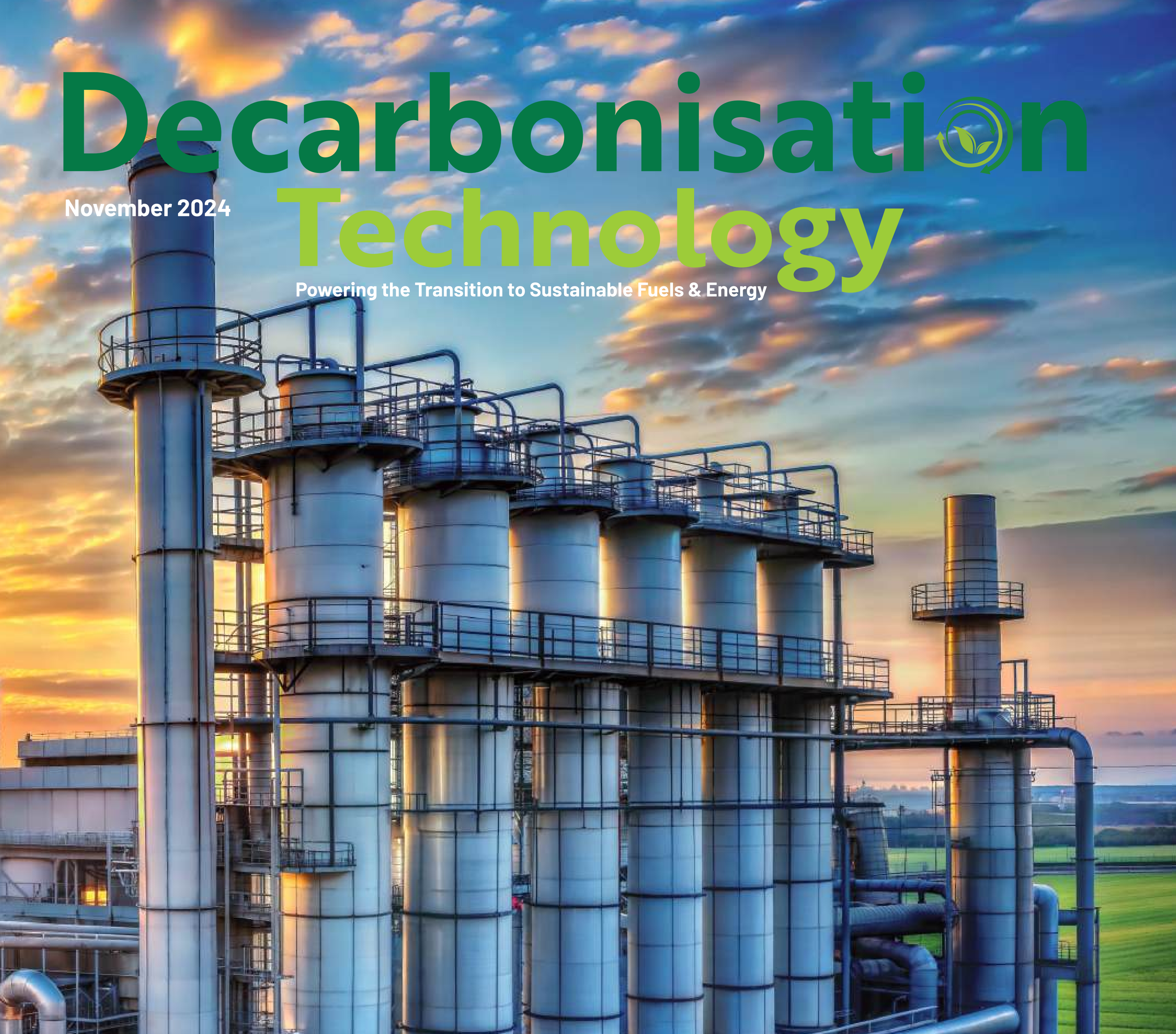
Decarbonisation Technology

November 2024

Powering the Transition to Sustainable Fuels & Energy



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November 2024

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Cover Story
nVent RAYCHEM mission-critical solutions keep processes running safely, efficiently, and reliably in biofuels, hydrogen, carbon capture and LNG facilities. **nvent.com/RAYCHEM**

The goal of the energy transition is to reduce emissions of greenhouse gases into the environment while continuing to meet the world's energy needs. While most often expressed in relation to the Paris Agreement goal to limit global warming to less than 2°C, the transition also underpins the UN's Sustainable Development Goal, SDG-7, "to ensure access to affordable, reliable sustainable and modern energy for all".

Another SDG, SDG-12, aims to "ensure responsible consumption and production, including the minimisation of waste going to landfill or otherwise polluting our planet". This goal also predicates the shift away from less sustainable energy crops to advanced biofuels.

The use of waste as a feedstock in refineries to reduce our reliance on fossil fuels supports both of these goals. Already, refineries have adapted hydrotreaters and are recycling used cooking oil (UCO). Processing UCO is straightforward, and the product, either in the form of hydrogenated vegetable oil (HVO) or hydroprocessed esters and fatty acids (HEFA), is drop-in fuels that can be blended in diesel or aviation kerosene fuels.

More complex waste streams include forestry and agricultural residues, the biogenic components of municipal waste, and unrecyclable waste plastic. These need more vigorous conversion processes, such as gasification, hydrothermal liquefaction, and pyrolysis. Gasification is a commercially proven technology, while the other two processes are at an advanced technical readiness level, ready for commercialisation. Increasingly, refiners are looking to invest and build to increase capacity. However, it will take decades for fossil fuels to become fully redundant. While some refineries are now dedicated biorefineries, others are coprocessing waste-derived feedstocks with crude oils.

Carbon dioxide (CO_2) is a waste stream from combustion or from chemical processes such as cement manufacture. Where possible, capturing the CO_2 from such processes is becoming a requirement. E-fuels and other uses for captured carbon are emerging and should be considered as an addition rather than an alternative to permanent storage. Both options reduce the emissions of CO_2 to the atmosphere, so can contribute towards the fundamental goal of the transition. However, a massive increase in the scale of carbon capture from industrial processes is mission-critical. Direct air capture (DAC) to draw down CO_2 from the atmosphere will also be essential. Achieving DAC at an impactful scale is one of the generational challenges for modern society. In the meantime, policy and regulation that disincentivise capture from industrial flues make no sense at all.

Renewable fuels such as ammonia or methanol, for shipping with kerosene range e-fuels for sustainable aviation fuels, although carbon neutral, will still result in CO_2 emissions. However, marine vessels fuelled by renewables and equipped with carbon capture raise the prospect of carbon-negative shipping.

Dr Robin Nelson

Power of carbon accounting in the low-carbon fuel industry

Why life-cycle assessments are essential for renewable diesel and sustainable aviation fuel producers to meet ESG and net-zero goals

Kristine Klavers
EcoEngineers

In today's carbon-conscious world, carbon accounting is essential for industries to measure, manage, and reduce greenhouse gas (GHG) emissions. It goes beyond compliance, helping organisations meet their environmental, social, and governance (ESG) and net-zero goals, optimise production processes, and tap into financial incentives that drive return on investment (ROI).

Emerging climate regulations, low-carbon fuel markets, subsidies, and tax credits offer significant opportunities to support companies and their stakeholders on their ESG journey, making literacy in carbon accounting and carbon markets all the more critical. Understanding carbon accounting and exploring the challenges involved is important for achieving compliance and strategic goals. As businesses market low-carbon products, they must be confident and transparent with the results they communicate to stakeholders, including the public, clients, and financial entities (see **Figure 1**).

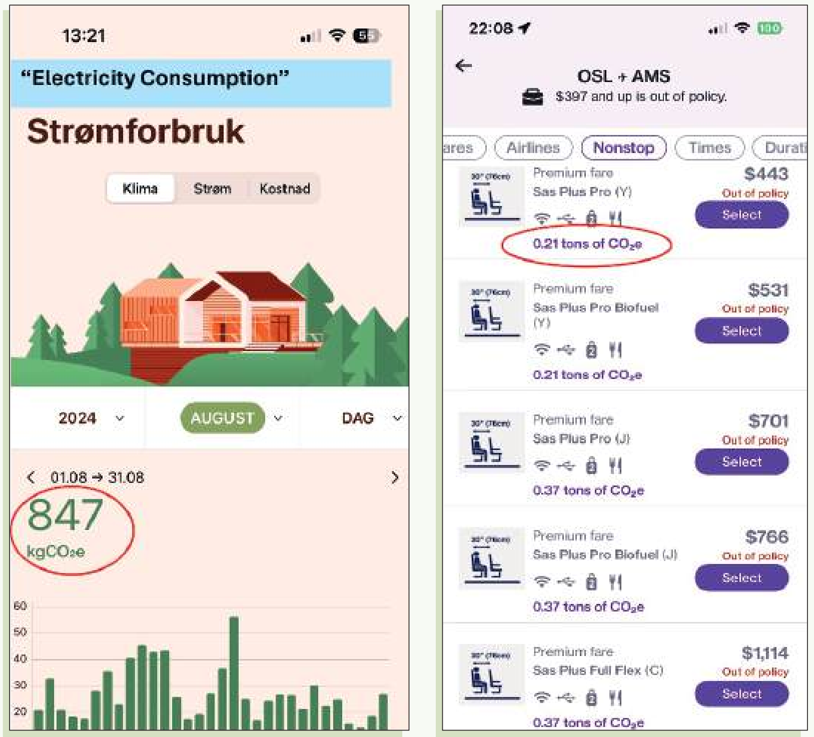


Figure 1 Many industries are focusing on reducing the carbon intensity (CI) of their products Source: *EcoEngineers*

A key to unlocking the power of carbon accounting is life-cycle assessments (LCAs). LCAs are particularly important in determining the carbon intensity (CI) of low-carbon renewable fuels such as renewable diesel (RD) and sustainable aviation fuel (SAF). Understanding carbon accounting enables businesses to communicate their low-carbon calculations effectively to stakeholders, positioning them for success in an increasingly regulated marketplace requiring minimum CI scores that are verified. This article is not meant to be a complete analysis of LCAs, but rather it is meant to reinforce their importance in the context of carbon accounting.

Foundations of carbon assessments

LCAs are the foundation of product-level carbon accounting. They are a systematic and comprehensive method for evaluating the environmental impact of a product, service, or system, from its inception to its end-of-life (cradle-to-grave). LCAs are a tool used to ensure

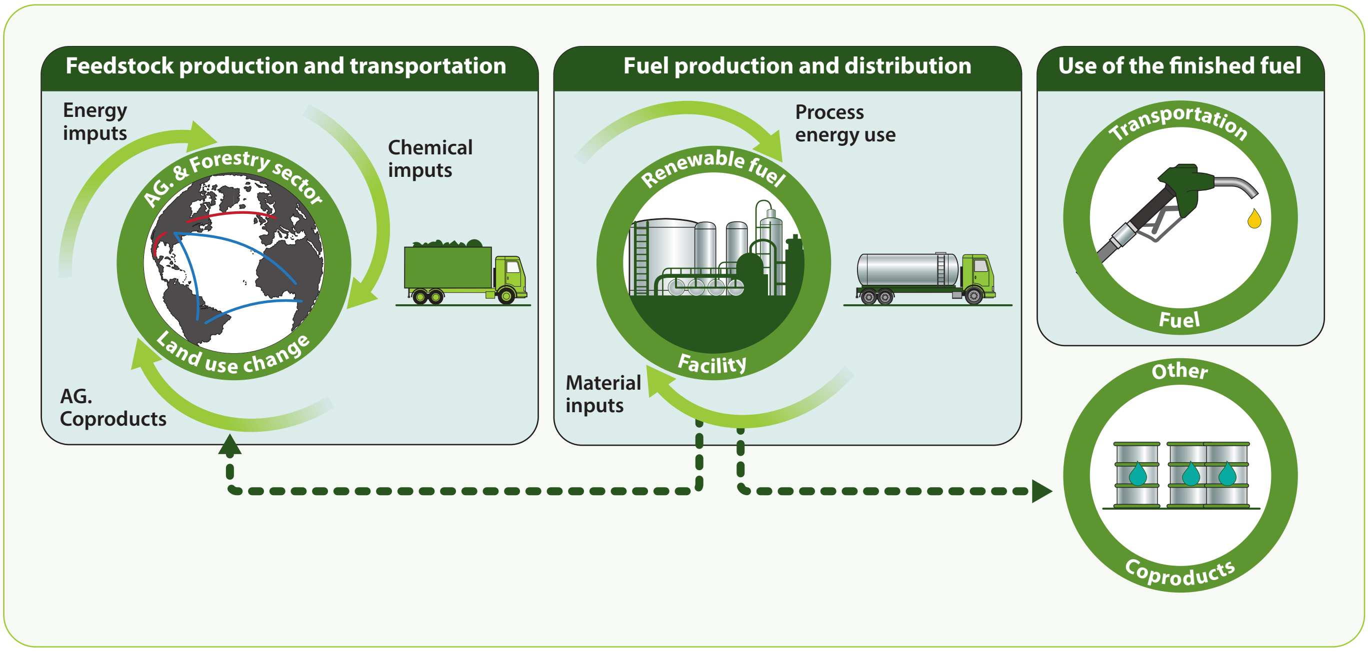


Figure 2 An LCA is used to assess the overall GHG impacts of a fuel, including each stage of its production and use *Source: US Environmental Protection Agency (USEPA, 2023)*

that emissions are quantified across the life-cycle of a product, including raw material extraction, production, transportation, use, and disposal using available data and established models.

In 2006, the International Organization for Standardization (ISO) published ISO 14040 (*ISO*, 2006), a framework for developing LCAs to measure a product's impact and facilitate environmental decision-making, helping to ensure consistency and the ability to compare products and processes.

ISO 14040 outlines four key phases to develop an LCA:

❶ **Goal and scope definition:** This phase builds the LCA framework and, among many variables, involves establishing the functional units, objectives, and boundaries for the assessment, defining the purpose of the study and identifying the product system to be assessed.

Using the same units for comparing LCAs is crucial. For example, CI measured in kilograms of carbon dioxide equivalent (CO_2e) per kg of product (kg CO_2e/kg) is different from one measured in kg CO_2e/MJ of product (megajoule). The main difference between these two units of measurement is that the former measures the CI based on the mass of the product, while the latter measures it based on the energy content. The system boundaries phase requires the boundaries to be clearly defined (for example, gate-to-gate, gate-to-grave, and overall cradle-to-gate). As RD and SAF production chains expand, upstream processes like farming practices and fertiliser use might need to be included in the system boundaries, which again will significantly impact the CI score (see **Figure 2**).

❷ **Inventory analysis:** During this phase, data is collected on all relevant inputs (such as raw materials, energy, and water) and outputs (such as emissions, waste, and byproducts) relating to the system boundary established in Phase 1. This inventory forms the foundation for the impact assessment, which will be described in Phase 3.

Data comes from sources such as process data, design data, industry data averages, public data, and/or set default values. All data and assumptions need to be referenced, and the collection process and timing of the data must be included. The better the data, the more reliable and accurate the calculations.

Depending on the model applied for determining the CI scores of RD and SAF, there are different default values available. This is especially clear when including the feedstock indirect land-use change (iLUC) value. Currently, the iLUC values of the different models available vary widely (see **Figure 3**).

❸ **Life-cycle impact assessment (LCIA):** This phase uses the results of the earlier phases to determine and evaluate the potential environmental impacts associated with the product or system. This is typically defined in the goal and scope phase. Key categories include global warming potential (GWP), resource depletion, and water use. Different impact categories are identified and quantified, from climate change to acidification and land use.

④ **Interpretation:** In this phase, the results are interpreted against the study's original goals and scope. This includes identifying significant issues, drawing conclusions, and making recommendations for reducing environmental impacts. It is essential to fully describe assumptions, describe sources of data, and test sensitivity to different variables used to calculate CI scores. Highlighting uncertainty and variability without explaining its context in the study provides no inherent value and can expose companies to reputational and regulatory risks.

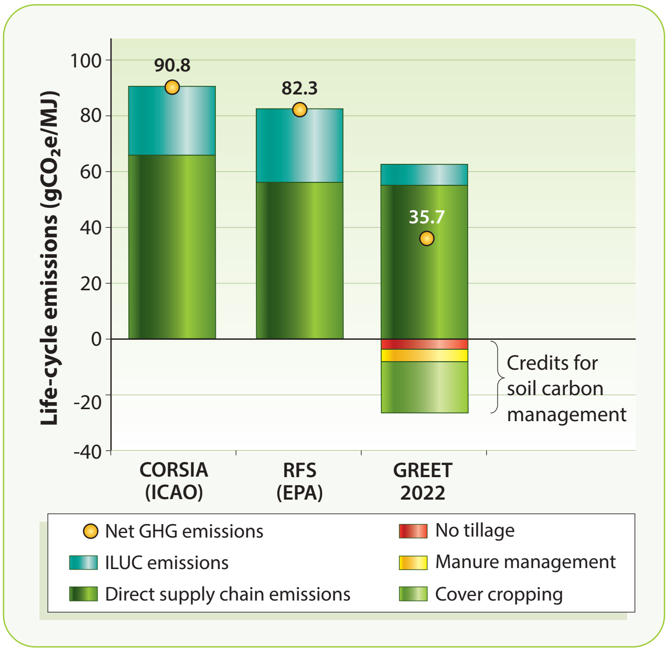


Figure 3 Different LCA models include different iLUC default values and yield different results. This chart shows life-cycle emissions estimates for corn ethanol-to-jet. *Source: The International Council on Clean Transportation (ICCT, 2023)*

Challenges in carbon accounting: Data, methodologies, and regulatory evolution

While the benefits of carbon accounting are clear, its implementation across diverse industries and regions presents several challenges. One of the most significant challenges is data identification, selection, availability, and quality. Carbon accounting involves the meticulous management of information and relying on precise and comprehensive data, which can be difficult to acquire, particularly for first-of-a-kind, new processes and industries with complex global supply chains. Although the data might be available, decisions on the formatting, collection, and sharing of the data are a challenge.

For example, the agriculture sector, which provides feedstocks for biofuels like RD and SAF, involves multiple stakeholders across different regions, each with its unique data collection practices. Inconsistent or incomplete data can lead to a high range of uncertainty in the calculated CI scores, jeopardising a company's compliance with regulatory programmes and its ability to participate in carbon markets.

Another challenge is the variability between carbon accounting models and methodologies. Models are the software tools used to calculate GHG emissions, while methodologies refer to the underlying frameworks that define how, when, where, and why data is assessed. Different industries and regions use various models, each with unique default values, units, and data requirements. For example, the Argonne GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies) model is commonly used in the US to calculate CI scores for transportation fuels, whereas regions like Canada may use models such as GHGenius or openLCA. The differences in methodologies make comparing CI scores across projects and geographies challenging.

Moreover, the regulatory landscape for carbon accounting is constantly evolving. Governments worldwide are updating and expanding their climate policies to meet local and global emission reduction targets. These updates often dictate the models and methodologies required for calculating compliance or participation within a regulated environment. Regulations set the rules for how carbon accounting must be conducted and can affect reporting requirements, which may complicate companies' efforts to align with these rules. Therefore, companies must proactively monitor regulatory changes and adjust their practices to maintain compliance.

Government incentives in renewable fuels

Today, the production of renewable fuels like RD and/or SAF needs substantial governmental incentives to be financially feasible, and many countries are incorporating them into their low-

Region	GHG reduction requirement RD and SAF (minimum)	LCA model requirement
US Renewable Fuel Standard (RFS)	Biomass RD and SAF (D4 and D5 Renewable Identification Numbers, or RINs); 50%	Not known
US State Low Carbon Fuel Standard (LCFS) Programmes	CI dependent	California: CA-GREET Oregon: OR-GREET Washington: WA-GREET
US Inflation Reduction Act (IRA)	Section 45Z, <50 $kgCO_2e/MMBtu$ Section 45V, CI <4 $kgCO_2e/kgH_2$	TBD 40VH2-GREET
Canada Clean Fuel Regulations (CFR)	CI dependent	openLCA
Canadian Provincial LCFS (e.g. British Columbia)	CI dependent	GHGenius
EU Renewable Energy Directive (REDIII)	Biofuels <65-80% Recycled carbon fuel (RCF) and renewable fuels of non-biological origin (RFNBOs) <70%	RED Specific
Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)	SAF <10%	ICAO-GREET

Table 1 Most fuel programmes have different GHG reduction criteria and use different models
Source: EcoEngineers

carbon fuel standards or ESG programmes. Some governments offer financial incentives to promote production, while others impose penalties on companies that fail to meet minimum renewable fuel quotas or carbon-reduction targets.

Depending on the regulatory programme, renewable fuel producers must adhere to published models and verification methodologies and ensure LCAs are conducted in a manner that complies with government regulations.

Regulatory programmes: A multi-layered approach

In the US, various regulatory bodies and programmes provide financial incentives to encourage renewable fuel production (see **Table 1**). Some key programmes include:

- **Renewable Fuel Standard (RFS):** This US policy requires obligated parties like refiners and importers to meet annual renewable volume obligations (RVOs) through the purchase and retirement of Renewable Identification Numbers (RINs). The RFS programme is structured into four nested categories (D3, D4, D5, and D6), each with specific GHG-reduction targets compared to their petroleum-based counterparts. However, USEPA, which administers and enforces the RFS, does not publicly disclose the precise calculation methodologies used to determine these GHG reductions. In certain cases, pre-defined GHG-reduction targets are outlined for specific processes.
- **California Low Carbon Fuel Standard (CA-LCFS):** California's LCFS programme is perhaps the most influential to the transportation fuels market in the US. It aims to reduce GHG emissions and dependence on petroleum-based fuels by increasing the use of low-carbon transportation fuels. The programme rewards producers of low-carbon fuels with credits, which can be sold to parties with deficits. These credits and deficits are calculated using the CA-GREET model, which is derived from Argonne (ANL) GREET and based on different ANL-GREET versions, including CA-LCFS-specific modifications and datasets.

Several other US states, such as Oregon, Washington, and New Mexico, have implemented similar LCFS programmes, often relying on slightly modified versions of the CA-GREET model to calculate CI scores. The state-level programmes generally mirror California's LCFS in design and purpose but may have different requirements and nuances.

International regulations: Harmonising CI calculations

On the international stage, countries like Canada and regions such as the European Union (EU) have also adopted carbon accounting frameworks that are designed to support the transition to renewable fuels (see **Table 1**):

- In Canada, federal regulations rely on the openLCA model to calculate CI scores for its Clean Fuel Regulations (CFR), while British Columbia uses the GHGenius model (an Excel-based spreadsheet model) for its LCFS programme. These models help to regulate and provide financial incentives for producers of renewable fuels while promoting adherence to carbon-reduction goals.
- In Europe, the Renewable Energy Directive (RED) III and its implementing measures set minimum blending mandates for RD and SAF at minimum GHG-reduction targets, incentivising producers to incorporate renewable fuels into their portfolios while supporting the EU's broader climate goals.
- Globally, the International Civil Aviation Organization (ICAO) regulates SAF through its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). To estimate and verify the CI scores of CORSIA-approved SAF pathways, ICAO has developed its version of the GREET model, known as ICAO-GREET, to help ensure compliance with global aviation emissions reduction targets.

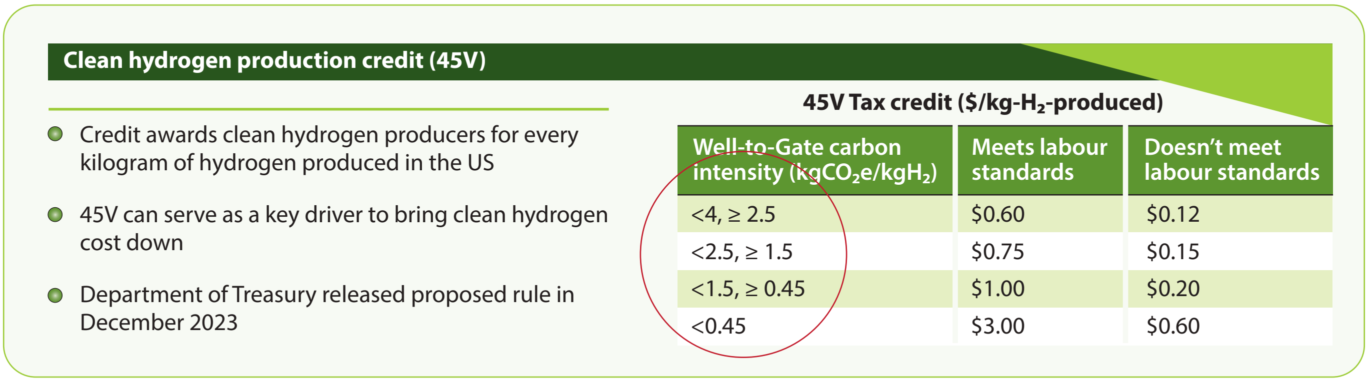
In the US, tax credits have become another key component of renewable fuel incentives, as demonstrated by several provisions in the Inflation Reduction Act of 2022 (IRA):

- **40BSAF-GREET:** This model, adopted by the US Department of the Treasury, calculates the CI score for a particular set of parameters for SAF production under the Sustainable Aviation Fuel Credit (Section 40B), including meeting other policies such as prevailing wage, US-made content, and apprenticeship requirement. The CI score determines the credit generation range of the produced fuel. In 2025, Section 40B is expected to be replaced by the Section 45Z Clean Fuel Production Tax Credit.
- **45VH2-GREET:** Another US Treasury-approved model, 45VH2-GREET, determines emissions rates for clean hydrogen production tax credits under Section 45V of the US tax code. These credits aim to incentivise clean hydrogen production, with substantial financial rewards tied to achieving low CI scores.

By establishing these frameworks, governments are encouraging producers to adopt more sustainable practices and meet increasingly stringent environmental requirements, driving the renewable fuel market forward, promoting innovation, and making low-carbon technologies more economically viable.

Optimising ROI by improving CI scores

Grasping the complexities and significance of data management and the timing of LCAs is central to success in regulatory compliance markets that use CI scores. However, managing CI scores alone is not equivalent to success in carbon accounting. Instead, companies must measure variables through LCAs that allow for calculating a CI score, representing one method or aspect of carbon accounting. Companies that understand the intricacies of CI-related compliance requirements, timing, data management, and the available LCA models can unlock substantial financial incentives.



Clean hydrogen production credit (45V)

- Credit awards clean hydrogen producers for every kilogram of hydrogen produced in the US
- 45V can serve as a key driver to bring clean hydrogen cost down
- Department of Treasury released proposed rule in December 2023

45V Tax credit ($/kg-$H_2$-produced)

Well-to-Gate carbon intensity ($kgCO_2e/kgH_2$)	Meets labour standards	Doesn't meet labour standards
<4, ≥ 2.5	$0.60	$0.12
<2.5, ≥ 1.5	$0.75	$0.15
<1.5, ≥ 0.45	$1.00	$0.20
<0.45	$3.00	$0.60

Figure 4 Section 45V under the U.S. IRA provides incentives for low-CI hydrogen
Source: US Department of Energy (US DoE, 2023)

Clean fuels tax credits (45Z)

- In January 2025, the sustainable aviation fuel tax credit transitions to a per-gallon credit for all clean fuel that incentives low-carbon fuels
- Law divides clean fuels into two categories:
  1) Sustainable aviation fuels (SAF) and 2) All other fuels
- The tax credit is in effect for three years, from 2025-2027
- **Registration is currently open and must be completed to claim credit**

Carbon intensity (gCO$_2$e/MU)	45Z Value - Non-SAF ($/gal)	45Z Value - SAF ($/gal)
47 or greater	0	0
38	0.20	0.35
24	0.50	0.88
9.5	0.80	1.40
0	1.0	1.75

Figure 5 Under the Section 45Z tax credit, SAF producers are incentivised to reduce the CI of SAF/RD
Source: US Department of Energy (US DoE, 2024)

Some programmes are considering penalties for entities that fail to meet minimum CI limits, making precise compliance with regulatory requirements essential.

For instance, under Section 45V of the US IRA, producers of clean hydrogen can earn up to $3.00/kg of hydrogen produced if the CI score is below 0.45kg CO_2e/kg of hydrogen, contingent on meeting other key requirements like prevailing wage and apprenticeship requirements (see **Figure 4**). Similarly, under the Section 45Z tax credit, which is expected to go into effect in January 2025, SAF producers can receive up to $1.75 per gallon (/gal) if they achieve a zero CI score in gCO_2/MJ (see **Figure 5**).

The ability to report on verified CI scores provides producers with several competitive advantages, including:

➊ **Increased financial returns:** By lowering CI scores, companies can potentially earn more tax credits and generate more credits in regulated fuel and voluntary carbon markets.

➋ **Access to new markets:** Governments worldwide are increasingly prioritising low-carbon products. By improving CI scores, companies can potentially access new markets with stricter carbon regulations or attract environmentally conscious buyers.

➌ **Enhanced brand reputation:** Companies with strong carbon accounting practices and low CI scores can enhance their brand reputation, appealing to investors, customers, and other key stakeholders.

➍ **Risk mitigation:** By adhering to evolving carbon regulations and continuously improving CI scores, companies can mitigate the risk of penalties or exclusion from key markets.

Summary

As the global economy transitions toward a low-carbon future, carbon accounting will play an increasingly central role in shaping the strategies and success of industries worldwide. The evolution of regulatory frameworks, financial incentives, and carbon markets presents opportunities and challenges for producers in the renewable fuel sector. By fully understanding and embracing carbon accounting practices, ensuring proper data management, and leveraging advanced tools, companies can better manage the complexities of the carbon economy and achieve their sustainability goals.

Renewable fuels like RD and SAF are poised to become critical components of the global energy transition, especially as governments set more ambitious climate targets. While production costs remain a challenge, combining financial incentives, tax credits, and carbon trading schemes can make low-carbon fuels a viable option for companies willing to invest in CI score optimisation and compliance.

Ultimately, proper carbon accounting offers a technical blueprint for organisations to drive their low-carbon strategy, meet regulatory requirements, and thrive in a low-carbon, competitive market. For companies across industries – from renewable fuels to manufacturing – carbon accounting is no longer optional but a key driver of long-term profitability and sustainability.

VIEW REFERENCES

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Key to scalable, sustainable hydrocarbon fuels

A novel iron-based catalyst and process directly convert CO_2 and green H_2 from water into jet fuel range hydrocarbons in one step, reducing Capex and Opex

Andrew Symes
OXCCU

To prevent global temperatures from surpassing the critical two-degree threshold, a rapid transition away from using fossil fuels must occur within the next 30 years. This has led some to assume that all refineries and petrochemical plants will have to shut down, but this is incorrect. While they need to change radically, and some may be replaced, they will not all be replaced entirely, as demand for hydrocarbons in certain sectors will remain.

Wherever possible, renewable electricity should be used directly due to efficiency, but only hydrocarbons will suffice in some sectors. The critical change will be the inputs. Refineries and petrochemical plants must rapidly move from using fossil fuels as their feedstocks to using a source of recycled carbon with green electricity, as articulated in a recently published paper in *Nature* (Vogt and Weckhuysen, 2024).

Continued need for hydrocarbons

Aviation will continue to need hydrocarbon fuels due to its energy density requirements. While some reduction in aviation fuel demand may be necessary, particularly where there is excessive flying – such as short flights – significant demand will remain. It is unrealistic to expect people to stop flying or demand that politicians ban it. In fact, rather than seeking to ban aviation, many want to ensure that flight is available for future generations and people in developing countries.

Flights without hydrocarbons remain a distant prospect. Electric or hydrogen planes for long-distance flights face huge challenges with safety, refuelling, and range due to energy density, and lighter-than-air flights (airships) will always be limited in terms of speed. Additionally, hydrocarbon fuels will always be needed in military operations. With the urgent need to reduce emissions, a source of sustainable hydrocarbon aviation fuel, SAF, will play a vital role in meeting these needs with far fewer emissions.

In the same way, hydrocarbons are essential for the production of plastics and chemicals. It is unrealistic to expect a total ban, especially where they are critical for medicine, healthcare, food production, transport, and electronics. Reducing the excessive use of plastic is important, particularly as many unnecessary single-use applications are causing a huge waste problem and the increasing issue of microplastics. Likewise, excessive chemical use should be stopped, as it can contaminate soil, water, and air, harming human health and biodiversity. However, some sectors will need to continue, or even increase, their use of chemicals and plastics to improve life expectancy, human prosperity, and economic growth. These must be made with fewer emissions to reduce their climate impact.

To supply these critical hydrocarbons with fewer emissions, fossil carbon, crude oil, coal, or natural gas must be replaced by a source of recycled or surface carbon and varying amounts of low carbon intensity hydrogen, such as that derived from electricity generated from renewable sources. The three options are biomass, plastic waste, or carbon dioxide (CO_2). Despite requiring the most green electricity input via green hydrogen, CO_2-based hydrocarbons are predicted to be the largest component over time due to the challenges with biomass or plastic waste as feedstocks.

Feedstock challenges

First-generation biomass feedstocks, such as oil

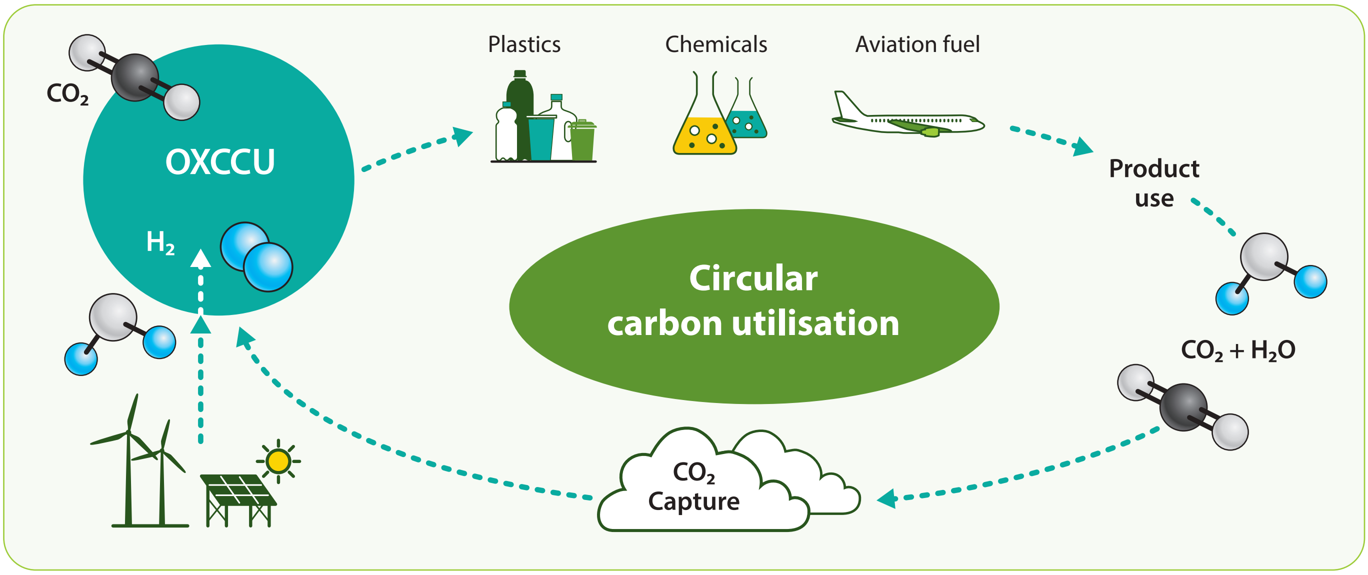

Figure 1 Circular carbon utilisation

crop-based biodiesel and SAF, produced through the hydrogenated esters and fatty acids (HEFA) process, and ethanol from corn fermentation, dominate biofuel and biochemical production today. However, their growth is severely limited by competition with food crops, land use constraints, and, in the case of ethanol, the costly requirement of additional units to convert ethanol into more valuable long-chain hydrocarbons through olefins and oligomerisation.

Second-generation carbon waste-based fuels form a diverse category with a wide variety of feedstocks and conversion processes but most commonly involve a type of lignocellulosic waste (biomass waste), municipal solid waste (rubbish), or plastic waste. The processes generally entail heating the waste without oxygen via pyrolysis to convert it to a liquid or turning the waste into gas through gasification and then converting that gas into a liquid. Crop waste fermentation to ethanol is also possible but still has technical challenges despite efforts over the last 20 years. All these processes can play a role in the biofuel and biochemical landscape. However, they all suffer from the same challenges: securing, aggregating, and sorting the feedstock and ensuring the intermediate liquid or gas in the process is free of the contaminants in the feedstock.

Power-to-liquids

This has led to excitement around the newest option, CO_2-based fuels, chemicals, and plastics, often called power to liquids (PtL). Here, CO_2 and green hydrogen are the feedstocks (see **Figure 1**), and this has some key advantages despite the significant requirement for green electricity. Most importantly, in utilising CO_2 as the feedstock along with green hydrogen from renewable energy, e-fuels or PtL have the potential for scale with minimal impact on land use.

The fuel can be circular if the CO_2 has recently originated from the atmosphere. CO_2, which was recently in the atmosphere, is made into a fuel and then returns there as CO_2 when burned. There are two types: direct air capture (DAC) CO_2, where a machine captures the CO_2 from the air using green energy, or biogenic CO_2, where a plant captures the CO_2 from the air to make biomass. The biomass is harvested and used to make a product, producing waste CO_2 in the process. This waste 'biogenic' CO_2 is captured and used to make a fuel that releases the CO_2 to the atmosphere when burned. Assuming the plant can regrow fairly quickly to make more biomass, capturing more CO_2 from the atmosphere, the process achieves circularity. Ethanol production and anaerobic digestion are continuous sources of biogenic CO_2 that is destined for the atmosphere anyway, derived from crops that will regrow.

Transition from fossil carbon to surface carbon

If fossil CO_2 is used, the byproduct of processes that use fossil fuels (or mineral CO_2 in the case of cement), a low-carbon fuel is created. It is not circular, as carbon originally trapped underground still ends up in the atmosphere as CO_2. However, the process substantially reduces total emissions, as fewer fossil fuels need to be dug up to supply the same amount of end product. In this scenario, CO_2 is recycled, which would otherwise have been emitted. This means getting two uses out of some of the carbon that has been dug up before it ends up in the atmosphere. It improves the world's carbon efficiency. It is progress, but not perfection.

The priority is still to eliminate the 38 billion tonnes of fossil CO_2 emitted annually, and being able to use it should not be an excuse to keep infrastructure, such as coal power plants, when these can be replaced by zero-carbon alternatives. However, in sectors like cement production, it is very unlikely that all CO_2 emissions will be eliminated in the short term. In such cases, reusing a fraction of that CO_2 to reduce oil demand and overall emissions is a logical step, while working towards a future where only biogenic or DAC CO_2 is used. Hence, while there must be a shift from fossil carbon to surface carbon (biomass, DAC CO_2, and biogenic CO_2), realistically this will take time and investment, and recycling fossil CO_2 during the transition represents a step in the right direction.

Ultimately, no fuel, chemical or plastic will ever be perfect in terms of emissions. Even if DAC and 100% renewable electricity are used, there are emissions embedded in the production of the equipment used, land use impacts of DAC in particular, non-CO_2 effects associated with aviation emissions due to contrails, and the potential for warming from hydrogen leakage. These will all need to be factored into a good life-cycle analysis (LCA). LCAs provide a comprehensive and accurate assessment of the total greenhouse gas (GHG) emissions associated with the fuel or product across its entire life-cycle. They cover all life-cycle stages, use consistent boundaries and reliable data, account for direct and indirect emissions, and convert all GHGs into CO_2e, enabling transparency and comparability. The source of CO_2 and H_2 will directly affect the overall environmental score. To qualify as SAF or a low-emissions chemical or plastic, emissions must be below a certain threshold.

Currently, the barrier to scaling PtL is cost. While over the longer term, the more difficult constraint could be access to surface CO_2, currently there are numerous biogenic CO_2 sources to use. The bigger challenge currently is accessing low-cost green hydrogen. The good news is that the electrolyser industry is starting to scale, and the cost of green electricity continues to fall as more and more renewable electricity is rolled out.

An efficient industrial process is needed to convert CO_2 and hydrogen into hydrocarbons. We want the minimum number of steps, the lowest energy input, and the highest selectivity, so the maximum amount of carbon and hydrogen goes into the product rather than byproducts. The production of water is inevitable because both oxygens have to be taken off the CO_2 and turned to water to make a deoxygenated hydrocarbon fuel. The goal is to have all the remaining hydrogen not making water, and all the carbon transformed into valuable hydrocarbon products.

The good news is that if enough hydrogen is used in the 3:1 ratio, the reaction is thermodynamically favoured (negative change in Gibbs free energy), and the reactor will release heat (exothermic) rather than requiring energy input. The challenge is twofold: the kinetic stability of the CO_2, and being able to direct the reactions that occur towards making longer deoxygenated hydrocarbon chains rather than methane, light hydrocarbon gases, or alcohols.

OXCCU's direct hydrogenation process

This 'direct hydrogenation' of CO_2 to long-chain deoxygenated hydrocarbons in a single step is a fairly new area of research. The vast majority of Fischer-Tropsch (F-T) research over the last 100 years has focused on syngas (CO and H_2) to fuels in countries that have coal or gas and want to reduce oil imports rather than using CO_2 and H_2. Hence, the main focus of PtL processes to date has been the 'two-step approach'. Here, CO_2 is first converted to CO via the reverse gas shift reaction, and then combined with H_2 to get to syngas, which can be used with conventional F-T catalysts (normally cobalt-based) (see **Figure 2**).

The challenge is that the first reverse gas shift step is expensive from both a Capex and Opex perspective, and it does not match well with the F-T process. This is because it is an endothermic reaction that operates at 700-1,000°C, while the F-T reaction is a highly exothermic reaction that is normally kept down at 280°C. Reverse water gas shift (RWGS) requires a large energy input, which cannot be efficiently provided by the low-

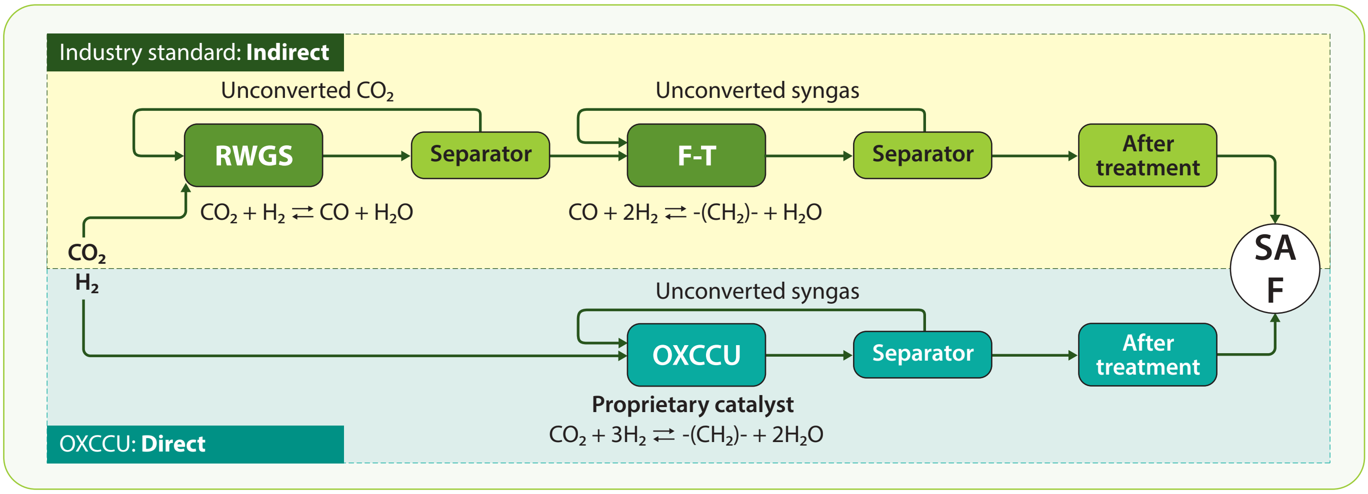

Figure 2 Indirect and direct hydrogenation of CO_2

temperature heat from the F-T reaction. RWGS also requires either a new, complex and difficult-to-scale electrically heated reactor design, or an autothermal reforming (ATR)-like reactor that burns hydrogen, resulting in significant energy loss and high operational cost. The F-T reaction itself can also require expensive reactor designs as it is very exothermic and, as mentioned earlier, needs to be kept down at 280°C.

The solution is a multifunctional heterogeneous catalyst with a surface on which both reactions, RWGS and F-T, can take place (see **Figure 3**). A metal surface can bind CO_2 and then encourage the F-T chain growth reactions, which form the long-chain hydrocarbons, to occur by lowering their activation energies while suppressing methane, light gas, and oxygenate formation.

The key was to go back to the iron F-T catalysts, and this is what OXCCU did. It is now scaling its patented, highly selective iron F-T catalysts for the direct hydrogenation of CO_2. Based on more than a decade of research within the University of Oxford chemistry department and then spun out into OXCCU (*Yao, et al.* 2020), novel catalysts with high conversion and selectivity have been developed, which result in a more efficient process with lower costs to convert CO_2 and H_2 directly to long-chain hydrocarbons. With fewer steps involved, there is a reduction in Capex and Opex, ultimately leading to lower fuel costs. This emphasis on cost reduction is supported by independent researchers from Imperial College London, who demonstrated that OXCCU's one-step technology has a 50% lower capital cost, lower operation costs, and a reduced environmental impact compared to other methods that utilise multi-step processes to create jet fuel.

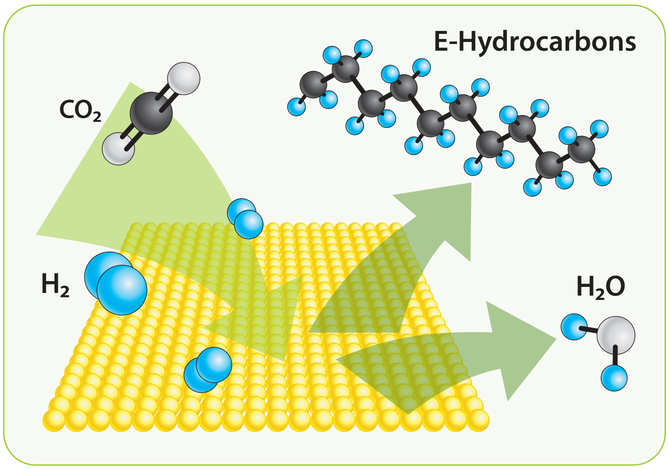

Figure 3 Dual-function catalyst for CO_2 conversion

Before selling as jet fuel, OXCCU will need confirmation that it is within the ASTM D7566 route for F-T SPK. Currently, the F-T SPK annex 1 refers to 'syngas' as the feedstock. While syngas is not specifically defined, it is generally understood that it consists mainly of CO and H_2, not CO_2 and H_2. The OXCCU process, while having only CO_2 and H_2 as the feedstock, still involves CO and H_2 on the surface. Sometimes CO_2 turns to CO on the surface and immediately undergoes a chain growth reaction. Other times, CO formed leaves the surface but is recycled, rebinds, and then undergoes F-T chain growth. Hence, all the CO_2 in the OXCCU process goes via 'syngas' and fits the standards. The only difference between the two-step F-T, which has already been confirmed as acceptable, and the OXCCU one-step F-T process is that the RWGS step happens on the same catalyst surface as the F-T. The intermediate is CO and H_2 (syngas) in both cases, as per annex 1.

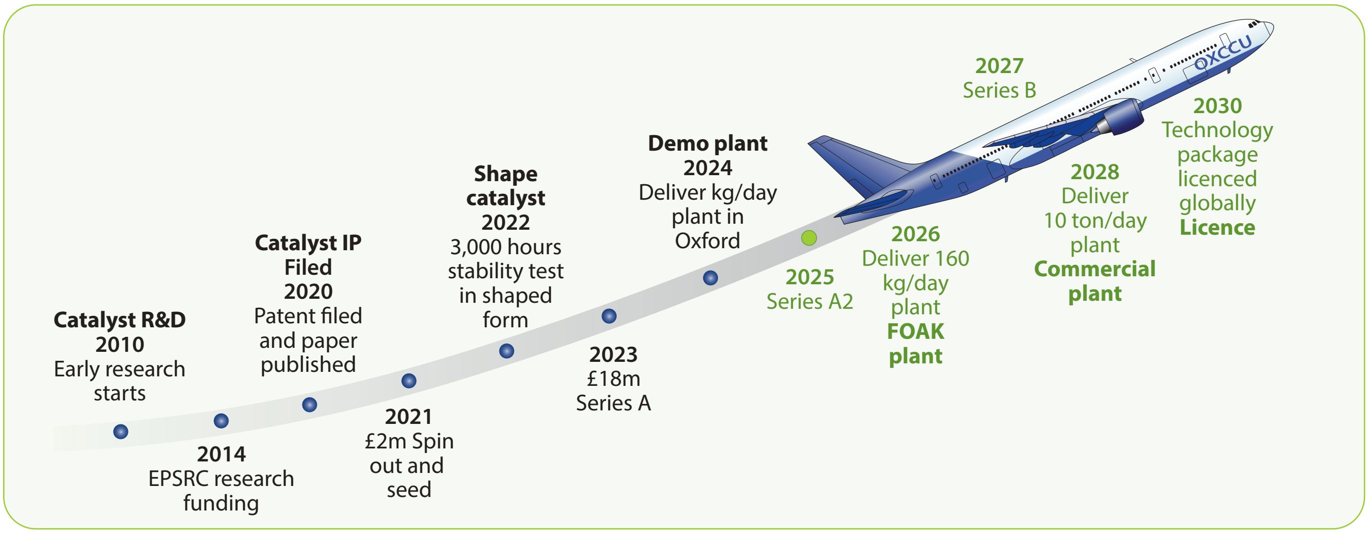

Figure 4 OXCCU's pathway to scale

Pathway to scale

With £2m seed funding, OXCCU built its own lab and established an excellent team of chemists and chemical engineers. It successfully replicated the results from the *Nature* paper over extended periods and in an industrial format.

In 2023, OXCCU secured an £18 million Series A funding round led by Boston-based Clean Energy Ventures, along with support from IP Group, Aramco, Eni, United Airlines, Braavos, Trafigura, University of Oxford, TEV, and Doral, with the purpose of building its OX1 plant in its new site in Oxford Airport. OX1 is now operational, producing 1.2 litres of liquid fuel per day, and will demonstrate the effect of the recycled gases in the recycle loop. It represents a significant scale-up from the lab by a factor of 1,000 and will be operated by OXCCU's growing chemical engineering team. In the OX1 kg/day plant, OXCCU is currently using bottled hydrogen and CO_2, so the fuel is not yet low-carbon. However, the purpose of this plant is to demonstrate its catalyst and process outside of the lab rather than to produce fuel with an excellent LCA. The key is that there is a clear roadmap for scaling and LCA improvement with OX2 (see **Figure 4**).

OXCCU's first-of-a-kind (FOAK) OX2 plant will be based in Saltend Chemical Park, Hull in Humberside and is set to produce 200 litres of liquid fuel per day. Operated by PX Group, it will use green hydrogen and biogenic CO_2. This will provide all the fuel and data required for OXCCU to be able to licence its process to commercial projects. Crucially, the reactor tube dimensions, diameter and height will remain the same, meaning the technology will be substantially derisked. The current target start date is 2026.

The OX3 plant will be OXCCU's commercial facility, which it plans to licence to a project developer, though it expects to be heavily involved. The company anticipates it will produce 10-20 tonnes of liquid fuel per day and generate both e-naphtha for chemicals and plastics, as well as e-SAF to help meet aviation fuel mandates. A key factor for success will be OXCCU's significantly reduced Capex costs compared to others due to the advantages of the one-step process and the ability to utilise existing refinery infrastructure where possible for distillation, hydrotreatment, and blending. ASTM allows up to 5% co-processing with F-T SPK, and current SAF mandates and recycled chemical and plastic regulations allow for mass balancing.

Conclusion

Hydrocarbons are incredible materials, deeply linked to human progress, and cannot always be substituted. The good news is that the fossil type do not have to be used; they can be obtained another way, which reduces their emissions, enabling their continued use. The most scalable is PtL, but the challenge is cost. OXCCU is focused on developing the lowest cost PtL pathway via direct hydrogenation of CO_2, eliminating the RWGS step, and has a path to scale its technology.

VIEW REFERENCES

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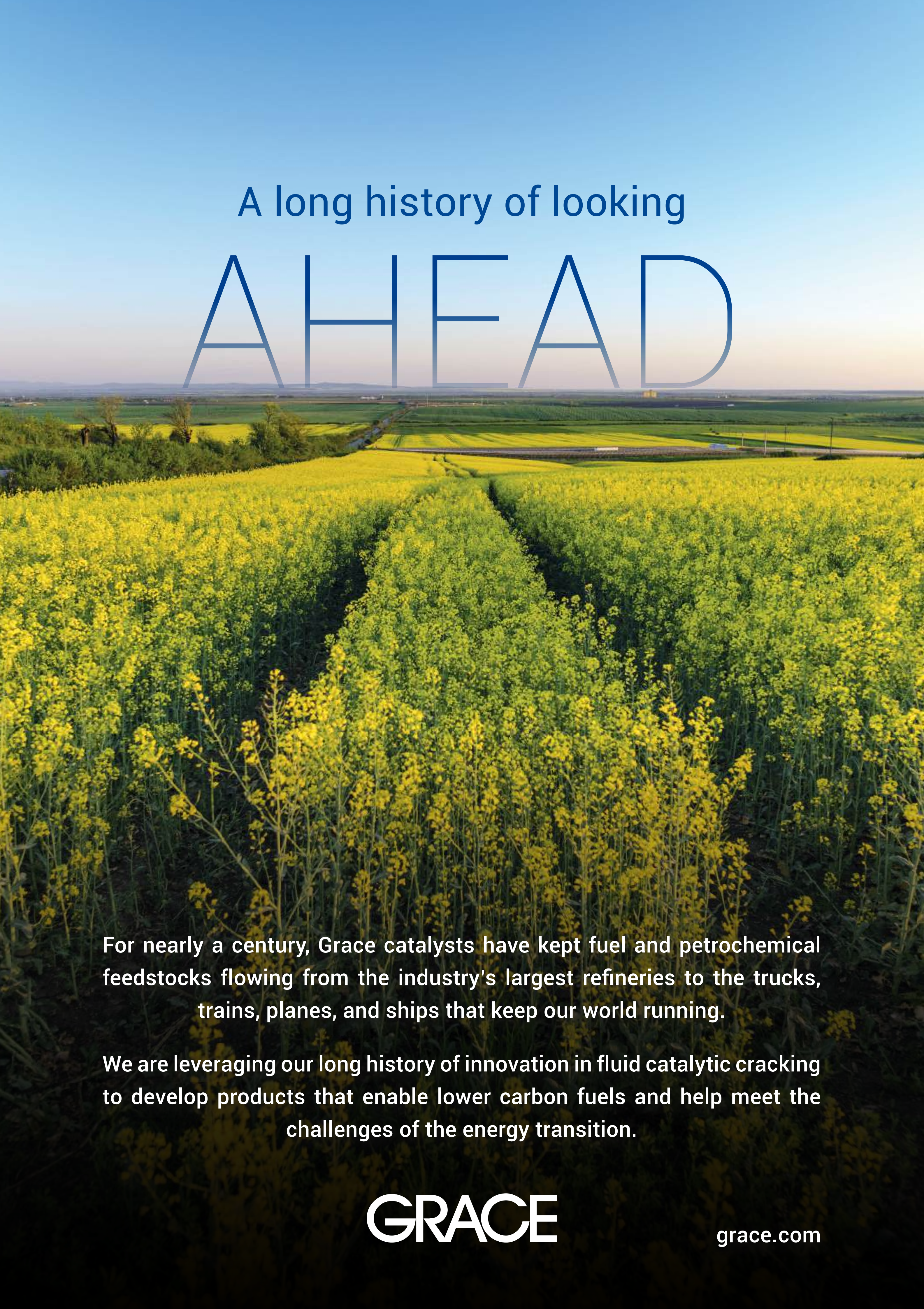

Advanced gasification for waste-to-energy products

Supportive policy needs to address development challenges

Amna Bezanty
KEW Technology

We are at the heart of two major parallel market evolutions; the energy trilemma, in which the UK, along with many other parts of the world, grapples with the affordability, security and sustainability of energy and the creation of a circular economy (see **Figure 1**).

The issue with waste and problematic non-recyclable and single-use waste continues to be a major challenge. There is much talk of creating circular economies where waste is reused or regenerated as a material or product, but how do we deal with the vast quantities of different waste generated worldwide?

At the top of the circular waste hierarchy (see **Figure 2**) is reduction. We all know we have to create less waste. Then, there is reuse and recycle. Travel down the pyramid, and you hit the well-known solutions of how we traditionally deal with waste – incineration backed up by disposal in landfill. For many years, this has been the primary way local authorities have managed their waste, working with waste management companies to take as much waste as possible away from landfill and incinerate.

However, we are facing a huge problem – not just with the vast amounts of waste still generated but also with the pathway to net zero. The waste sector is a significant carbon emitter, with incineration accounting for around 4% of the UK's total emissions, and this is set to rise.

Emissions Trading Scheme (ETS)

The government has also announced that, from 2028, domestic maritime transport, waste incineration, and energy from the waste sector will be added to its Emissions Trading Scheme (ETS) for the first time. Designed to tighten limits on emissions across key sectors such as industrial and aviation as the UK pushes for net zero, this change will have major implications.

In an effort to ensure a level playing field across different technologies, the scheme is targeting incineration, combustion, and energy recovery from waste, including emerging technology like

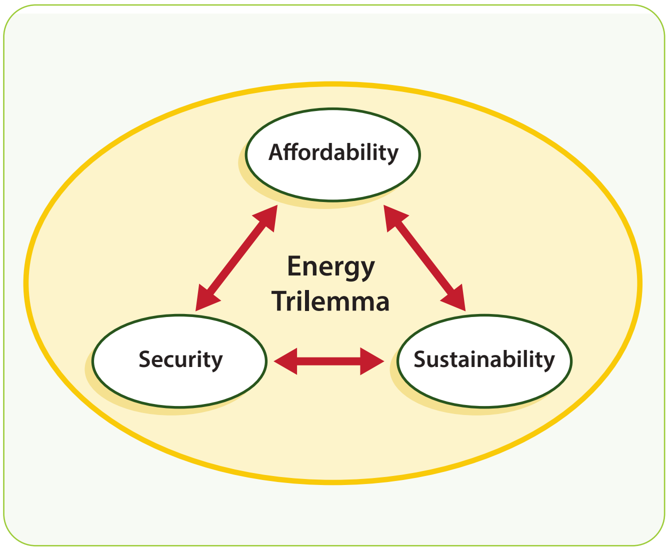

Figure 1 The energy trilemma

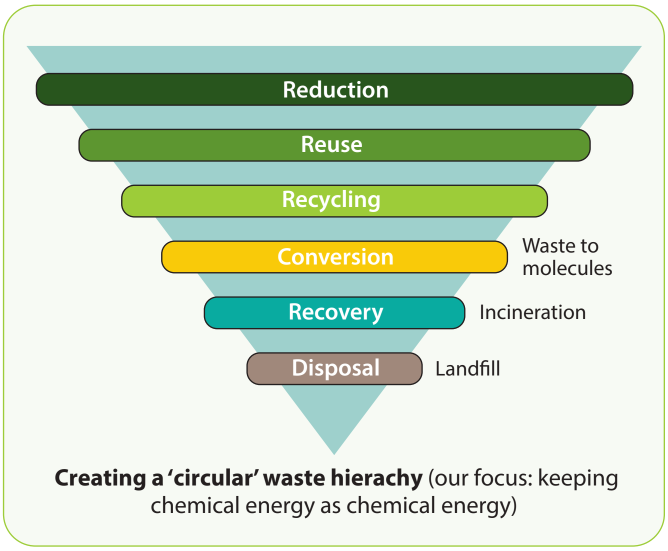

Figure 2 Circular waste hierarchy

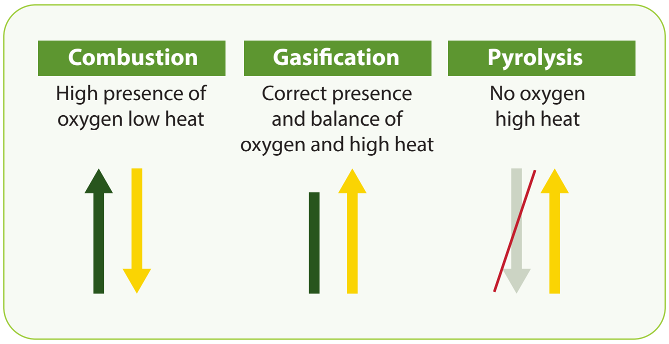

Figure 3 Combustion, gasification, and pyrolysis differ in their requirement for oxygen and heat

Advanced Conversion Technology (ACT), such as advanced gasification, or Advanced Thermal Treatment (ATT), such as pyrolysis.

Waste management in the UK currently relies heavily on incineration and combustion, both of which produce significant fossil CO_2 emissions. However, by including innovative technologies that can transform waste into valuable resources while reducing carbon emissions, some emerging technologies will be severely disadvantaged.

Given the lead times for changing waste management practices, many waste suppliers are looking for viable pathways to net-zero solutions and are currently trying to decarbonise via economically and technically challenging heat offtake or carbon capture, use and storage (CCUS).

The expansion of the scheme while solutions are still needed puts it at risk of becoming counterproductive. Taxing waste-to-energy, such as waste-to-syngas and similar products, without a policy support scheme in place acknowledging their lower carbon nature could undermine their potential to reduce greenhouse gas emissions by placing too great an economic burden on their innovation. These technologies could fundamentally change the waste management system by decarbonising waste before it hits incineration and landfill.

KEW's advanced gasification technology

The use of ACT operating at elevated pressure gasification (8 bar rather than atmospheric) allows the higher-efficiency conversion of carbon-rich feedstocks such as waste and non-recyclable materials and biomass into valuable products such as syngas (a mixture of hydrogen and carbon dioxide, CO_2).

A feedstock can essentially be anything you put into the process, such as municipal solid waste (MSW) from households, commercial and industrial waste, medical waste, and biomass, including wood, crops, agricultural and forestry waste, and sewerage sludge.

Unlike incineration, which burns waste materials in the presence of excess air to produce heat and ash, gasification uses limited oxygen to partially oxidise the feedstock (see **Figure 3**). This process generates syngas and reduces the volume of residual ash, offering a cleaner and more controlled approach to waste conversion.

Being able to achieve a consistent hydrogen-rich, tar-free syngas composition regardless of the feedstock type and composition is a critical pathway to high-value energy molecules.

Ideally co-located on waste disposal sites, it means any feedstock can be used to produce the same consistent compressed fuel (syngas), halving the energy needed to compress captured CO_2 and drastically reducing costs and greenhouse gas emissions (see **Figures 4 and 5**). This could allow waste suppliers to convert their 'dirtiest' waste, which costs them (and


Non-recyclable waste from household, textiles and C&I and municipal solid waste

Agricultural biomass, forestry residues, virgin or waste wood biomass

Sewage sludge, digestate

Industrials' byproduct waste e.g. pulp and paper clients, glass recycling clients

Figure 4 A variety of feedstocks can be used for gasification

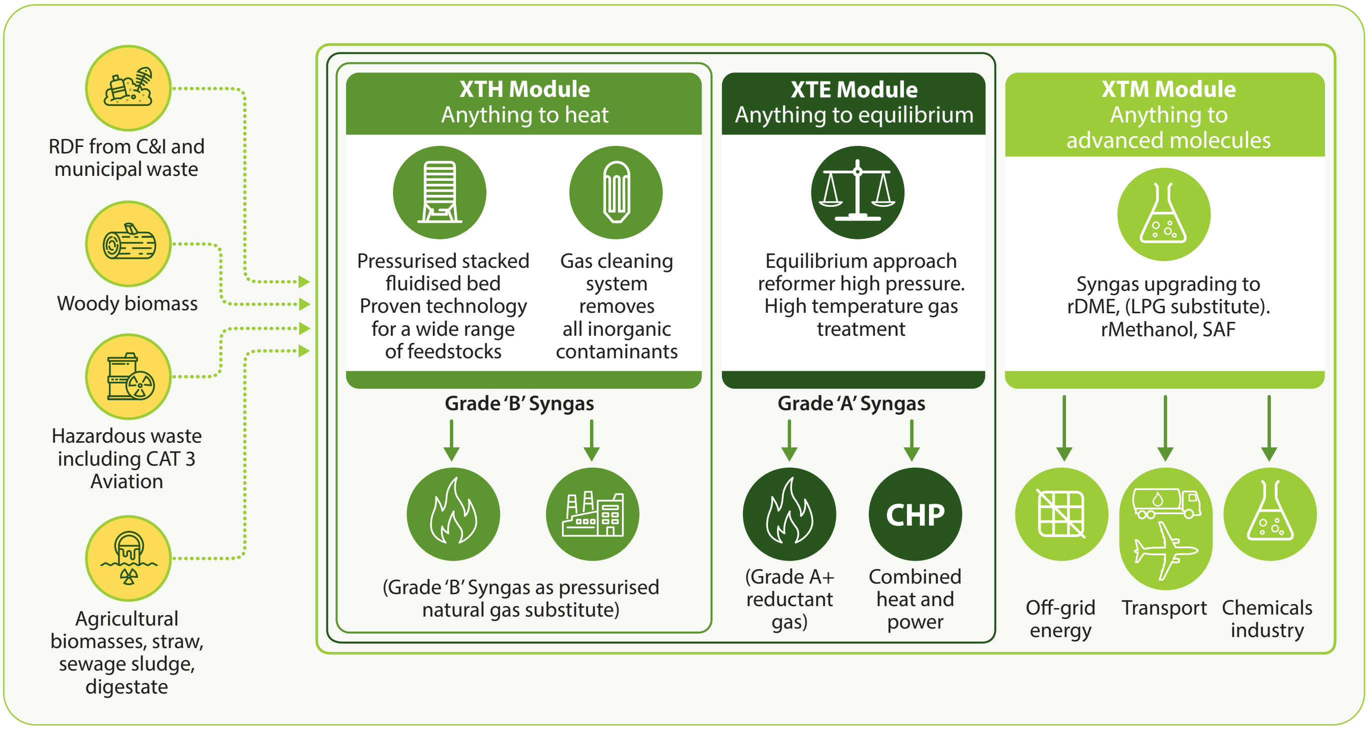

Figure 5 The gasification process can be tuned for different outputs and products

companies) the most to 'deal with', into a stable, clean gas that cuts carbon.

Put in a bag of waste or low-grade biomass, and it can be recycled into high-value molecules such as renewable and recycled carbon natural gas substitutes, hydrogen, methanol, and dimethyl ether, a low-carbon liquefied petroleum gas (LPG) and diesel substitute. The gas that comes out is a hydrogen-rich gas (syngas), which is the building block for everything that can then be converted into multiple fuels.

Feedstock challenges

However, while waste is all around us, sourcing and handling this waste 'feedstock' is not straightforward. The availability of waste is often grossly understated, dependent on type and where it is in relation to where it is needed.

The UK government recognises the importance of ACT technology in reaching net zero and has investigated and reported on the volumes and availability of different feedstocks, with biomass, household waste (MSW), and commercial and industrial waste generated in significant quantities.

Residual MSW and commercial and industrial waste contains almost 50% biogenic matter, with the rest coming from fossil fuels. Biogenic matter, a renewable feedstock input, generates significant CO_2 savings and must be prioritised for more efficient processes targeting the harder-to-abate sector.

The government's review into advanced gasification technologies recognises the attractiveness of MSW and commercial and industrial waste as a fuel, given that it costs money to dispose of and the importance of diverting these waste streams away from landfill to avoid the release of carbon (90% methane) from landfill.

Despite the potential, many high-profile ACTs around the world, including recent examples in America, have struggled or failed. This is not only due to inherent flaws in some of the technologies, but because these projects pursued large-scale implementations. The absence of a smaller-scale validation phase led to unforeseen technology challenges and difficulties in managing the practicalities of waste feedstock logistics. Consequently, these projects often faced insurmountable issues related to feedstock specification and operational feasibility, highlighting the critical importance of phased validation and scale-up processes.

The age-old adage 'build it and they will come' does not work. The key issues of sourcing and preparing feedstocks needs to be discussed and planned right from the start, working across the value chain to ensure an effective flow of waste and energy output.

Figure 6 KEW's demonstration plant

For innovative solutions to succeed, waste suppliers and technology providers must collaborate effectively across the value chain. It is essential for technology providers to work closely with waste companies to ensure a seamless integration of waste management processes and technology implementation. This collaboration helps address challenges related to feedstock quality and operational efficiency, ultimately driving the success of ACTs.

The preparation of feedstock is another challenge. Pretreatment in its many different forms needs to be recognised as a significant barrier to this emerging sector. Feedstocks for ACTs and ATTs require preparation. The wider ACT sector has yet to adequately address the true challenge of consistently processing waste at a competitive gate fee position within commercial-scale plants. Projects in this space often struggle to balance the cost of processing with the quality and specification of the waste feedstock.

Waste as a valuable resource

There has been an increased understanding of waste-to-X projects in recent years, leading to a growing recognition of waste's inherent value.

Emerging ACT technology is opening up new revenue streams as waste is potentially more valuable as a feedstock for energy solutions in harder-to-decarbonise energy vectors. These include off-grid heating, aviation, and transport, as well as industries such as chemicals, glass, cement, metals, and ceramics. This again comes with challenges related to the commercial viability of projects and the availability of feedstocks.

Despite the hurdles, emerging technology demonstration already exists in the UK and is being proven in a commercial demonstrator facility (Sustainable Energy Centre) in Wednesbury in the West Midlands (see **Figure 6**). However, we need to be realistic about the challenges of scaling up emerging technologies in the waste-to-value space especially. A 'start small to build big' approach is crucial for risk mitigation, resource efficiency, stakeholder engagement, and flexibility, ultimately enhancing our chances of long-term success.

Challenging the status quo

Incinerators currently handle large amounts of waste with throughputs of 300-500k (Tpa, AR), whereas modular technology converting waste to syngas/advanced molecules typically handles 200-300k. As many incinerators approach their end of life after 25 years and local authorities look at retendering their waste services, there needs to be a new approach by waste companies. We cannot just maintain the status quo.

The sector needs to be decentralised, with waste management and, ultimately, multiple waste-to-energy and modular solutions operating on a local level using waste generated locally. This tailored approach would not only respond to the differing types of waste produced around the country and, indeed, worldwide, but it could also reinvent waste to energy by meeting the differing fuel needs of local communities, industry, and transport.

It can all sound so simple: localised waste creation and conversion into fuel used locally by industry and communities, powering a truly circular economy overcoming the issues of feedstock supply and fuel demands. However, despite the proven effectiveness of ACT in reducing waste and CO_2 emissions, policy and regulatory barriers, reporting, and verification requirements pose a threat to the progress made so far. KEW's ACT emits circa 70% less CO_2 per MJ of energy output vs incineration and fossil fuel displacement without CCUS.

The expansion of the UK ETS presents a critical opportunity for decarbonisation, but its implementation needs to be right to ensure effectiveness. Innovative solutions must be reflected in policy frameworks to ensure they remain economically viable and continue to develop at scale. The UK ETS framework must encourage, rather than penalise, innovative solutions that contribute to decarbonisation with appropriate support mechanisms on ACT/ATT projects targeting hard-to-abate sectors.

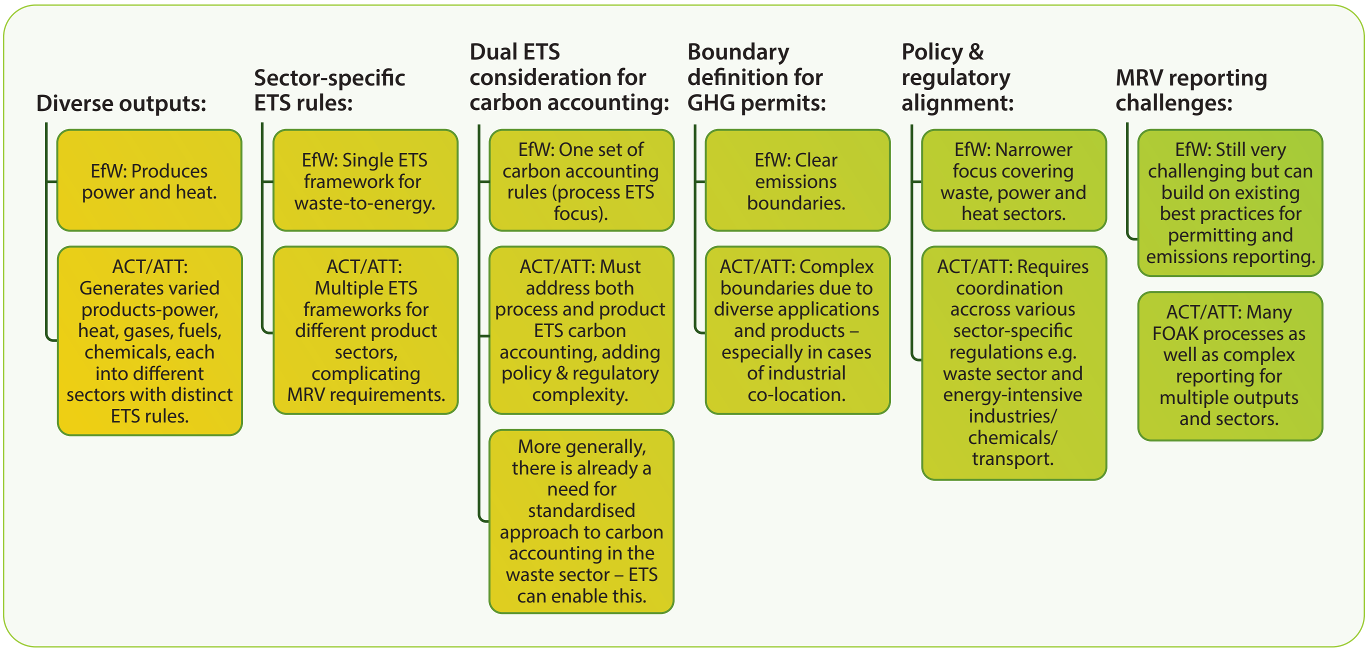

Figure 7 The challenge of including ACT/ATT in the ETS

Recycled carbon fuel (RCF)

Like many others in the sector, we support adopting the Recycled carbon fuel (RCF) methodology to apply an ETS discount on the fossil fuel portion of ACT/ATT emissions, particularly when these technologies are targeting hard-to-abate sectors (see **Figure 7**).

RCFs are derived from non-recyclable waste materials, such as MSW and waste industrial gases, which would otherwise be combusted or landfilled. RCFs are already widely recognised and used effectively within the transport sector in the UK and European Union as credible ways of supporting decarbonisation in other hard-to-abate sectors. Adopting the RCF methodology to apply an ETS discount would facilitate the fair inclusion of advanced technologies in the UK, potentially resulting in cost savings for ETS customers like local authorities. However, this discount must be carefully calibrated to account for existing support mechanisms available, such as some downstream applications.

Like the way RCFs are recognised in transport sector accounting, we would like to see the creation of a standardised carbon accounting methodology that can be developed into an accounting framework for the waste sector. Unlike the Low Carbon Hydrogen Standard (LCHS) for hydrogen and the Renewable Transport Fuel Obligation (RTFO) for transport, there is no consistent and transparent emission reporting for the waste sector.

Varying feedstocks and the need to work backwards to the point of origin make monitoring, reporting, and verification extremely complicated. Certification schemes such as the International Sustainable Carbon Certification (ISCC), which provides a stamp for the end product, are difficult when you would need to know the waste's history and and its exact point of origin, for example, which town or city and which local authority.

Cross-departmental collaboration, particularly in the wake of a new government, needs to happen as soon as possible. It is crucial that the Department for Energy Security and Net Zero (DESNZ), the Department for the Environment, Food and Rural Affairs (DEFRA), the Department for Transport (DfT), and other relevant bodies work together to develop strong ETS frameworks.

The picture, as it has been for the past decade of KEW Technology, is complicated and challenging but not insurmountable with a shared goal of a world without fossil fuels. If we create an environment that fosters innovation and sustainability across all sectors on a level playing field, we can reach net zero collaboratively. It will be many technological solutions, not one golden bullet, that get us there.

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Circular syngas with biomass and plastic waste gasification

Solid and liquid gasification has the potential to unlock and convert advantaged feeds into high-value, bio-based and circular fuels, chemicals, and plastics

Harold Boerrigter and Sven Felske
Shell Catalysts & Technologies

As the energy transition gathers pace, more and more refiners and chemical manufacturers are evaluating the benefits of upgrading existing gasification units to produce lower-carbon and more circular products.

Gasification of hydrocarbon feedstocks to generate syngas and related products is a well-established process. However, with new advancements in pre-conversion technologies – capable of processing more complex materials like mixed plastics, biomass, and unsorted waste streams – gasification has the potential to become a key technology for producing lower-carbon synthetic biofuels and enhancing plastic circularity.

Crucially, revamping gasification units to accept pre-converted biomass and waste streams can be done quickly and cost-effectively.

Energy transition: The case for change

The United Nations Framework Convention on Climate Change's (UNFCCC) recent stocktake on global climate action made it clear that the world is behind where it needs to be in efforts to mitigate the impacts of climate change. Indeed, recent estimates suggest that the global carbon budget to limit global warming to 1.5°C has shrunk to just 275 $MtCO_2$ – less than seven years of carbon emissions at current rates.

With fossil-based transport fuels contributing about 20% of global carbon dioxide (CO_2) emissions, there is a growing imperative to switch to lower- and zero-carbon fuels. For example, the EU's ReFuelEU aviation initiative mandates a progressive increase in the use of sustainable aviation fuels (SAF) and synthetic aviation fuels. By 2035, aviation fuel supplied at EU airports must contain at least 20% SAF – a 900% increase compared to 2025 requirements.

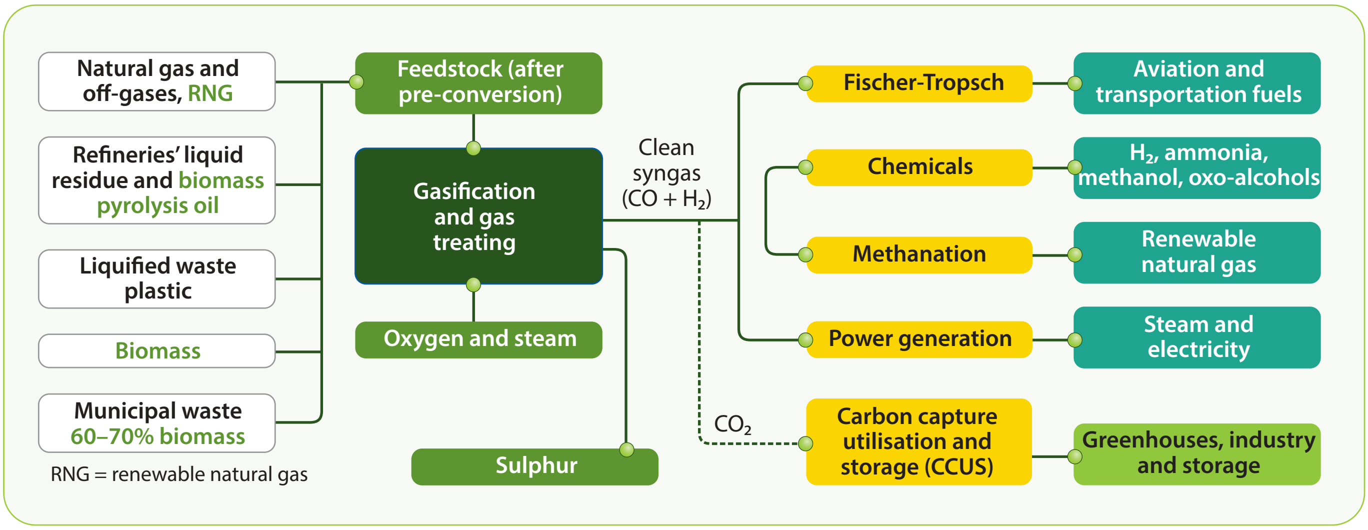


Figure 1 Gasification can produce low-carbon-intensity syngas for conversion into a wide range of lower-carbon and more circular products

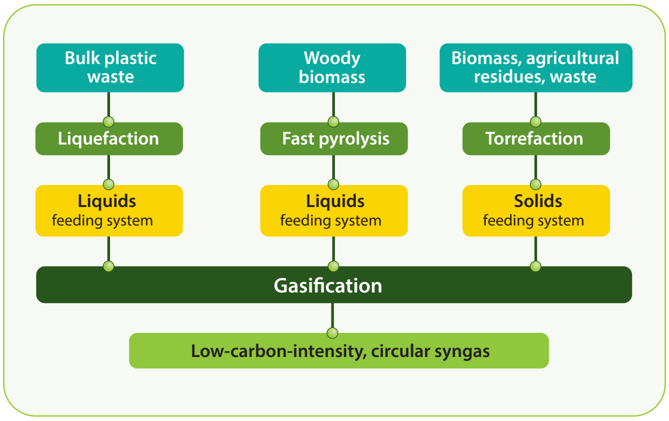


Figure 2 Shell and its strategic partners have developed a range of pre-conversion technologies suitable for a wide range of waste streams

At the same time, the world has a growing waste problem, generating more than 2 billion tonnes of solid waste annually – a total expected to grow by more than 80% by 2050.

> “Adapting production sites with existing gasification units to process low-value mixed municipal, biomass, or unsorted plastic waste is an efficient and cost-effective approach”

In particular, plastic waste makes up as much as 12% of global solid waste, the majority of which ends up in landfill or incineration, or is mismanaged.

Indeed, less than 10% of global plastic waste is recycled each year, leading to greater efforts to increase recycling rates and plastic circularity. For example, the EU has introduced a ban on member states exporting hazardous or hard-to-recycle plastic to non-OECD countries. It has also set stringent waste-reduction targets, which include increasing its plastic recycling rate to 55% by 2030 and sending less than 10% of municipal solid waste (MSW) to landfill by 2030.

The gasification opportunity

Gasification is an established process – one that Shell has been pioneering for almost 70 years by combining continual research with real-world learnings from gasification projects around the world.

Today, thanks to new pre-conversion technologies developed by Shell and its strategic partners, gasification can convert a wide range of low-value, mixed municipal, biomass, and unsorted plastic waste and residues into a valuable syngas. Syngas is a versatile intermediate feedstock that can be used instead of virgin hydrocarbons to produce fuels, electricity, chemicals, and plastic (see **Figure 1**).

Crucially, adapting production sites with existing gasification units to process low-value mixed municipal, biomass, or unsorted plastic waste is an efficient and cost-effective approach (compared to greenfield projects) that provides companies with two key opportunities.

First, they can leverage low-value biomass waste, such as sustainable wood residues

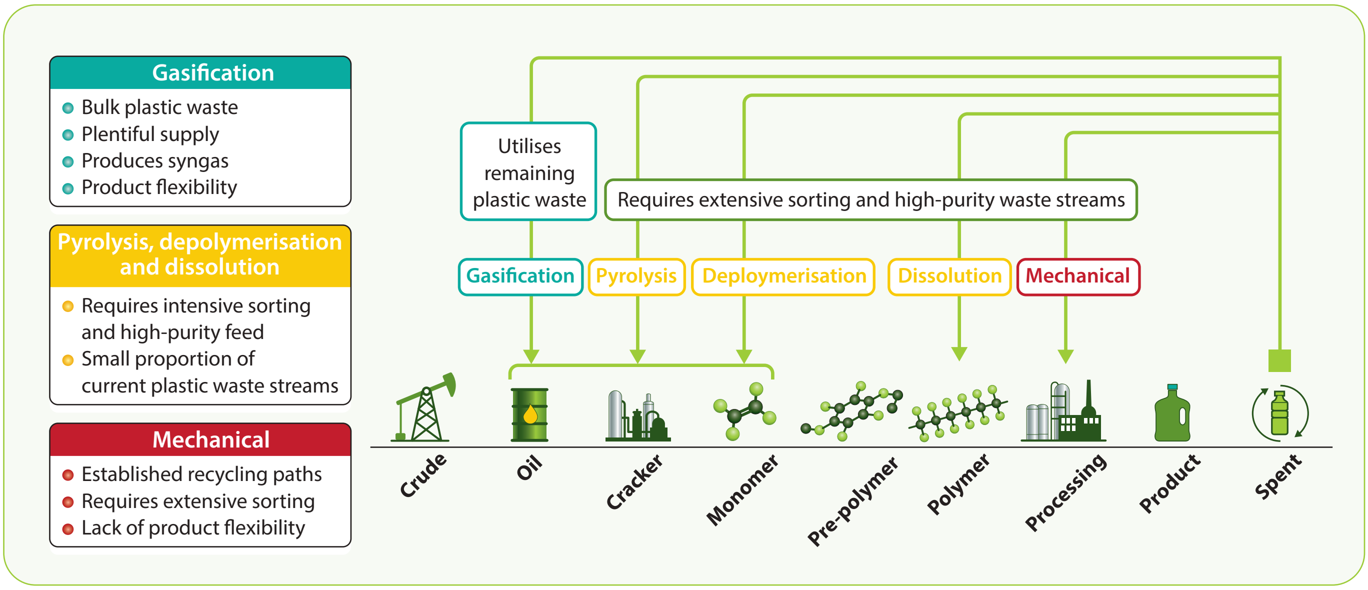
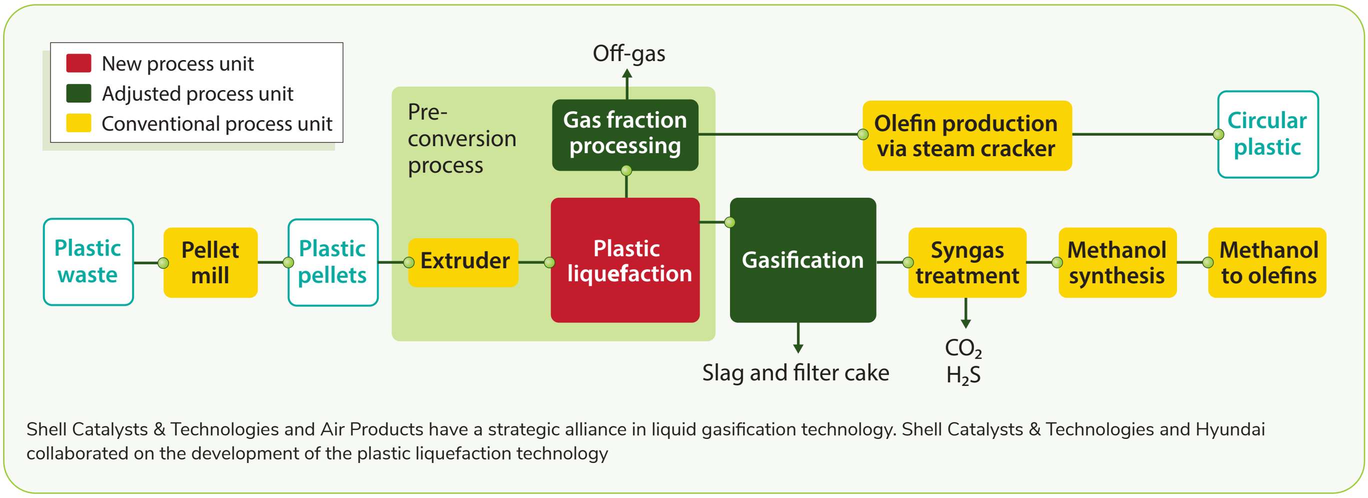


Figure 3 Gasification can be used to complement other plastic-recycling methods to produce syngas that is equivalent to virgin feedstock



Shell Catalysts & Technologies and Air Products have a strategic alliance in liquid gasification technology. Shell Catalysts & Technologies and Hyundai collaborated on the development of the plastic liquefaction technology

Figure 4 Plastic liquefaction pre-conversion technology can be installed upstream of an existing gasification unit

from industrial biomass processes, to produce low-carbon, bio-based fuels with significant margins. Doing so can help reduce the carbon footprint and circularity of operations and products. Second, operators can produce high-value, circular plastic by leveraging the growing supply of low-value plastic waste.

Pre-conversion of waste for gasification

Pre-conversion is a key process that can convert a diverse range of materials (such as unsorted plastic waste and biomass) into intermediate feedstocks for gasification units. Shell has developed a range of pre-conversion technologies that offer operators flexibility to use waste feeds that best suit their circumstances: liquefaction for bulk plastic waste, fast pyrolysis for woody biomass, and torrefaction for biomass and agricultural residues (see **Figure 2**).

Plastic liquefaction for bulk plastic waste

Today, as much as 85% of plastic waste is sent to landfill, incineration, or left unmanaged, largely because current methods, including mechanical recycling and chemical recycling by pyrolysis, require well-sorted, high-purity plastic waste streams, which are costly and resource-intensive to create.

Plastic liquefaction, however, can take plastic waste unsuitable for other recycling methods and pre-convert it into gasification feedstock to produce syngas that is equivalent to virgin feedstock (see **Figure 3**). Importantly, when used alongside existing plastic recycling methods, plastic liquefaction has the potential to play an important role in helping to close the plastic circularity loop. So, how does plastic liquefaction work?

The plastic liquefaction technology, developed as part of a strategic collaboration with Hyundai, features a novel liquefaction unit that can be installed immediately upstream of an existing gasifier (see **Figure 4**). With no additional units required, deployment is quick and can be done with relatively little cost. See the Feasibility study overleaf for an example of how a European refiner has evaluated switching to waste gasification to produce high-value circular chemicals.

	Conventional feedstock	Liquefied plastic feedstock
C:H ratio	7.7:10.8	<7
Oxygen	<1.5 wt%	>1.5 wt%
Sulphur	**<7 wt%**	**<0.1 wt%**
Nitrogen	<1.5 wt%	<1 wt%
Viscosity	<300 cSt by temperature	<300 cSt by temperature
Halides	**<75 ppmw**	**>300 ppmv**
Ash	**<0.2 wt%**	**>1 wt%**
Main ash components	Ni, V, Fe	Al, Ca, Si, Ti, Fe
Ash behaviour	**Non-slagging, only soot**	**Slagging + soot**
Higher heating value	>38 MJ/kg	>38 MJ/kg

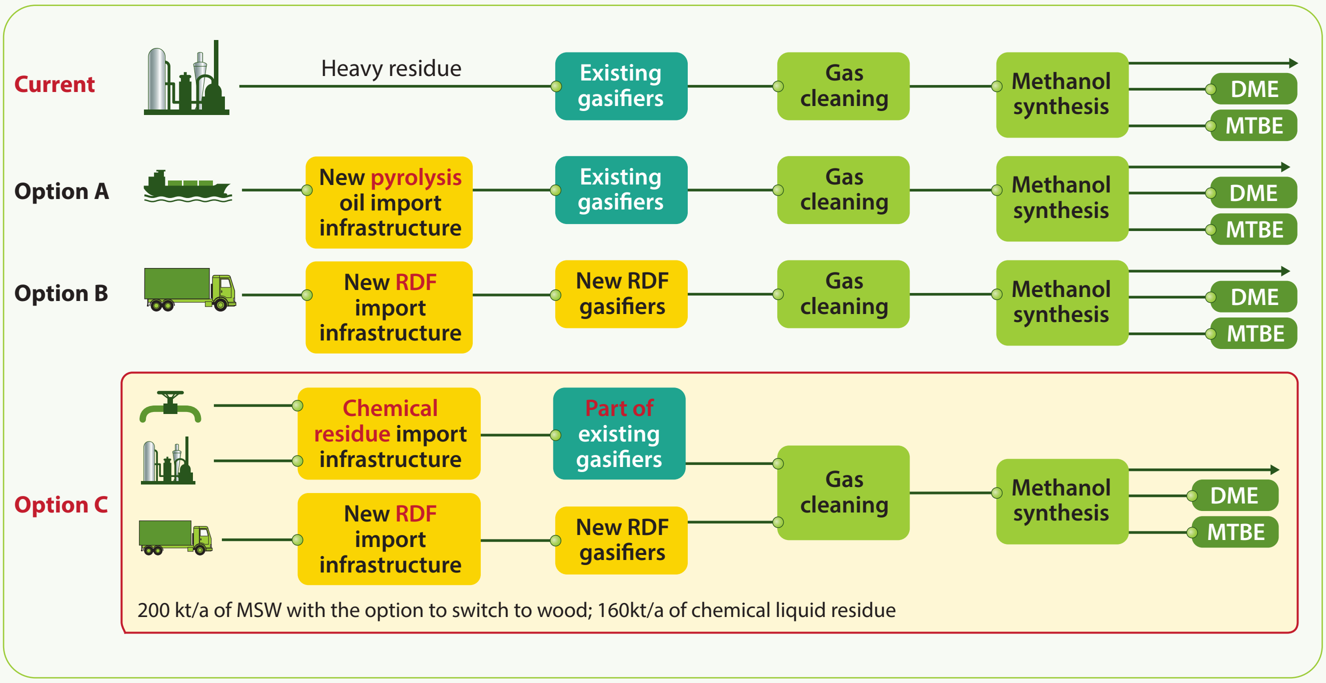
Table 1 Comparison of conventional (hydrocarbon) and plastic liquefaction gasification feeds. Important differences are highlighted in bold

Feasibility study: Repurposing a European refinery for circular chemicals

A European refiner wanted to explore the potential to produce circular[*] and/or bio-methanol (bio-MeOH)[*], dimethyl ether (DME), and methyl tert-butyl ether (MTBE) while using existing equipment.

Shell Catalysts & Technologies evaluated three options:

- **Option A** assessed switching gasification feedstock from heavy residue to imported pyrolysis oil. This option would require investment in new pyrolysis oil import infrastructure. However, existing gasifiers and infrastructure would remain unchanged.
- **Option B** evaluated switching to imported refuse-derived fuel (RDF), which would require investment in new gasifiers (tuned to the feed type) and new RDF import infrastructure.
- **Option C** considered two gasification feedstocks: (1) chemical residues sourced from neighbouring chemical plants and (2) municipal solid waste, with the option to switch to wood according to waste availability. This option would require investment in chemical residue and RDF import infrastructure and new RDF gasifiers that would work alongside existing gasifier units.



Significant upside potential

Option C provides the most upside potential and return on investment when considering Capex, cost of gasification feedstocks, and potential revenue from circular and bio-methane.

Yield potential: 380 kt/a of mixed methanol

- 20% circular methanol
- 30% bio-methanol
- 50% methanol derived from fossil-fuel-based waste[**]
- Methanol can be used as sustainable fuel or processed into MTBE or DME according to market demand.

[*] Circular methanol is derived from plastic waste; bio-methanol is derived from organic waste, including biomass residues from industrial processes.

[**] Fossil-fuel-based waste includes liquid chemical waste streams from nearby chemical plants.

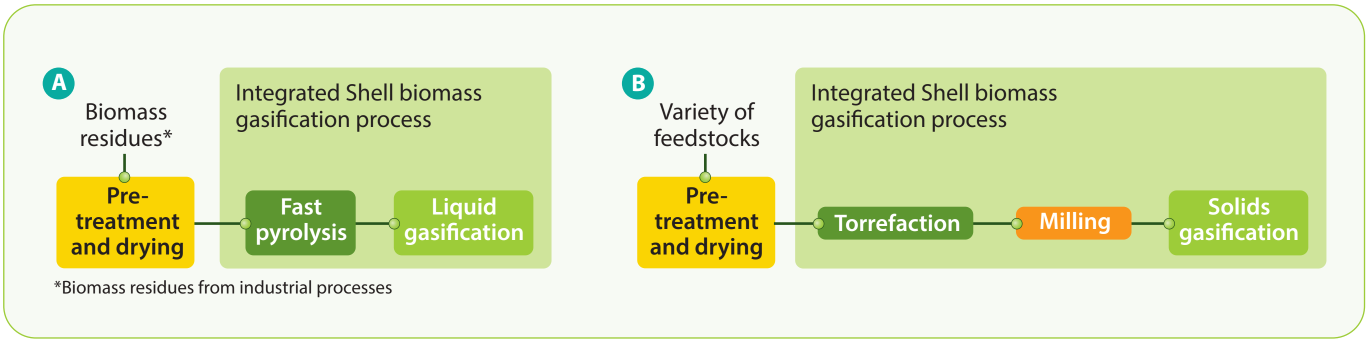


Figure 5 Integrated Shell biomass gasification process with **(a)** fast pyrolysis and **(b)** torrefaction

A key consideration is the characteristics of plastic-derived gasification feedstock produced by liquefaction, which differ slightly from fossil-based feeds. For example, **Table 1** highlights differences in sulphur, halides, ash, and ash behaviour. While these differences are important, they can be managed with only minor adjustments to an existing gasifier and connected equipment. For example:

- Reconfiguration of upstream feedstock system to deal with different fouling and cracking behaviour.
- Change refractory material to withstand fluctuating slag composition.
- Addition of slag removal system (proven system used in goal gasification).
- Upgrade materials based on expected chloride levels.
- Simplify wastewater and sour gas treatment (plastic waste is relatively poor in sulphur).

Fast pyrolysis for woody biomass

Fast pyrolysis converts woody biomass, such as waste wood from industrial processes, into pyrolysis oil suitable for gasification (see **Figure 5a**). As part of the integrated Shell biomass gasification process, fast pyrolysis can be deployed in existing liquid/residue gasifiers with only minor adaptions to the feed system. Moreover, because fast pyrolysis is relatively simple and quick to deploy, it can contribute to a faster reduction in carbon intensity and the production of low-carbon products when used with existing gasifiers.

Torrefaction for solid biomass, residue and unsorted waste materials

Torrefaction converts a wide range of biomass and unsorted waste into a product with similar properties to lignite that can be easily ground into a fine, homogeneous powder suitable for the entrained-flow gasification of solids (see **Figure 5b**). With similar properties to lignite, torrefied biomass can be used in commercially proven lignite gasification units. Moreover, lower unit technical costs make torrefaction more attractive for greenfield projects compared with the fast-pyrolysis route.

> **“Solid and liquid gasification has the potential to unlock advantaged feeds and convert them into high-value, bio-based and circular fuels, chemicals, and plastics with attractive margins”**

Quick and cost-effective deployment today

As demand for lower-carbon and more circular products grows, solid and liquid gasification has the potential to unlock advantaged feeds, such as low-value biomass residues and unsorted plastic waste, and convert them into high-value, bio-based and circular fuels, chemicals, and plastics with attractive margins.

Using existing gasifiers with only minor adaptions and novel pre-conversion technologies, gasification can be a quick-to-deploy and cost-effective way for refiners to meet changing market preferences and align with increasing regulations on carbon emissions and circularity.

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Ammonia: a cracking opportunity for hydrogen

The rapid expansion of ammonia as a storage medium and a method for transporting hydrogen positions it as a potential key player in the energy transition

Joachim Harteg Jacobsen
Topsoe

Ammonia's increasingly rapid growth as an energy carrier and storage medium for hydrogen is a fairly recent phenomenon. As the world shifts towards low-carbon energy, ammonia has stepped forward as a potentially central player in the energy transition both as a fuel and transportation method for hydrogen. However, knowledge and experience are key to cracking open the available opportunities.

The robust and scalable nature of the ammonia supply chain has solidified its appeal. With more than 20 million tons of ammonia already traversing the globe, along with the emergence of mega-scale blue hydrogen and ammonia projects and advancements in green production, the market is witnessing unprecedented interest.

Hydrogen can be easily turned into ammonia using the established Haber-Bosch process. As ammonia can be transported as a liquid and has a much higher energy density than compressed hydrogen gas, it is an extremely efficient way to transport hydrogen globally. Once the ammonia reaches its destination, it can be converted back into hydrogen through the ammonia cracking process.

Basics of ammonia cracking

Ammonia cracking is a chemical process that converts ammonia (NH_3) into its constituent elements: nitrogen (N_2) and hydrogen (H_2). This reaction is typically carried out at high temperatures and can be catalysed by various catalysts. The process is endothermic, meaning it requires the input of heat energy. The catalyst helps to lower the activation energy required for the reaction to occur, thus increasing the reaction rate.

The most basic layout for an ammonia cracking process includes at least the following steps:

- Vaporisation and preheating of the raw ammonia feed.
- Catalytic decomposition of ammonia.
- Removal of unconverted ammonia and purification of the hydrogen product.

Large-scale ammonia cracking

Many people mistakenly believe that ammonia cracking is a new or emerging technology. In a short time, it has attracted interest from established energy and fuel companies seeking a new business stream and from new players driven by innovation and ambition.

Ammonia cracking is an important industrial process with several applications. One of its main uses is in the transportation of hydrogen gas, which is a valuable fuel and feedstock for various industries. Hydrogen can be turned into ammonia, a derivative product, via the Haber-Bosch synthesis, as explained below. The ammonia is then transported and converted back into hydrogen via the process of ammonia cracking. The resulting hydrogen can be used for the production of power, fuels or steel, natural gas replacement, and various industrial and chemical processes.

The technology used in large-scale ammonia cracking is proven and has been in industrial use for decades. Topsoe's first ammonia cracking technology was developed in 1978, with a focus on heavy water production. The largest ammonia cracking facility, capable of cracking 2 x 2,400 MT per day of ammonia in two parallel lines, was built in Argentina in 1993.

Ammonia cracking can be centralised on a

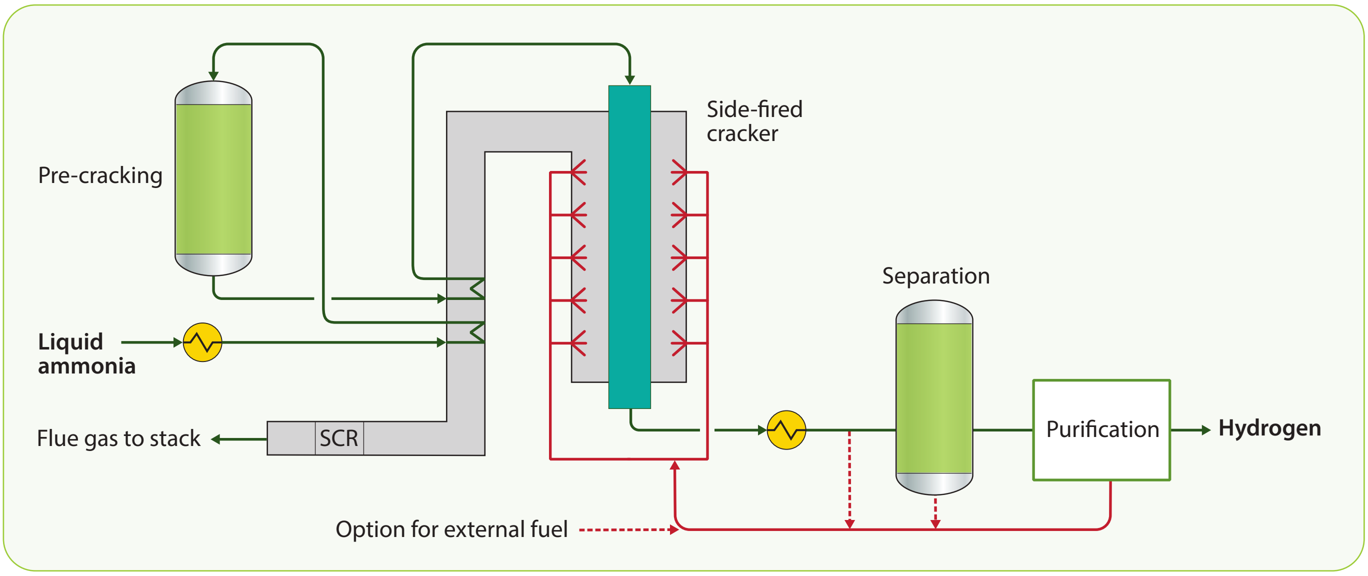

Figure 1 Ammonia cracking process

large to mega-scale, with hydrogen transported to the end-use through extended hydrogen grids, as planned in Europe. It can also be decentralised on a large-scale and co-located with large hydrogen off-takers, possibly via local hydrogen grids. Finally, it can be done on a small-scale and decentralised, for example, at hydrogen filling stations.

Solid transportation method for hydrogen

Ammonia is considered an important transportation method for hydrogen for several reasons. First, it is energy-dense, with a higher energy density than compressed hydrogen gas. This means that a larger amount of energy can be stored and transported in the form of ammonia compared to compressed hydrogen, making it more efficient for long-distance transportation. Ammonia is also free of carbon, making it the highest energy-density, non-carbon medium.

Crucially, ammonia can be stored and transported as a liquid at -33°C, so it does not require high-pressure or cryogenic storage. It is also easier to handle and has well-established safety protocols and regulations.

The second reason is that the infrastructure for ammonia is mature, and safety best practices already exist. Ammonia has an extensive infrastructure for production, storage, and transportation. It is already produced in large quantities for various industrial applications, such as fertiliser production. Leveraging this existing infrastructure can help facilitate hydrogen transportation without needing significant new infrastructure development.

Finally, the process of converting ammonia back into hydrogen through ammonia cracking is simple and has been successfully demonstrated on a large scale. This means that hydrogen can be extracted from ammonia at the point of use, enabling the utilisation of ammonia as an ideal and flexible hydrogen carrier.

Using ammonia to transport hydrogen

Hydrogen needs to be transported to different regions for several reasons. Regions with high energy demand may not have sufficient local hydrogen production capabilities, while other regions may have access to cheaper or more reliable feedstock. Regions rich in renewable energy sources, such as wind or solar, can produce green hydrogen through electrolysis. Transporting this green hydrogen to other areas supports the integration of renewable energy into the broader energy system.

By using ammonia as a carrier, end-point users can take advantage of cheaper or more readily available feedstocks and production processes elsewhere on the globe. Additionally, ammonia's ability to be liquefied allows it to be transported at a lower cost than hydrogen. These benefits help offset the costs of conversion and make the process economically efficient.

There are three main stages in transporting hydrogen using ammonia as a carrier:

① **Conversion of hydrogen to ammonia:** H_2 is first converted to NH_3 through a process called

Haber-Bosch synthesis. This process involves reacting hydrogen with N_2 under high pressure and temperature in the presence of a catalyst. The resulting ammonia is then liquefied and stored for transportation.

❷ **Transportation of ammonia:** Ammonia is transported using existing infrastructure such as pipelines, ships, or trucks, as it is already produced and transported in large quantities on a global scale. The ammonia can be stored and transported as a liquid at -33°C, making it easier and safer than transporting hydrogen, which requires high-pressure or cryogenic storage.

❸ **Conversion of ammonia back to hydrogen:** At the destination, the stored ammonia is converted back to hydrogen through ammonia cracking. The process begins by heating and evaporating liquid ammonia, which is initially at -33°C. Once vaporised and heated to the reaction temperature, the ammonia is directed to the cracking section where ammonia cracking occurs.

In ammonia cracking, the ammonia vapour is further heated to high temperatures in the presence of a catalyst. This causes the ammonia to decompose into N_2 and H_2 according to the reaction:

$$2NH_3 \leftrightarrows N_2 + 3H_2.$$

The hydrogen produced from ammonia cracking can be used for various applications, such as in fuel cells, natural gas replacement, and in various chemical processes. This hydrogen can be stored, distributed, and utilised in the same way as hydrogen produced from other sources.

The critical areas when choosing ammonia cracking as a new business opportunity are:

❶ **Process efficiency – technology choice:** The cost of the ammonia feed is the primary cost factor in producing hydrogen from ammonia cracking. Therefore, it is essential to choose the most efficient and optimised technology available. Any losses or inefficiencies will directly affect the hydrogen yield and result in extra energy-related costs. It is important to optimise the ammonia cracking process to minimise losses and maximise hydrogen yield.

Topsoe's technology, H2Retake (see **Figure 2**), for instance, utilises the energy input in the side-fired ammonia cracker to drive the decomposition reaction and effectively preheat and evaporate the raw feed with minimal wastage. The high efficiency is achieved through a streamlined ammonia cracking design, optimised heat and off-stream integration, and careful catalyst selection, resulting in an impressive energy efficiency of 96%.

❷ **Catalyst selection:** The choice of catalyst for ammonia cracking is crucial. Selecting a highly active, stable catalyst with high strength and minimum pressure drop is essential for an effective and energy-efficient process. Understanding the performance and durability of the catalyst under different operating conditions is important to ensure optimal conversion rates and minimise catalyst degradation.

❸ **Safety – location and permitting:** Ammonia is both toxic and corrosive but also a long-standing and widely used substance. As a result, well-established safety procedures ensure proper safety measures are in place for the storage, handling, and transportation of ammonia. Assessing and implementing appropriate safety protocols, materiality of infrastructure, and training is critical to mitigate any potential risks associated with ammonia handling.

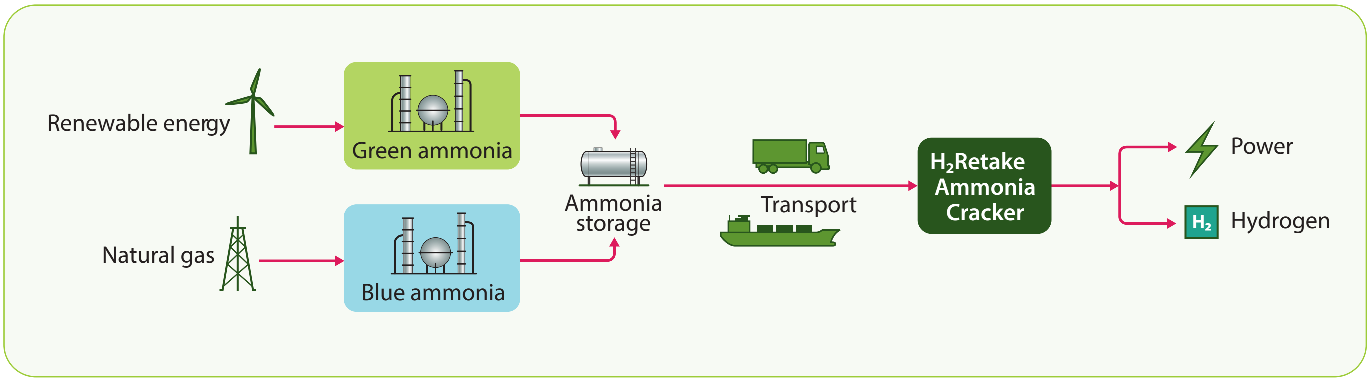

Figure 2 Topsoe's H2Retake technology

The location of ammonia cracking facilities can be important in permitting approval. For instance, ammonia handling at ports is often well-established, with a surrounding safety ecosystem, such as handling infrastructure, communications accessibility, security, and emergency response protocols, already in place. Locating facilities inland can mean additional complexities, especially if close to population centres.

④ **Carbon intensity:** Depending on the sustainability goals of the project, environmental impact and carbon intensity should be considered. The source of energy used for the process can impact the overall carbon footprint. Evaluating the environmental implications and exploring the use of renewable or low-carbon energy sources for ammonia production and cracking can help minimise the environmental impact. For instance, green methods that use renewable energy have the lowest environmental impact, while blue/low-carbon methods can result in low or very low carbon intensity, depending on the efficiency of carbon capture and potential upstream emissions.

⑤ **Fuel choice for ammonia cracking:** When choosing a fuel for ammonia cracking, it is important to consider factors such as overall efficiency, environmental impact, and economic viability of the process. The economic viability of ammonia cracking is influenced by the cost and availability of the fuel, so if ammonia itself is being used, it is important to ensure that its usage is as efficient as possible to maximise the amount of hydrogen produced. Using ammonia as a fuel decreases hydrogen yield. However, it ensures that all process energy originates from ammonia, leading to a hydrogen product with zero carbon intensity (provided the ammonia itself has zero carbon intensity).

Utilising external fuels boosts hydrogen yield, but it may cause CO_2 emissions. However, if using carbon-neutral fuels such as biogas or biomethane, these CO_2 emissions will not impact the product hydrogen carbon footprint. This can help align with environmental regulations and sustainability goals.

⑥ **Know-how and experience:** Ammonia cracking is a growth area with many new players involved. Working with experienced technology providers ensures you have a partner with a deep understanding of ammonia cracking processes, catalysts, and reactor design, accumulated over years of research, development, and practical application.

This expertise and proven track record of successful implementations allows them to offer valuable insights, optimise the process, and troubleshoot any challenges that may arise during the project. Established technology providers often offer reliability and performance guarantees and have well-established project management processes and support systems in place, covering the entire project lifecycle.

For instance, Topsoe has extensive experience in large-scale industrial ammonia cracking, spanning several decades. This experience in catalyst development and manufacturing, coupled with numerous insights gained over decades of operation, allowed us to launch the first large-scale ammonia cracking technology for commercial hydrogen production in 2022.

Any new ammonia cracking venture has a focus on profitability, which requires high production efficiency. The energy and hydrogen efficiency of H2Retake technology ensures the best possible business case for an ammonia cracking plant. This is achieved through a streamlined ammonia cracking design, optimised heat and off-stream integration, and careful catalyst selection. H2Retake achieves an impressive energy efficiency of 96%, making it a highly cost-effective and sustainable solution.

Time to get cracking?

The rapid growth of ammonia as a hydrogen energy carrier and storage medium has given it a vital role in the global energy mix. The scalability and efficiency of ammonia cracking, particularly with advanced technologies like H2Retake, present significant opportunities for the burgeoning industry. Leveraging decades of experience and continuous innovation, Topsoe is ready to guide ventures through the complexities of ammonia cracking, helping them achieve profitability and efficiency.

H2Retake is a trademark of Topsoe.

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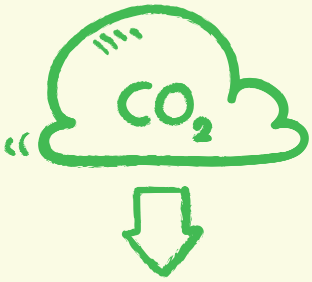

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Propelling the maritime industry to sustainability with methanol

Sustainable methanol is emerging as a promising solution towards achieving ambitious emission reduction goals in the maritime industry

Zinovia Skoufa
Johnson Matthey

The shipping industry is hard to decarbonise, but renewable methanol is emerging as a key option as maritime transport looks to reduce its greenhouse gas (GHG) emissions, transition away from fossil fuels, and make use of renewable feedstocks. Methanol engines are already available and being used on vessels, making this fuel a promising pathway for reducing emissions in maritime transportation today.

The sector is pivotal in the global economy, serving as the backbone of international trade and commerce. With more than 80% of the world's goods transported by sea, maritime shipping facilitates the movement of raw materials, commodities, and finished products across continents and oceans. By connecting markets and facilitating trade, the industry enables businesses to access diverse markets, source materials globally, and distribute goods efficiently. This interconnectedness fosters economic growth, drives industrial development, and supports job creation worldwide.

Current impact of shipping on global emissions

The shipping industry, while indispensable to global trade, also contributes significantly to GHG emissions and environmental pollution. Accounting for around 2-3% of global emissions, it represents a substantial yet often overlooked source of carbon dioxide (CO_2), nitrogen oxides, sulphur oxides, and particulate matter released into the atmosphere.

Despite efforts to improve fuel efficiency and adopt cleaner technologies, the sheer scale of shipping operations means that even incremental reductions in emissions can have a substantial impact. The reliance on heavy fuel oils and the operation of large, often inefficient vessels exacerbate the industry's environmental footprint.

Increasing awareness of climate change and the urgency to mitigate its effects are putting growing pressure on the shipping industry to adopt more sustainable practices and driving it towards cleaner fuels, energy-efficient technologies, and alternative propulsion systems.

Both e-methanol and bio-methanol offer renewable and lower carbon intensity pathways to decarbonise shipping

However, decarbonising the shipping industry presents a formidable challenge. One of the primary hurdles is the reliance on fossil fuels, particularly heavy fuel oils, which are deeply ingrained in maritime operations. Moreover, ships' long lifespans, often spanning decades, complicate the rapid adoption of cleaner technologies. Additionally, the diverse nature of the global fleet, comprising vessels of various sizes, ages, and operational profiles, further complicates decarbonisation efforts.

Regulatory frameworks, while essential for driving industry-wide change, also pose challenges. The IMO GHG Strategy target is to reduce the carbon intensity of shipping, which is calculated based on the CO_2 emissions produced per tonne-mile of cargo transported, by at least 20% by 2030 and 70% by 2040 compared to 2008 levels. By, on, or around 2050 the target is net-zero emissions. Achieving these targets requires developing and deploying zero-emission vessels powered by alternative fuels or energy sources.

Methanol and ammonia as alternative fuels

Both methanol and ammonia offer promising pathways towards reducing GHG emissions. Although both have a lower energy density compared to some conventional fuels, they can still provide sufficient energy to power large ships over long distances. This makes them a practical option for long-haul maritime routes. However, ammonia in liquid form needs to be stored in pressurised tanks or at low temperatures, adding complexity to onboard fuel storage and handling systems.

Ammonia has an established global production and distribution infrastructure. It is widely produced and used in industries such as agriculture and chemicals, facilitating its integration into the maritime fuel supply chain. Furthermore, it can be synthesised using renewable energy sources through processes like electrolysis, which produce green hydrogen that is then combined with nitrogen from the air to produce green ammonia. This green ammonia production pathway makes ammonia a sustainable marine fuel option, contributing to a significant reduction in emissions and one that will certainly support the industry in the future.

Methanol, on the other hand, has lower toxicity than ammonia, reducing safety concerns for marine habitats and during handling, storage, and bunkering operations. It also has significant advantage in the short term as methanol engines are already commercially available and in production. Like ammonia, grey methanol is widely produced today and has established infrastructure, making integrating it into existing supply chains and refuelling infrastructure easier. This existing infrastructure reduces the upfront investment required for adoption and facilitates a smoother transition for maritime operators.

In e-methanol plants, the recycle ratio emerges as a critical design parameter, impacting feedstock efficiency and production costs

Different routes to sustainable methanol

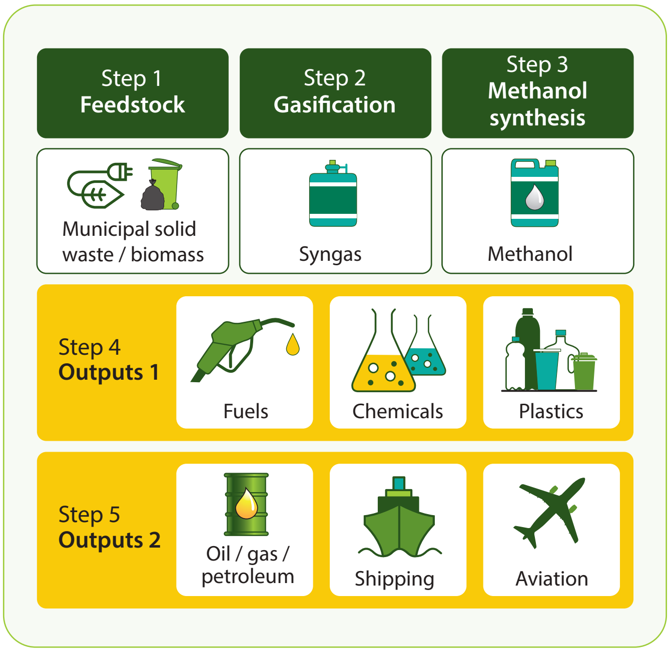
In traditional operations, methanol is primarily derived from synthesis gas sourced from fossil fuels. However, as renewable methanol production expands, it offers a viable solution for the decarbonisation of diverse transportation sectors, including shipping.

Both e-methanol and biomethanol offer renewable and lower carbon intensity pathways to decarbonise shipping. Production relies heavily on the choice of feedstock, each with its own set of advantages and limitations. One common feedstock is biomass (biomethanol), which offers the advantage of being renewable and widely available. However, if not managed properly, the use of biomass can raise concerns about land use competition, food security, water use, and biodiversity loss. The use of municipal solid waste (MSW) or waste biomass feedstocks, such as agricultural waste, mitigates the above concerns.

Using waste biomass feedstocks requires biochemical or thermochemical conversion processes. Biochemical pathways involve microorganisms fermenting organic materials, such as agricultural residues or forestry waste to produce biogas. This biogas, typically a mixture of methane and CO_2, can be reformed to produce syngas that is then converted to methanol. Thermochemical processes, such as gasification, convert biomass into syngas, which is then catalytically converted into methanol.

Johnson Matthey (JM), in partnership with MyRechemical, licences a high feedstock efficiency waste-to-methanol solution (Circular Methanol technology) that integrates waste-to-chemical technology with well-proven methanol synthesis technology and high-performance catalysts. The process uses municipal and industrial waste that cannot be mechanically recycled and chemically recycles it into synthesis gas via a partial oxidation process. The synthesis gas is then purified and conditioned, transformed into methanol, and distilled to the required purity level. Methanol can subsequently be used as a marine fuel or, further, can be converted into other sustainable fuels and chemicals. JM uses its own highly robust methanol synthesis catalyst, offering high stability and methanol productivity.

The Circular waste-to-methanol process has also been designed to incorporate green hydrogen, which approximately doubles the amount of methanol that can be produced with the same quantity of waste. The addition of hydrogen may eliminate the requirement for syngas conditioning step(s) and may reduce the carbon intensity of the process even further. The methanol synthesis loop is also able to receive renewable syngas obtained from the gasification of biomass or organic waste to produce biomethanol.



Stages to sustainable methanol

Another feedstock option for the production of renewable methanol is CO_2, captured from industrial processes or the atmosphere. This CO_2 is then combined with H_2 produced by electrolysis in a catalytic process to produce e-methanol. Waste CO_2-based methanol production offers the potential to recycle carbon emissions as an alternative to extracting fossil fuels. However, the availability and concentration of CO_2 sources can vary, and capturing and processing CO_2 can be energy-intensive and costly. Moreover, electrolytic hydrogen production is the highest contributor to e-methanol production costs, with green H_2 prices ranging from $6/kg (Spain) to $8/kg (US) today. The cost of electrolytic hydrogen is expected to decrease with advances in electrolyser technology and renewable electricity prices. It is expected to drop to $2-3/kg in 2030 in these markets; nevertheless, its current cost poses challenges for the production of e-methanol.

Higher feedstock costs and further technical factors mean that the optimisation focus for the design of e-methanol plants shifts to maximising hydrogen and CO_2 conversion into methanol. Methanol synthesis from carbon oxides (COx) and hydrogen is an equilibrium reaction favoured by low temperatures and high pressures. A typical methanol process is operated at 80 bara pressure with peak reaction temperatures of 280°C. At these conditions, the maximum methanol concentration at the outlet of the converter is around 14 mol%. Therefore, as the per-pass conversion of synthesis gas to methanol is limited by equilibrium, in order to achieve high conversion, the methanol synthesis section is arranged as a loop, recycling unreacted feedstock.

Crucially, in e-methanol plants, the recycle ratio, which is the ratio between the flow of unreacted circulating gas at the outlet of the circulator and the flow of fresh make-up gas, emerges as a critical design parameter, impacting feedstock efficiency and production costs, particularly as renewable power costs influence the levelised cost of methanol production. With its eMERALD technology, JM has optimised the e-methanol synthesis loop to deliver excellent performance, efficiency, and low carbon intensity when compared with conventional reforming.

> **“Adopting sustainable methanol, encompassing both e-methanol and biomethanol, represents a significant step forward in addressing the shipping industry’s emission challenges and regulatory landscape”**

As the CO_2 to methanol reaction yields a notably higher level of water formation than conventional methods, it necessitates a resilient catalyst capable of withstanding the hydrothermal conditions in the reactor to maintain optimal activity and throughput. JM’s premium catalyst, eMERALD 201, sets a new standard in stability and performance, delivering excellent methanol productivity across an extended lifespan. Its distinctive composition offers superior hydrothermal stability, ensuring consistent operation and longevity.

JM technology in action

The performance of this advanced offering has been recognised by HIF Global, which selected Johnson Matthey as the methanol licensor for its Paysandú e-fuels project in Uruguay. The facility, cited as South America’s inaugural e-fuels plant, will employ electrolytic (green) hydrogen and biogenic CO_2 to manufacture carbon-neutral e-methanol. Utilising JM’s eMERALD technology, the plant aims to produce 700,000 tonnes per year of e-methanol. This output will serve the burgeoning marine market demand and act as a feedstock for e-gasoline production via a methanol-to-gasoline process, thereby contributing to the decarbonisation of more than 150,000 vehicles.

The HIF Global partnership stems from the successful demonstration of JM’s technology in the Haru Oni project in Patagonia, Chile, where it licensed its technology and supplied the catalyst. The demonstration plant has operated effectively for more than 12 months, generating methanol for further processing into gasoline. Construction of the Uruguay plant is planned for 2025 and is anticipated to create 1,500 jobs during construction, with an additional 300 permanent operational positions.

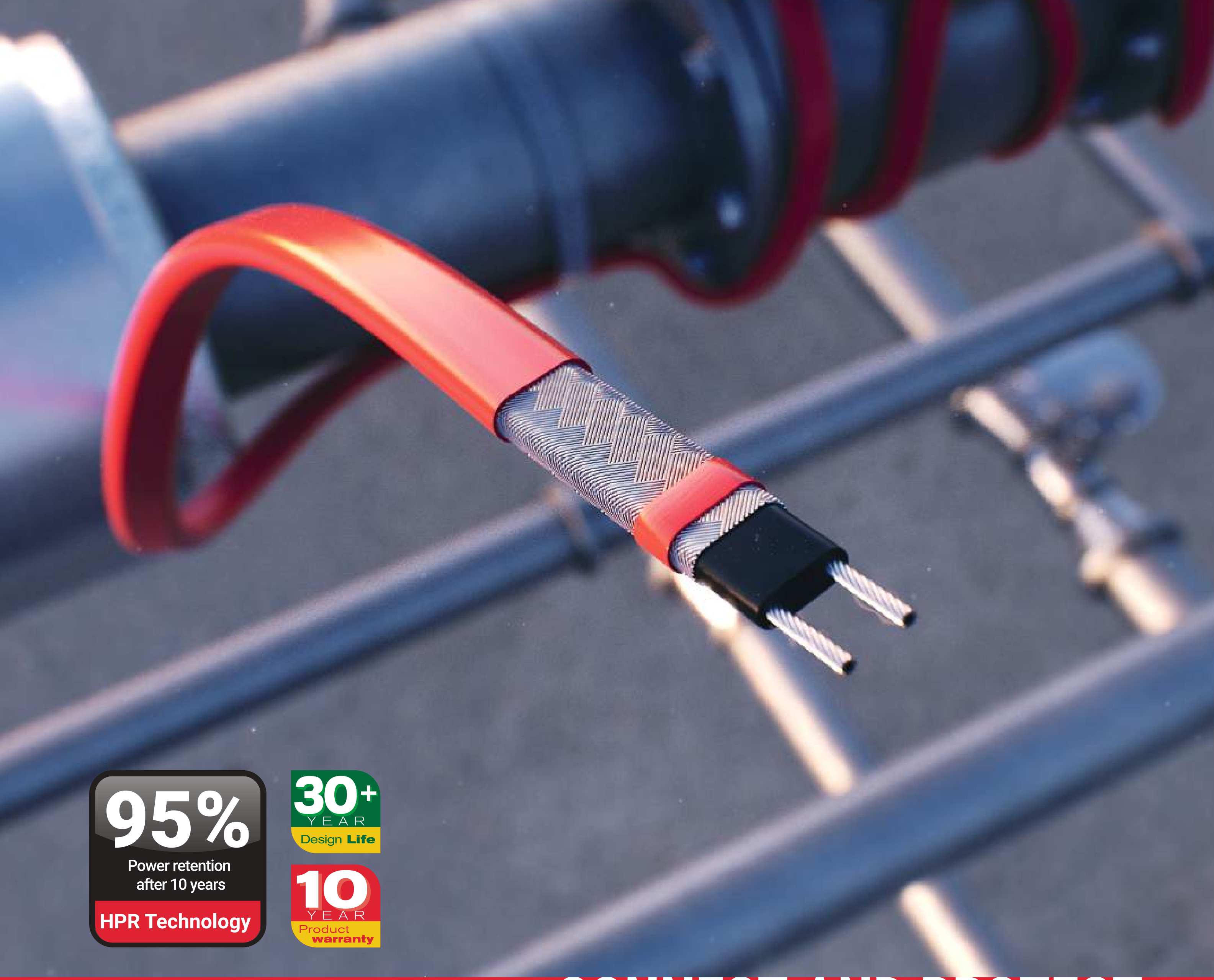
Conclusion

Adopting sustainable methanol, encompassing both e-methanol and biomethanol, represents a significant step forward in addressing the shipping industry’s emission challenges and regulatory landscape. These sustainable alternatives offer renewable and low-carbon solutions to propel the maritime industry towards achieving ambitious emission reduction goals.

With the support of innovative technologies like JM’s eMERALD CO_2-to-methanol and Circular waste-to-methanol processes, sustainable methanol production holds the potential to revolutionise the sector, providing a pathway to decarbonise maritime transportation while fostering economic growth and environmental sustainability. As the industry continues to navigate towards a low-carbon future, collaboration, innovation, and investment will be crucial in realising the full potential of sustainable methanol and driving meaningful progress towards a greener ship

eMERALD and CIRCULAR METHANOL are trademarks of Johnson Matthey.

Zinovia Skoufa


95%
Power retention
after 10 years
HPR Technology
30+
YEAR
Design Life
10
YEAR
Product
warranty

Integration of biomass feedstocks directly into refineries

Integrating biomass feedstocks directly into refineries requires evaluation of feedstock availability/composition, infrastructure, and commercial viability

Vahide N Mutlu and Başak Tuncer
SOCAR Türkiye Research & Development and Innovation Inc.

In modern society, petroleum refineries and the petrochemical sector remain vital for economic progress, yet their traditional practices have significant ecological impacts. The growing demand for environmental sustainability has driven a re-evaluation of these industries' reliance on fossil fuels. Renewable alternatives, such as agricultural residues, forestry byproducts, energy crops, and municipal solid waste (MSW), allow a diversification of feedstocks. However, such diverse feedstocks bring new challenges due to the different forms of biomass and, within each form, regional and seasonal variations in composition and availability. Evaluating these biomass feedstocks and how to integrate them into the production of fuels and chemicals is crucial for sustainable development. This requires deploying various newer conversion technologies such as pyrolysis, gasification, and fermentation alongside traditional refining processes such as hydrotreating, catalytic cracking, and isomerisation.

Decarbonisation efforts must target emission reductions throughout the life-cycle of petrochemical products, from production to disposal. Additionally, the issue of plastic pollution demands improved life-cycle management to reduce landfill and environmental contamination. Biomass integration, alongside conventional plastic recycling, can promote a circular economy, while biopolymers offer the potential for biodegradable alternatives (see **Figure 1**).

Diversity of biomass types and feedstocks

Lignocellulosic biomass, sourced from agriculture and forestry waste streams, provides a sustainable form of biomass when it does not compete with food production or

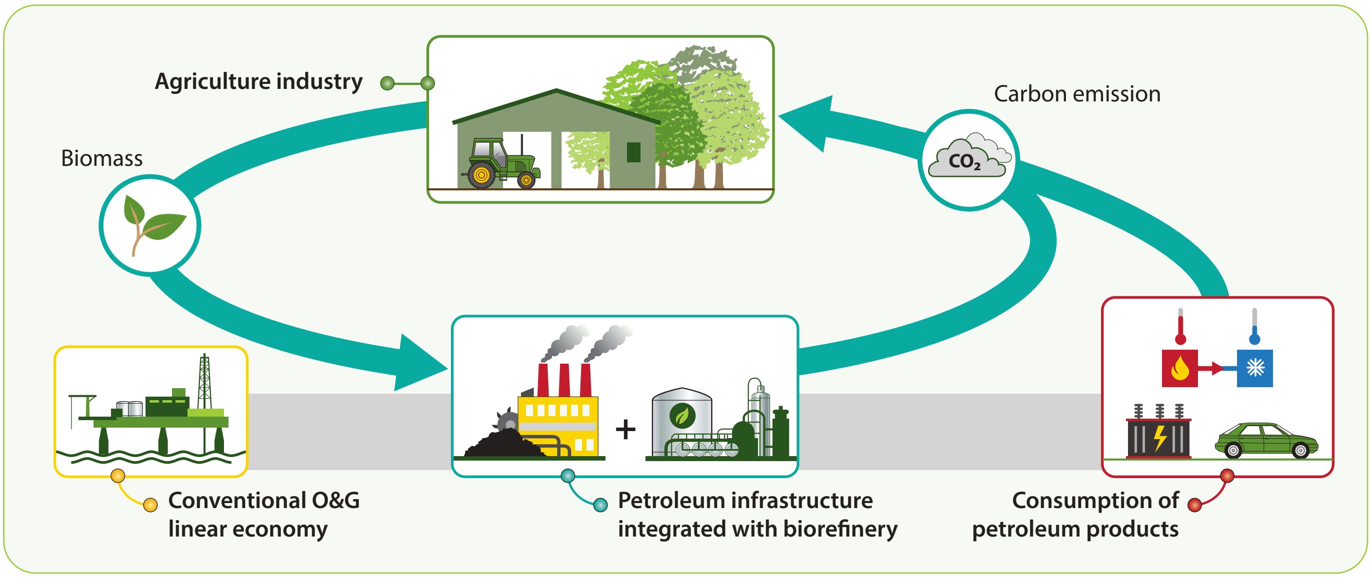


Figure 1 Integrated biorefinery in the oil and gas industry as part of the circular economy (Yeo, et *al.*, 2023)

cause deforestation. Despite the annual global production of 146 billion tons, only a fraction is currently used for biofuels and biochemicals. Forest residues, which totalled 274 million tons in 2011, are expected to become the dominant feedstock for biorefineries, reaching 6 billion tons annually by 2050 (*Guragain & Vadlani, 2021*).

Algae, known as 'green gold', offer another promising biomass source due to their unique lipid and carbohydrate compositions. The potential of algae in the petrochemical industry depends on efficient cultivation, lipid extraction, and scalability for both fuel and non-fuel products (*Chandra, Iqbal, Vishal, Lee, & Nagra, 2019*).

MSW provides an unconventional, yet valuable biomass source. Global MSW production was 1.3 billion tons in 2011, and is projected to reach 2.6 billion tons by 2025 (*Kurian, Nair, Hussain, & Raghavan, 2013*). The primary challenge is not the availability of biomass feedstock but the innovation required to convert these diverse streams into usable feedstocks. Strategic biomass selection must consider the final product requirements, regional availability, and environmental impact to optimise integration into petrochemical processes.

Technological advancements in biomass integration

Integrating biomass conversion processes into existing petroleum refinery configurations can result in significant capital savings by eliminating the need for constructing separate biofuel production facilities, thereby enhancing the competitiveness of biofuels (*Prasetyo, et al., 2020*). Over the last 15 years, several petroleum refineries have been converted into biorefineries to hydrotreat used cooking oils in the production of hydrogenated vegetable oil (HVO) for use as renewable diesel and, more recently, sustainable aviation fuel (SAF). Biomass feedstocks such as lignocellulosic biomass, the organic fraction of MSW, and the chemical recycling of plastic all require a conversion process to break down complex hydrocarbons into simpler molecules. These conversion technologies include:

❶ **Pyrolysis:** Pyrolysis, a thermal decomposition process, uses high temperatures in the absence of oxygen to break down organic materials like lignocellulosic biomass into valuable byproducts. This process produces a bio-oil or py-oil, which needs further treatment, usually by co-processing with petroleum feeds within the current refinery infrastructure to yield biofuels. From an economic perspective, the cost of retrofitting a petroleum refinery for py-oil co-processing is deemed financially feasible. Pyrolysis of biomethane has also been developed as a low-carbon intensity route to renewable hydrogen.

❷ **Gasification:** Gasification converts biomass into synthesis gas (syngas), a mixture of carbon monoxide and hydrogen. The syngas can then be used to produce various fuels and chemicals and generate electricity. The exploration of gasification within the petrochemical context delves into its adaptability, environmental impact, and the intricacies associated with seamlessly integrating gasification technologies into existing infrastructures.

❸ **Fermentation:** Fermentation is a traditional process used to produce alcohol in the food and drink industry. More recently, it has been deployed as a more eco-friendly route to producing fuels and chemicals. Microorganisms convert organic materials into ethanol, which is blended with gasoline or used in the Alcohol-to-Jet route to SAF.

Effective integration of biomass into a petroleum refinery

When integrating biomass into a petroleum refinery (see **Figure 2**), it can be introduced and processed using relatively minor modifications of existing processes. The choice of insertion point depends on factors such as the type of biomass, existing refinery infrastructure, and desired end products.

Feedstock pre-processing is vital and includes size reduction, drying, and impurity removal. Depending on the feedstock, additional treatments, like chemical or enzymatic processing, may be applied. These steps optimise the compatibility of the biomass with refinery technologies, improving the efficiency of gasification or liquefaction and ensuring smooth integration into refinery operations.

Integration with hydrotreatment units

Hydrotreatment units are ubiquitous in modern refineries. The process involves preheating and

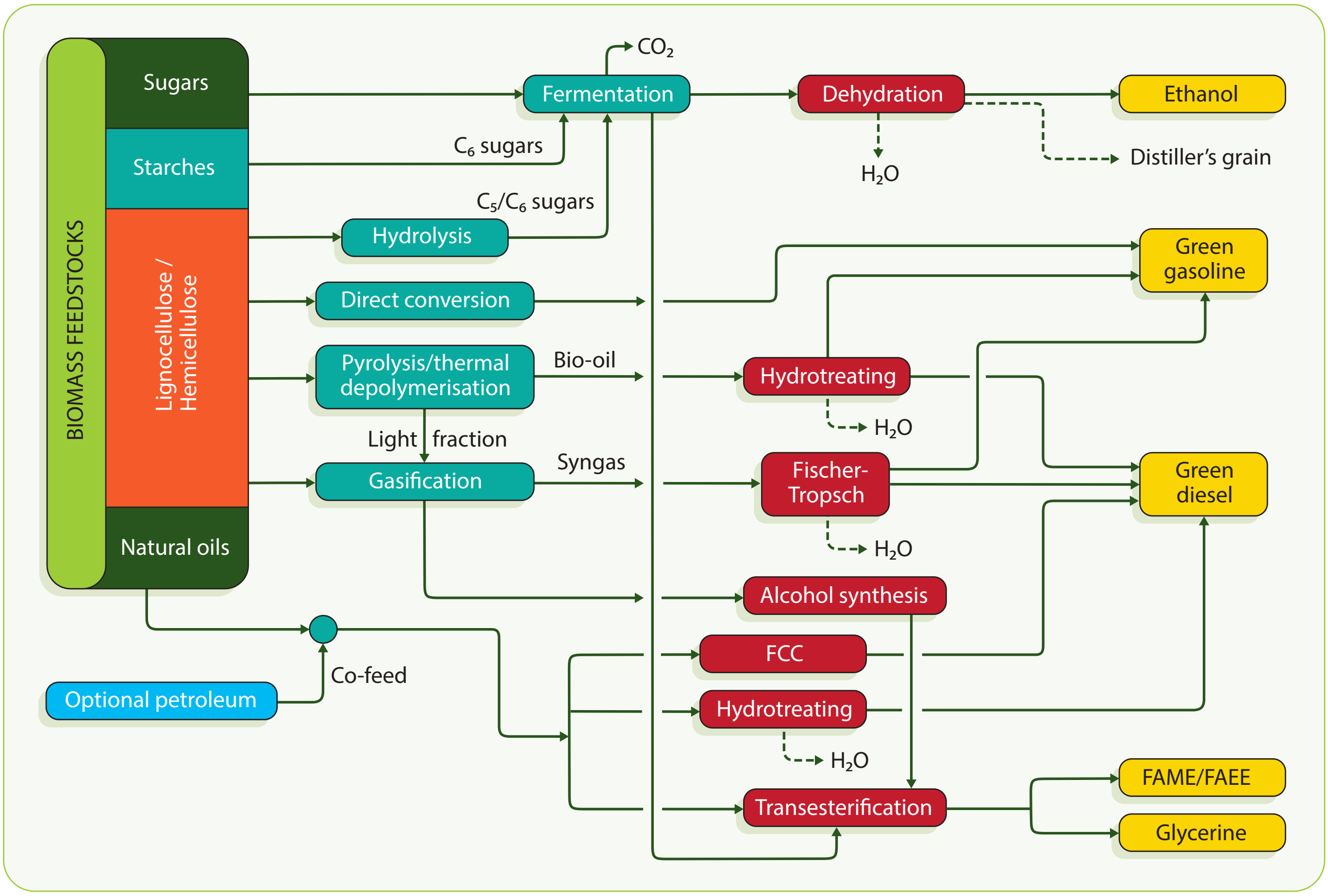


Figure 2 Integration of biomass conversion processes within a refinery

mixing the feedstock with hydrogen in a high-pressure reactor with a catalyst composed of nickel, cobalt, and molybdenum metals supported on alumina. This setup removes impurities such as sulphur, nitrogen, and metals while saturating olefins and aromatics to improve the stability and combustion properties of the final products.

Vegetable oils and animal fats are particularly well-suited for hydrotreating, producing renewable diesel and jet fuel by hydrogenating triglycerides and free fatty acids, removing oxygen, and creating hydrocarbons similar to those from fossil fuels. This process reduces emissions to produce fuels compatible with existing infrastructure, and enhance fuel stability and performance.

The main challenge is the variability in biofeedstock quality, which can affect catalyst efficiency and longevity. Refineries may need to adjust operating conditions or modify existing units to optimise biofeedstock processing. Some refineries opt to co-process fats and oils with fossil streams, while others have dedicated hydrotreaters for their biostreams.

Integration with fluid catalytic cracking unit

Fluid catalytic cracking (FCC) units are crucial for converting heavy hydrocarbons into lighter, more valuable products. Integrating pyrolysis oils from biomass into FCC units allows refineries to produce renewable fuels and chemicals using existing infrastructure.

After pretreatment to remove impurities that could poison the FCC catalyst, biofeedstocks can be blended with fossil-derived streams and fed to the FCC unit. The blend is heated to around 500°C, where the hydrocarbons vaporise, mix with the catalyst, are cracked, and then separated into various product streams, including gasoline, light olefins, light cycle oil (LCO), and heavy cycle oil (HCO).

This integration offers benefits like producing renewable fuels and reducing carbon intensity. Again, introducing biocomponents brings challenges due to feedstock variability and potential catalyst poisons. As with any change in feedstock there is a need for process optimisation. The variable composition and quality of bio-based feedstocks affects the cracking process, while contaminants like metals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increase catalyst deactivation. Additionally, economic feasibility depends on the cost and availability of these biofeedstocks.

Integration with steam crackers

Steam cracking is the main interface between the refinery and petrochemical plants. In the steam cracking process, the steam is used to break down heavier (longer chain) hydrocarbons to produce hydrogen and light olefins, including ethylene, propylene, and butadiene. Thus, integrating bio-based feedstocks in the steam cracker feed can yield renewable olefins and chemicals. The process operates between 750°C and 875°C and at short residence times to convert saturated hydrocarbons into unsaturated ones. Unlike FCC, steam cracking relies on thermal decomposition and is non-catalytic.

Suitable bio-based feedstocks include bioethanol, biogas, and pyrolysis oils. Bioethanol can be dehydrated to bio-ethylene, while biogas can be converted to syngas for use in the methanol-to-olefins (MTO) processes. Biomass-derived pyrolysis oils can be used directly or blended with conventional feedstocks.

Integration involves pretreating biofeedstocks to remove contaminants and adjust properties. For instance, bioethanol needs dehydration, and biogas requires reforming to produce syngas for further chemical conversion. After pretreatment, the feedstocks are preheated and mixed with steam in the furnace. The steam lowers the partial pressure of hydrocarbons, reducing coke formation. The mixture is then rapidly cooled to stabilise the products.

Cracked gases are separated into fractions using fractionation columns. The different fractions are then compressed, cooled, and further separated through distillation. The olefins produced from steam cracking bio-based feedstocks are the building blocks for renewable polyolefins and synthetic rubbers.

The benefits of using bio-based feedstocks include renewable product output and reduced carbon intensity. The process can be adapted to biofeedstocks with minimal changes to existing infrastructure. Again, challenges include feedstock variability, contaminants, and the need for adjustments in operating conditions. Bio-derived pyrolysis oils often contain higher levels of oxygenates, unsaturated compounds, and impurities, leading to increased coke formation in the cracker furnaces. Coke build-up on furnace walls reduces heat transfer efficiency, leading to higher energy consumption and frequent maintenance shutdowns for decoking. The presence of contaminants like alkali metals can accelerate coke deposition, requiring a more rigorous pretreatment and precise control of cracking conditions. Additionally, fluctuations in biofeedstock quality can affect the rate of coke formation, creating operational challenges. Along with the cost of the biofeedstocks, economic feasibility is also impacted by their availability, as they may require significant adjustments to optimise the process conditions and minimise coking issues.

Integration of syngas from biomass gasification into petroleum refineries

Syngas from biomass gasification can be integrated into existing petroleum refineries at multiple points within the refinery process line-up. The most common insertion point is within the hydrocracking or catalytic reforming units. In these units, syngas can be used to produce hydrogen and, with the carbon, can be converted into valuable liquid fuels and chemicals.

Challenges in integrating biomass-derived syngas into petroleum refineries include variability in syngas composition, which affects process efficiency and product quality. Impurities in the syngas, such as sulphur compounds and particulates, can damage equipment and require clean-up. Existing refinery infrastructure may need modifications to accommodate syngas, and the economic feasibility depends on the cost and availability of biomass feedstocks.

Biomass-derived syngas can be converted into hydrogen for refining processes or used to produce liquid fuels such as diesel and gasoline via Fischer-Tropsch synthesis and chemicals such as methanol. Additionally, it can be used in combined heat and power systems to provide energy for refinery operations, reducing reliance on external sources.

Effective biomass integration often involves a combination of these insertion points, with the choice depending on the type of biomass, conversion technologies available, and the specific goals of the refinery. A thorough analysis of the existing infrastructure and the characteristics of biomass feedstocks is essential for successful integration. It is important to note that the selection of the insertion point depends on factors such as the availability and characteristics of the biomass feedstock, existing refinery configuration, desired product slate, and the technical and economic feasibility of integration. Detailed techno-economic assessments, process simulations, and pilot-scale studies are typically conducted to determine the optimal insertion point for integration in a specific petroleum refinery.

Standalone biorefinery integration

Integrating a standalone biorefinery with an existing petroleum refinery offers a way to leverage renewable biomass resources alongside conventional fossil feedstocks, creating a more sustainable and versatile refining operation.

A standalone biorefinery operates independently to process biomass into valuable products such as biofuels, biochemicals, and bioplastics. These biorefineries typically use processes like gasification, hydrothermal liquefaction (HTL), or fermentation to convert biomass into intermediates or final products. Several strategies can create synergies between a biorefinery and a conventional petroleum refinery:

- **Product blending:** One common approach is to blend biofuels from a biorefinery, such as biodiesel or biojet fuel, with traditional fossil fuels. This blending can be done at various points in the refinery, including during storage or as a component in the blending pool to meet the product specifications prior to distribution. This method allows the refinery to utilise existing infrastructure while incorporating renewable components into its product slate.
- **Feedstock substitution:** Biomass-derived intermediates, like biocrude from hydrothermal liquefaction (HTL), can be co-processed with conventional crude oil in the refinery's distillation or upgrading units. This approach helps to reduce the carbon footprint of the refinery's products while using existing refining technology.
- **Hydrogen integration:** Many biorefineries produce hydrogen as a byproduct, which can be valuable for petroleum refineries. Hydrogen can be used in hydrocracking and hydrotreating (desulphurisation) processes to improve the quality of petroleum products. Integrating this hydrogen into the refinery's operations can enhance the overall efficiency and sustainability of the refining process.
- **Energy and heat recovery:** Biomass-based biorefineries often produce excess energy or heat that can be utilised by adjacent petroleum refineries. This integration allows for the use of renewable energy to meet some of the refinery's energy demands, reducing reliance on external energy sources and improving overall energy efficiency.

Challenges in biomass integration

As the push for sustainability drives the integration of biomass into fossil fuel refineries and petrochemical industries, it is crucial to acknowledge and address the challenges inherent in this transformative process. While biomass integration offers promising solutions, several complexities must be navigated for successful implementation:

- **Feedstock variability:** Biomass feedstocks vary widely in composition, moisture content, and energy density. This variability requires adaptation of existing refinery processes, which involves optimising and controlling new parameters. Ensuring the sustainability of biomass production is also crucial. Current certification schemes, such as those under the EU Renewable Energy Directive (*EU, 2018*), cover only a small fraction of biomass sources and often focus on immediate practices rather than long-term sustainability. Effective integration necessitates a more rigorous and long-term commitment to sustainable biomass management.
- **Catalyst deactivation:** Biomass feedstocks can introduce compounds that poison or deactivate catalysts, impacting their efficiency and longevity. A particular challenge is coke formation, where carbonaceous deposits build up on the catalyst surface, causing a reduction in catalytic activity and potentially leading to permanent deactivation. Additionally, the high heat release during the processing of renewable feedstocks, due to their increased presence of unsaturated molecules and oxygen, can exacerbate catalyst deactivation. This requires robust quenching systems to manage the thermal load. Furthermore, the increased water content in biomass-derived products necessitates the use of drainage systems or salt filters to control moisture levels effectively.

- **Diversity in product types:** Biomass may not always produce chemicals and materials at the same scale and cost as crude oil and natural gas. While biomass can lead to innovative products, such as bioplastics and biosolvents, these products may differ in chemical properties and market demand. The integration of biomass often results in the production of different substances compared to traditional petrochemical processes, necessitating adjustments in product formulation and refining processes. It is anticipated that an increased displacement of petrochemicals by bio-based products will lead to the introduction of various plastics, such as polyethylene furanoate, as a substitute for polyethylene terephthalate (PET) (*Zhang & Deng, 2015*). Similarly, d-limonene and Cyrene serve as bio-preferred alternatives to petrochemical solvents.
- **Technological compatibility:** Integrating new biomass conversion technologies like pyrolysis or gasification into existing refinery infrastructure requires ensuring that these technologies interact seamlessly with traditional processes. Additionally, scale-up challenges arise when transitioning from laboratory-scale biomass processes to industrial-scale operations. Consistent, economically viable production at larger scales demands precise engineering and operational adjustments.

Investment costs are substantial, as retrofitting existing refineries for biomass integration can be costly. Securing funding for these modifications is a persistent challenge. Infrastructure adaptation is needed to accommodate the unique characteristics of biomass, including ensuring resistance to corrosion and optimising materials for new feedstock types.

Logistical challenges include managing the procurement, transport, and storage of biomass feedstocks on a large scale, which requires efficient supply chain systems. Public perception and acceptance of biomass integration also play a role; factors like land use, resource competition, and environmental impacts influence public support. Regulatory compliance involves adhering to stringent environmental and safety standards, which necessitates ongoing monitoring and adjustments.

- **Assurance and certification processes:** The diversity of biofeedstocks and their integration with conventional refinery and petrochemical processes also pose the issue of assurance. This necessitates a certification process, which provides assurance throughout the supply chain that the products purchased, whether as intermediates for further processing or as finished products, are from sustainable sources and meet regulatory requirements for renewable fuels and chemicals (*ISCC, 2024*). Collaboration among industry stakeholders, international agencies, policymakers, and researchers is vital to develop solutions that effectively address these challenges.

Life-cycle emission reduction

Life-cycle assessment (LCA) is a critical tool for evaluating the environmental impact of biomass integration. Unlike fossil fuels, which release carbon that has been sequestered for millions of years, biomass feedstocks such as agricultural residues, forestry byproducts, and algae absorb CO_2 during their growth phases. This biogenic CC offsets the emissions produced during the conversion processes, creating a more balanced carbon cycle.

For instance, the production of bioethanol from lignocellulosic biomass can result in much lower greenhouse gas (GHG) emissions than conventional gasoline. Studies indicate that bioethanol can achieve up to a 90% reduction in GHG emissions on a life-cycle basis. Similarly, bioplastics derived from plant starch or vegetable oils exhibit lower emissions throughout their life-cycles compared to their petroleum-based counterparts.

Conclusion

Integrating biomass feedstocks directly into refineries requires evaluation of feedstock availability and composition, processing infrastructure, and commercial viability. Alternatively, refineries can partner with biorefineries, which offers sustainability benefits while managing infrastructure and operational risks. The choice depends on a refinery's capabilities and strategic goals, with both pathways offering distinct advantages and challenges.

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Quantify and reduce risk for acceleration of new projects

Understanding and reducing the uncertainty associated with new sustainability projects will close the gap between actual and targeted levels of investment

Ana Khanlari and Ron Beck
Aspen Technology

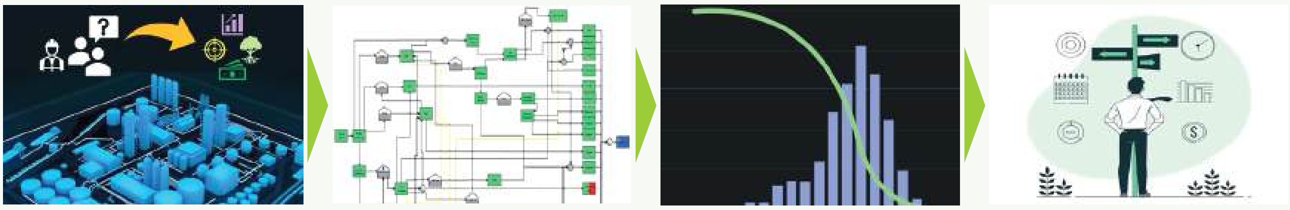
In the fast-evolving landscape of sustainable chemical manufacturing, vetting projects and making final investment decisions can present difficult choices. Some of these complexities include the flurry of emerging technologies, conflicting objectives, uncertain future economics, and re-shoring momentum. A lack of delivered assets operating at scale to benchmark against can hinder the progress of any new project. Decisions made along the lifespan of the project without considering future changes might be counterproductive or even put the project in jeopardy. Having a complete, quantitative system view to show the trade-offs of every decision can bring a fact-based measure of risk for the project's owners. Through such a holistic system model, owners can examine end-to-end dependencies, evaluate market and financial projections, and forecast future returns and performance without being caught off-guard.

Today's decarbonisation and circularity imperatives are driving the industry towards new modes of operation. Electrification and utilisation of dedicated renewable power are decarbonisation steps that come with embedded stochastic and cyclical patterns of solar and wind.

Additionally, new value chains (such as plastics recycling and renewable-based chemical synthesis) introduce uncertainties like quantity and quality of raw material supply. Other uncertainties include weather, future material pricing, supply chain disruptions, and a dizzying array of optionalities in putting together new end-to-end systems. A probability-based system model can account for these uncertainties to predict future constraints and offer mitigating solutions.

Monte Carlo simulation is a statistical approach that uses repeated random sampling to predict a range of potential results. The method takes its name from the Monte Carlo Casino frequented by physicist Stanislaw Ulam's (method inventor) uncle. This method was introduced effectively during World War II to improve decision-making under uncertain conditions. Since then, the application of the Monte Carlo method has expanded to all fields of science, finance, engineering, and project management. Conducting a Monte Carlo analysis on the most likely future pricing of material and labour is an established application in large capital project biddings. Augmenting this statistical approach with a model of the 'connectivity' of a system (understanding interrelationships like materials flow, and electricity) creates a sophisticated tool to rigorously evaluate a wide range of investment and operational alternatives across a system.

There are many opportunities for de-risking new projects using a Monte Carlo systems assessment. A system's lifecycle cost can be minimised, production maximised, and availability predicted. For example, by considering equipment failure rates, maintenance costs, and spares availability, a 'connected' Monte Carlo model can improve the system's reliability. The efficiency and productivity of the design can be improved by identifying optimal places to put redundancies, bypasses, and intermediate storage elements. Lifecycle emissions can be minimised by leveraging renewable energy sources while assigning emissions an opportunity cost in the model. Finally, Capex can be minimised by predicting performance and throughput changes, maintenance intervals, and



Define business objective and system scope

Objectives: Production throughput, revenue, costs, asset utilisation, asset availability

Scope: Equipment, process, plant site, enterprise supply chain

Model the appropriate detail

Different parts of the system can be modelled at different levels of detail

Simulate all required scenarios

Different redundancy levels, storage capacities, system configurations, alternate operation/maintenance strategies

Analyse and compare simulation results

Identify best scenario, option or alternative, based on business objective

Provide insights on Capex/Opex vs system performance trade-offs

Figure 1 Aspen Fidelis workflow from objectives to results

weather patterns as well as other sources of uncertainty.

Aspen Fidelis is a commercial software system for de-risking capital projects, as described above. It explores multiple system configurations during conceptual design and improves the design by performing reliability, availability and maintenance (RAM) analysis. This could include alternative conversion technologies (such as CO_2 to chemicals), alternative feedstocks, power reliability options, storage options, and the like. Creating design flexibility supported by 'nested' models with different levels of detail is the strength of this system. Through this analysis, subsystems initially identified as the highest project risk can be modelled in higher granularity. Once the plant is operational, Fidelis can drive asset performance management to identify critical equipment and events. **Figure 1** shows how the software helps to detangle capital projects.

Performance analysis to debottleneck sustainability projects

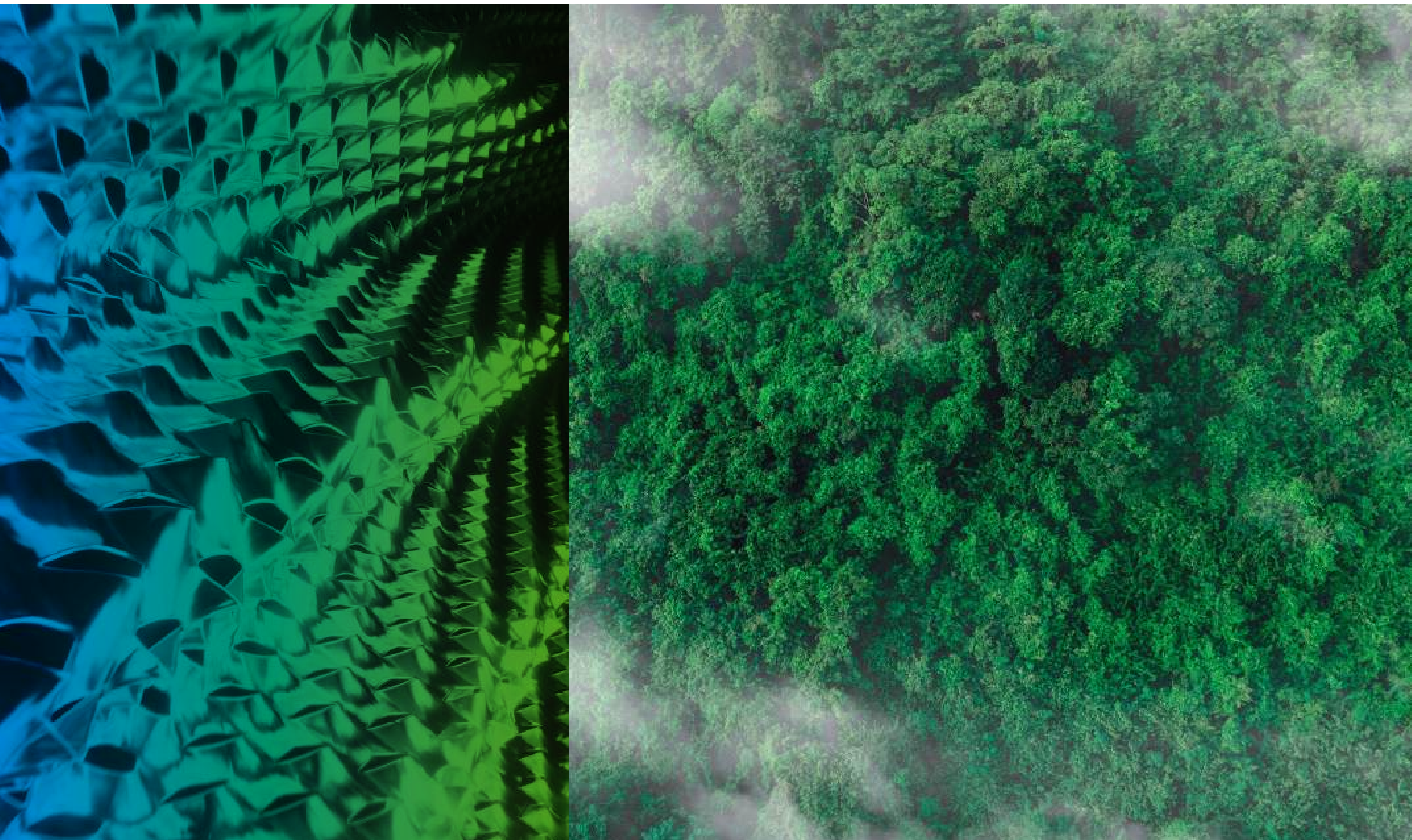
One of the most beneficial areas of risk analysis is to understand opportunities and challenges associated with sustainability projects. Understanding risk levels and how to mitigate them can bring confidence to project owners and lenders alike. In the following sections, we will review some examples of sustainability projects that can be de-risked using Aspen Fidelis.

Carbon capture projects risk analysis

Let us assume a rigorous model of a carbon capture process. Several flue gas streams (for example, from a boiler, gas turbine, and tertiary sources) are combined and sent to a carbon capture unit for amine absorption. We assume a nominal capacity of 419.6 t/y for the plant. If we assume 9.6t/y reduced capacity due to unplanned downtime, the system must deliver the remaining 410 kt/y performance with a probability of 85% or more. From a reliability and risk point of view, the question is whether the current design can meet the performance targets and if not, what can change to meet or exceed the expected performance?

For this hypothetical process, Aspen Fidelis simulated 100 different scenarios over a lifecycle period of 20 years. The main criterion was tons of captured CO_2 per year. The software reported a best-case scenario capture of 408 kt/y and identified a list of culpability. To redress the reduced capture rate, spare equipment (in this case pumps) needed to be considered. After adding spare pumps to the model and running the scenarios again, the system would capture at least 410 kton/y with a probability of 88% (identified with a red dot on **Figure 3**).

Here we have simplified the model and process flow diagram. However, there are other nuances involved in designing a new carbon capture plant, including pipe flows, storage tanks, dynamic behaviour of the system, and total cost. The Fidelis model incorporates all these uncertainties to predict the future performance of the system and what actions can be taken today to ensure meeting process targets.



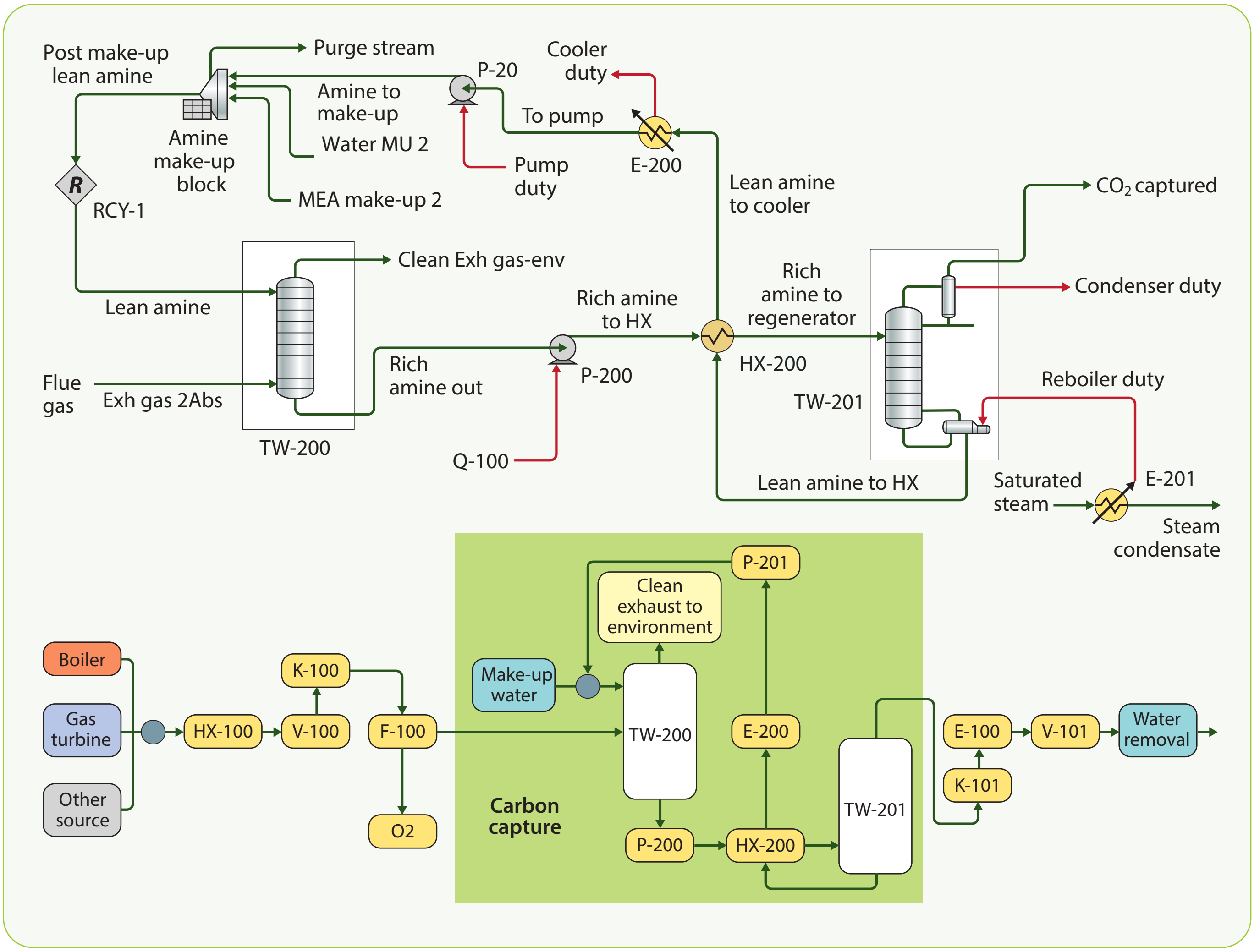


Figure 2 Carbon capture project de-risked using Aspen Fidelis

Green hydrogen and ammonia projects risk analysis

Among other sustainability pathways, green hydrogen and ammonia production involve many choices. Optionality involved in these projects can become quickly confusing and overwhelming. The project team needs to progressively pin down questions such as location and type (or mix) of green-power sources, electrolyser design, energy storage options, and transport strategies. Whether to consider hydrogen, ammonia or battery storage, what to expect from dynamic weather patterns, and demand projections and prices are among the independent variables to consider. Aspen Fidelis provides performance metrics, including levelised cost of hydrogen (LCOH) and ammonia, net present value (NPV), and discounted cash flows to facilitate the decision-making process.

Recently, a global petrochemical company investing in green ammonia used Fidelis to de-risk investment and ensure proper allocation of its capital spending. The team created a detailed probabilistic end-to-end model covering renewable energy sources, hydrogen and ammonia production, storage, distribution, and sales. They tracked Opex and Capex flows over time, including equipment replacement costs, energy, product flows, revenues, and performance losses due to events. In the end, they had identified $500MM in Capex savings opportunities. Once the plant is operational, the Fidelis model will be utilised to optimise decision-making in operations, maintenance, and logistics throughout the asset's lifecycle.

Another example of the software's application in green hydrogen and ammonia comes from Samsung E&A in South Korea. Previously, the engineering company was using Microsoft Excel spreadsheets and relied on daily averages of renewable power profile. This approach provided a simplified representation of renewable power variation. Conversely, in Aspen Fidelis simulations, they utilised a more

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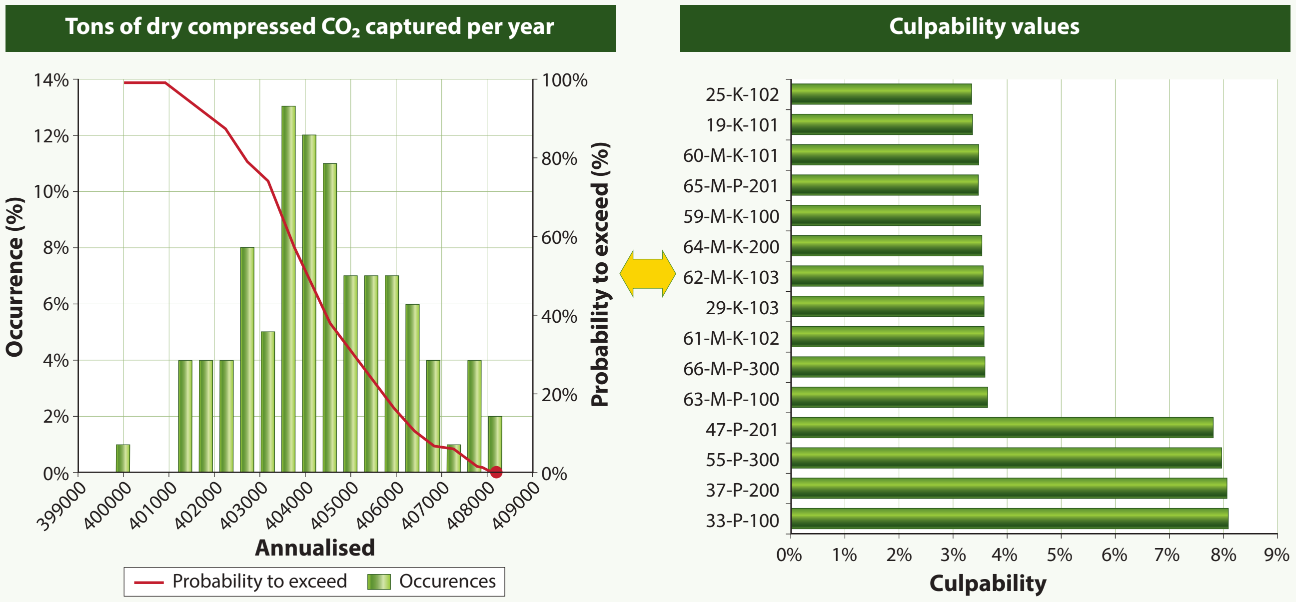
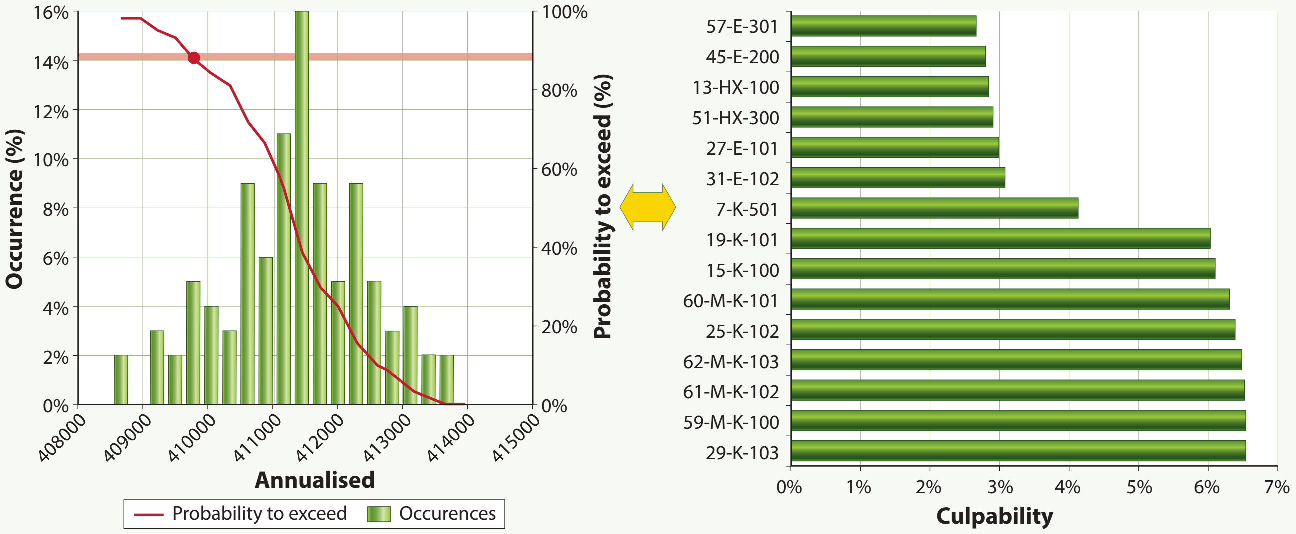


The Base Case system will capture at most 408.2 t/y, which is below target (410 kt/y)

Pumps P-100, P-200, P-300, and P-201 are the major contributors to system performance losses



The system will capture at least 410 kt/y with a probability of 88% (meets the target)

The focus now should be shifted to compressor K-103, K-102, K-100, and K-101 and corresponding motors

Figure 3 Debottlenecking a carbon capture projects through Aspen Fidelis

detailed dataset comprising 8,760 hours of renewable power data. This level of granularity allowed for a more accurate and comprehensive analysis of how renewable power fluctuations impact project dynamics. This approach avoided system bottlenecks on the one hand and over-design on the other (see **Table 1**).

Fidelis model input and output variables were:
Input: Power input profile, model configuration (such as flow, unit, and storage), initial material balance, objective functions, and constraints.
Output: Production profile (daily, weekly, monthly, and annual), average capacity factor, and storage level profile.

Roadmap to manage long-term emissions

In Qatar, the Ras Laffan Olefins Company (RLOC) and Qatar Chemical Company (QChem) complex (the largest ethylene crackers, polyethylene, and aromatics producer in Qatar) have used Aspen Fidelis to review current performance and to create a roadmap to incrementally reduce emissions. After creating a detailed model of the three complexes and their interconnectivity, the study provided marginal abatement cost curves along with total required investments. Variables such as furnace combustion optimisation, use of solar panels, steam metering and distribution network, and

		Electrolyser	Ammonia
Excel calculations	Name plate capacity (A)	100,000	360,000
	Annual production capacity (B)	42,200	215,640
	Capacity factor: (B)/(A)	42.2%	59.9%
Fidelis	Annual production capacity (C)	40,500	208,440
	Capacity factor: (C)/(A)	40.5%	57.9%

Table 1 Excel spreadsheet model vs Aspen Fidelis model

wireless infrastructure were considered. The results of the study allowed for prioritisation of projects based on their impact on emissions for the next 10 years. Some of the prioritised projects include the electrification of hot oil furnaces and refrigeration compressors, flaring reduction, and implementation of an energy management information system.

Conclusions

Despite having only shared a few Fidelis use cases, numerous other projects have benefited from its capabilities, including biofeedstock to chemicals, plastics down-cycling or recycling, and expansion projects. Many major global energy and chemicals companies have embraced the software at various stages of their projects to increase confidence and reliability. Understanding and reducing the level of uncertainty associated with new sustainability projects will help close the gap between the actual and targeted levels of investments needed for a successful energy transition.

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Enhancing decarbonisation through tracer technology

Tracer technology can be effectively employed across various types of CCUS projects, regardless of the chosen storage method

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Carbon capture (CC), including carbon capture and storage (CCS) and carbon capture, utilisation, and storage (CCUS), is a cornerstone technology for advancing global energy transition objectives. It is critical for cutting emissions from conventional energy sources that are challenging to decarbonise, and it serves as a key strategy for tackling the dual goal of mitigating climate change while also maintaining energy security during the shift towards a low-carbon economy.

The energy sector is experiencing a new-found excitement for CC, reflecting a global shift towards understanding it as an essential rather than an optional strategy. Earlier doubts about its cost and efficacy are slowly fading, replaced by acknowledgement of its critical role, especially as electricity demand continues to soar.

Nonetheless, while CCS/CCUS is set to play a leading role in the energy transition, its success depends on scaling up its implementation. To meet the ambitious emission goals, CC capacity needs to increase more than 100-fold over the long term. Any setbacks in rolling out CC technologies could have a substantial effect on future emissions. Hence, the quest for effective CC solutions has never been more critical, and central to these efforts is the need for precise monitoring and verification of carbon dioxide (CO_2) storage.

Tracer technology for CO_2 monitoring and verification

Tracer technology is at the forefront of advancements in environmental monitoring, offering significant benefits for the decarbonisation agenda. A tracer is a specific identifiable substance that follows a transport process in a reservoir in a predictable manner without affecting the transport process or being affected by the process. Tracers cause no degradation, sorption to rock, known phase partitioning, or natural occurrence in reservoir fluids (see **Figure 1**)

Tracers are unique, non-naturally occurring substances introduced into storage reservoirs to allow tracking of CO_2 movement. They serve as distinct markers for tracking CO_2 as it moves through geological formations, acting as unique fingerprints for CO_2 leakage identification. They are inert, non-radioactive, and safe with low toxicity, providing high benefits at a low cost.

Tracer technology application in offshore and onshore carbon capture projects

There is currently an ongoing industry debate regarding CCUS – is it more advantageous to use offshore or onshore aquifers vs depleted

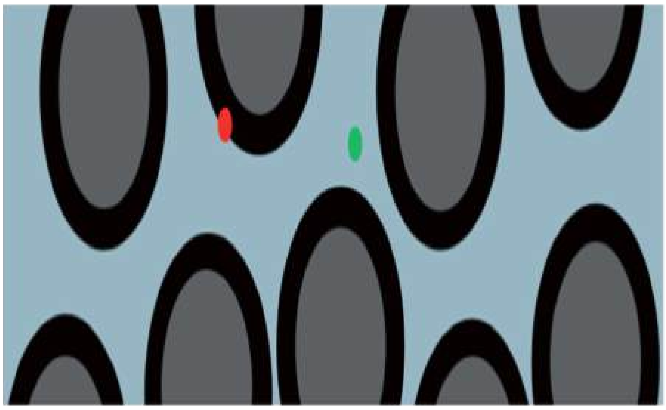

Figure 1 Inert tracers travel uninterrupted through the subsurface, moving within the fluid phase to which they have an affinity. This allows for quantifiable interpretations of mass fluid transport

reservoirs? Tracer technology offers a valuable solution to this debate, as it can be effectively employed across various types of CCUS projects, regardless of the chosen storage method. In this article, we discuss two projects where tracer technology was applied successfully in different types of reservoirs.

K12-B gas field

Tracer technology has been applied in the K12-B gas field on the Dutch continental shelf to advance our understanding of CO_2 storage and migration. This allows us to better appreciate its role in optimising CCUS efforts and ensuring the long-term integrity of CO_2 storage.

Background

The K12-B gas field, situated about 150km (about 93.21 mi) northwest of Amsterdam in the Dutch North Sea, has been central to research on CO_2 injection and storage. The project aims to evaluate the feasibility of injecting and storing CO_2 in depleted natural gas fields on the Dutch continental shelf towards developing a permanent CO_2 injection facility. This mature field has been producing natural gas since 1987.

Traditionally, the CO_2 separated from this gas was vented into the atmosphere, but recent efforts have redirected it into the same reservoir from which it originated, at a depth of around 4,000 metres (about 2.49 mi).

The initiative at K12-B is part of the Dutch government's CRUST project, which aims to evaluate the feasibility of CO_2 injection in depleted natural gas fields and assess the associated environmental and legal aspects. This project, subsidised by the Dutch Ministry of Economic Affairs and operated by Gaz de France Production Nederland B.V., represents a pioneering effort in offshore CO_2 storage.

Challenge

The integration of CO_2 storage into existing gas fields presents several challenges. There are inherent uncertainties surrounding the long-term behaviour of CO_2, the effectiveness of enhanced gas recovery (EGR), and the potential environmental impacts of such storage solutions. Specifically, the challenge lies in accurately assessing the behaviour of injected CO_2, understanding its migration pathways, and ensuring that it remains securely stored without unintended leakage.

In this depleted gas reservoir nearing the end of its life, the objective was to track the movement of CO_2 and enhance the understanding of the reservoir's behaviour. The study revealed that CO_2 exhibited similar behaviour to methane in certain areas of the reservoir but diverged significantly in other regions. This discrepancy introduced uncertainties, even though this mature reservoir was well-understood.

Solution

During the analysis of CO_2 breakthrough, tracer data was used in conjunction with analogue equipment from the well. CO_2 was injected into the same field from which it originated, with the aim of enhancing gas recovery while the field remained in production. A CO_2 tracer was incorporated to optimise the injection scheme and successfully identify the breakthrough of re-injected CO_2.

The tracers served multiple purposes:

- **Tracking CO_2 migration:** By following the path of the tracers, the movement of CO_2 through the reservoir could be accurately mapped. This included measuring the CO_2 injection rate, composition, and the physical interaction between injection and production wells.
- **Assessing reservoir behaviour:** Tracer data helped evaluate the sweep efficiency of the injected CO_2 and the overall flow behaviour within the reservoir.
- **Ensuring well integrity:** The tracers also provided insights into the condition of the CO_2 injection tubing and the quality of the cement bond in the injection well.

Results

The application of RESMAN's tracer technology at K12-B yielded valuable insights into the CO_2 storage process. Tracers detected the CO_2 as soon as it broke through, whereas traditional gauges did not register any change for months. The analogue equipment, with its lower resolution, detected the breakthrough with a delay compared to the tracers. This immediate detection by tracers provided a much clearer and more timely resolution of the CO_2 movement, highlighting the superior sensitivity and effectiveness of tracer technology in monitoring such processes.

The tracers accurately assessed the flow behaviour and sweep efficiency of the injected CO_2. Without them, it would have been difficult to differentiate between the injected CO_2 and the naturally occurring CO_2 in the reservoir, complicating the determination of physical movement between injectors and producers.

The most significant findings include:

- **Detection of physical communication:** Tracers confirmed physical communication between the CO_2 injection well (K12-B6) and the nearest producer well (K12-B1). Tracers were detected in the gas stream of K12-B1 approximately four months after the start of CO_2 injection, validating the expected migration paths and reservoir connectivity.
- **Understanding reservoir dynamics:** Tracers facilitated a better understanding of reservoir behaviour and pressure dynamics. The data obtained helped interpret complex down-hole pressure data, which is crucial for optimising storage and recovery processes.
- **Early detection of issues:** The precision of tracer technology enabled the early detection of potential issues, such as unexpected pressure disturbances. This early warning capability is essential for proactive management and mitigation of any risks associated with CO_2 storage.

Conclusion

The K12-B case study highlights the transformative impact of tracer technology on CO_2 storage and monitoring. By providing accurate tracking of CO_2 migration and verifying the integrity of storage sites, tracer technology offers a robust solution to the challenges of CCS.

The successful application of tracer technology at the K12-B site underscores its potential to enhance our understanding of CO_2 storage and recovery processes. The ability to track CO_2 movement with high precision and detect leaks or migration issues early contributes significantly to the overall safety and effectiveness of CCUS initiatives.

Harnessing experience from the In Salah CO_2 storage project

The In Salah CCS project in central Algeria is a pioneering example of onshore CO_2 capture and storage. With a history of more than two decades, this project has amassed a wealth of relevant knowledge for CC initiatives worldwide.

Background

This project captures CO_2 from multiple gas fields at a central processing facility. The captured CO_2 is then compressed, transported, and injected into a 1.9km deep carboniferous sandstone formation at the Krechba field. Since its inception in 2004, the project has successfully stored more than 3.8 million tons of CO_2.

Challenge

The In Salah project involved an aquifer with limited prior knowledge. A unique aspect of this project was the effort to reduce costs associated with CO_2 storage and to cut the costs by using CO_2 from their own operations. Abated CO_2 from the Krechba field helped to address the issue of high CO_2 content in their natural gas, which affected its marketability. The primary risk for the project was regulatory scrutiny and stakeholder concerns. Authorities needed assurance that the CO_2 was being properly monitored and not being reintroduced into the production stream, which could be seen as fraudulent. Ensuring that CO_2 was not re-emerging was critical to avoid potential penalties.

> “Developing a comprehensive and cost-effective monitoring strategy was essential to verify that the CO_2 remained securely stored”

Developing a comprehensive and cost-effective monitoring strategy was essential to verify that the CO_2 remained securely stored. This required a diverse portfolio of monitoring technologies to track the behaviour of the CO_2 and detect any potential leaks.

Additionally, the project faced geological and geo-mechanical complexity. The storage reservoir consisted of low permeability and fractured sandstone, making it crucial to understand the intricate geological characteristics and the behaviour of CO_2 within this complex environment.

Solutions

To ensure effective monitoring, a broad array of geophysical and geochemical techniques have been employed, including time-lapse seismic imaging, micro-seismic monitoring, wellhead sampling with CO_2 tracers, down-hole logging, core sampling, surface gas monitoring, groundwater analysis, and satellite InSAR data. These methods have been instrumental in developing robust protocols for data collection and interpretation, offering critical insights into measuring, monitoring and verification (MMV) practices for CO_2 storage.

Several tactics were employed:

- **Risk management and adaptation:** A pre-injection risk register was established, guiding the development of the monitoring program. Regular quantitative risk assessments (QRAs) were conducted to update and refine risk management strategies.
- **Risk of migration:** InSAR data and updated reservoir modelling identified potential risks of CO_2 migration beyond the intended storage area, leading to adjustments in injection strategies.
- **Well integrity:** Issues with well integrity were addressed through increased monitoring and well maintenance. Measures included the suspension of CO_2 injection at certain wells and enhanced inspections.
- **Vertical leakage:** Seismic data indicated potential vertical leakage pathways, prompting adjustments in CO_2 injection pressures and additional geo-mechanical studies.

Tracer technology application

Advanced tracer technology was employed to investigate CO_2 movement within a saline aquifer situated in the same stratigraphy as a producing field. Although various technologies were employed in the MMV process, tracers emerged as the most effective tool for distinguishing between natural and stored CO_2.

Results

The use of RESMAN's tracer technology enabled precise tracking of CO_2 sources and confirmed that CO_2 detected in production wells was not attributable to injection activities. Different CO_2 tracers were injected into each of the three CO_2 injection wells. The results revealed that CO_2 breakthrough was detected after approximately five years. This finding provided both source identification and proof of mass transport, which were not evident from seismic or other data.

In this project, tracer technology achieved detection levels of parts per quadrillion (PPQ), providing remarkable resolution in the industry. Importantly, tracers are organic and safe, offering a high level of precision while maintaining a favourable safety and environmental profile.

The In Salah project has yielded several critical lessons that can be applied to other CCS projects:

- **Thorough geological and geo-mechanical characterisation:** Understanding the detailed geology and geo-mechanics of both the reservoir and the overburden is crucial. In Salah's success underscores the importance of a comprehensive assessment of the subsurface environment. This includes evaluating rock properties, reservoir pressure, and the integrity of the cap rock to ensure the long-term stability of the CO_2 storage.
- **Regular and integrated risk assessments:** The project highlights the need for ongoing risk assessments that integrate multiple data sources. By continuously evaluating data from various monitoring techniques, the project team can identify and mitigate potential risks early. This approach enhances the reliability of CO_2 storage and helps prevent unforeseen issues.
- **Flexibility in system design and operation:** The experience from In Salah emphasises the importance of flexibility in the design and operation of CO_2 capture, compression, and injection systems. Adapting to new data and evolving conditions ensures that the infrastructure remains effective and efficient throughout the project's life cycle.

Implications for future CCS projects

The In Salah project offers several implications for future CCS endeavours:

- **Enhanced monitoring techniques:** The diverse portfolio of monitoring methods used in In Salah sets a benchmark for future projects. Implementing a similar range of techniques can improve the accuracy of CO_2 tracking and the overall safety of storage operations.
- **Comprehensive risk management:** Future CCS projects can benefit from the rigorous risk assessment practices demonstrated at In Salah. Regular, integrated evaluations of geological, operational, and environmental data will help in managing and mitigating risks more effectively.

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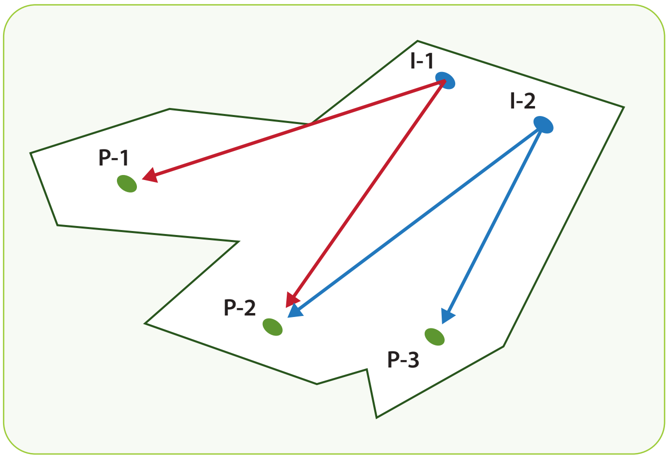

Figure 2 Proof of connection

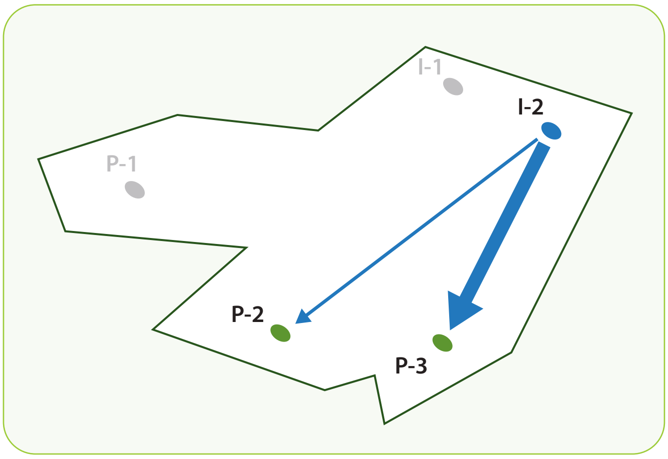

Figure 3 Proof of significance

- **Adaptive infrastructure design:** The flexibility demonstrated in In Salah's system design and operation provides a valuable lesson for other CCS projects. Ensuring that systems can adapt to changing conditions and new information will support more resilient and successful storage operations.

Conclusions

The In Salah CO_2 Storage Project is a landmark achievement in CCS. Its successful implementation and the extensive knowledge gained offer a rich source of insights for other CCS projects worldwide. By adopting the lessons learned from In Salah – ranging from thorough geological characterisation to flexible system design – future projects can enhance their effectiveness and reliability.

Benefits of tracer technology in offshore and onshore CO_2 capture projects

Tracer technology has been applied successfully with other MMV technologies to enhance the viability and safety of CO_2 storage projects. Seismic imaging alone is necessary to visualise the plume, but tracers complement seismic and other technologies by offering additional insights and validation. When used with seismic imaging, tracers enhance the monitoring and verification process and are detectable at extremely low concentrations.

Chemical tracers provide clear and unambiguous evidence of CO_2 origins, pinpointing CO_2 leaks swiftly. They eliminate the need for extensive geochemical surveys or conventional monitoring technologies, resulting in significant cost savings and improved

		CCS/CCUS field type				
		Depleted reservoir		Saline aquifer		Pressure management
Tracer type	Information from tracer	Onshore	Offshore	Onshore	Offshore	
CO_2 tracer @ injections	RTD-sweep volume-curve typing	✓	✓	✓	✓	
	Connectivity	✓	✓	✓	✓	
	Boundary assurance	✓	✓	✓	✓	
	Surface monitoring	✓	✓	✓	✓	
	Nearby additional storage	✓	✓	✓	✓	
	CO_2 injection	✓	✓	✓	✓	
	Low-cost insurance	✓	✓	✓	✓	
	Natural CO_2 vs injected	✓	✓	✓	✓	
	Future monitoring wells	✓	✓	✓	✓	
SWCTT	SWCTT - oil saturation	✓	✓			
PITT	PITT - oil saturation	✓	✓			
Production tracer	Inflow tracer in producing wells	✓	✓	✓	✓	
All	Calibration with other technologies	✓	✓	✓	✓	

Table 1 Information obtained through tracer technology

clarity of monitoring results. Advanced tracer technology operates at low detection levels, as low as parts per trillion (PPT) or even PPQ.

As demonstrated through application in K12 and In-Salah projects, tracers provide the ultimate proof of connection in the Interwell communication patterns (see **Figure 2**), significance, or quantification of magnitude of communication (see **Figure 3**), and coverage or sweep (storage) (see **Figure 4**) volume. Using tracers is not merely about confirming the presence or absence of a connection. Tracers enable the quantification of the magnitude of communication between different areas, allowing for a detailed analysis of storage volume. This approach provides quantitative data rather than just qualitative insights, offering a more precise and measurable understanding of the CO_2 storage dynamics. **Table 1** shows the type of information obtained from tracer technology applied in K12 and In-Salah projects.

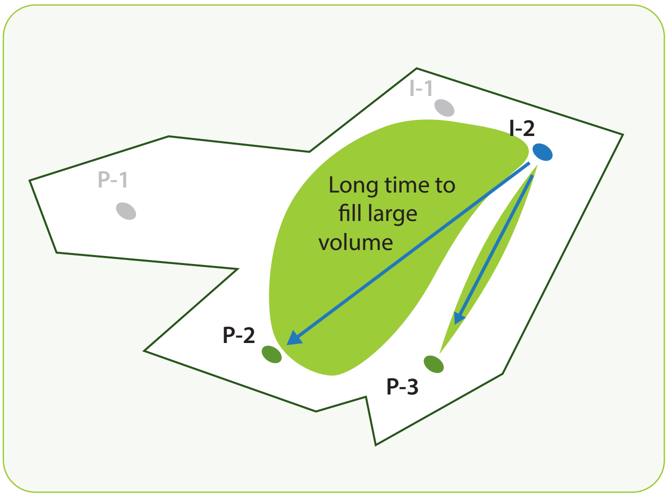

Figure 4 Proof of coverage

Conclusion

In summary, tracers present a promising technology for understanding CO_2 migration by offering direct measurement of CO_2 and a unique CO_2 plume tracking per injection point. Tracers offer a direct, unambiguous physical proof of mass transport and physical differentiation of CO_2 sources.

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Smart tank storage solutions for new biofuel feedstocks

Mission-critical heat tracing systems and innovative tank insulation help tank farm owners with flexible, energy-efficient storage

Kees Oerlemans, Koen Verleyen and Pele Myers
nVent

Seismic change is on the horizon for the chemical storage sector. For many years, the industry has relied on oil production as its main source of new investment streams. In 2020, however, this well-established trend was challenged. As a result of the pandemic, worldwide oil production dropped from 100 million bpd to 88 million bpd – a downturn felt even more keenly by the US market, which fell by a staggering 20% (*Nagle, 2020*).

In the US, overall biofuels production capacity – which includes renewable diesel, biodiesel, ethanol, and other biofuels – reached 23 billion gallons per year (gal/y) in January 2023, a 6% increase in total production capacity from January 2022. Fuel ethanol accounted for 78% of US biofuel production capacity, renewable diesel and other biofuels accounted for 13%, and biodiesel accounted for 9% (*EIA, 2023*).

While both demand and production levels have risen sharply (*IEA, 2021*), this dramatic shift is likely a sign of the market developments to come. The increasing move to renewable feedstocks and the consequent need for storage of both fossil products and renewable products are driving demand for additional tank storage.

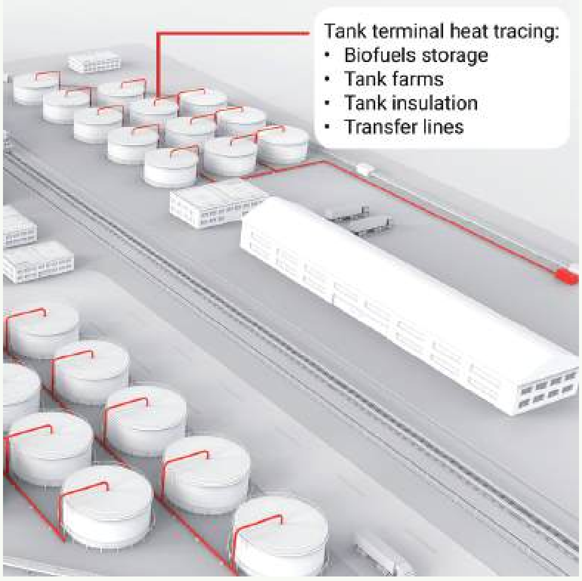
With mounting pressure from governments to reduce reliance on fossil fuels and limit global warming to below 2°C in line with the Paris Agreement, crude oil's position as the primary growth driver for the tank storage sector seems set to change permanently (*Davies, et al., 2020*).

Shifting focus

The growing demand for electric vehicles and other carbon emission reduction initiatives have led to some facility owners choosing to repurpose their existing oil refining infrastructure for renewable energy production (*Davies, et al., 2020*).

As the petrochemical market pivots to focus on high-quality, high-margin chemical feedstock products, investment in tank storage sites are growing, as evidenced by global organisations, including Vopak and Ineos, announcing major new sustainability-focused storage projects in the past year (*Vopak, 2021; Ineos, 2020; Ineos, 2020b*).

New growth opportunities are now opening up for tank farm operators. To take advantage, though, owners will have to contend with a range of evolving challenges, from storage flexibility demands to improving energy efficiency and taking site safety to the next level. Smart heat tracing systems, paired with the



Biofuels production at a smart tank farm

MATERIALS
Jacket*

Aluminium	.024 in (0.6 mm)
Stainless steel	.016 in (0.4 mm)
Coated steel	.024 in (0.6 mm)

*Jacket material can be coated for corrosive environments and coloured for aesthetics

Insulation

Polyisocyanurate	K = .19 BTU • In/Hr • FT • °F	Tmax = 250°F (121°C)
Fibreglass	K = .24 BTU • In/Hr • FT • °F	Tmax = 850°F (454°C)
Mineral wool	K = .26 BTU • In/Hr • FT • °F	Tmax = 1,200°F (649°C)
Cellular glass	K = .30 BTU • In/Hr • FT • °F	Tmax = 900°F (482°C)
Calcium silicate	K = .34 BTU • In/Hr • FT • °F	Tmax = 1,200°F (649°C)
Expanded perlite	K = .34 BTU • In/Hr • FT • °F	Tmax = 1,200°F (649°C)

K-factor based on 100°F (38°C) mean temperature, per manufacturer data sheets.

Table 1 Trac-Loc materials table

latest tank insulation strategies, can empower tank farm owners to navigate these issues with confidence and establish technologically advanced, safe, and sustainable sites that will shape the future of the chemical sector.

Quick setup, easy scale-up

To keep up with current demand – and the opportunities it presents – tank farm operators need heat tracing and insulation systems that can be installed quickly. However, to ensure the site can remain agile, scalability should also be a core concern.

Standing seam insulation panels can be made from one or more industrial insulating materials. Jacket materials come in a wide range of colours and conform to industry standards (see **Table 1**).

Unlike traditional systems, standing seam insulation panels are prefabricated off-site while the tank walls are being raised at the facility. This means the insulation can be installed immediately following tank construction without the need for scaffolding. The panels can be easily lifted into place with a cherry picker or hanging basket.

To further fast-track the installation process, the latest smart heat tracing systems feature intelligent hazardous area control panels that can be installed in the field close to pipe circuits, as opposed to a central control room. Based on nVent Raychem internal design and power distribution comparisons of executed projects 2015-2020, this seemingly simple feature can reduce the heat tracing system's power infrastructure and communications cabling requirements by 20% or more for lower total installed cost and faster installation. In addition, smart heat tracing controllers allow site owners to easily incorporate new piping circuits as their facility expands by seamlessly integrating the new local controllers with the existing control system.

Smart heat tracing systems Elexant 4010i

Keeping environmental costs down

Energy efficiency and the reduction of carbon emissions are fast becoming primary concerns for chemical producers when selecting a tank storage

Certified cables are placed around the tank. Stainless steel clips fixed on this cable are captured within the seam made between two panels, resulting in a mechanically superior system with inherent expansion and contraction properties.

Prefabricated panels are stored in containers or a warehouse on site.

Panels are installed easily and quickly by using a hanging basket or cherry picker, eliminating scaffolding requirements.

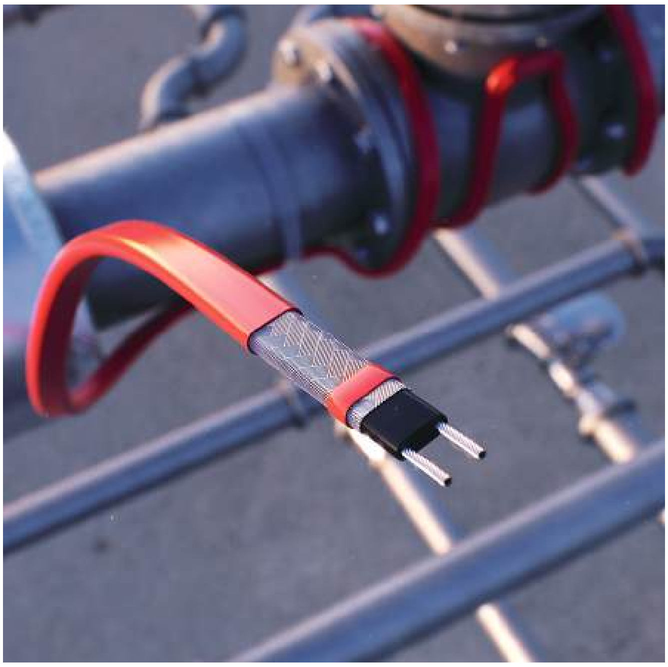
Prefabricated standing seam insulation panels installation

facility. Investing in the most efficient tank insulation and heat tracing controls can also help tank farm operators offer a more cost-effective storage solution to potential customers, especially considering that tank and pipe heating are often charged as additional cost on top of rental rates.

Providing a more effective and hardwearing alternative to traditional insulation, high-quality standing seam insulation panels are the best option for facility owners looking to maintain tanks at a consistent temperature, sustainably. In contrast to traditional systems, we also offer closed-cell insulation materials (such as polyisocyanurate, PIR) that do not degenerate or lose insulation capacity over time, meaning no extra heating power is needed to mitigate increased heat loss towards the end of the tanks' lifetime. In a direct evaluation of two newly installed systems, closed-cell materials represent superior performance when compared with mineral wool, thanks to their lower thermal conductivity rating (*greenspec*, 2024). The overall result is a storage facility that offers the environmental responsibility producers increasingly expect, with the economic benefits they need to maintain that all-important competitive edge.

Accurate control for adaptable tank storage

Regardless of size or location, precise temperature control of chemical fluids during transport to and from loading sites is a foundational consideration. At their most basic level, in-feed line heat tracing systems must be able to maintain the optimum temperature for product quality and safety. However, to allow customers to shift their storage strategies in line



Self-regulating heating cable

Customer control room

with commodity prices and market demand, site owners also need pipe heat tracing circuits that can be reconfigured quickly to accommodate any type of critical liquid.

The most advanced heat-tracing controllers deliver flexibility via a combination of tried-and-tested line sensing temperature monitoring and more recently introduced 'true power' control. This feature enables the heat tracing system to measure voltage and current in real-time and to adjust the power output to match the precise temperature requirements of any chemical product – both for storage and transportation. This high degree of accuracy represents an improvement in the performance of more traditional heat tracing controllers, minimising the risk of excessive power use while also allowing for greater cable standardisation across the entire installation.

> **“The most advanced heat-tracing controllers deliver flexibility via a combination of tried-and-tested line sensing temperature monitoring and more recently introduced 'true power' control”**

This feature also offers facility managers the benefits of variable voltage capabilities. It allows them to better manage differences between the initial design and the system as built and ensure critical pipe infrastructures can be quickly and accurately configured to transport any chemical fluid.

Maximising reliability and ROI

To keep tanks operating profitably throughout their entire service life, facility owners need durable, low-maintenance insulation solutions that can withstand increasingly harsh and unpredictable weather conditions. When seeking to maximise the longevity of any tank installation, particularly in coastal regions, a crucial consideration is corrosion under insulation (CUI). CUI can potentially reduce the life of a tank down from 40 to as few as 10 years, all the while damaging profitability further through the deterioration of insulation performance and the need for frequent maintenance.

Standing seam insulation panels are helping to make CUI a challenge of the past with their dense structure, unique double-folded seam methodology, and seamless interlocking installation method, which removes the need for outer screws. These panels absorb far less water over their lifetime and are more resilient to even the worst weather conditions, delivering reliable and long-lasting insulation performance (*nvent/Raychem*, 2024b).

Case study 1: Self-regulating heating cable for process temperature maintenance and Trac-Loc panels for seamless tank insulation

A major client was expanding its biodiesel terminal in Winnipeg, Manitoba, in order to store B100, a pure biodiesel product. As this has a higher gel point than regular diesel, it required a more precise temperature. The customer's mission-critical objective was to find a complete heat management solution for the piping that would maintain the pre-determined temperature for this temperature-critical application, as well as insulation of the tank that would store the B100 – all within its aggressive schedule. nVent engineers designed a system using Raychem XTV heating cable due to its design flexibility to maintain an accurate temperature. Raychem The Trac-Loc advanced interlock standing seam panel system was used to insulate the tank. Since Trac-Loc panels are prefabricated off-site, this insulation solution eliminated the need for scaffolding, resulting in a seamless and timely system installation.

Case study 2: Trac-Loc panels for seamless tank insulation for upgraded tank terminal reliability

A major client was upgrading its terminal tanks in Rotterdam (NL), Antwerp (BE), and Fawley (UK). The customer's mission-critical objective was to find an energy-efficient, cost-effective tank insulation solution that offered high rigidity, reduced moisture ingress, and minimised CUI. nVent engineers designed prefabricated Trac-Loc panels using PIR closed-cell insulation material and aluminum metallic jacketing, with a double-locking vertical seam construction to insulate the tanks. Trac-Loc prefabricated panels simplified installation because they minimised material handing and eliminated the need for scaffolding, resulting in minimal operational disruptions, fewer onsite man-hours, and less cost. Additionally, the prefabricated standing seam insulation panels and double-seam attachment technique offer a system with long-term reliability and performance, significantly reducing maintenance costs associated with CUI-related issues. Finally, the system resulted in substantial energy savings for the client, further supporting operational efficiency and reduced carbon footprint.

Keeping tanks safe and sound

These advanced tank insulation and heat tracing solutions must also improve site safety. With companies investing in more large-scale storage facilities for sensitive or hazardous chemicals, tank farm owners are searching for systems that can help the industry expand production without increasing risks to people, property, or the environment.

In addition to true power control, smart heat tracing controllers are equipped with intelligent features like self-test functions, bespoke alarms, and continuous system monitoring, which means faults are identified and resolved before they can threaten site safety. Meanwhile, the long-term durability and corrosion resistance offered by standing seam insulation minimises the risk of tank fissures or harmful chemical leaks, protecting the health of workers on site, as well as precious natural landscapes.

Summary

Despite current challenges, the future is looking bright for the chemical storage sector. Demand for specialised chemicals to fuel new technologies and renewable energy generation projects is already driving investment, and as decarbonisation efforts continue, further growth opportunities are on the horizon.

> “Flexible, energy-efficient storage sites will play a critical role in helping the chemical sector navigate fluctuations in price and policy”

The watchword for tank farm operators must be ‘adaptability’. Flexible, energy-efficient storage sites will play a critical role in helping the chemical sector navigate fluctuations in price and policy. Smart, adaptable solutions like the Raychem heat-tracing systems offered by nVent Thermal Management can help to futureproof tank sites. Armed with these technologies, tank farm owners can capitalise on expanding demand and be confident that their facilities are primed to thrive, whatever the future may hold.

VIEW REFERENCES

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Accelerate SAF R&D with high-throughput catalyst testing

The required ramp-up in SAF production can be achieved more easily and efficiently with the support of high-throughput catalyst testing technology

Giada Innocenti, Benjamin Mutz, Christoph Hauber, Jean-Claude Adelbrecht, Ioan-Teodor Trotus
hte GmbH

Rising CO_2 emissions are a constant source of concern for both the public and government agencies due to their implications for global warming. Regulators have been setting stringent specifications to decarbonise every industrial sector, triggering a rethink of the refining and petrochemical industries. The European Green Deal has set the very ambitious target of decreasing the European Union's greenhouse gas emissions by at least 55% by 2030 to reach climate neutrality by 2050. The European Union has launched the ReFuelEU initiative, which progressively increases the target amount of sustainable aviation fuel (SAF) that must be used to ensure that the aviation sector also reaches carbon neutrality. The goal of 70% SAF by 2050 can only be achieved if a ramp-up in SAF production from different sources is pursued.

The technologies for producing SAF are at different technology readiness levels depending on the type of raw material used (syngas, used cooking oils, animal fats, alcohols, algae, and so on). It is clear that state-of-the-art tools are needed to provide the requisite momentum for the development and optimisation work required to enable a quick increase in SAF production. SAF production efficiency can be accelerated through the use of high-throughput experimentation. This technology enables the rapid collection of large datasets to develop kinetic models, test the impact of upsets, or identify the most efficient catalyst in a benchmarking study. By providing a large amount of data in a short timeframe, high-throughput technology can support the retrofit of existing facilities or the choice of either the best catalyst or the optimal operational conditions for newer dedicated production plants.

The most technologically advanced routes to SAF are shown in **Figure 1** and will be discussed in this article.

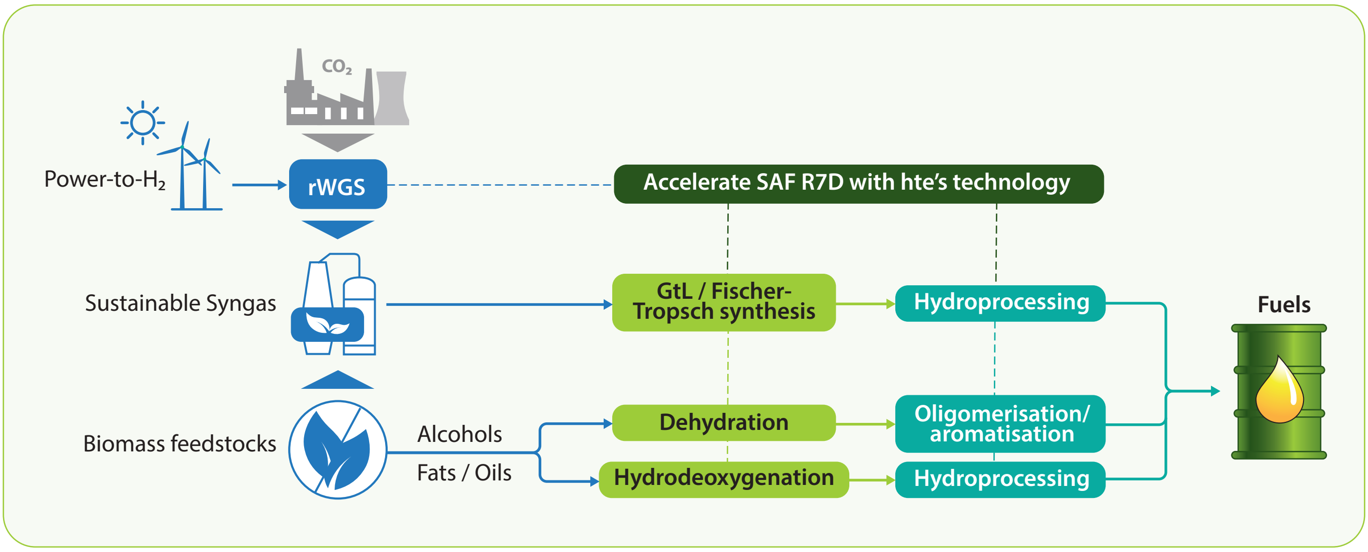

Figure 1 Main routes to producing SAF

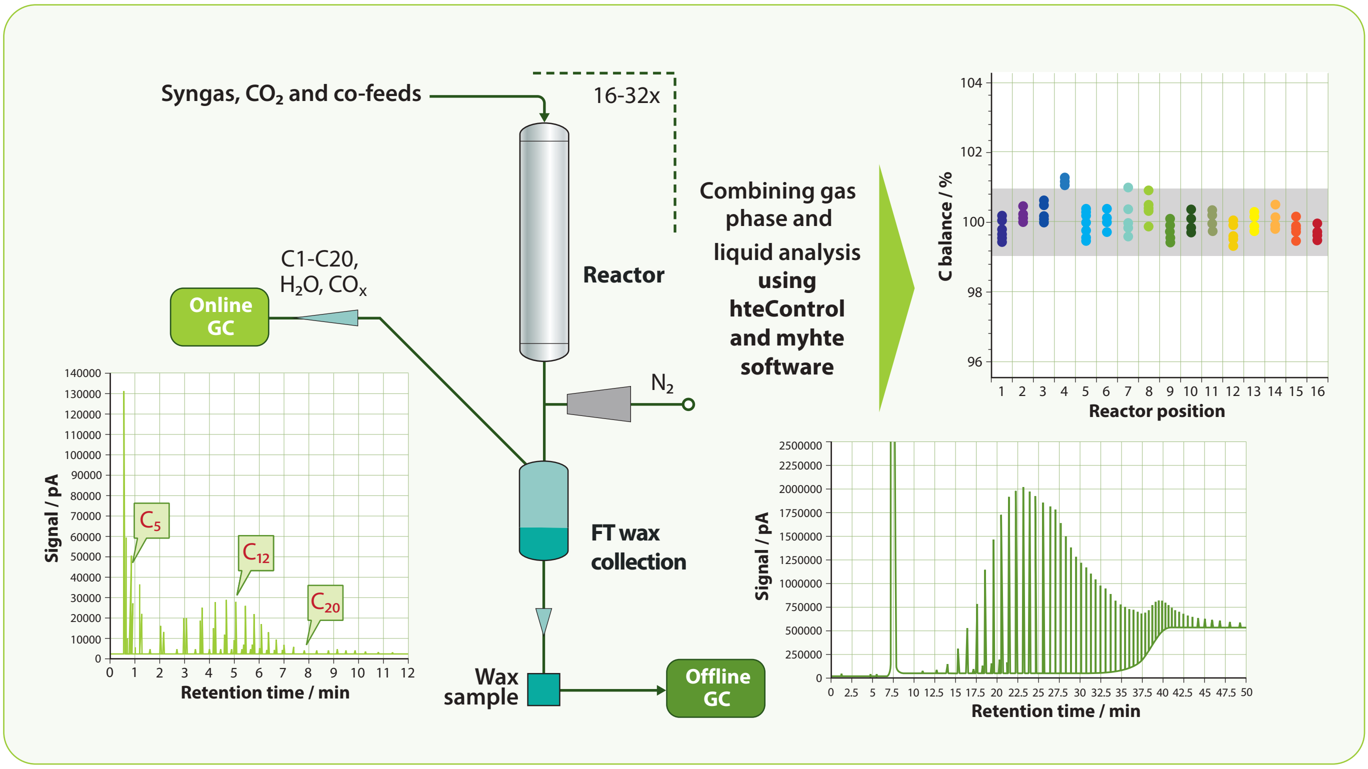

Figure 2 Fischer-Tropsch workflow at hte's high-throughput test unit

Syngas to liquid hydrocarbons via Fischer-Tropsch synthesis

Fischer-Tropsch synthesis (FTS), which produces liquid hydrocarbons from CO/H_2 mixtures, is the central process of the SAF route via syngas. FTS technology was originally developed for the conversion of natural gas or coal into fuels. Recently, however, FTS has been attracting more attention as a way to produce value-added fuels and chemicals from unconventional feedstocks such as biomass or municipal solid waste.

The hydrocarbon product spectrum from FTS follows an Anderson-Schultz-Flory distribution, which can be influenced by process conditions and catalyst selection. To target the highest yield of SAF, the formation of long-chain paraffinic hydrocarbons has to be favoured. Downstream hydroprocessing is then required to reach the desired fuel specifications.

Sustainable syngas composition and purity vary widely; it is, therefore, necessary to enhance process efficiency by improving the catalyst and selecting the right reaction parameters to achieve a targeted product distribution. Catalyst and parameter screening, kinetic studies, quality control, and catalyst upscaling towards extrudate testing can be accelerated by high-throughput technology featuring a robust and reliable gas-to-liquid workflow, as detailed in an earlier publication (*Knobloch, et al., 2015*).

hte's well-established reactor packing protocols ensure stable plug flow conditions and prevent thermal runaways, enabling a broad range of conversion rates and reproducible performance data. The fully integrated data warehouse allows accurate quantification and real-time calculation of conversion, product formation rates, and mass balance (see **Figure 2**). The mass balance can be closed to 100±2% by combining the products generated in both the gas and liquid phases, each quantified via fast online detection and integral wax analysis, respectively. hte's multicolumn/multidetector gas chromatography (GC), configured in-house, makes it possible to reliably discern paraffins, olefins, isomers, and alcohols.

The great flexibility of high-throughput experimentation allows ranking among possible candidate catalysts with a one-to-one comparison. For example, the effect of the pore structures in different samples of Co/TiO_2 was highlighted by running 48 experiments within a five-week timeframe. This was achieved using 32 reactors in parallel to explore the parameter space of the kinetically controlled regime (*Schulz, et al., 2021*). As another example, an hte customer reported using hte technology for intensive testing of bifunctional FTS catalysts (*Kibby, et al., 2013*).

FTS is considered to be very promising for CO_2 emissions abatement when used in the production of SAF. The sustainability of FTS would be ensured by integrating reverse water gas shift (rWGS) of captured CO_2 with the use of green H_2 as feedstock for the process. Direct coupling of both processes can be realised by operating the rWGS reactor at 30-40 bar, which requires high temperatures to convert CO_2 into CO.

To address this challenge at laboratory scale, it is essential to have a suitable reactor concept that allows the catalyst activity to be isolated from any potential reactor wall activity. hte technology ensures data reliability and accuracy by using reactors with a ceramic inlay tube that can operate at conditions such as 780°C and 50 bar, thus combining high temperatures and elevated pressures. Such reactors can be used to carry out different types of chemical reactions and are suitable for both low-conversion kinetic studies and high-conversion stability tests (*Mutz, et al., 2022*).

> **“As an alternative route towards hydrocarbons, CO_2 can be directly used to synthesise methanol, which can then be further converted within the methanol-to-olefins process”**

Once the FTS waxes are obtained, they require hydroprocessing, carried out in trickle bed units, to ensure they meet the specifications for SAF. With the use of both gas phase and trickle bed high-throughput units, hte has enabled its customers to carry out FTS first, followed by wax hydroprocessing (*Roberts, et al., 2020*). Details about the latter process step are provided in the following sections.

The direct conversion of CO_2 as FTS feedstock without the use of a separate reactor to operate rWGS can be achieved using shift-active Fe-based catalysts. However, it presents additional challenges and limitations requiring a rethinking of the process. As an alternative route towards hydrocarbons, CO_2 can be directly used to synthesise methanol, which can then be further converted within the methanol-to-olefins (MTO) process. Screening of the activity for different catalytic systems and testing of the different operating conditions for this type of reaction can be readily achieved by using hte's catalyst-testing technology (*Haas, et al., 2019*). Finally, the olefins produced via MTO can be further processed by means of oligomerisation to produce SAF.

Oligomerisation of renewable ethylene

The process of converting alcohol to jet fuel (alcohol-to-jet) is another promising route to meeting the necessary blend mandates in the coming years. Such a process is currently being commercialised by a variety of companies. The upgrading of ethanol to SAF first requires a dehydration step to produce ethylene, followed by a purification step and oligomerisation to produce long-chain alkanes. The production of SAF is achieved by employing a two-step oligomerisation route rather than direct ethylene oligomerisation to better control the selectivity to C_8-C_{16} alkenes.

Accordingly, ethylene is first converted to butenes and hexenes on Ni-based catalysts at low temperatures, and subsequently the olefin mixtures produced are further upgraded over an acidic catalyst at higher temperatures. Finally, the products are hydrogenated to transform all the olefins into alkanes and meet the SAF specifications, as defined by ASTM D7566.

While olefin hydrogenation is a well-known process, the testing and scale-up of oligomerisation catalysts and process conditions require both catalyst and process optimisation. hte operates various gas-to-liquid high-throughput units, which could be used to rapidly screen a large number of potential catalysts.

One of the major concerns with oligomerisation is controlling the large amount of heat generated by the reaction. hte's technology can handle this issue by loading a limited amount of catalyst (up to 3 mL) diluted with inert material as well as diluting the olefinic feed with inert gas.

Once the optimal catalyst is selected, it is possible to move on to the process optimisation stage. This part typically requires the use of a bench-scale unit capable of holding more catalyst (up to 150 mL) to process larger amounts of feed. In this configuration, the catalyst dilution may not be sufficient to carry out the large heat of reaction generated, and an oil-heated double-walled tubular reactor becomes the preferred option.

The choice of the feeding system for ethylene depends on the required operating pressure. For low-pressure operations, a simple mass flow meter can be employed, whereas for high-pressure operation, ethylene in a supercritical state can be fed with a syringe pump. Similarly, if recycling operations need to be simulated, longer-chain olefins can be co-fed as liquids. The homogeneous distribution of the liquid or gas feed is ensured through capillary distribution systems. Since the feed distribution directly affects the mass balance, it is important to ensure that the physical state within the capillaries is not subject to change due to evaporation or condensation in the distribution system.

If the conversion is not complete, product sampling needs to be tuned to ensure that all the molecules in the complex product mixture are taken into account. Therefore, it is necessary to depressurise the downstream section of the reactor prior to the separator to favour the stripping of liquified light components such as propenes, butenes, and pentenes. Quantification of the C_3-C_5 components in the gas phase will improve the mass balance and minimise safety concerns. Finally, it is important to keep the temperature of the sampling section high to avoid clogging due to the possible formation of longer-chain alkanes with higher boiling points.

The mass balance is closed by accurate online and offline quantification and characterisation of the gas and liquid phases, respectively. Offline simulated distillation (SIMDIST) is used to analyse the liquid phase, quantifying the yield and selectivity to the specific product range. The yields and selectivities are then reconciled with the online GC gas phase quantification.

If a more detailed analysis of the molecules in the mixture is required, GC-MS, GCxGC, or hydrogenation GC can be used. These techniques can distinguish the olefins, paraffins, isomers, and aromatics, providing even more information about the fuel composition. The hydrogenation GC allows an easy quantification of the ratio between branched and unbranched molecules in the product mixture. An example of the power of hydrogenation GC as a technology with respect to a simple GC is reported in **Figure 3**.

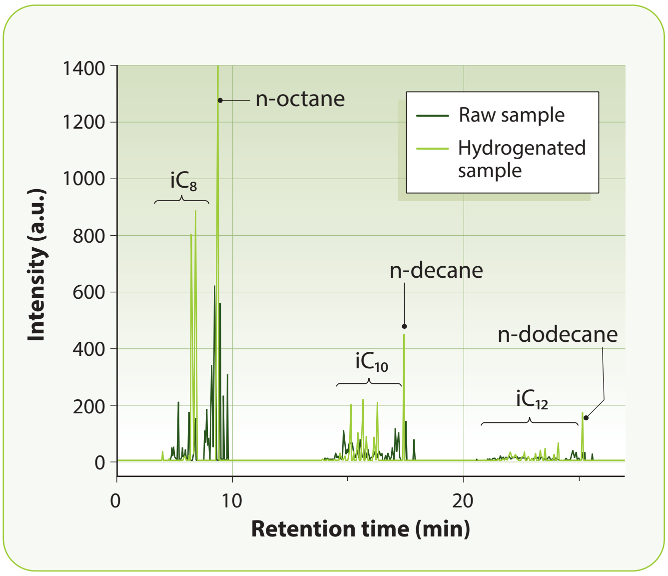

Figure 3 Oligomerisation product sample measured by GC (dark green) and hydrogenation GC (light green). The overlay displays the simplification of the complex product composition, allowing for evaluation of the ratio of branched to unbranched products during catalyst screening

Hydroprocessing (dewaxing)

SAF can be produced from vegetable oils (or animal fats) by means of hydroprocessing. Fischer-Tropsch waxes can also be hydroprocessed to meet the desired SAF specifications. Best practices for laboratory testing for the conversion of vegetable and pyrolysis oil to fuels and chemicals are described elsewhere (*Innocenti, et al.*, 2023). This section focuses on the treatment of paraffins with hydrogen to increase the concentration of isomers, improving the cold-flow properties of the fuel. The fuel cuts obtainable by hydroisomerisation of renewables are naphtha (C_5-C_7), SAF (C_8-C_{16}-C_{18}), and diesel (>C_{16}-C_{18}).

Isomerisation catalysts are very sensitive to impurities, so a thorough characterisation of the feedstock is required. It is important to assess the concentrations of sulphur (S), nitrogen (N), and oxygen (O), which can deactivate/passivate the hydroprocessing catalyst. Additionally,

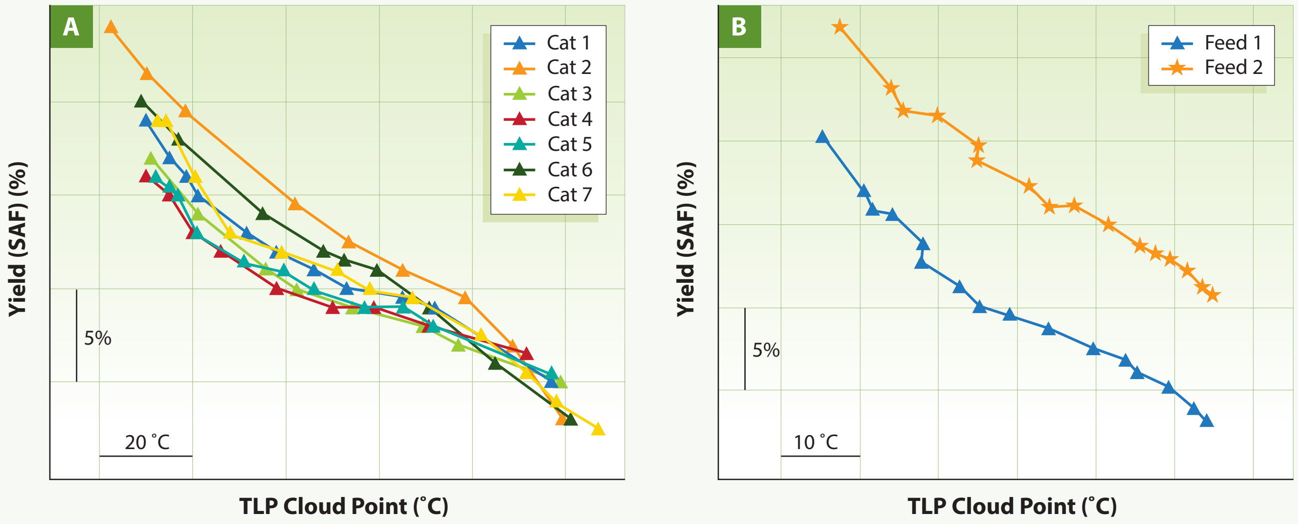

Figure 4 Yield of SAF against total liquid product cloud point. Panel A: difference in SAF yields promoted by different catalysts. Panel B: difference in SAF yield promoted by different feeds

it is good practice to check for the presence of longer-chain paraffins (number of carbon higher than 30). The presence of large amounts of linear long-chain paraffins is detrimental to the final cold-flow properties of the total liquid product (TLP). The SAF yield as a function of cloud point for two feedstocks with a different hydrocarbon composition and different levels of S, N, and O is reported in Figure 1 panel B. The SAF yield, obtained by processing both feeds with the same catalysts, decreased by ~7-8% at all cloud points, with the feed containing the least amount of S, N, and O (Figure 1 panel B).

> “To ensure accurate quantification, it is important to perform an accurate calibration of the mass flow meters at the inlet and outlet of the unit”

Hydroisomerisation processes are usually operated with a GTO above 300 Nm³/m³ to ensure good hydrogen availability. The hydrogen consumption is typically low, in the order of 0.1-0.3 wt% of feed. To ensure accurate quantification, it is important to perform an accurate calibration of the mass flow meters at the inlet and outlet of the unit. During the course of a test, the mass flow meters may also begin to drift slightly, showing a marginally increasing trend or perhaps moderately negative values. Negative hydrogen consumption might also be observed due to the experimental error in the subtraction of two large numbers. These possible experimental errors make it difficult to compare hydrogen consumption among different tests in terms of absolute numbers. This type of additional complication in comparing performances can easily be avoided by employing high-throughput experimentation – where up to 16 reactors can be compared without run-to-run variability.

In hte’s high-throughput units, after the reactor, there is a separator (condenser) that is used to remove and quantify the light ends of the fuels employing an online GC. The separator temperature is optimised from test to test, not only to fine-tune the mass balance but often also to keep the naphtha fraction, which would artificially lower the TLP cloud point in the gas phase as much as possible.

A typical benchmarking test compares the performance of different catalysts at least at two to four different TLP cloud points. The temperature of each reactor is adjusted to the needs of the specific system loaded in it to match the target cloud point. After three days on stream, it is possible to automate the temperature adjustment of the reactors thanks to a continuous feedback loop between the myhte data warehouse and the test unit controlled by hteControl. The performance of the catalysts can be ranked as shown in **Figure 4** panel A, and the data generated can be used by the operators in their economic evaluations. In general, to produce on-spec SAF, the target TLP cloud point would be lower than -25°C (-10°F).

Finally, in this type of benchmark testing, it is very important to have a full characterisation of the final product properties and not rely solely on the TLP cloud point. Therefore, in the conditions of interest, it is recommended to collect larger amounts of products (~300-500 mL) to perform a distillation to characterise each specific fuel cut. It is important to know the cloud point for the renewable diesel and the freezing point for the SAF fraction to ensure that they meet the specifications of the market for which they are intended. Any additional product-specific properties such as density, flash point, or viscosity, can also be evaluated on the specific fuel cut.

Conclusions

The required ramp-up in SAF production can be achieved more easily and efficiently with the support of high-throughput catalyst testing technology. Rapid collection of large datasets to develop kinetic models, testing the effects of upsets, or identifying the most efficient catalyst can significantly speed up SAF production by supporting the retrofit of existing assets or selecting the best catalyst for new dedicated production plants.

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Empowering mission-critical applications in LNG, biofuels, hydrogen, and carbon capture facilities

In the realm of mission-critical applications, particularly within industries such as LNG, biofuels, hydrogen, and carbon capture, the importance of precise and reliable heat management cannot be overstated. nVent Raychem TracerLynx 3D heat management system design software stands as a pinnacle of technological innovation, offering comprehensive solutions that cater to the stringent requirements of these sectors.

Advanced design capabilities

The TracerLynx software is renowned for its advanced design capabilities, which enable engineers to take advantage of all attributes of 3D models in the design of heat management systems. This precision gained through the use of these model attributes is crucial in applications where temperature control is vital for safety, efficiency, and operational integrity. TracerLynx utilises the customer's 3D master plant model data, leveraging the benefits of the 3D model environment throughout the front-end planning, detailed engineering, procurement, construction, start-up, and operation phases.

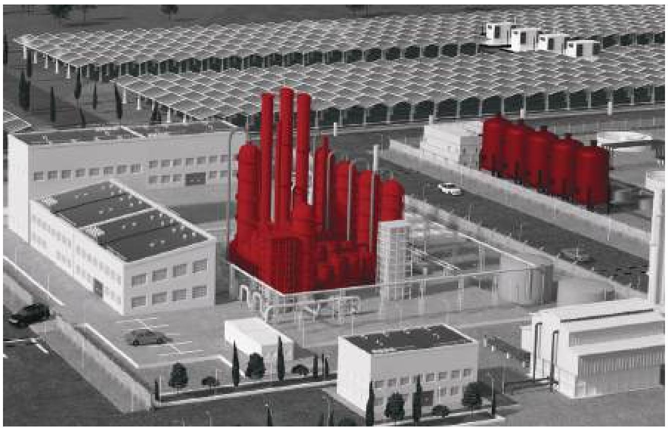

Figure 1 The TracerLynx 3D heat management system offers comprehensive solutions for LNG, biofuels, hydrogen, and carbon capture facilities

The software allows users to visualise complex piping, equipment, and instrumentation, ensuring that every component is correctly integrated into the overall system. Integration of structural steel, power, and instrument cable trays and area classification breaks provide the comprehensive detail required to mitigate risks and prevent potential failures that could compromise mission-critical processes.

Customised solutions

One of the standout features of TracerLynx is its ability to provide customised solutions tailored to the specific needs of each application. For liquefied natural gas (LNG) facilities, where cryogenic temperatures are a constant challenge, the software supports specialised designs that ensure optimal insulation and temperature maintenance. In biofuels and hydrogen production, where precision heating is essential for chemical reactions and process stability, TracerLynx enables targeted solutions that enhance productivity and safety. Similarly, in carbon capture facilities, the software allows for the intricate heat management required for efficient CO_2 separation and storage.

Efficiency and optimisation

Efficiency and optimisation are at the core of the TracerLynx software's functionality. The software not only assists in the initial design phase but also plays a crucial role in ongoing system optimisation. Our proprietary TracerLynx heat mapping technology allows engineers to determine and consider a facility's trace heating loads in sizing and optimally placing transformers and power distribution/control panels early in the design phase. During detailed engineering, the overlay of structural steel, power, and instrument cable trays, in addition to the pre-located transformers and panels, provides further optimisation within the 3D environment, resulting in substantial power distribution savings and total installed

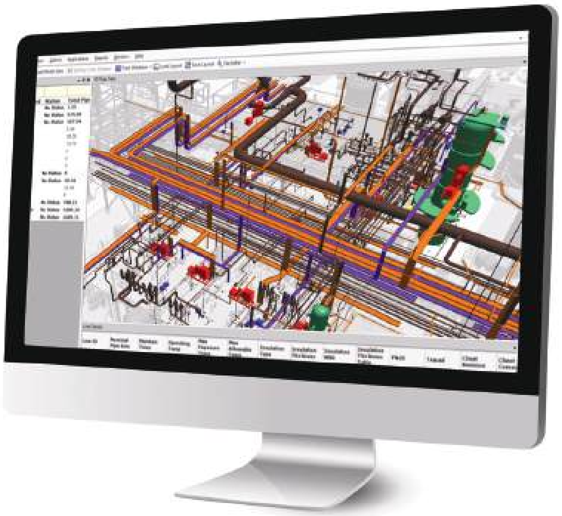

Figure 2 TracerLynx is renowned for its advanced design capabilities

cost (TIC). Additionally, the software's intuitive interface and automation capabilities quickly identify scope additions and engineering change, reducing engineering time and eliminating human error during the critical project engineering and execution phases.

Enhanced safety and compliance

Safety is paramount in mission-critical applications, and TracerLynx excels in ensuring compliance with industry standards and regulations by utilising Smart Scripts. This software feature helps engineers to design within safety guidelines and avoid potential hazards in the design phase. For example, in LNG facilities, where the risk of gas leaks and explosions is a constant concern, TracerLynx provides safety checks and balances in the design phase to minimise these risks. By adhering to stringent safety protocols, the software helps facilities maintain compliance with regulatory requirements, thereby safeguarding personnel and assets.

Scalability and flexibility

TracerLynx is designed to be scalable and flexible, accommodating the evolving needs of large-scale industrial projects. It is fully compatible with customer 3D modelling systems, enabling global work sharing through regional engineering teams with concurrent multi-user access and is a fully integrated single database system. The software can quickly identify the impact of piping and process changes, providing customers with the most efficient and accurate electrical heat tracing (EHT) system design and reducing TIC (inclusive of the costs associated with power distribution materials and construction labour).

Whether a facility is expanding its operations or integrating new technologies, the software can adapt to changing requirements. This scalability ensures that the heat management system remains robust and effective, regardless of the size or complexity of the application. nVent maintains a full-time software development team dedicated to enhancing the flexibility of TracerLynx. This ensures seamless integration with other systems and technologies into the future, further enhancing its utility in diverse industrial environments.

Advanced Work Packaging

TracerLynx supports Advanced Work Packaging (AWP) to aid in safety, labour efficiencies, and equipment and material management throughout the entire project work cycle. TracerLynx allows for easy segmentation of the work in alignment with the project execution schedule and execution work fronts (modular scopes, stick-built scopes, and multiple contractor scopes). The benefits of AWP include up to a 25% increase in field productivity and a 10% decrease in TIC through site schedule optimisation. The utilisation of TracerLynx AWP for EHT projects results in predictable schedules, reduced site rework, and enhanced safety performance.

Conclusion

In conclusion, nVent Raychem TracerLynx 3D heat management system design software is an invaluable tool for engineers working in LNG, biofuels, hydrogen, and carbon capture facilities. Its advanced design capabilities, customised solutions, efficiency optimisation, safety features, and scalability make it a cornerstone of mission-critical applications. By leveraging the power of TracerLynx, facilities can achieve greater reliability, safety, and efficiency, ultimately driving success in their respective industries.

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