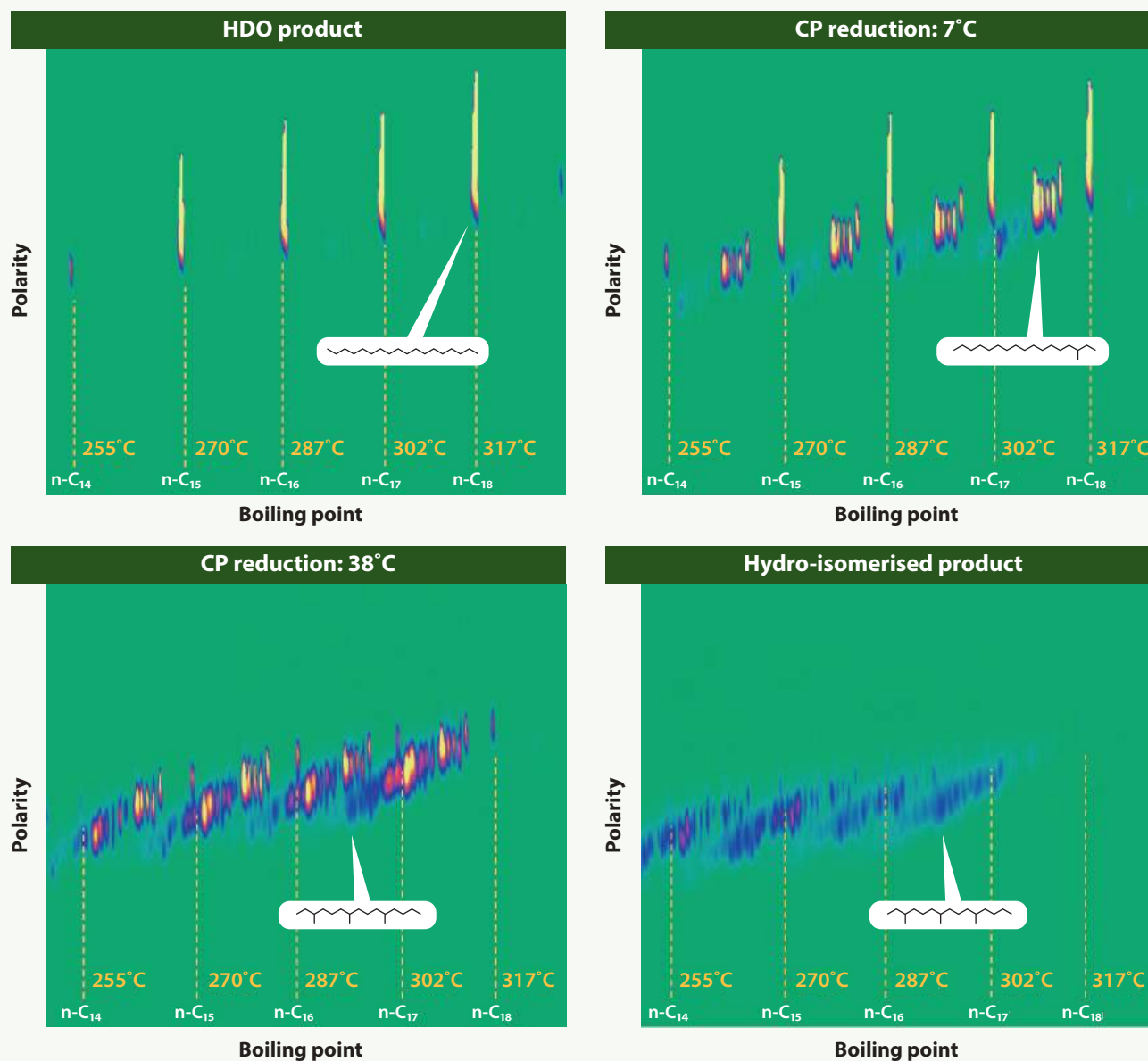
**Figure 3** HDO selectivity (defined as the ratio between C<sub>17</sub> and C<sub>17</sub>+C<sub>18</sub> n-paraffins in the HDO product) for ReNewFine 204 catalyst applied as a full load (yellow) and as a 50/50 load with a conventional catalyst (green), as a function of operating T as compared to operation with a conventional HDO catalyst (grey)

reactor, as this would result in the formation of high molecular weight compounds that can severely impact the properties of the final product.

Considering the range of different reactions that need to be catalysed in the HDO reactor, it is inevitable that an optimal HDO reactor

**“Another important aspect of an HDO catalyst is its ability to selectively remove oxygen via the hydrodeoxygenation pathway splitting off oxygen as H<sub>2</sub>O instead of CO or CO<sub>2</sub> during the HDO step”**

loading consists of several different HDO catalysts, each with a specific function. For this reason, Ketjen has developed its ReNewFine portfolio, which includes guard bed catalysts (ReNewFine 100 series), HDO catalysts (ReNewFine 200 series), and HDN catalysts (ReNewFine 300 series). By combining the catalysts in this portfolio, an optimal ReNewSTAX reactor loading can be designed for each HDO unit, tailored to the unique operational requirements to ensure minimum N-slip and oligomerisation, as well as maximum cycle length.

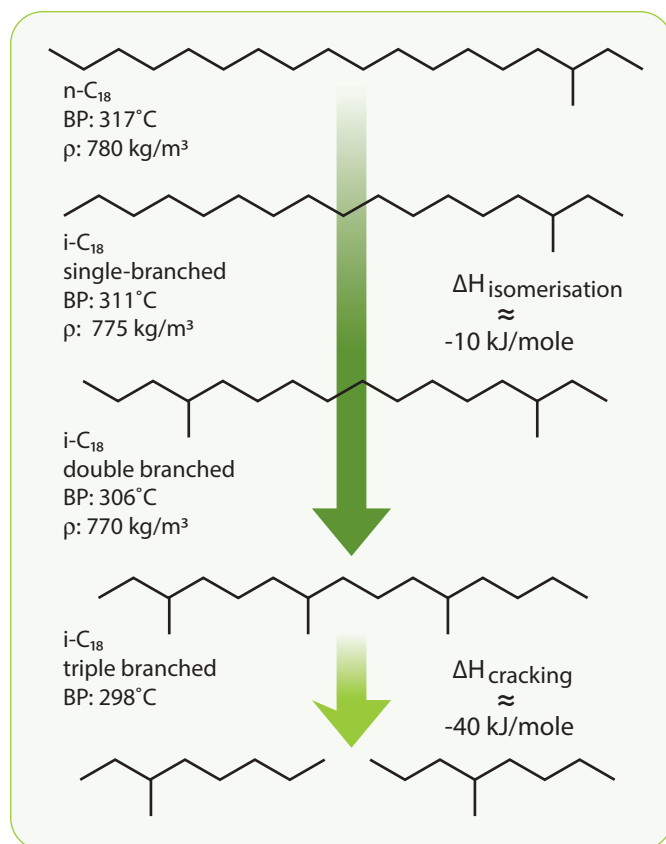


**Figure 4a** GCxGC traces of HDO product and hydroisomerised products with different degrees of isomerisation

### Hydroisomerisation

Once a stream of n-paraffins has been produced in the HDO step, the required reduction in boiling point range and freezing point must be achieved via isomerisation and selective cracking. The GCxGC traces of a typical HDO product and products from an HI reactor with increasing degrees of isomerisation and decreasing cloud point are presented in **Figure 4**. In these traces, each dot represents the concentration of a single molecular compound with a unique combination of boiling point (on the x-axis) and polarity (on the y-axis). Starting from a mixture of linear paraffins (a single dot for C<sub>15</sub>, C<sub>16</sub>, and so on n-paraffins, as shown

in the top-left trace), isomerisation results in the formation of single and double branched isomers with a lower boiling point compared to the parent n-paraffin (top-right trace). Further increasing the degree of isomerisation results in the formation of triple-branched isomers (bottom-left trace) and a complete removal of n-paraffins (bottom-right trace). This process significantly reduces the cloud point, boiling point distribution, and density of the product. The objective is to achieve deep isomerisation while preventing the unselective cracking of branched paraffins, which would result in excessive yield loss, a significant exotherm, and higher H<sub>2</sub> consumption.



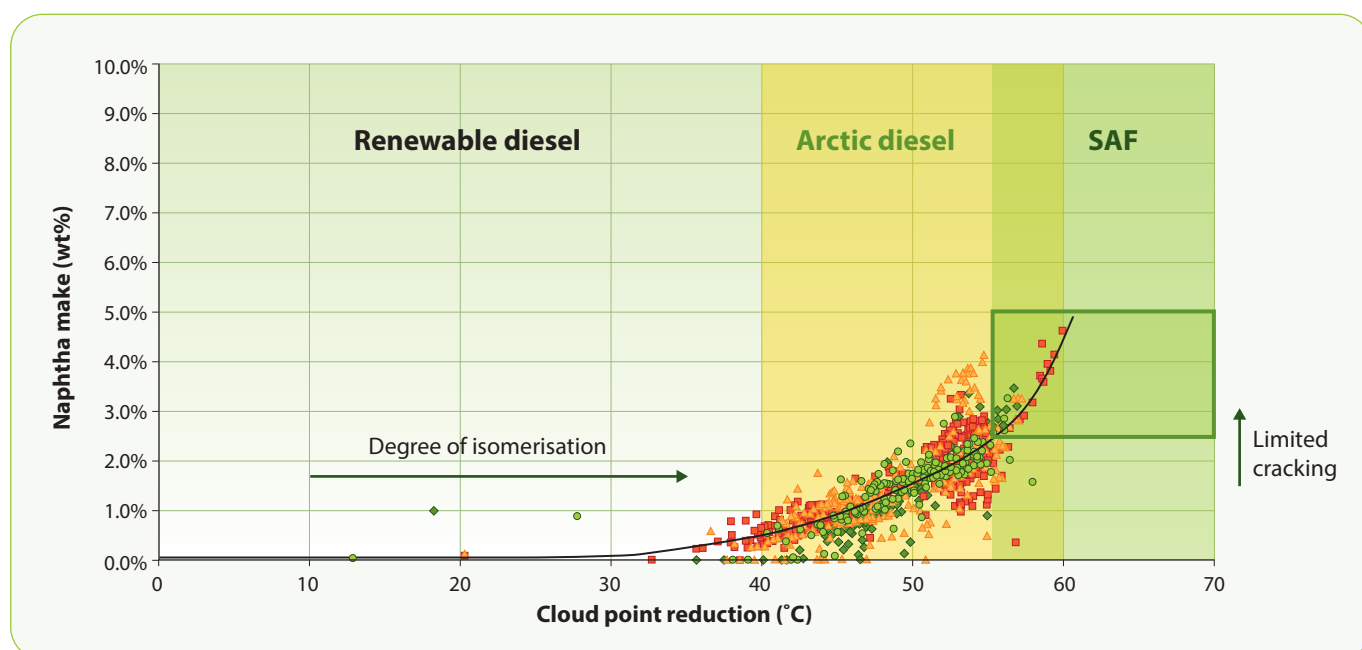
**Figure 4b** A simplified reaction scheme for isomerisation of n-C<sub>18</sub>, illustrating the decrease in boiling point and density that can be obtained via isomerisation

When operating an HI unit, the degree of isomerisation is tuned depending on the target product. For renewable diesel production, the operating temperature (T) will be relatively low,

resulting in a lower degree of isomerisation and minimal yield loss due to cracking. Conversely, for the production of high-quality arctic diesel or SAF, deep isomerisation is required, and the operating temperature will be increased. **Figure 5** presents the observed production of naphtha as a function of cloudpoint reduction for various commercial HI cycles where ReNewFine 5005 was applied. It can be observed that the amount of naphtha produced remains remarkably low, even when the unit is operated in arctic diesel or SAF production mode.

### Commercial SAF production

Neste, a pioneer in SAF production, has achieved remarkable results using ReNewFine catalyst solutions in its NEXBTL units. This journey has provided invaluable experience that is now available to the industry. The results of a dedicated campaign to produce SAF, where the HI reactor loaded with ReNewFine 5005 was run under high-severity conditions, are presented in **Figure 6**. A liquid product with an average cloud point of -46°C was achieved over a one-year period, demonstrating highly effective isomerisation. Throughout this year, no significant deactivation of the catalyst system was observed, as evidenced by the stable weighted average bed temperature (WABT), highlighting the remarkable stability of the ReNewFine 5005 catalyst. Typical cycle lengths



**Figure 5** Naphtha make as a function of cloud point reduction for a number of commercial HI cycles using ReNewFine 5005



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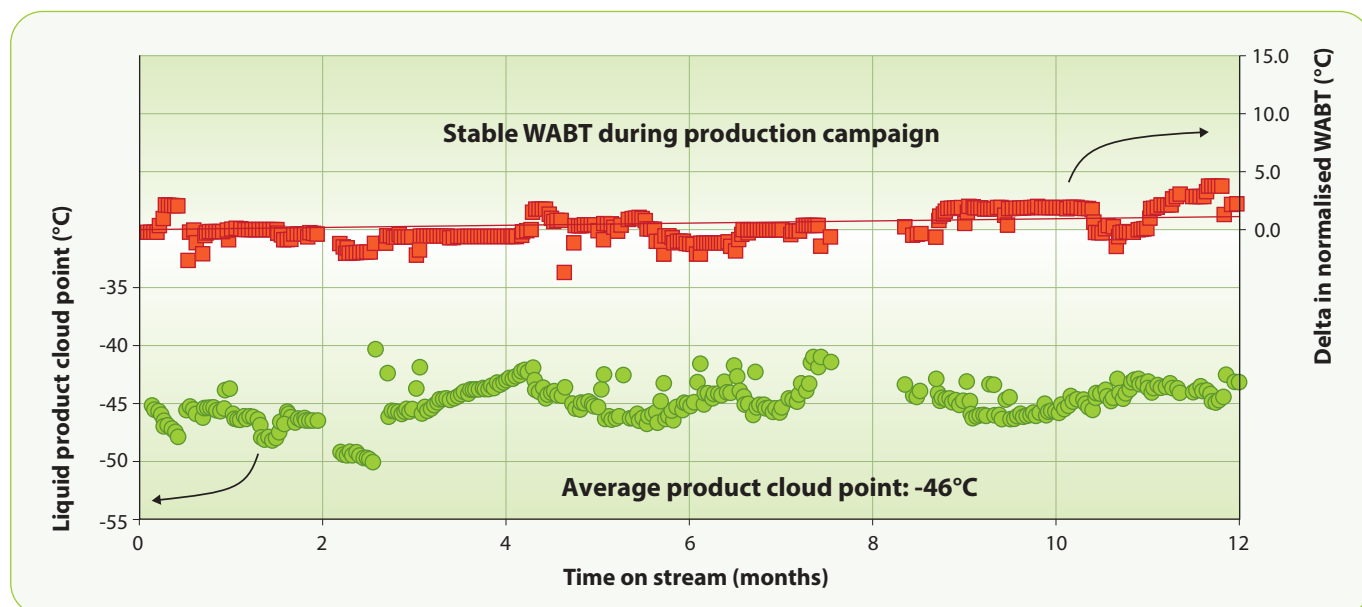
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**Figure 6** Liquid product cloud point and WABT during a year-long SAF production campaign

for this catalyst are, therefore, well beyond five years. Using residue and waste streams as feedstocks during this campaign resulted in significant concentrations of N-compounds in the feed, which could potentially affect the activity and stability of the HI catalyst. Hence, the observed stability also indicates that the ReNewFine HDO catalyst system upstream was effective in preventing nitrogen slip to the hydroisomerisation stage.

During this campaign, total liquid product yields exceeded 90% on a litre product per litre HEFA feed basis. **Table 2** presents the relevant properties of the total liquid product, along with the SAF and renewable diesel fractions obtained from it. Fractionation resulted in 74 wt% SAF, which comfortably met all product specifications, while the remaining fraction was high-quality renewable diesel. The challenge

in producing SAF is to maximise the SAF yield compared to renewable diesel while minimising yield loss to renewable naphtha or lighter products through unselective cracking. Severe isomerisation requires higher temperatures, making it even more difficult to prevent the formation of light products. The high yields obtained during this campaign demonstrate the high isomerisation selectivity of the ReNewFine catalyst system. Additionally, this selectivity prevented operational issues such as severe exotherms or excessive product vaporisation caused by uncontrolled cracking.

The examples in this article vividly demonstrate the crucial role of the catalyst system in producing SAF from waste and residue oils and fats via the HEFA route. A highly selective HI catalyst is essential for achieving the deep isomerisation and selective cracking necessary for SAF production, without incurring excessive yield loss to light products. However, this catalyst can only operate at its peak efficiency when safeguarded by an effective HDO catalyst system.

ReNewFine, ReNewSTAX, and NEXBTL are trademarks of Ketjen.

## References

S&P Global SAF Market Outlook, February 2025.

	Total liquid product	SAF fraction 74 wt% yield	Renewable diesel fraction 26 wt% yield
Density (kg/m <sup>3</sup> )	775	771✓	787
Cloud point (°C)	-46		-30
Freezing point (°C)		-52✓	
Flash point (°C)		40✓	

**Table 2** Average properties of the total liquid product ex HI and the SAF and renewable diesel fractions obtained during a dedicated SAF production campaign



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# Unlocking the fuel of the future: integration strategies for eSAF

Collaboration between Johnson Matthey and Honeywell UOP demonstrates the potential of methanol-to-jet technology in producing sustainable aviation fuel

Zinovia Skoufa **Johnson Matthey**  
Leigh Abrams **Honeywell UOP**

## Introduction

As the world grapples with the pressing need for sustainable energy solutions, the aviation industry stands at a pivotal juncture. Integrating sustainable aviation fuel (SAF), particularly eSAF, into the fuel supply chain is critical to achieving ambitious climate goals. Recent legislative changes underscore the urgency of this transition, mandating higher blends of SAF in a number of different geographies, including the EU, UK, Brazil, Canada, Indonesia, and Japan. The EU SAF blend requirements are shown in **Figure 1**. The collaboration between Johnson Matthey (JM) and Honeywell UOP exemplifies the innovative approaches being adopted to produce SAF from diverse feedstocks, leveraging advanced technologies like Fisher-Tropsch (FT) and methanol-to-jet (MtJ) fuel pathways.

## Legislative changes and the role of SAF

The EU has ambitions to reduce net greenhouse gases by 55% by 2030, with the ultimate goal of Europe becoming the world's first climate-neutral continent by 2050. The aviation sector is an important part of this, and while alternative propulsion technologies are advancing, SAF will play a crucial role in decarbonising the aviation sector before 2050.

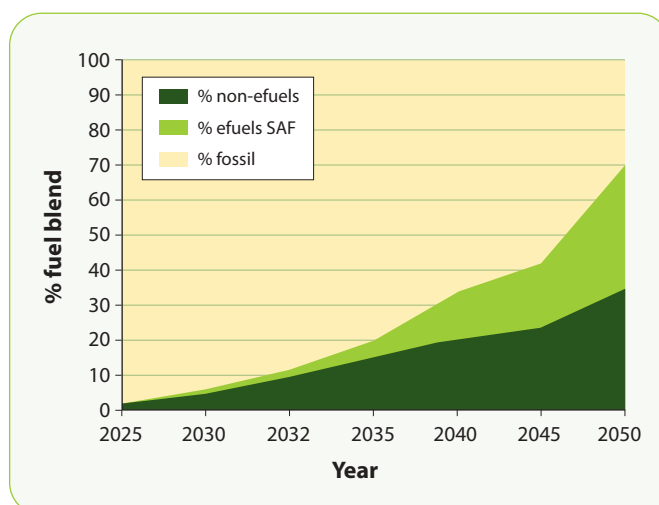
SAF demand is driven by government incentives and mandates, with long-term demand expected to grow to nearly 28.6 million tonnes by 2050 (European Alternative Fuels Observatory, 2025). eSAF-specific incentives and mandates are also significant, with ReFuelEU requirements increasing significantly over time from 1.2% in 2030 to 35% in 2050.

## SAF production pathways

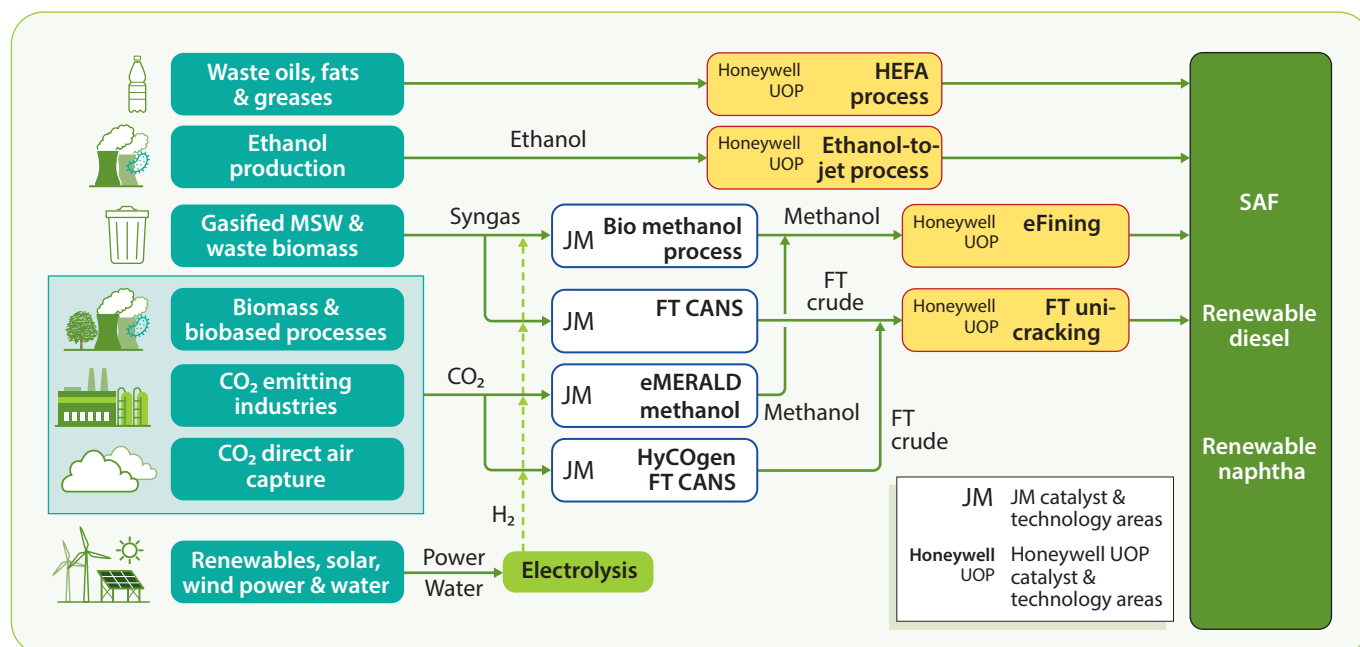
SAF can be made using a number of different synthesis routes utilising different feedstocks, as shown in **Figure 2**.

SAF production via the most popular hydroprocessed esters and fatty acids (HEFA) route has feedstock constraints as available volumes of waste oil, fats, and greases are far below the volume needed to meet global targets, with supply becoming more scarce by 2030. Other pathways are needed to meet 2050 targets, such as FT, MtJ, and ethanol-to-jet routes to enable the use of alternative feedstocks such as waste biomass, municipal solid waste, and CO<sub>2</sub> from ethanol production.

The collaboration between JM and Honeywell UOP aims to produce SAF from various feedstocks. This initiative builds on an existing memorandum of understanding (MOU) on low-carbon hydrogen and carbon capture, expanding to include SAF production through the FT and MtJ fuel routes.



**Figure 1** EU SAF blend requirements over time



**Figure 2** Different routes to producing SAF

### Methanol-to-jet value chain

#### Production of methanol

Methanol can be produced through various routes from different feedstocks, as shown in **Figure 3**. Renewable methanol made from waste, biomass, or green hydrogen can reduce the cradle-to-gate lifecycle emissions of methanol when compared with fossil-based methanol (Johnson Matthey, 2025) and is a key solution to decarbonising hard-to-abate transport sectors such as aviation and shipping.

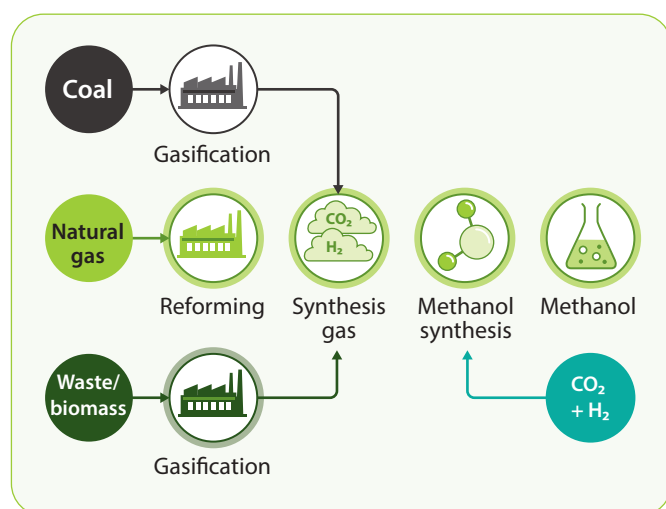
JM's eMERALD technology produces renewable methanol from green hydrogen and biogenic CO<sub>2</sub> and is engineered to maximise the feedstock efficiency of the highly valuable green hydrogen, contributing to the smaller

electrolyser capacity needed upstream of the e-methanol plant.

The flowsheet is designed based on JM's tube cooled converter (TCC). The methanol synthesis reaction is equilibrium-limited; therefore, a high circulation loop is key to maximising feed efficiency (Longland & Cassidy, 2023). JM's TCC is well suited to a high circulation loop as it uses a catalyst in shell design, which facilitates high circulation rates while managing the pressure drop across the catalyst. The eMERALD flowsheet features a high degree of heat integration, reducing the need for external heating and helping to drive down operating costs while ensuring reliable production.

Together with eMERALD 201, a catalyst designed to enhance hydrothermal stability and extend catalyst life, the eMERALD flowsheet reduces the levelised cost of methanol production by 9% (compared with a baseline 100 ktpa plant in China), making sustainable methanol projects more financially viable.

Finally, the eMERALD flowsheet is well placed to cope with the additional demands arising from the intermittent nature of renewable electricity required for e-methanol production, seamlessly managing hydrogen intermittency and enabling flexible operation.

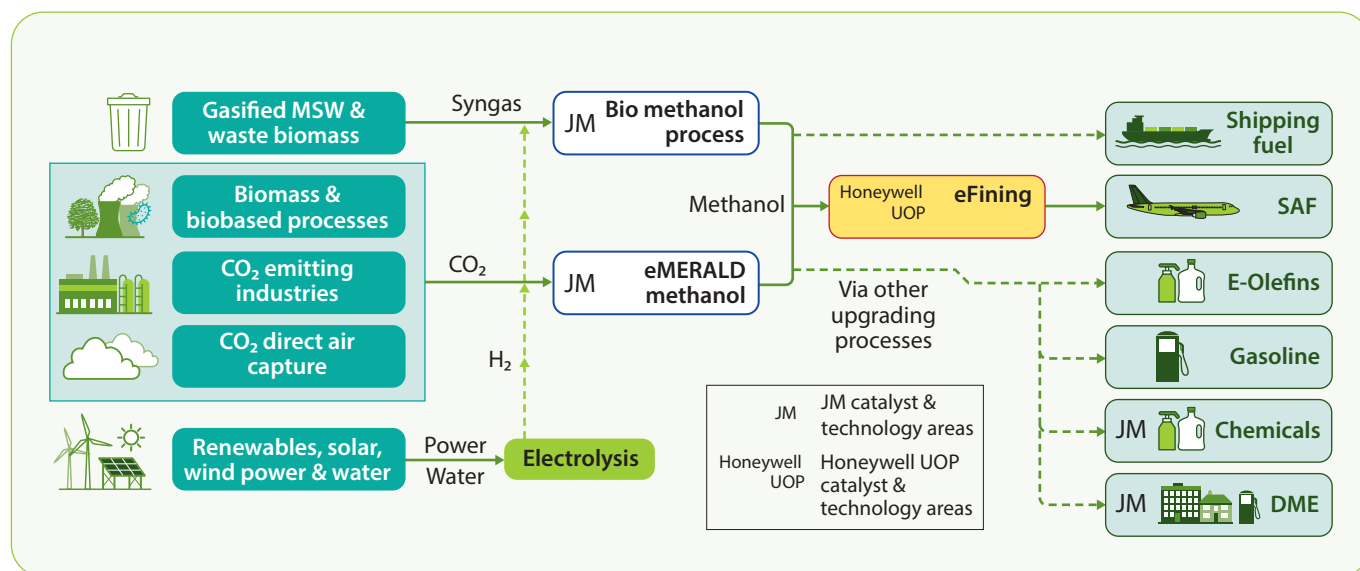


**Figure 3** Summary of methanol production using different feedstocks

#### Technology in action

The world's first CO<sub>2</sub>-to-methanol plant was completed in 2012, with its first phase built under





**Figure 4** Key areas for methanol off-takes

licence from JM and using JM catalyst focused on CO<sub>2</sub> utilisation. Since then, JM's evolving technology has been selected in a number of e-methanol and biomass-based methanol projects of significant size across the world, totalling an announced capacity of 4,772 tpd of methanol production. Key projects are as follows:

- Built and operational since 2021, the Haru Oni pilot plant, located in Patagonia, Chile, leverages high-capacity wind power to generate green hydrogen and utilises biogenic CO<sub>2</sub> to produce methanol (Johnson Matthey, 2021).
- HIF Global's Paysandu eFuels facility in Uruguay, one of the world's largest planned e-methanol plants at 700 tpa, has chosen JM's CO<sub>2</sub>-to-methanol technology. The plant is expected to start construction in 2025 (Johnson Matthey, 2024).
- La Robla NE in Spain, one of Europe's largest planned e-methanol plants at 140 ktpa, has also selected JM's CO<sub>2</sub>-to-methanol technology, with operations expected by 2027 (Johnson Matthey, 2025).
- ET Fuels' e-methanol Texas plant, with a capacity of 120 ktpa, has selected JM's CO<sub>2</sub>-to-methanol technology and is planned for completion by 2029 (Johnson Matthey, 2024).

### Methanol off-takes

There are three key areas for methanol off-takes, as shown in **Figure 4**:

- 1 Methanol as a fuel for shipping.
- 2 Methanol to produce olefins for plastics and petrochemicals.

- 3 Methanol to SAF, which is seen as an attractive route for customers.

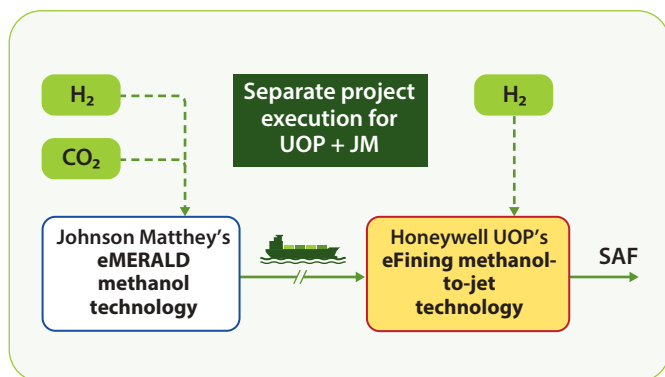
### Methanol-to-jet technology

In the UOP eFining process, methanol is converted to light olefins, which are then chained together in an oligomerisation process, 'building up' molecules of a desired length. The stepwise nature of the oligomerisation reaction means that the eFining process is inherently highly selective to isoparaffinic SAF-range molecules, with very few light or heavy byproducts.

The first step in the Honeywell UOP eFining process is built on its commercially demonstrated methanol-to-olefin technology, UOP/Hydro MTO process (MTO), which optimises methanol feed for maximum olefin yield and cost-effective, uninterrupted operations. The technology offers the most efficient utilisation of methanol feed, aiming for the lowest production costs and prioritising reliable operations.

The methanol produced by JM's eMERALD technology is a versatile intermediate between CO<sub>2</sub> and SAF. As methanol is already produced and traded globally, the eMERALD process yields a proven sellable, marketable, and easily transportable liquid in today's marketplace, which helps mitigate project risk through staged investment and phased start-up.

Methanol as a feed to downstream SAF production also enables a hub-and-spoke approach to feed consolidation, where



**Figure 5** Hub-and-spoke approach to SAF production

methanol from several sources can feed into a single Honeywell UOP eFinishing unit, or a customer can co-produce SAF and renewable methanol, or even renewable olefins. As the second step in the eFinishing process, Honeywell UOP's olefins-to-jet fuel process is founded on significant experience with oligomerisation technologies.

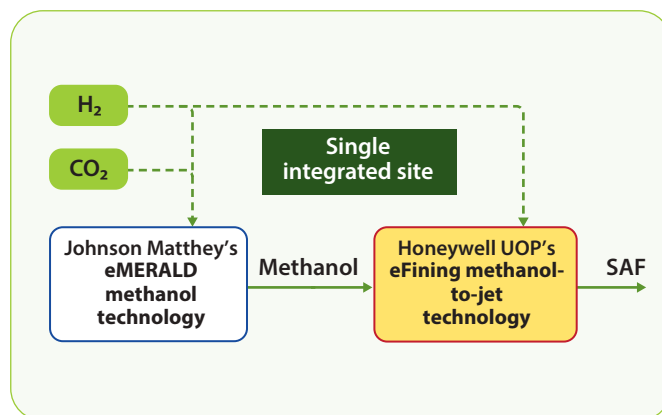
Overall, Honeywell UOP eFinishing can reduce greenhouse gas emissions by up to 88% compared to conventional jet fuel. This technology enables rapid access to SAF by converting e-methanol, produced from renewable energy sources, into jet fuel. The process is scalable, reliable, and offers high SAF yield and selectivity. The integrated solution with JM's eMERALD technology provides efficient hydrogen feedstock usage for SAF production, unlocking additional annual revenues and lowering costs.

Honeywell UOP are members of an ASTM task group actively pursuing qualification for MtJ as an approved pathway to SAF to fully meet the requirements for its use as an aviation fuel.

### Integrated and hub-and-spoke approaches Hub-and-spoke model

The hub-and-spoke model is based on multiple small methanol plants providing methanol to one centralised MtJ facility. This enables methanol producers to have multiple potential off-takes for their product. It also allows MtJ producers to take advantage of economies of scale as they can source methanol from multiple locations.

The hub-and-spoke model is ideal for methanol production locations with abundant



**Figure 6** Integrated approach to SAF production

renewable electricity and carbon sources. MtJ facilities can be located close to high SAF demand centres such as Western Europe, leading to cheaper SAF production.

Considerations regarding the shipping of methanol need to be made when using this strategy. Methanol is an easily transportable liquid at ambient temperatures and is a globally traded commodity. However, when sourcing methanol globally, it is important to consider the additional carbon intensity from shipping, as this will contribute to the overall SAF carbon intensity.

### Integrated approach

JM's eMERALD methanol process and Honeywell UOP's eFinishing process can be integrated when located on the same site. This gives several benefits to the overall facility, including combined utility savings, hydrogen efficiency improvements, and interface optimisation.

Hydrogen efficiency improvements can be achieved by recycling MTJ off-gases to the methanol synthesis plant. This process recovers hydrogen and increases methanol production by an additional 1.2%. Further optimisation of hydrogen recovery in methanol synthesis can enhance this process. These integrations mean that an integrated facility produces more SAF per tonne of hydrogen feedstock. This additional SAF production can be worth \$8.3 million in additional annual revenues based on a 242 ktpa SAF plant.

Secondly, integration reduces utility requirements for the overall facility by 30% through heat and carbon integration, which

not only lowers the energy consumption but also lowers the cost of production.

Finally, this integrated solution enables projects to have shorter project execution timelines, as JM and Honeywell UOP have worked together to align battery limit conditions and standard deliverables.

The integrated approach is ideal for projects that have access to low-cost renewable power (<\$40/MWh), biogenic CO<sub>2</sub> or biomass sources, and a final market for jet fuel.

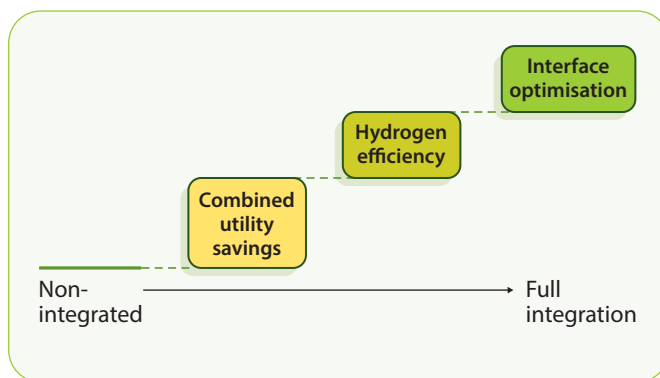
In the US, the HIF eSAF facility adopts a co-located methanol and MtJ model, producing e-methanol through JM's eMERALD technology. This e-methanol is then transformed into eSAF utilising Honeywell UOP's eFinishing technology.

This project highlights the benefits of integrating the licensed technologies of these companies to provide a unified interface for customers. This integrated approach combines key elements that enhance bankability and streamline the project deployment process, thereby adding value and reducing costs, particularly in the conversion of CO<sub>2</sub> and hydrogen to jet fuel.

## Conclusions

When evaluating routes to MtJ production and the hub-and-spoke model versus an integrated solution, several factors come into play. The hub-and-spoke model might be more advantageous in regions where there is an abundance of renewable electricity and scattered sources of CO<sub>2</sub>. This model allows for the production of methanol at multiple points, which can then be transported to a central location for conversion into SAF. This approach leverages the benefits of economies of scale, reducing the overall cost of production and increasing efficiency.

Conversely, the integrated approach may be more appropriate for projects that have a consistent and concentrated supply of renewable power and biogenic CO<sub>2</sub>, as well as a nearby market for jet fuel. This method reduces operational complexity by consolidating processes into a single location, streamlining production, and minimising logistics costs. Integrated projects can also offer a unified interface for customers, enhancing commercial



**Figure 7** Representation of the value created from an integrated offer

viability and simplifying the deployment of technology.

Ultimately, the choice between the hub-and-spoke model and the integrated solution depends on the specific circumstances of each project, including the availability of resources, infrastructure, and market demand. By carefully assessing these factors, stakeholders can determine the most

**“The integrated approach is ideal for projects that have access to low-cost renewable power (<\$40/MWh), biogenic CO<sub>2</sub> or biomass sources, and a final market for jet fuel”**

cost-effective and efficient approach to methanol-to-SAF production, ensuring sustainable and scalable outcomes.

The collaboration between JM and Honeywell UOP demonstrates the potential of MtJ technology in producing SAF. With proven and commercialised technologies, this initiative offers a reliable and efficient pathway for SAF production.

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## VIEW REFERENCES



**Zinovia Skoufa**  
zinovia.skoufa@matthey.com



**Leigh Abrams**  
leigh.abrams@honeywell.com

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# Catalysts for renewable fuels production

Catalysts play an essential role in renewable fuels production and can help to overcome the challenges associated with processing renewable feedstocks

Henrik Rasmussen  
Topsoe

**T**he global energy landscape is undergoing constant change as energy security and diversification shape the future of fuel. Among the most promising avenues in this transition is the production of renewable fuels, which offer a viable alternative and supplement to traditional fossil fuels.

Hydrotreating is a ubiquitous technology present in every refinery in the world. It is commonplace for a refinery to have several different hydrotreating units, each designed and optimised to treat different fractions from the initial distillation of crude oil, including naphtha hydrotreaters, diesel hydrotreaters, and FCC pretreat units. The process conditions and catalyst systems are tailored to the specific requirements of the different feed streams while meeting the required specifications for each product stream.

At one level, adapting hydrotreating technology to process renewable feedstocks to produce hydrotreated esters and fatty acids (HEFAs) represents one of the lowest-cost, easiest-to-implement options in the transition from fossil to renewable-based products.

However, the production of renewable fuels for both existing refiners and new producers is not without its challenges when it comes to the catalytic processes involved. The catalyst system must be designed to manage the specific characteristics of renewable feedstocks and produce high-quality fuels. This article explores the critical role of catalysts in renewable fuels production, the challenges associated with processing renewable feedstocks, and the innovative solutions that are driving the industry forwards.

## Complexities of renewable feedstock processing

Hydrotreating catalyst systems have evolved over the years such that most units today are loaded in layers of catalysts, each with different catalytic functions. The top layer comprises guard bed catalysts specifically designed to remove contaminants such as nickel and vanadium metals from fossil feed streams while minimising the build-up of pressure drop to ensure this function does not limit the operating cycle of the unit.

**“The complex reaction mechanisms involved in hydrotreating renewable materials differ significantly from those of conventional petroleum refining”**

The next layers comprise catalyst developed for maximum hydrogenation efficiency to remove sulphur and, if needed, also saturate aromatics. The system may include catalysts to remove nitrogen if this is required (for example, for hydrocracking units). At the bottom of the hydrogenation unit is a catalyst layer designed to minimise sulphur recombination.

Renewable feedstocks, such as vegetable oils, animal fats, and waste oils, pose unique challenges compared to traditional fossil-based feedstocks. The complex reaction mechanisms involved in hydrotreating renewable materials differ significantly from those of conventional petroleum refining. If catalysts are not specifically designed to handle

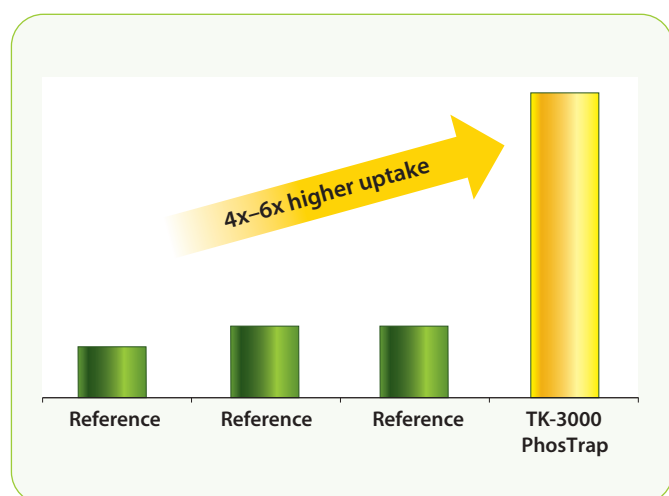


**Figure 1** TK-3000 PhosTrap catalyst for improved phosphorus control

these complexities, the consequences can be severe: poor product yield, byproduct formation, accelerated catalyst deactivation, and pressure drop build-up.

Additionally, the hydrotreated product has to meet the required product specifications, namely ASTM D-975 for diesel and D-7566 for SAF, including the cold flow properties, which are critical for fuel performance in colder climates (diesel) or at altitude sustainable aviation fuel (SAF).

To address these challenges, catalyst systems must be tailor-made for renewable feedstock processing. This involves developing catalysts that can effectively manage the hydrodeoxygenation (HDO) of renewable feeds, improve cold flow properties through isomerisation, and maintain stable operation under varying conditions.



**Figure 2** Phosphorous pick-up of TK-3000 compared to previous-generation P-trap

To meet these complex requirements, Topsoe has developed specialised catalysts for these purposes, enabling the production of on-spec renewable diesel and SAF without operational issues.

### Catalyst innovations for renewable fuels

Central to this has been the introduction of a range of dedicated catalysts designed specifically for the hydroprocessing of renewable feedstocks. Recently launched to the market are third-generation Topsoe HDO catalysts selective for the hydrogenation route designated TK-3001, TK-3002, and TK-3003. These will provide producers with better HDO selectivity via the hydrogenation route, higher activity, and high metals, resulting in a significantly longer cycle length. The higher HDO selectivity throughout the cycle length of the catalyst will result in a significantly higher average product yield compared to the previous generation of HDO catalysts, which will increase the profitability of the plant.

The catalyst loading also includes an isomerising dewaxing catalyst to ensure that the renewable diesel and SAF meet the required cloud point and freeze point of the final product. The specialised guard beds catalysts are designed to pick up the contaminants in the feedstock, such as P, Na, K, Ca, Mg, Fe, Ni, and V. The most significant poison is typically phosphorus (P). To address this, Topsoe has developed a more efficient P guard, TK-3000 PhosTrap (see **Figure 1**), which picks up four to six times as much P on a volume basis as its previous P guard in renewable service (see **Figure 2**).

### Reduced complexity and lower costs

In addition to picking up contaminants, the guard bed catalysts are designed to use the hydrogenation route like the main bed catalyst to ensure that the oxygen in the triglyceride is converted to water instead of CO<sub>2</sub>. The hydrogenation route improves the product yield and will not make CO<sub>2</sub> as opposed to the decarboxylation route, which produced significant amounts of CO<sub>2</sub>.

The fact that Topsoe's specialised HDO main bed catalysts and guard bed catalysts

produced almost no CO<sub>2</sub> is the reason why its licensed process technology called HydroFlex does not include an amine unit in the high-pressure loop. The elimination of the amine unit from the process layout has many advantages, such as reduced Capex and Opex, lower carbon intensity (CI score), and decreased operating complexity.

The effectiveness of these HDO and dewaxing catalysts has been demonstrated in more than 25 industrial units, and many of Topsoe-licensed units have used loads of its HDO and dewaxing catalysts.

### Choosing the right catalyst for co-processing

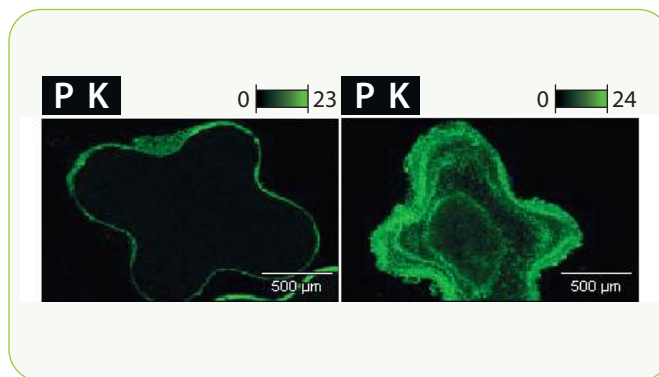
Introducing even minor amounts of biomaterial into a fossil diesel or kerosene hydrotreater requires a thorough understanding of the implications and strategies to mitigate potential risks. Co-processing renewable and fossil feedstocks introduces additional complexities. The hydrotreater must still convert all organic sulphur and nitrogen in the fossil portion of the feed to meet product specifications, while the HDO catalysts must convert all of the renewable feed.

To achieve these multiple objectives, the HDO-graded bed catalysts are typically loaded on top of a NiMo fossil catalyst. The trick is to load the right amount of each type of catalyst so that the cycle length of the HDO catalyst matches that of the fossil NiMo catalyst while maintaining a stable pressure drop across all the catalysts. The ratio of the different types of catalysts is, of course, governed by the percentage of co-processing.

It is also important to determine if a dewaxing catalyst is needed in the bottom of the reactor (below the fossil catalyst) to ensure that the mixture of fossil and renewable diesel still meets the required cloud point. Topsoe is experienced in designing the loading of a co-processing unit to meet all product and cycle length objective and has more than 20 hydroprocessing units currently in operation in co-processing mode.

### Conclusion

The production of renewable fuels represents a significant step forwards in the diversification of



**Figure 3** Phosphorous penetration in catalyst pellet of previous-generation P-trap compared to TK-3000

the global energy landscape. However, success depends on the development and deployment of advanced catalysts that can handle the unique challenges of renewable feedstock processing. Topsoe's third-generation HDO catalyst, selective towards the hydrogenation route, and its specialised graded bed HDO catalysts are effective in both co-processing and standalone units.

**“Success in the production of renewable fuels depends on the development and deployment of advanced catalysts that can handle the unique challenges of renewable feedstock processing”**

The catalyst and process technology not only ensure the production of high-quality renewable fuels but also enhance the profitability of the unit by increasing the product yield and extending the cycle length, thus improving the onstream performance. The enhanced capacity for picking up contaminants, including phosphorus, helps the refiner process lower-quality renewable feedstocks to further enhance the profitability of the operation.

As the industry continues to evolve, the role of catalysts in enabling the energy future cannot be overstated.



Henrik Rasmussen  
HWR@topsoe.com





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# Economically viable refinery decarbonisation scenario

How the integration of a synthetic fuels unit inside an existing fuels complex can be financially viable while reducing carbon footprints

Juan Carlos Latasa López  
IDOM Consulting

**T**he article analyses a technically feasible, economically viable alternative configuration for refineries, which integrates synthetic fuels units with existing fossil fuels units by installing carbon capture and using the captured carbon dioxide (CCU) in combination with low carbon intensity hydrogen (blue and green) for the production of synthetic fuels.

The future of the fuels industry cannot rely, in the short or even medium term, on electrification and green or blue fuels alone. The transition is possible, but the planned fast transition or the theoretical disruption of fuels supply, as reported by some authorities and other sources, is not only an impossible dream but a mistake that is provoking the most absolute inability to meet published plans for the energy transition,

Many governments around the world continue to fall short of delivering their commitments made in existing nationally determined contributions (NDCs) even though they have the ability to increase such commitments in successive revisions of their NDCs. In general, these plans include unachievable targets in terms of timescale and the level of decarbonisation of both industry and broader society. Many are overly reliant on electrification and the shift to renewable sources of electricity generation. Renewable electricity should be considered one of the measures required for decarbonisation, but not the sole target.

The evolution of national energy transition plans can be clearly assessed using the emissions register and how the energy environment has changed in recent years. New 'players' in the energy environment need to be

considered, such as society's increasing reliance on data centres and the emergence of artificial intelligence. Another unfortunate factor that has a real impact on global emissions is the escalation of conflicts.

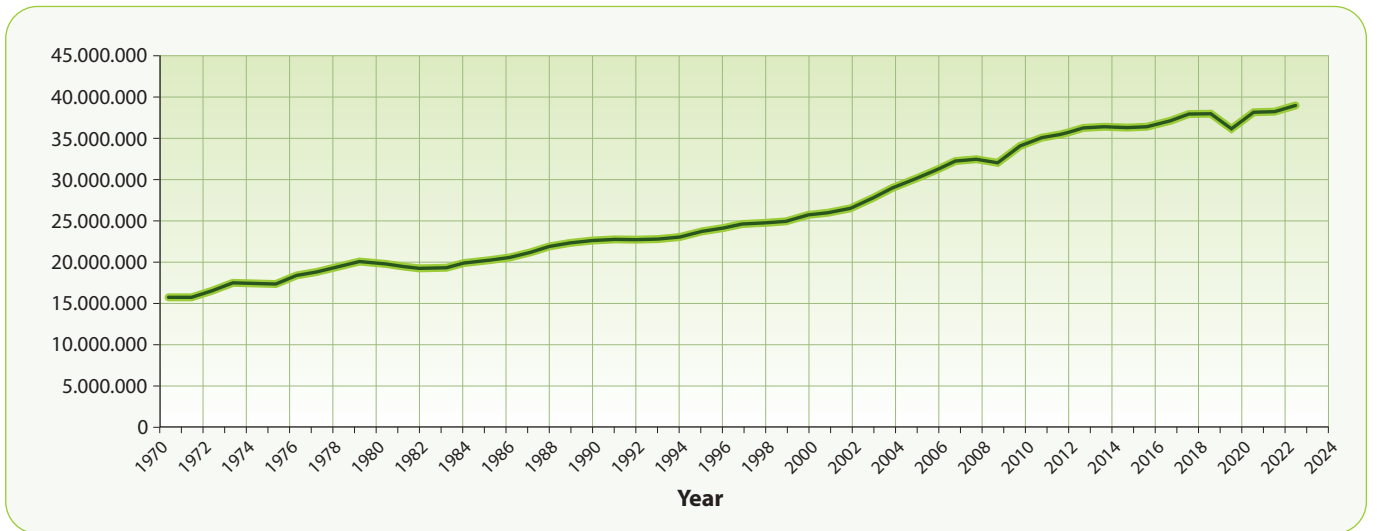
Furthermore, energy transition plans in regions such as the European Union are inducing reduced competitiveness and an economic and technical 'cul-de-sac'. This is caused, among several additional

**“The future of the fuels industry cannot rely, in the short or even medium term, on electrification and green or blue fuels alone”**

considerations, by unrealistically disruptive fuel and mobility strategies and not driven by practicable efficiency and techno-economical parameters.

## Evolution of global emissions – existing trends and the need for change

EDGAR is an open-access database developed by the Joint Research Centre (JRC) of the European Commission to monitor trends in global anthropogenic emissions of greenhouse gases and air pollution under the United Nations Framework on Climate Change (UNFCCC). The EDGAR database uses a consistent methodology to collect and analyse data provided by more than 220 countries. **Figure 1** shows a steady increase in carbon dioxide (CO<sub>2</sub>) emissions from 1970 through 2023, despite the combined efforts of all signatories to the Paris Agreement.



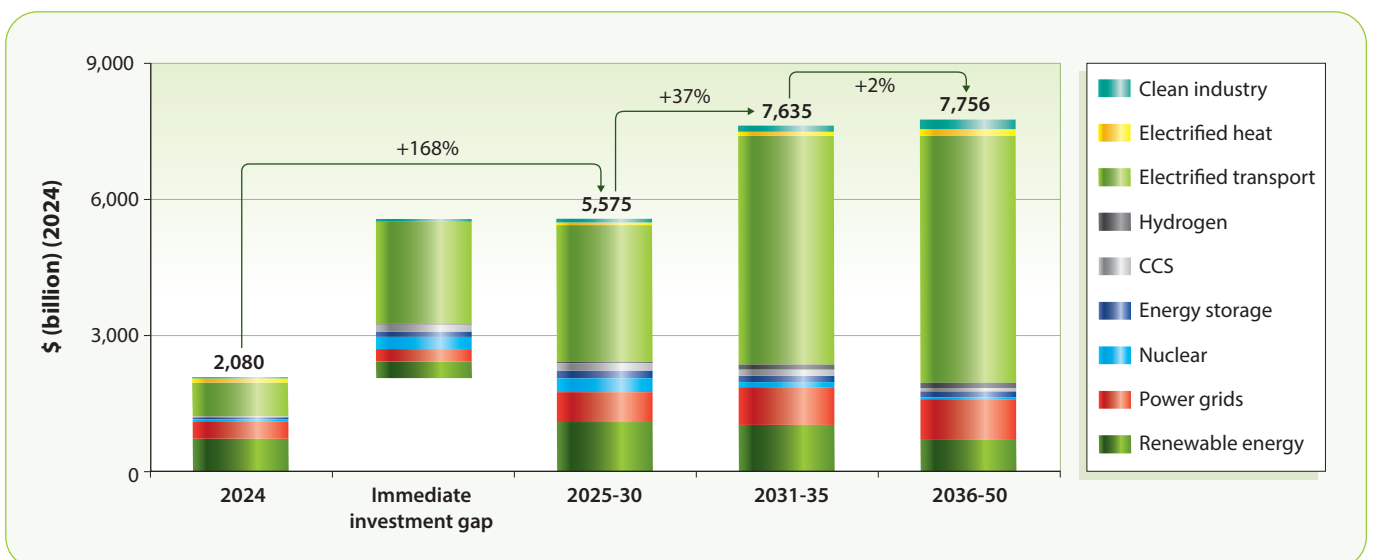
**Figure 1** Global carbon dioxide emissions from 1970 to the present day. Data extracted from the JRC EDGAR database (JRC, 2025)

It is widely recognised that there is a gap between the announced measures in the NDCs from each country and the level of reductions needed to curtail global emissions. Additionally, the implementation of these plans is both slow and inadequate. One analysis by Bloomberg NE shows there to be an investment gap of 168% due to a combination of regulatory, market, and financial uncertainties (see **Figure 2**).

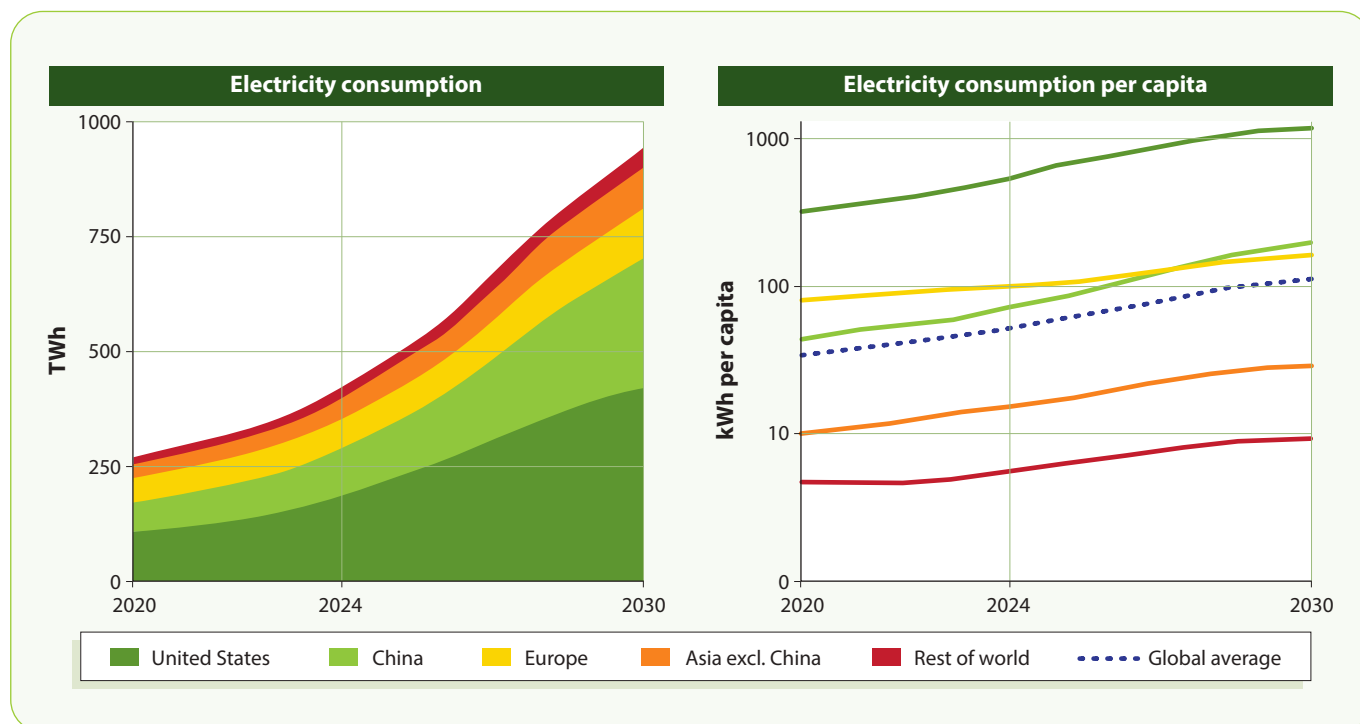
The situation is even more complicated as some new and existing ‘players’ (large emission sources) were not accounted for when the Net Zero Plans were first prepared. These additional sources significantly increase energy demand and consequential GHG emissions.

Energy demand from the rapid growth of data centres and the emergence of AI data centres was not fully anticipated in earlier datasets. Such demand is sizeable and increasing and is estimated to reach more than 1,000 TWh/year by 2050 (see **Figure 3**).

In the work to achieve the global consensus needed at the Paris Agreement in 2015, it was agreed that reporting emissions from military activities should be voluntary. Even during peacetime, emissions from military activities may constitute as much as 7% of global emissions (Scientists for Global Responsibility, 2022). An additional, though less predictable, source of emissions is from armed conflicts,



**Figure 2** Comparison of 2024 energy transition investment vs required annualised levels under the Bloomberg NEF Net Zero Scenario (NZS). Future values are obtained from the New Energy Outlook (NEO). Source: (Bloomberg NEF, 2025)



**Figure 3** Current and anticipated growth in energy demand from AI and data centres (IEA, 2025)

with current examples including the Russian invasion of Ukraine, the Israeli/Gaza conflict, and civil wars in Sudan and Myanmar. Just one act of sabotage, the rupture of the Nord Stream pipelines in 2022, was estimated to have released 150 thousand tonnes of methane (Wikipedia, 2024).

Although the world's leaders are most unlikely to agree to stop future armed conflicts, other actions should be considered to reduce the investment gap. A smart combination of decarbonised downstream, natural gas generation, and renewable sources can increase energy security resilience. The EU should set technology-agnostic targets for the decarbonisation of the European automotive and fuels industries.

Synthetic fuels should be considered complementary to electrification, allowing a more rapid and affordable reduction in the carbon footprint of road transport while also reducing crude oil imports. The effective integration of synthetic fuels within an existing refinery represents a realistic, feasible, non-disruptive fuels strategy.

This article describes how the integration of a synthetic fuels unit inside an existing fuels complex can be financially viable while allowing the reduction of carbon footprints, both during production (Scope 1 and 2 emissions) in the

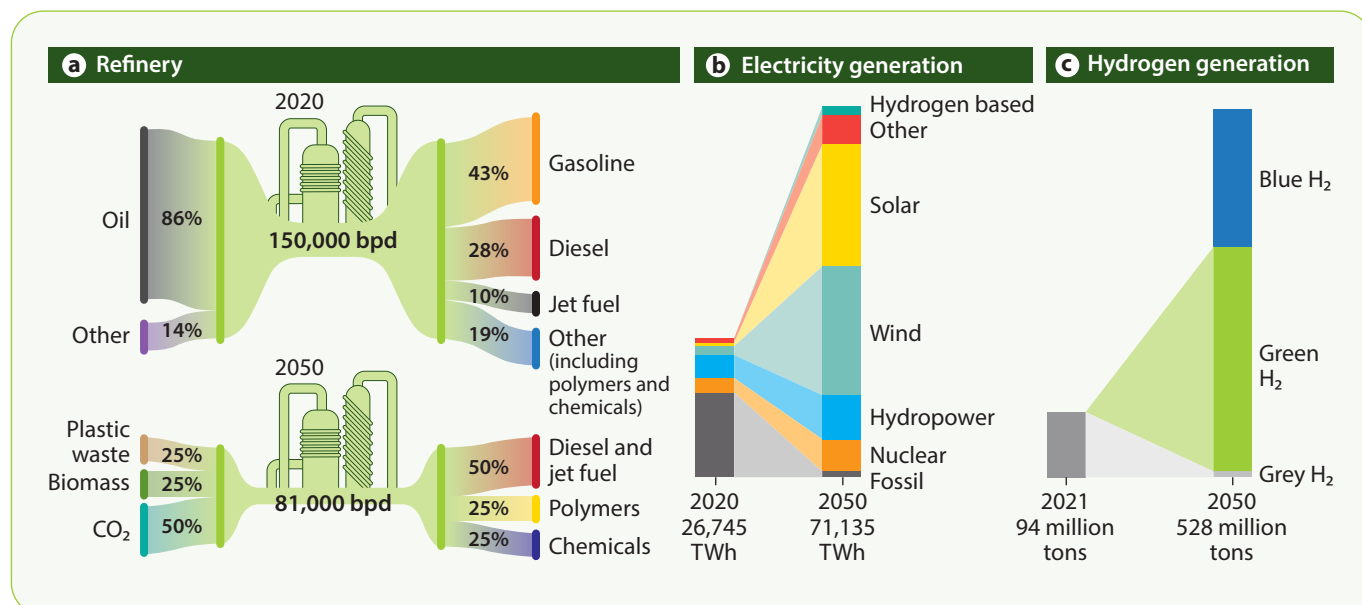
fuels complex or refinery, as well as Scope 3 emissions from the use of fuels in road, air, and marine transport.

The reconfiguration of the refineries for the integration with new synthetic fuels units and a carbon capture scheme is analysed considering the following cases:

- Base case: operation of an existing modern, high-conversion refinery.
- Hybrid case: Introduction of e-fuel production units.
- Comparison of cases to explore the optimum balance, which maximises emissions reductions while meeting demand.

A techno-economic analysis was used to explore the optimum reconfiguration; considerations included:

- Conservation of most of the existing assets.
- Introduction of some new units while avoiding mega investments.
- Reducing the Scope 1 and 2 carbon emissions or carbon footprint of the refinery.
- Reducing the crude oil intake so that it becomes a feedstock to improve financials.
- Providing a combination of low-carbon and sustainable fuels that reduce the emissions from transport on a life cycle basis (Scope 3 emissions).
- Meet future energy demand while also driving decarbonisation.



**Figure 4** Evolution of refinery feedstocks and products 2020-2050 (Vogt and Weckhuysen, 2024)

### Refinery configuration for integration of synthetic fuels

#### General considerations

The development of a feasible, realistic, and fundable synthetic fuels unit, along with the introduction of circular economy concepts, needs to consider the following evolution of feedstocks and products.

As shown in **Figure 4**, the overall demand for hydrocarbon products within the EU is expected to fall between 2020 and 2050 in line with the transition to renewable electricity and e-fuels. In the following analysis, the starting point is a high-conversion refinery of 100,000 BPD

(barrels per day) capacity under a modern but classical configuration.

### Configuration, capacity, and emissions of a traditional refinery

The detailed refinery configuration was determined using a model based on USC-SPIRAL to assess the size, product slate, and associated CO<sub>2</sub> emissions for each production unit and the overall refinery complex, as shown in **Table 1**. See refinery process configuration online: [bit.ly/4cHVcsW](https://bit.ly/4cHVcsW)

### Proposed new 'hybrid' configuration

The analysis and concepts presented by the author modify the base case refinery configuration of the 21st-century concept of 'hybrid configurations' or configurations where traditional refinery units coexist with carbon capture from the main CO<sub>2</sub> producers, blue and green hydrogen, and the production of synthetic fuels. This 'hybrid' concept is designed to facilitate the progressive incorporation of advanced and circular economy concept fuels, minimising the impact on existing refinery units,

Unit	Description	Capacity (kBPD)	CO <sub>2</sub> emisissions (MTPA)
CDU1	Crude atmospheric distillation unit	100	112,803
HVU1	Vacuum distillation unit	42	65,589
HCU	VGO hydrocracking unit	44	218,424
LNHT	Light naphtha hydrotreating unit	6	108,038
HNHT	Heavy naphtha hydrotreating unit	16	319,930
HTD	Distillates hydrotreating unit	8	101,644
ISOM	Light naphtha isomerisation unit	6	275,733
REFOR	Heavy naphtha reforming unit	16	208,438
SATGAS	Saturated gas unit	5	39,983
<b>Total process units</b>			<b>1,450,580</b>
HMU	Hydrogen production unit	70	629,370
<b>Base case total CO<sub>2</sub> emissions</b>			<b>2,079,952</b>

**Table 1** Base case – generic 100 kBPD refinery capacity for each process unit with CO<sub>2</sub> emissions as output from the model



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which allows the feasible continuation of operations with an economically attractive scheme.

The new configuration includes the following elements that are the basis of a feasible, technically sound, and financially beneficial transition:

- The production of the existing, traditional refinery is reduced to a level of 80% in order to continue production, with the production of e-fuels making up the remaining 20% for an acceptable investment.
- A methanol-dimethyl ether (DME)-oligomerisation unit, which consumes CO<sub>2</sub> captured from the hydrogen manufacturing unit (HMU) ('blue' hydrogen unit of the refinery), as well as an electrolysis unit to produce 'green' hydrogen is considered in the analysis.

See new refinery process configuration online: [bit.ly/4cHVcsW](http://bit.ly/4cHVcsW)

The new configuration for the refinery provides the following interesting insights:

- Overall CO<sub>2</sub> by-product is reduced, as the refinery load has been reduced to 80%.
- The CO<sub>2</sub> from the traditional hydrogen reformer

Unit	Description	Capacity (kBPD)	CO <sub>2</sub> emissions (MTPA)
CDU1	Crude atmospheric distillation unit	80	90,242
HVU1	Vacuum distillation unit	33	52,534
HCU	VGO hydrocracking unit	34	166,679
LNHT	Light naphtha hydrotreating unit	5	85,070
HNHT	Heavy naphtha hydrotreating unit	13	255,209
HTD	Distillates hydrotreating unit	8	101,644
ISOM	Light naphtha isomerisation unit	5	229,778
REFOR	Heavy naphtha reforming unit	12	166,751
SATGAS	Saturated gas unit	4	32,326
SFU	Synthetic fuel unit		-576,000
Jet	Jet A1	3.615	
	Standard diesel	1.916	
<b>Total process units</b>			<b>604,233</b>
HMU	Hydrogen production unit	56	503,496
<b>Hybrid case total CO<sub>2</sub> emissions</b>			<b>1,107,729</b>

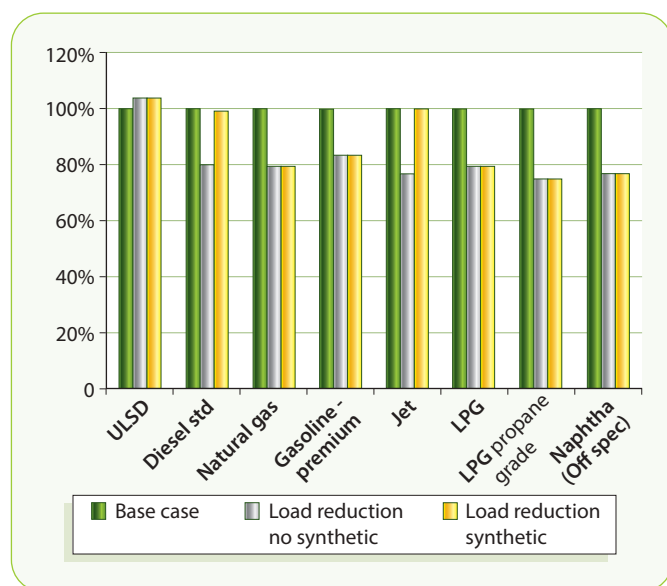
**Table 2** Hybrid case – unit capacity and CO<sub>2</sub> emissions from each process unit

unit (otherwise one of the main CO<sub>2</sub> emitting units in any refinery) is captured and used.

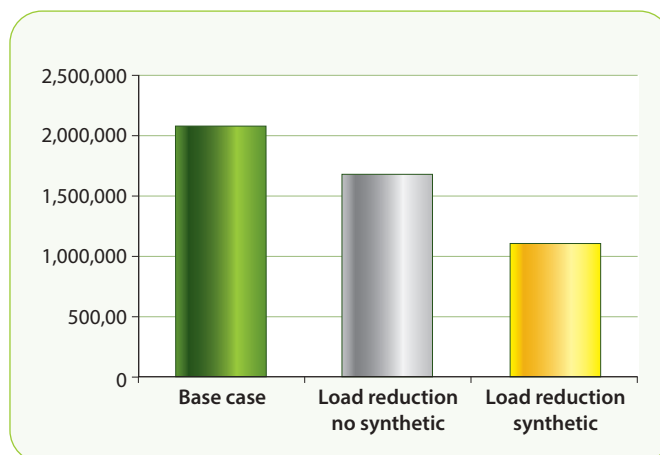
- The shortfall in jet fuel and diesel from the load reduction on existing units is now produced by the synthetic fuels unit, using the captured CO<sub>2</sub> combined with low carbon intensity blue and green hydrogen.

The criteria for sizing the synthetic fuels unit (SFU) was to cover the production of jet fuel with SAF and use 100% of the CO<sub>2</sub> captured from the HMU.

The new configuration for the refinery provides the unit capacity and products slate, as seen in **Table 2**. The emissions of CO<sub>2</sub> now have been reduced in a very interesting range.



**Figure 5** Comparison of products from the base and hybrid cases (before and after the synthetic fuels capacity is added)



**Figure 6** Comparison of CO<sub>2</sub> emissions from the base and hybrid cases

### Comparison of traditional vs proposed hybrid configuration

The production yields and CO<sub>2</sub> emissions from both the base case and the hybrid case are compared in **Figure 5**. This shows that the refinery emissions are reduced by as much as 50% in the hybrid case, while yields of products are the same for the main products (jet fuel and SAF, gasoline, diesel) and very similar for the remaining secondary products.

**Figure 6** shows that the carbon footprint is notably reduced in the hybrid fuel complex.

### Financial considerations

The hybrid configuration provides the following positive and additional incomes to refinery operations:

- 20% cost reduction of feedstock (crude) due to reduced intake.
- Jet fuels income from the eSAF market (with a premium price forecast).
- CO<sub>2</sub> emissions cost is reduced to the range of 50% vs the original case.

These improvements allow for a reasonable and feasible return on investment for the

new unit (SFU), facilitating the incorporation of synthetic fuels into existing refineries, yielding positive results and presenting an attractive opportunity for both lenders and the environment.

Fuel and chemical production centres will continue to be an essential part of modern society during the transition and in any future low-carbon emissions environment. These centres must be considered vital contributors now and in the future. They must get the appropriate encouragement and support to facilitate the reduction in the carbon footprint of feedstocks, processes, and products.

The modelling work summarised here shows that investments to produce synthetic fuels can be economically viable additions to existing refineries. At the very least, this should encourage more detailed studies for any refinery considering such an investment.

### VIEW REFERENCES



Juan Carlos Latasa López  
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# Woody residue gasification: a dual solution for decarbonisation

Utilising woody residue from forest thinnings can support new fuel production and mitigate wildfire risk

Shrinivas Lokare and Andrew Kramer **SunGas Renewables Inc.**  
Bryan Tomsula **CPFD Software**

**A**s the world confronts growing energy demands through the first quarter of the 21st century, the shift from traditional fuels to renewable and cleaner fuels continues to grow. These renewable fuels can help companies meet their carbon reduction obligations and comply with specific government requirements. Solid feed gasification is a proven and established process that can be a major component in expanding the production of these renewable fuels and presents a viable option for conversion of renewable feedstocks into fuels and chemicals at scale (see **Figure 1**).

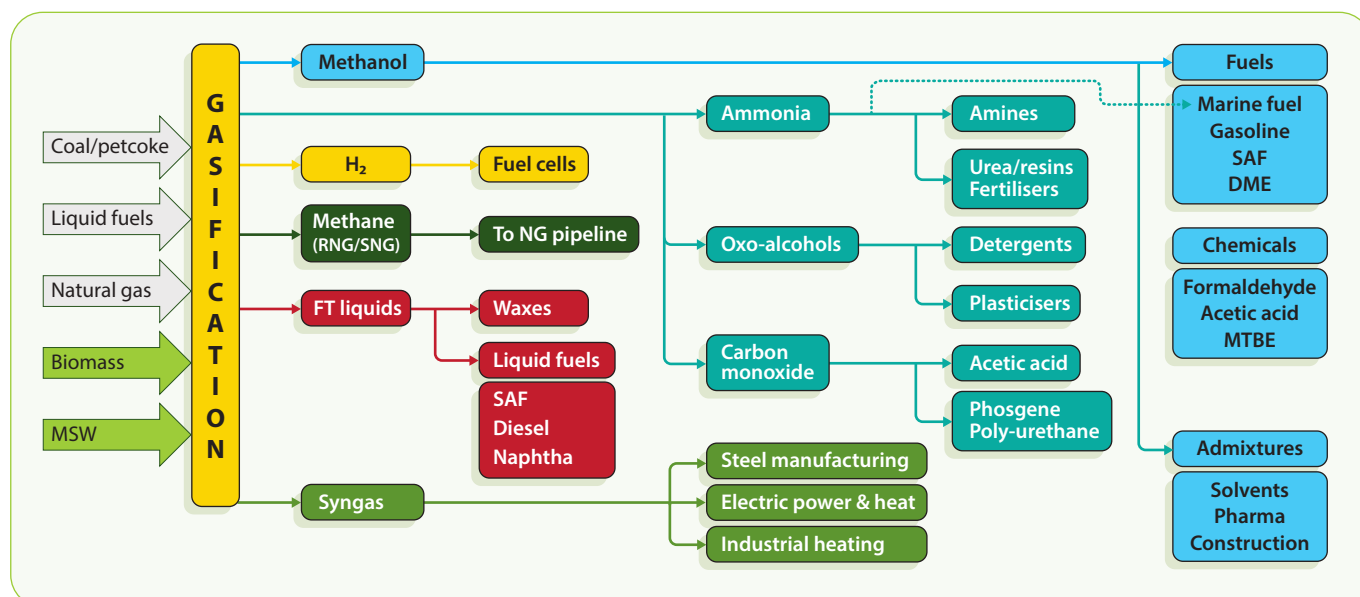
Biomass residues and municipal solid waste (MSW) feedstocks are two abundant feedstocks that can produce alternatives to conventional fuels. Biomass, comprising organic materials such as agricultural residues, energy crops, and forestry residues, offers a renewable and

abundant source of energy. MSW consists of non-recyclable organic waste, such as food scraps, low-grade plastic, and garden waste.

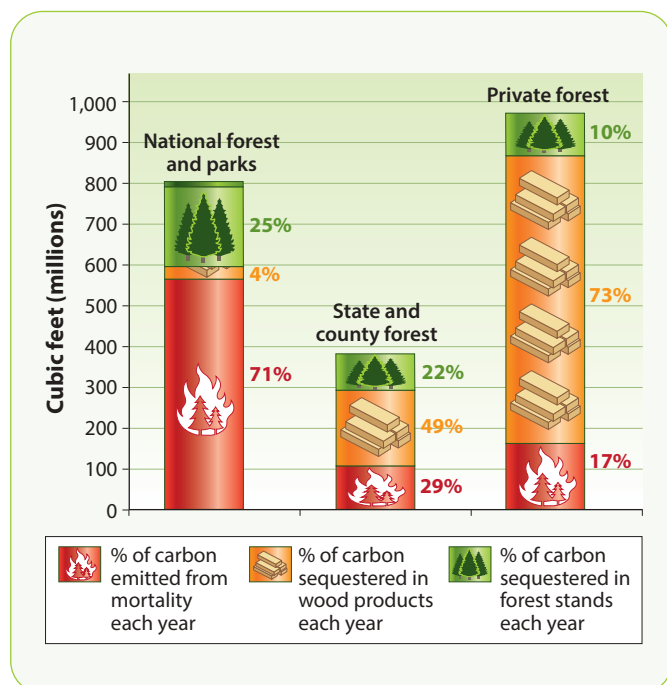
However, MSW faces challenges like contamination and the need for sorting and cleaning. Sourcing and processing MSW is further complicated by inconsistent segregation, high transportation costs, and limited infrastructure for advanced waste treatment. Although advanced technologies are being developed and put into practice to improve MSW quality and conversion efficiency, these difficulties adversely impact project feasibility as feedstock cost is directly proportional to the extent of pretreatment it requires before feeding it to the gasifiers.

## Forest residues – a low-hanging fruit

Woody biomass – primarily sourced from forest



**Figure 1** Gasification pathway to convert any feedstock to a variety of end products



**Figure 2** Better forest management leads to lower carbon emissions

Source: WFPA, 2023

thinning and wood processing industry – offers a lower cost and practical option for renewable fuels and chemicals manufacturing, as it is a clean and readily available feedstock. According to the US Department of Energy’s 2023 Billion-Ton Report, nearly 150 million dry short tons of forestry wood are currently used each year for energy (DOE, 2023). This quantity alone can produce about 20% of the total sustainable

**“Woody biomass offers a lower cost and more suitable option for renewable fuels and chemicals manufacturing, as it is a clean and readily available feedstock”**

aviation fuel (SAF) demand of the US or about 10% of the total methanol demand of the world.

Traditionally, forest thinnings are a significant source of feedstock for the pulp and paper industry. Removing the younger trees and underbrush allows the remaining trees to grow larger, producing high-quality material for construction lumber. The woody residues generated from the thinning provide a sustainable raw material source for the pulp and paper industry to produce various types

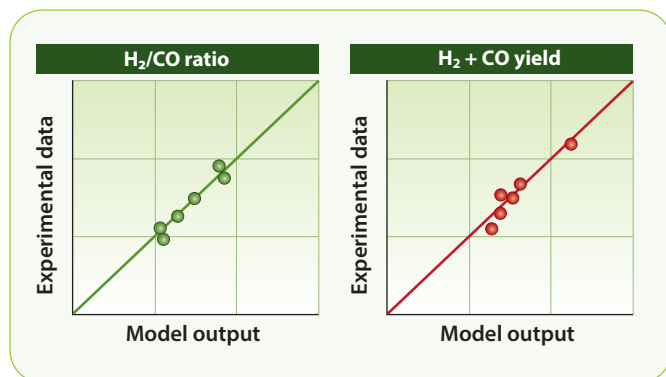
of pulp, including kraft and thermomechanical pulps (TMP), suitable for paper products. With the rise of digital technologies, the pulp and paper industry has seen its market shrink, prompting the closure of many facilities and a search for new uses for forest thinnings. At the same time, limited thinning and forest management – particularly in private, non-working, and public forests – has worsened an already serious environmental concern. Renewed forest management and forest thinning are beginning to result in additional feedstock availability. Forest thinning is also a crucial wildfire prevention strategy that involves selectively removing trees and underbrush to reduce combustible material and wildfire risk (see **Figure 2**). Private working forest practices have demonstrated how to use thinning to control the risk of wildfires and result in healthier and larger timber. Improved forest management practices in non-working forests will minimise carbon emissions, reduce fire risks, and lead to an increase in standing forests.

### Dual challenges: one sustainable solution

The dual challenges of needing alternatives to fossil fuels and preventing wildfires can be addressed through a complementary solution: utilising woody residue from forest thinnings in gasification processes to produce renewable fuels and chemicals.

SunGas Renewables (SunGas), a company dedicated to transforming organic waste into advanced clean fuels, has designed a system that offers this solution.

SunGas’ technology uses a bubbling fluidised bed gasifier and cyclone as core components. This process has been proven across a variety of process conditions, including solid feedstocks, scale, operating pressure and temperature, and bed materials. Based on the extensive developmental work and feedback from 21 commercially operating gasifiers, SunGas has established sophisticated process and computational fluid dynamics (CFD) models. The Aspen-based process modelling tool is used to establish gasification cases for all the various conditions as referenced earlier and validated against the experimental/field data. The comparative analysis, as shown in **Figure 3**,



**Figure 3** SunGas process validation parity plots for woody biomass feedstocks

highlights the robustness of process models in predictions of product quality ( $H_2/CO$ ) and yield ( $H_2+CO$ ).

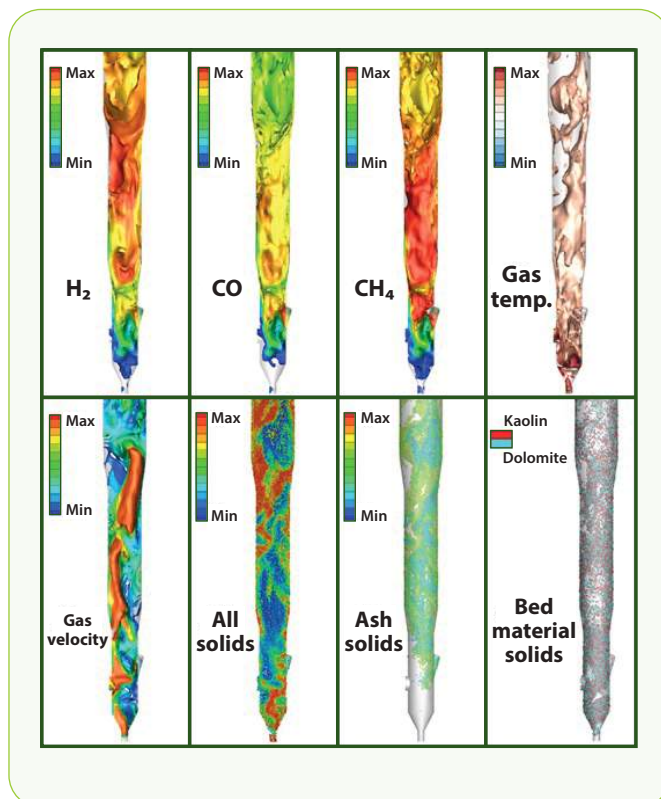
In fluidised bed reactors, the interaction between the solids and gas is very important to enhance contact between reactants and maintain a consistent thermal profile throughout the bed. The commercial CFD software, Barracuda Virtual Reactor, developed by CFPD Software, is a robust tool used throughout industry to study these complex fluidised bed systems.

The CFPD models help provide insight into the fluidisation behaviour under various conditions and verify key design and scale-up considerations during commercial product development. **Figure 4** shows sample results for key process variables, which are used to generate an insight into reactor performance and scale-up.

### SunGas' integrated solution for decarbonisation

SunGas' S1000 product is an integrated system consisting of key components engineered to provide excellent performance (see **Figure 5**).

The process starts with drying biomass to the required moisture content. The dried biomass is fed into a fluidised bed gasifier, reacting with steam and oxygen at  $850^{\circ}\text{C}$ . Inside the gasifier, biomass undergoes pyrolysis, breaking down into volatile gases and char. The char reacts with steam and oxygen to produce syngas, a mixture of hydrogen, carbon monoxide, carbon dioxide, methane, and other trace gases. The fluidised bed ensures thorough mixing and heat transfer, promoting greater than 95% conversion of the carbon in the feedstock. The



**Figure 4** Syngas component profiles and solids distribution results from CFPD model

resulting syngas is cleaned of impurities and can be used for power generation or processed into advanced clean fuels and chemicals.

In the quest for advanced clean fuels, one of the challenges is the heterogeneous nature of feedstocks, requiring tailored pretreatment for consistent quality. High moisture content reduces conversion efficiency, and impurities like ash and sulphur require additional treatment and processing steps. Reliable feedstock supply chains and economic viability are also concerns, needing robust logistics.

SunGas' S1000 system, designed to process woody residues from forest thinnings, effectively addresses many of these challenges. These residues contain low levels of ash and other contaminants (such as sulphur and chlorine), which minimises the need for extensive feed pretreatment. After chipping, the only treatment needed is drying the chips to target moisture content, which is accomplished by low-level heat integration between the S1000 and wood dryers, enhancing overall process efficiency. The S1000 feeding system is designed for wood chips that are already widely used in the pulp and paper industry and biomass power plants. Thus, much of the production and transportation



**Figure 5** S1000: an integrated gasification system for syngas production from woody biomass

logistics are already established in the industry and readily leveraged to improve the feedstock economics.

### Syngas conversion to clean fuels

Syngas, a mixture of hydrogen, carbon monoxide, and carbon dioxide, has been converted into various valuable products for decades. For renewable natural gas (RNG), syngas undergoes methanation, where hydrogen and carbon monoxide react to form methane and water. To produce hydrogen, syngas is subjected to a water-gas shift reaction, increasing the hydrogen content. For methanol production, syngas is catalytically converted into methanol through reactions involving hydrogen and carbon monoxide. To produce SAF, naphtha, and/or diesel, the Fischer-Tropsch process is an established pathway. Additionally, syngas can be processed

into other chemicals like ammonia, dimethyl ether, and synthetic hydrocarbons, supporting diverse industrial applications.

By producing low to negative carbon intensity fuels, SunGas significantly reduces carbon emissions, contributing to global efforts to combat climate change. For example, the S1000 technology, coupled with carbon capture and sequestration, can produce advanced fuels with deeply negative carbon intensity from -60 to -100 gCO<sub>2</sub>e/MJ of fuel.

### Pioneering facility for sustainable fuel production

SunGas' Beaver Lake Renewable Energy (BLRE) facility in Central Louisiana will convert ~1 million tons of dried wood residue into more than 500,000 metric tons of bio-methanol annually, marking a significant contribution to sustainable energy production. This \$2 billion facility will be built at the former International Paper site in Rapides Parish, expected to create more than 1,100 construction jobs, 300-400 indirect jobs, and 100 full-time jobs to the local economy. The renewable methanol produced at the facility is slated to be used primarily as a marine fuel but may also be used as a low-carbon feedstock for SAF and renewable dimethyl ether (rDME). Renewable DME is a drop-in fuel that can decarbonise the carbon footprint associated with the use of propane.

**Figure 6** provides a visual summary of the project scope.

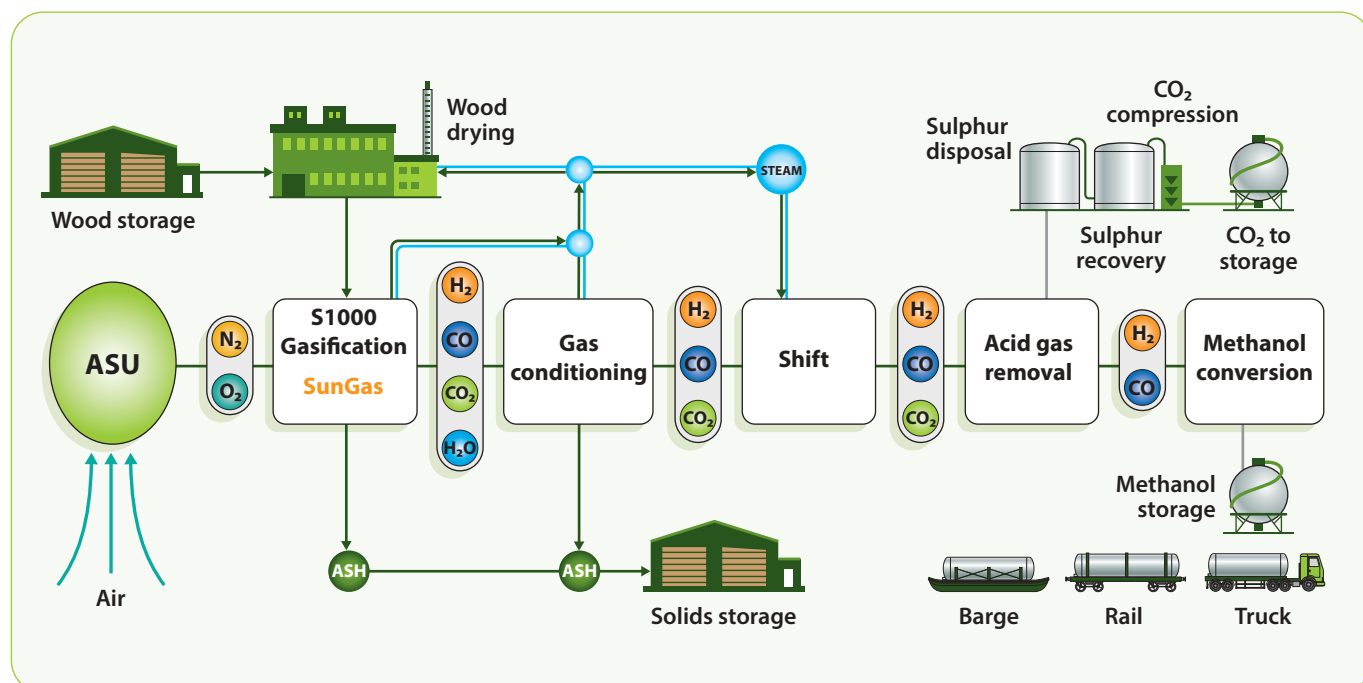
In 2024, SunGas announced a strategic partnership with C2X aimed at developing, owning and operating multiple green fuel production facilities in North America to increase the supply of sustainable fuels and advance global decarbonisation of hard-to-abate industries like aviation and marine shipping.

SunGas' focus on advanced clean fuels supports local economies by creating jobs, attracting new investments, and supporting sustainable and resilient technology development.

### Prospects and opportunities

SunGas envisions a promising future, driven by strategic partnerships and innovative technologies. SunGas has already put its strong





**Figure 6** BLRE: biomass-to-methanol project in Louisiana, USA

foot forward with deployment of its mature technology through the BLRE project.

As the need for processing more challenging types of feedstocks (such as MSW, plastic, and agricultural wastes) increases, SunGas' development roadmap includes expanding the feedstock envelope for S1000 to include these more challenging feedstocks. The established process tools and CFD models will play an important role in bringing insight into processing these feedstocks and helping identify solutions to navigate the challenges posed by them.

S1000 is a trademark of SunGas Renewables Inc.

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**Shrinivas Lokare**  
slokare@sungasrenewables.com



**Andrew Kramer**  
akramer@sungasrenewables.com



**Bryan Tomsula**  
bryan.tomsula@cpfd-software.com

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# Advancing the circular economy for waste plastic

Advanced recycling processes can turn what was once considered a waste product into a valuable commodity

Geoff Brighty  
Mura Technology

In September 2024, scientists at the University of Leeds published the results of an experiment that used real-world data and machine learning to simulate waste disposal numbers in countries around the world for the year 2020 (Cottom, Cook, & Velis, 2024). They calculated that more than 52 million tonnes of mismanaged plastic waste entered the environment that year, with 70% of it coming from just 20 countries.

This problem has only grown in scale over time. Even since 2020, the production of plastics has continued to climb (Statista, 2024), and much of the plastic produced each year is disposed of within a year of being manufactured (Hopewell, Dvorak, & Kosior, 2009). So far, humanity has struggled to find solutions to manage the volume and range of plastics produced.

Plastic has become ubiquitous in our global economy due to its many essential applications. However, this variety – the differences in chemical makeup between various types of plastic – makes mixed streams of plastic waste durable but very difficult to recycle, leading to mismanagement and the pollution of our natural environment. Solutions that can scale to meet this global challenge are urgently required.

As the world attempts to transition away from the use of fossil resources in sectors such as power generation and transport, parts of the world are also attempting to transition from a linear to a circular economy. To accomplish this, a new set of technologies intended to revolutionise how petrochemical products are used in the manufacture of plastic packaging are beginning to reach key stages of successful commercial implementation.

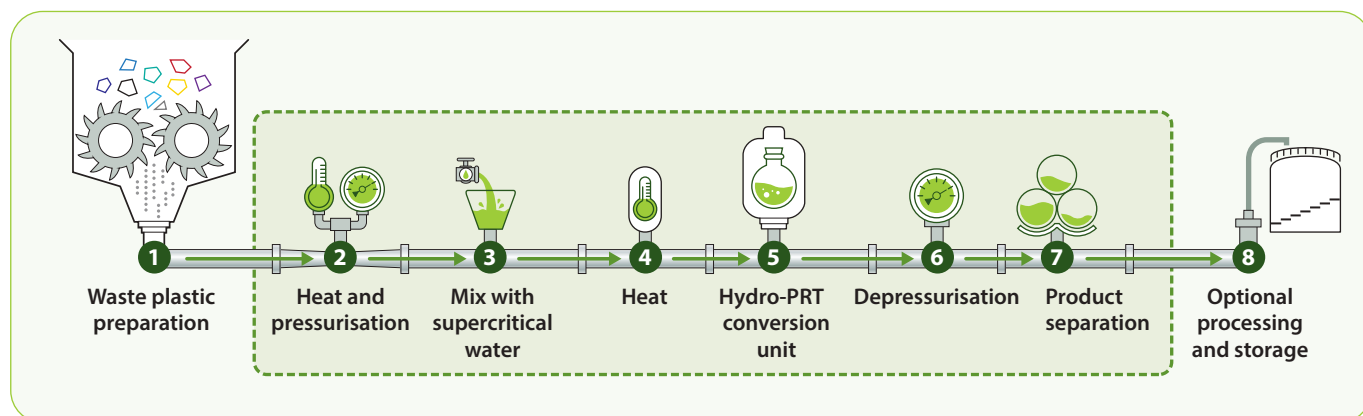
Despite not currently being defined in any European regulation, a wide array of advanced recycling (sometimes referred to as ‘chemical recycling’) technologies is poised to transform how the global economy manages and re-circulates the mountains of plastic waste it produces every year.

## Advanced recycling technologies

Traditional mechanical recycling can process some of the world’s plastic waste, particularly single-polymer types. This process involves sorting, shredding, washing, and separating the waste into similar polymer groups, which are heat treated to remove odour and then melted and formed into pellets. These pellets can be remelted, becoming the constituent ingredients for new plastic products, albeit not those intended for contact-sensitive applications, such as food or medical packaging. However, a considerable proportion of plastic waste cannot be mechanically recycled, such as contaminated food-contact films or layered materials. This is where advanced recycling comes into play.

The European Coalition on Chemical Recycling broadly defines advanced recycling as “converting polymeric waste by changing its chemical structure to produce substances used as products or raw materials”. Importantly, this definition excludes processes that yield products “used as fuels or [as] means to generate energy”.

There is a need for recycling solutions that can process a wider variety of polymer types together, such as the mixed streams of hard-to-recycle plastic waste produced by households, economically and with minimal impact on the environment. It is with these considerations in



**Figure 1** The Hydro-PRT process flow diagram showing the end-to-end hydrothermal advanced plastic recycling process

mind that the hydrothermal liquefaction (HTL), process, trademarked as Hydro-PRT, was developed by Mura Technology.

### Introducing Hydro-PRT

In brief, Hydro-PRT is an end-to-end hydrothermal advanced plastic recycling process that uses supercritical water to crack post-consumer, multi-layer flexible and rigid mixed plastic waste streams into industry-ready, circular hydrocarbons. Mura develops its own build-own-and-operate Hydro-PRT recycling facilities and sells licences for use of the technology through Mura's exclusive Global Licensing Partner, preferred engineering partner, and investor, KBR. KBR has already agreed licences for the Hydro-PRT technology with organisations including LG Chem and Mitsubishi Chemical.

This next-generation process is unique when compared with other advanced recycling technologies. It is differentiated by its use of supercritical water, which is water brought to a state of increased temperature and pressure until it exceeds its critical point, where it exhibits both the properties of liquids and gases. Using supercritical water in this way brings numerous benefits when treating plastic waste streams, ultimately making possible the processing of those waste streams usually considered unrecyclable by other existing recycling technologies.

Hydro-PRT is insensitive to organic contaminants such as paper labels and cardboard or organic matter like food residue, making it an ideal solution for the contaminated plastic waste streams that typically get incinerated within the

UK and Europe. A 2024 study estimated that as much as 46% of UK household plastic waste is incinerated (Greenpeace UK, 2024). By providing an alternative destination to energy-from-waste facilities for plastic waste, the greenhouse gas emissions resulting from incineration are consequently avoided.

Unlike pyrolysis, an alternative form of advanced recycling, the use of supercritical water during conversion allows for highly efficient and homogeneous heat transfer, as it surrounds the plastic waste rather than heating from an external source. The use of supercritical water also offers a source of hydrogen, which can saturate the broken chemical chains in the recycling polymers, with the hydrogen transferring from the water into the end products. The presence of supercritical water in the reaction also limits the formation of char, meaning the quality of the final output product is not affected.

These homogenous reaction conditions, in turn, allow the cracking rate to be controlled during operation, acting as a suppressant to unwanted free radical reactions. This ultimately makes very high yields of high-quality circular hydrocarbon products possible and gives them increased stability.

Practically, the process begins with the transportation of post-consumer plastic waste, which could not otherwise be processed via traditional mechanical recycling, to a Hydro-PRT facility. The waste is shredded, and any contaminants such as stones, glass, metal, and non-target plastics are removed. Once sorted, the plastic is moved into an extruder where it is melted and pressurised before being injected into the main conversion unit where the Hydro-



**Figure 2** The Mura Wilton advanced plastic recycling facility

PRT process takes place. The supercritical water acts as ‘molecular scissors’ to break down or crack the carbon bonds in the plastic, donating hydrogen to create shorter-chain hydrocarbons. Following conversion, pressure is released from the reactor, and this energy is then recovered during flash distillation.

The mix is then separated via fractionation into distinct hydrocarbon products. Petrochemical companies can use these circular hydrocarbon feedstocks from Hydro-PRT as a replacement for fossil-based resources in the manufacture of virgin-grade plastics. The output products include:

- **Circular liquid hydrocarbons:** These products from Mura’s Hydro-PRT process can be used to replace fossil naphtha in the manufacture of new plastic products, chemicals, waxes, and oils.
- **Heavy residual oil:** This high-boiling hydrocarbon product can be used as an additive in the production of bitumen or asphalt for the construction of roads.
- **Light vapour product:** This process gas can be either recycled as a feedstock or reused to bring the water used in the process to a supercritical state, reducing the need for additional energy in future reactions.

### Wilton facility

Set to be operational in 2025, Mura Wilton is Mura’s first facility, sited at the Wilton International Industrial Park in Teesside,

Northeast England (see **Figures 2 and 3**). When operational, it will have an output capacity of 20 kta, with scope to treble production from the site, encouraged by the inherent scalability of the Hydro-PRT process. Petrochemical companies that will act as offtaker to Mura’s products from the Wilton facility include Dow Chemical and Neste, with a third offtaker to be announced in due course.

### Life cycle assessments

As Mura grows, the company is guided by central sustainability principles, including the maximisation of global recycling capacity for plastics currently considered unrecyclable, the minimisation of environmental impacts across operations, and the application of scientific evidence to drive sustainability action. With this in mind, independent life cycle analyses (LCAs) of Mura’s advanced recycling process have been performed to help better evaluate the impacts, including the carbon footprint of the process, in support of Mura’s sustainability pathway to net zero.

In 2023, an LCA published by the Joint Research Centre, the science and knowledge service of the European Commission, benchmarked Hydro-PRT as one of five waste treatment processes for a bale of mixed waste plastic packaging. The assessment compared three different thermal advanced plastic recycling technologies against both traditional mechanical recycling processes and waste-to-energy (the burning of waste to power an electric generator turbine) (Garcia-Gutierrez, et al., 2023).

The study found that all plastic recycling processes it analysed, whether mechanical or advanced, were preferable to waste-to-energy (incineration) from material recovery and carbon emissions perspectives (Garcia-Gutierrez, et al., 2023). Although mechanical recycling came in with the lowest carbon intensity overall, it still had a high proportion of ‘non-recyclable’ flexible material, which would still need to be incinerated – the feedstock that Hydro-PRT has been designed to target.

However, the report also concluded that Hydro-PRT had the highest net savings in terms of emissions of the three thermal advanced recycling processes assessed (Hydro-PRT and two unnamed pyrolysis technologies). The



output products from Hydro-PRT (referred to as CR(III) in the published LCA report) are produced with around 55% lower global warming potential than fossil resources (Garcia-Gutierrez, et al., 2023).

Importantly, recognising the need to conserve carbon within the circular economy, Hydro-PRT was also found to be the most resource-efficient recycling process when compared with mechanical and chemical recycling processes, indicating the highest yield of hydrocarbon products that displaces equivalent, virgin fossil products.

An LCA published in 2023 by Warwick Manufacturing Group of the University of Warwick assessed the carbon and wider environmental impacts of processing waste plastic at Mura Wilton in Teesside.

The most significant finding of the LCA study was that the technology can generate up to an 80% reduction in climate change impacts when compared to the incineration of waste plastic, understood by the study to be the most common approach for disposing of hard-to-recycle films and flexible plastics (Ozoemena & Coles, 2023). In addition, the LCA demonstrated that for each tonne of plastic recycled, more than five barrels of fossil oil were saved. The study also indicated a 50-70% reduction in carbon intensity from the Hydro-PRT hydrocarbons, against the equivalent fossil oils, based on values in the Life Cycle Inventory from ecoinvent (ecoinvent, 2025).

### Commercial prospects

As well as being the sustainable alternative to incineration, the Hydro-PRT process has a robust economic argument to make for itself. A research report found that after a short first-use cycle, 95% of plastic packaging material value, worth between 80 and 120 billion US dollars annually, is lost to the economy alongside the associated carbon (World Economic Forum, Ellen MacArthur Foundation, & McKinsey & Company, 2016). Hydro-PRT returns economic value to plastic waste that the global economy has considered valueless for many years, providing a low-carbon



**Figure 3** Mura Technology's 20 kta Wilton site

alternative for plastic waste and also limiting the cost of environmental collection and clean-up. Furthermore, the end-of-life destination provided by the technology can displace plastic waste from reaching waste-to-energy plants; as incineration does not produce a product to retain in the system, there is a further cost of the production of virgin material to replace the plastic that is lost from the system and, ultimately, a lost opportunity for circularity.

There are also ambitions to further explore what is possible with Hydro-PRT. Early in 2024, Mura Technology signed a five-year research partnership with the Laboratory for Chemical Technology at Ghent University, dedicated to minimising the environmental impact of chemical processes. As part of this research partnership, a continuous flow pilot-scale testing facility will be constructed at the laboratory, which will then be used for a range of research programmes to evaluate what other materials Hydro-PRT is capable of processing and to help Mura's industry partners better understand the potential of its output products.

The Wilton facility's commencement of operations this year will be a key milestone for Mura and advanced recycling as a whole. The sector remains focused on advancing the circular economy for waste plastic and turning what was once considered a waste product into a valuable commodity.

Hydro-PRT is a registered trademark of Mura Technology.

### VIEW REFERENCES



Geoff Brighty

# Solutions for heat tracing in the decarbonisation of cement

Heat tracing solutions are instrumental in addressing several challenges in the cement industry, playing a pivotal role in reducing its carbon footprint

Koen Verleyen  
Chemelex

**T**he cement industry is at a critical juncture in its journey towards net-zero emissions. As one of the most energy-intensive and carbon-emitting industries (~8% of global CO<sub>2</sub> emissions (Facts on climate, 2019), cement manufacturing faces numerous technical challenges in reducing its carbon footprint (Lehne & Preston, 2020). These challenges are primarily related to the inherent nature of cement production, which involves high-temperature processes and significant CO<sub>2</sub> emissions.

Heat tracing solutions are emerging as a key technology to enhance process efficiency, reduce energy consumption, and facilitate the integration of low-carbon technologies.

## Technical challenges in cement industries:

### ① High-temperature process requirements

Cement production involves several high-temperature steps, particularly in the kiln, where raw materials are heated to 1,450°C (2,642°F) to produce clinker. This process is not only energy-intensive but also results in significant CO<sub>2</sub> emissions due to the decomposition of limestone (calcination) and the combustion of fossil fuels. The challenge lies in finding ways to reduce energy consumption and emissions without compromising the high temperatures required for clinker production.

### ② Energy efficiency and heat loss

The high-temperature processes generate significant heat, much of which is lost to the environment due to poor insulation and process inefficiencies. Improving energy efficiency is essential to reducing the carbon footprint of cement production, but this requires innovative solutions to capture and utilise the excess heat generated during the process.

### ③ Integration of alternative fuels

The cement industry is exploring the use of alternative fuels, such as biomass, waste-derived fuels, and hydrogen, to replace traditional fossil fuels. However, these alternative fuels often have different combustion characteristics, affecting the stability and efficiency of the kiln operation. Biomass and waste-derived fuels have lower calorific values and higher moisture content, which can lead to incomplete combustion and higher energy consumption. Ensuring consistent and efficient combustion of alternative fuels is a significant technical challenge.

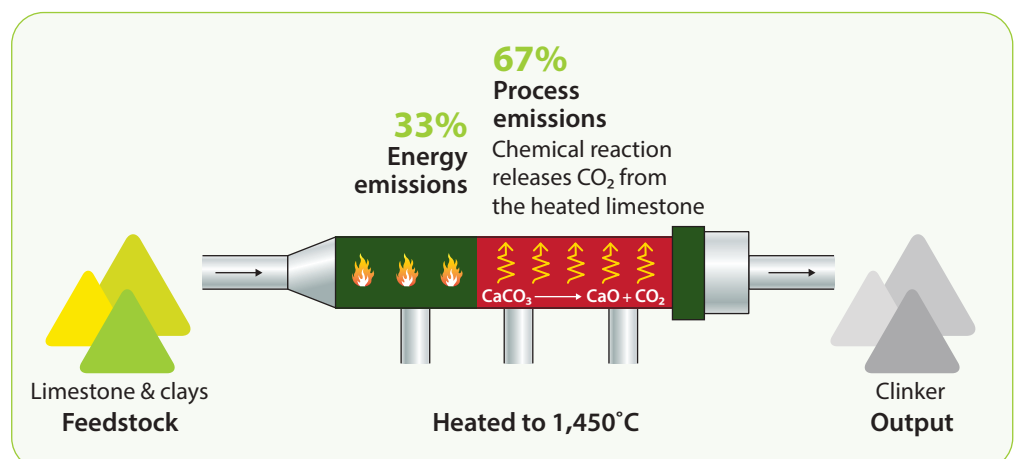
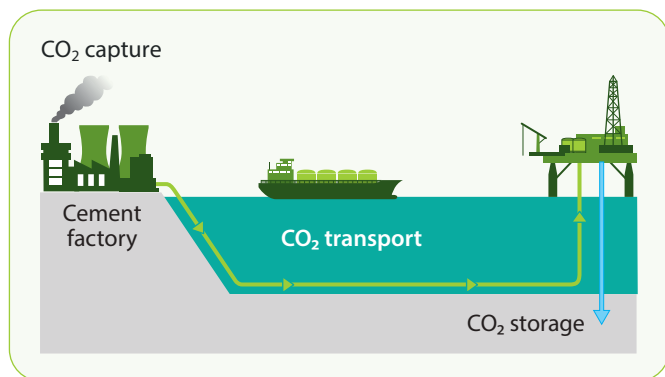


Figure 1 Process emissions during concrete production



**Figure 2** Carbon capture and storage schematic

#### ④ Carbon capture utilisation and storage

Carbon capture and storage (CCS) or carbon capture, utilisation and storage (CCUS) technologies are critical to reducing the industry's carbon footprint. However, capturing CO<sub>2</sub> from the high-temperature flue gases of cement kilns presents technical challenges.

The flue gases should be cooled before CO<sub>2</sub> can be captured, which involves further energy input.

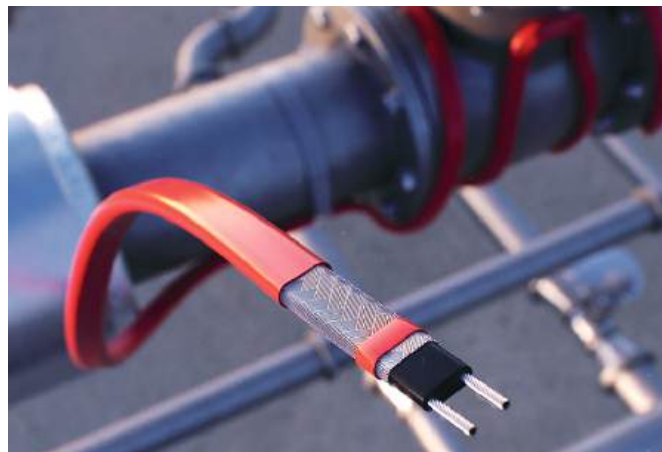
Additionally, for CCS to be effective, precise thermal management is required. The process of capturing CO<sub>2</sub>, whether through post-combustion, oxy-fuel combustion, or pre-combustion technologies, involves several temperature-sensitive steps. Maintaining optimal temperatures is crucial for the efficiency of solvents, membranes, or other capture mediums. Any deviation from the required temperature range reduces the CCS efficiency and increases its energy consumption.

#### Role of heat tracing

Heat tracing involves the application of electrical heating cables to pipes, vessels, and other equipment to maintain or elevate temperatures to a desired level. In the context of the cement industry, heat tracing solutions are instrumental in addressing several challenges outlined above.

#### ① Enhancing energy efficiency

Heat tracing systems can significantly improve the energy efficiency of cement plants by minimising heat loss in critical areas. For instance, in the clinker production process, heat tracing can be applied to maintain the temperature of raw materials and prevent heat loss during transportation through preheaters, kilns, and coolers. This ensures that less energy is required to maintain the high temperatures necessary



**Figure 3** Self-regulating heating cable maintains or elevates temperatures to a desired level

for calcination, thereby reducing overall energy consumption and CO<sub>2</sub> emissions.

Heat tracing can also be used to optimise the operation of heat exchangers and waste heat recovery systems, which are integral to improving energy efficiency in cement plants. By maintaining optimal temperatures in these systems, heat tracing helps maximise the recovery of waste heat, which can then be reused in the production process, further reducing the need for external energy inputs.

#### ② Supporting the use of alternative fuels

The integration of alternative fuels into cement production processes requires careful thermal management to ensure consistent and efficient combustion. Heat tracing solutions can be employed to preheat alternative fuels with high moisture content, such as biomass, before they enter the kiln. This preheating reduces the moisture content of the fuel, improving its combustion characteristics and ensuring a stable and efficient burning process. As a result, the use of alternative fuels becomes more viable, helping to reduce the industry's reliance on fossil fuels and lower its carbon footprint.

#### ③ Optimising CCUS processes

Heat tracing plays a crucial role in the optimisation of carbon capture systems. In post-combustion carbon capture, for example, flue gases must be cooled to a specific temperature range before CO<sub>2</sub> can be efficiently captured. Heat tracing systems can be used to precisely control the cooling process, ensuring that flue gases reach the required temperature

## Case study: Empowering world's first CO<sub>2</sub> capture facility in the cement industry

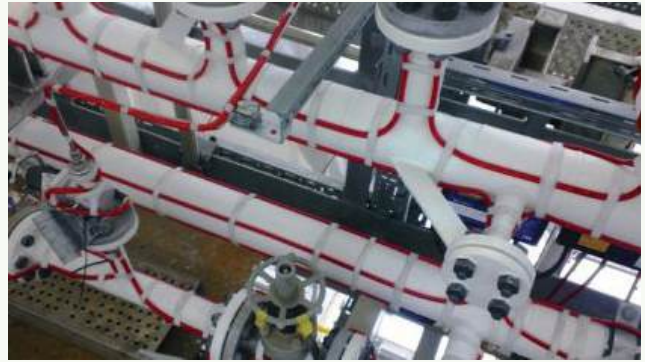
A global cement manufacturer selected Chemelex Raychem heat tracing solutions for the construction of the world's first full-scale CCS plant, located in Norway.

One of the main ingredients in cement, clinker, is made by heating limestone ( $\text{CaCO}_3$ ) to extreme temperatures. This process releases carbon trapped in the stone, which reacts with oxygen in the atmosphere to form  $\text{CO}_2$ . The client owns many cement factories around the world and plans to reduce its footprint drastically over the coming years by investing in CCS installations. This Norwegian project is the first of its kind and was completed in 2024.

The CCS process involves three key steps: capture, transport, and storage of  $\text{CO}_2$  emissions. The capture technique in this plant is  $\text{CO}_2$  amine absorption, and has the following equipment:

- Pre-scrubber to cool down the flue gas and remove particles.
- Absorber (or scrubber) to bond  $\text{CO}_2$  to a chemical amine (at  $\sim 50^\circ\text{C}/120^\circ\text{F}$ ).
- Desorber (or stripper) to release the  $\text{CO}_2$  from the amine (at  $\sim 160^\circ\text{C}/320^\circ\text{F}$ ).
- Reboiler: 4-5 bar (58-72 psi) steam required to heat the desorber.

The captured  $\text{CO}_2$  will then be liquefied and transported for final underground storage 3,000 metres under the seabed in the North Sea. Chemelex played an important role in supplying electrical materials, including heat tracing solutions. Raychem HTV high-temperature self-regulating heating cables with high power retention (HPR) and BTV heating cables proved ideal for this plant's freeze protection and

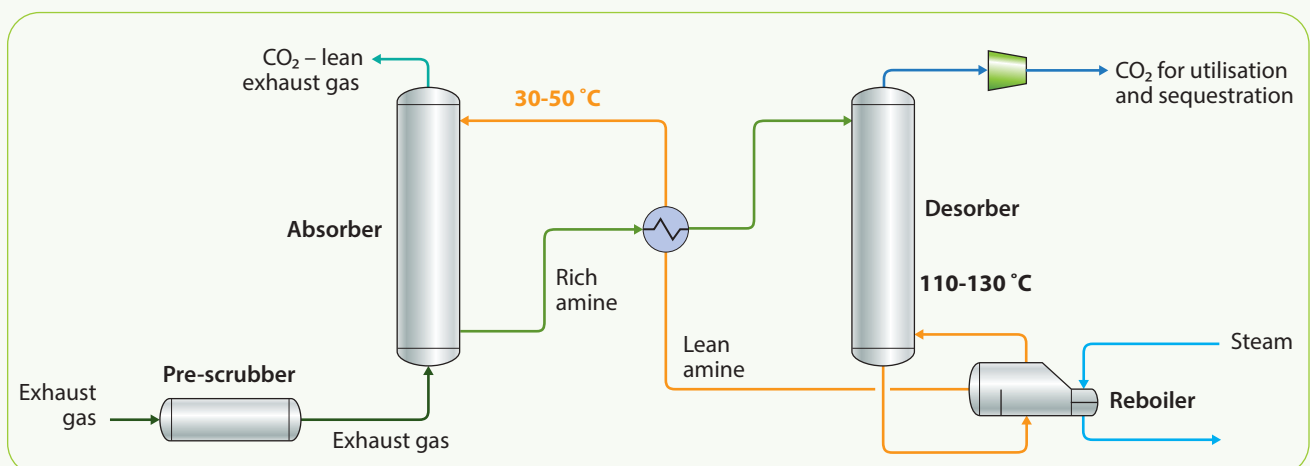


**Figure 5** Raychem heating tracing installation

process maintenance applications. Chemelex engineers also provided design assistance to ensure the best performance and system longevity and to reduce power distribution requirements, lowering total installed costs.

The high-temperature Raychem HTV self-regulating heating cables boast impressive performance, retaining more than 95% of their power even after 10 years of use. With a design life of 30+ years, they provide long-lasting reliability. Additionally, Chemelex provides customers with peace of mind through its 10-year product warranty.

Through its Raychem brand, Chemelex has an extensive track record of bringing heat tracing experience to CCS projects. Since 2012, its heat tracing solutions have been playing a crucial role in the operation of the world's first CCS demonstration plant in Mongstad, Norway. Also, it continues to bring its heat tracing experience to CCUS projects worldwide, in oil and gas, biofuels, power and other industries, fostering a more sustainable future.



**Figure 4** Diagram of typical carbon capture process



for optimal CO<sub>2</sub> absorption by solvents or membranes.

Furthermore, heat tracing is essential in maintaining the temperature and pressure conditions required for the transportation and storage of captured CO<sub>2</sub>. By preventing temperature fluctuations in pipelines and storage vessels, heat tracing helps maintain the integrity of the carbon capture process, ensuring that CO<sub>2</sub> is safely and efficiently transported to storage sites or utilisation facilities.

**4 Enhancing process control and stability**

In cement production, process stability is critical to maintaining product quality and reducing energy consumption. Heat tracing solutions provide precise temperature control, which enhances the stability of key processes, such as kiln operation and fuel combustion. By maintaining consistent temperatures, heat tracing minimises the risk of process disruptions, which can lead to energy inefficiencies and increased emissions.

For example, in oxy-fuel combustion systems, maintaining the correct temperature is vital for efficient combustion and CO<sub>2</sub> capture. Heat

tracing ensures that the oxygen supply, fuel lines, and other critical components remain at the optimal temperature, preventing issues such as condensation, freezing, or incomplete combustion.

**Conclusion**

The journey to decarbonising the cement industry is challenging, particularly given the high-temperature processes and carbon-intensive nature of cement production. However, heat tracing solutions offer a powerful tool to address these challenges. By enhancing energy efficiency, supporting the use of alternative fuels, optimising carbon capture processes, and improving process stability, heat tracing can play a pivotal role in reducing the cement industry’s carbon footprint. Through innovative applications of heat tracing, the industry can move closer to its goal of reducing emissions while maintaining the high standards of quality and efficiency that are crucial to its operations.

**VIEW REFERENCES**



**Koen Verleyen**  
Koen.Verleyen@chemelex.com



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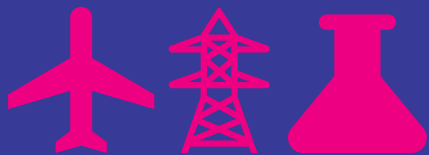


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