

Olefins production pathways with reduced CO₂ emissions

Regulations call for use of renewable feedstocks and electrification via unconventional, sustainable, and circular routes to ethylene, propylene, and other petrochemicals

Christopher R Dzedziak and John J Murphy
The Catalyst Group (TCG)

The focus of recent R&D and commercial developments for novel processes and catalysts for olefins production goes well beyond traditional thermal steam cracking, fluid catalytic cracking (FCC), and propane dehydrogenation (PDH) routes, to include 'green' and circular approaches. These routes include, but are not limited to, the utilisation of biomass or waste plastic, renewably produced methane and syngas, direct CO₂ conversion, and the electrification of reactors. All of these approaches must address certain critical factors affecting technology viability, notably the CO₂ footprint, lifecycle analysis, and overall sustainability in a move towards 'Net Zero 2050' for the chemical and polymer industries.

The 'energy transition' is impacting and changing the priorities and thinking on conventional olefins production, compelling a closer examination of the shifts toward:

- 1 Biomass and recycled waste feedstocks to the cracker and FCC units, trending toward the higher production of bioethylene and biopropylene for bio-PE and bio-PP
- 2 The significant investment and progress toward electrification, highlighted by The Cracker of the Future Consortium
- 3 The emphasis on ESG, CO₂ emissions reduction, and improved energy efficiency.

Historical context and drivers

Refiners and petrochemical companies have seen demand for fuels, petrochemical intermediates, plastics/rubbers, and other products change, with calls for increased circularity and environmental consideration increasing. While they contain favourable demand growth projections above GDP levels, when combined, ethylene and propylene account for the second highest greenhouse gas (GHG) emissions (~250 Mt CO₂e).

For decades, steam cracking has been the dominant method to make olefins. However, the same pitfalls that existed in the past will continue going forward, such as high energy requirements, large quantities of produced GHG emissions (mainly in the form of CO₂), the ethylene/propylene ratio and propylene deficit, and feedstock inflexibility. This has led to a flurry of R&D interest in developing novel processes and catalysts that go beyond traditional thermal steam cracking, FCC, and PDH.

Over the last several years, nations and oil/petrochemical

companies have been increasing their pledges towards lowering GHG emissions, in some cases to zero. Consumer goods companies are ramping up efforts to produce less, reuse more waste, and lower their carbon footprints, while consumers and investors are demanding that companies do more to address these environmental issues. How producers and process licensors respond to these changes moving forward will largely determine which chemical and plastics producers will remain leaders.

CO₂ reduction pathways

In 2021, TCGR completed a multi-client study on the topic of unconventional catalytic olefins technologies, addressing topics like the propylene deficit, feedstock availability and flexibility, world-scale production vs stranded facilities, modular or small-scale production, and environmental issues pertaining to resource utilisation, life cycle analysis, and GHG emissions.¹

Highlighting the study's findings, focusing on pathways towards reduced CO₂ emissions in olefins production, should provide the readers with a better understanding of where their own technology fits in this landscape or possibly which solutions are right for their own operations. They can identify technological gaps and hurdles to overcome and how to plan their strategic and/or commercial objectives in the coming years. Lastly, they should also comprehend the important role that catalysis will play in addressing the challenges for olefins production and, more broadly, the petrochemical/chemical industry.

Fluid catalytic cracking

Recovery of ethylene and propylene from FCC off-gas has gained importance. FCC units have long been a source of propylene as a valued by-product of gasoline production. Specialised process designs and catalysts have been developed to increase FCC-derived propylene production. Technology licensors have developed and offer FCC technologies that span the propylene production range from 8 to 20+ wt% propylene yield on fresh feed. Several new catalysts with substantially larger propylene yields have been invented, as demonstrated in a recent review on light olefins production via FCC.²

The selective production of light olefins from waste

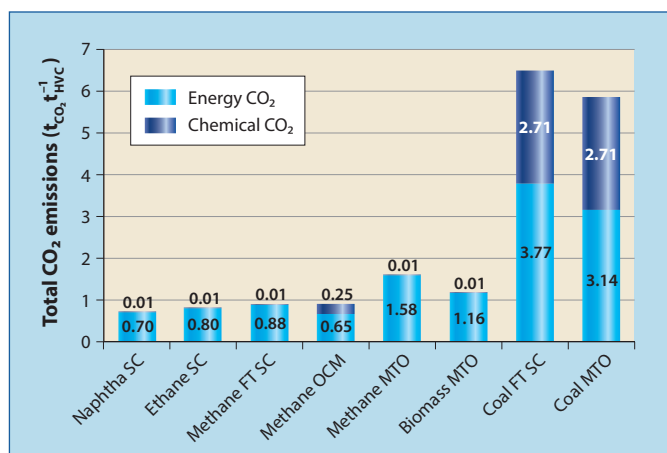


Figure 1 Total CO₂ emissions [tCO₂/tHVC] for different technologies⁴

polyolefins in a single step could be a fundamental and economically viable solution to deal with a waste stream that has proven notoriously difficult to recycle. At present, under ideal lab-scale conditions, maximally 75% of C₂-C₄ olefins can be produced via thermal or catalytic pyrolysis if pure polyolefin feeds are used. For industrial reactors, yields are typically lower than 60%.

Zeolite and zeo-type catalysts with micropores in the range between 4 and 5.6 Å (8 or 10 MR) are favoured due to their high activity and favourable selectivity for light olefins. In line with the tuning of zeolite catalysts for high olefin selectivity, modifications such as bimodal microporous-mesoporous matrices and promoters with, for example, phosphorus are beneficial for improving the selectivity in polyolefins' catalytic cracking and to reach targets of 90%.

Propane dehydrogenation

PDH is a growing catalytic technology utilised for propane- to-propylene conversion. On-purpose propane technologies are today responsible for approximately 20% of propylene production. PDH has been an invaluable technology for providing additional propylene supply at economical prices, and as with many other petrochemical processes, carbon intensity remains an issue. The scaling of renewable propane feedstock will be key to addressing the lifecycle footprint of PDH as well as the use of renewable utilities and off-gas CO₂ capture and utilisation. If these improvements are not introduced, PDH technologies could be disrupted by newer, up-and-coming unconventional olefins technologies.

Several industrial and academic research groups are collaborating to further develop, scale up, and demonstrate a toolbox of novel, efficient, and flexible PDH technologies. Specifically, two electrically heated catalytic reactor concepts (EHCR) are under investigation. One system is based on ohmic heating rods inserted in optimally designed 3D catalytic structures, and the second one is an intensified catalytic membrane reactor (CMR) with electrically conductive catalyst supports.³

Dehydrogenation of ethane over Cr or Pt catalysts is limited by equilibrium and allows only very poor yields of ethylene. This route is not competitive with conventional

routes. Two new entrants in PDH, Dow's FCDh and KBR's K-PRO are challenging the status quo, UOP's Oleflex and Lummus' Catofin technologies. Both Dow and KBR have developed fluidised catalyst reactors and regenerators and claim propane consumption on par with UOP and Lummus. KBR's process is interesting because their proprietary catalyst uses nonprecious metals and no chromium.

Dow announced in 2019 that it would retrofit the FCDh technology in a Louisiana mixed-feed cracker. KBR announced in early 2020 a 600 kt/y unit in Asia and another licence in Pakistan in 2021. Linde's EDHOX (oxidative dehydrogenation) converts ethane and oxygen to ethylene and acetic acid, with a claimed combined yield of more than 93% and lower Capex compared to an ethane steam cracker. There is also the ability to recover purified CO₂ for a 60% reduced CO₂ footprint.

Methanol-to-olefins

Methanol-to-olefins (MTO) is a technology where methanol is catalytically dehydrated and partially converted to ethylene over alumina and zeolite catalysts. To be competitive vs mega-scale ethane crackers with feedstock cost advantages, methanol has to be produced in huge quantities of approximately 5 × 10⁶ t/y, leading to an olefins output of approximately 2 × 10⁶ t/y of ethylene and propylene. MTO, even based on methane, is not a sustainable option based on the carbon footprint.

Figure 1 shows total CO₂ emissions, in tons CO₂ per ton of high-value chemicals (HVC), such as ethylene, propylene, and aromatics. A distinction is made between the CO₂ emission resulting from the process's energy requirement (fuel combustion) and the chemical CO₂ produced in the reaction. It is clear from the figure that steam cracking (SC) is still the best-performing technology, even from a CO₂ point of view.

If the process were to be electrified, the emissions would fall 80-90%. There is nearly no chemical CO₂ produced, and the process's energy efficiency has been optimised so that the process CO₂ is also very low in comparison to the other techniques. Oxidative coupling of methane (OCM) also looks very promising, as it has the lowest process CO₂. However, because of the relatively low ethylene selectivities, the chemical CO₂ for this technology is still quite high. From a sustainability point of view, coal-based techniques are difficult to justify, both energetically and chemically.⁴

Ongoing MTO research includes modifications for improving light olefin yields, reducing catalyst consumption costs, increasing single-train unit capacities, and expanding the sources of raw material feedstocks. Carbon capture and storage can be applied to MTO (also coal-to-olefins, or CTO) to reduce CO₂ emissions by about 73%. There is currently a lot of research activity to further improve CO₂ recovery from process streams by using amine systems enhanced with more selective amines or other process configurations. These will likely further reduce the CO₂ footprint for CTO and other pathways to light olefins.

Oxidative coupling of methane

Several companies have been developing these bespoke light olefins processes via OCM. Examples include Siluria

Technologies (now part of Lummus), Sulzer Chemtech GTC Technology, Grillo AG, and Sinopec. Another prospective light olefins process is via non-oxidative coupling of methane (NOCM). Examples include SABIC/Dalian Institute of Chemical Physics (DICP)/China National Petroleum Corporation (CNPC).

OCM is considered one of the most promising routes to convert methane into ethylene directly. OCM suffers from the conversion-selectivity challenge typical for many selective oxidation processes due to oxidation of the C₂ products in secondary reactions, high methane conversions correspond to poor C₂ selectivities and a high yield of undesired CO_x products. This trade-off between conversion and C₂ selectivity is the main reason why OCM is currently unable to achieve the 30-35% C₂ yields suggested to make the process industrially relevant.⁵

A second important challenge for OCM is the extreme exothermicity of the process. Commercially viable OCM will depend on process intensification, like innovative reactor and process design, such as the vortex reactor.⁶ While OCM may never reach the scale necessary to compete with steam cracking, smaller scale or modular reactors, using renewable feedstocks like biomethane, could offer a decarbonised solution to producing olefins.

Biogas, mainly CH₄ and CO₂ typically produced via anaerobic digestion of organic waste material, is envisioned to be key in achieving the EU's 2030 decarbonisation targets

Electrification and novel reactor concepts

The Cracker of the Future is a consortium of chemical majors based in Flanders, Belgium, North Rhine-Westphalia, Germany, and the Netherlands. The consortium came together in 2019, chaired by the Brightlands Chemelot Campus, to investigate the operation of naphtha and gas steam crackers using renewable electricity instead of fossil fuels. Two consortium members, BASF and SABIC, plan to develop an electrically heated cracker supported by Linde Engineering.

The project partners have made a funding application to the EU Innovation Fund and the funding programme 'Decarbonization in Industry' run by the German Federal Ministry for the Environment. The project would see a multi-megawatt demonstration plant sited at BASF's Ludwigshafen site with an on-site date of 2023 if the funding application is successful. The electrically heated steam cracker is stated in theory to be able to save up to 90% of the emissions from conventional fossil fuel steam crackers.

Dow and Shell are working on improving steam crackers and developing an electric cracker. In 2021, they were awarded €3.5 million from the Dutch government, and the Institute for Sustainable Process Technology (ISPT; Amersfoort, the Netherlands) were added as project

partner. A wide range of technological improvements are being studied, including computational fluid dynamics, electrical design, hydrocarbon technology, and metallurgy.

The concepts are being evaluated and validated against their emissions benefits. Patent filings are being made with respect to the inventions, and suppliers for equipment are being identified. A larger demonstration at the multi-MW scale is slated for 2025. The Coolbrook Rotor Dynamic Reactor (RDR) technology is an electrically powered naphtha cracking concept originating from science developed for the Russian space program. Total olefin yields achieved as of 2018 were over 55%, outperforming conventional naphtha cracking technologies by 9-11%.

The technology has received more than €12 million in funding from government and private investors for a new pilot plant to scale up the technology. With the very high-speed moving parts, the mechanical robustness of the system will need to be proven, and an estimate of plant maintenance and lifetime provided with more certainty. The technology will have to compete with other electrically heated crackers, which are much further ahead in the marketplace, such as the Dow/Shell system.

CO₂ to olefins

The discovery and development of efficient technologies enabling the use of CO₂ as a starting material for chemical synthesis (at scale) is probably one of the biggest scientific challenges of our time. Two approaches to convert CO₂ to olefins (and other valuable chemicals) being taken by Avantium (via its VOLTA technology) and the Stanford spin-out Twelve are noteworthy. While each has expressed goals to convert CO₂ directly to ethylene, both seem to have shifted focus to other routes – oxalic acid for Avantium and CO for Twelve.

Other notable examples of CO₂ conversion to olefins include The University of Toronto, The University of Illinois/Braskem, and Tokyo-based IHI Corporation/Singapore's Agency for Science, Technology, and Research (A*STAR). While significant progress has been made over the last few years, the performance of state-of-the-art technologies seems to not yet at the level required for an economically viable large-scale process. Aside from activity and selectivity issues, rapid deactivation of the catalysts, which leads to a shift in the product distribution favouring the hydrogen evolution reaction (in the case of electrochemical CO₂ reduction), is also one of the main challenges.

In most cases, catalyst lifetime is under 100 hours.⁸ Other methods of CO₂ conversion include dry reforming of methane (DRM) and super dry reforming of methane (SDR). Conventional DRM, typically involving a Ni-based catalyst, has gained much attention recently. It reduces GHGs, applies CO₂ as a carbon source, and provides the opportunity to utilise biogas and natural gas with a significant amount of CO₂.^{9,10}

Biogas, a mixture of mainly CH₄ (40 to 75 vol%) and CO₂ (25 to 60 vol%) typically produced via anaerobic digestion of organic waste material, is envisioned to be one of the key resources in achieving, for example, the EU's 2030 decarbonisation and renewable energy targets.

Key challenges include the development of DRM reactor technology, in particular the improvement of thermal efficiency, as well as catalysts that can deal with varying (bio)-gas compositions and operations at pressures and under fully dry conditions. DRM typically converts one CO₂ molecule per molecule of CH₄ and produces syngas. SDR of methane is a strongly intensified CO₂ conversion process as it converts up to three CO₂ molecules per molecule of CH₄ into a pure CO stream.¹¹ In 2022, the first super dry reforming unit will be operating at pilot level (1 kg CO₂/h). This pilot unit has a multi-reactor configuration, allowing continuous steady-state CO production and inherent H₂O separation from CO/CO₂.

Bio-based routes to olefins

Braskem's bio-based ethanol production technology called '1M GREEN' uses sugar cane, a renewable source, as feedstock to produce ethanol. This is then converted into bio-based polyethylene (bio-PE), bio-based EVA (a resin used in the automotive and footwear sectors), and bio-PE wax. Bio-PE is a renewable drop-in replacement to conventional fossil-based PE. Braskem operates a 200,000 tpy bio-ethylene plant in Brazil, followed by the addition of 60,000 tpy at the time of this writing. Biomass availability and the price gap with petrochemical ethylene are the two most important determinants for the future of bio-ethylene. However, bio-ethylene can also contribute to chemical feedstock security in oil-importing countries.

Neste's NEXBTL is a solution for producing bio-based or renewable products and incorporating recycled feedstocks. The company's bio-based olefins and isoalkanes production utilises a renewable flexible mix of raw materials ranging from waste and residue oils to vegetable oils and animal fats. The hydrotreatment process produces bio-naphtha and bio-propane, which then can be used as feedstocks for bio-ethylene and bio-propylene production.

With regards to the process itself, pretreatment of the renewable raw materials is crucial as it ensures impurities, such as phosphorus, sulphur, and metals (Na, Ca, Mg, and Fe), are removed before refining. UPM, in collaboration with Topsoe, has developed a biofuels production pyrolysis process utilising wood-based residue available from its own pulp production business. The proprietary BioVerno process

produces biodiesel and bio-naphtha. UPM's BioVerno naphtha is 100% bio-based and has identical physical properties to fossil-based naphtha. In 2020, INEOS and UPM Biofuels announced a long-term agreement to supply a renewable raw material (bio-naphtha) for new and innovative bio-attributed polymers to be produced at the INEOS plant in Köln, Germany.

Technip Energies has developed a process to convert ethanol to ethylene through dehydration. The technology uses a proprietary heteropolyacid (HPA) supported catalyst, operating at a lower temperature, higher pressure, and higher selectivity than first-generation processes. The company claims that the proprietary Hummingbird technology includes a 'toolkit' for the clean-up of bioethanol feedstocks. In May 2021, Technip Energies signed its first catalyst supply agreement with LanzaJet Inc., a sustainable aviation fuel (SAF) producer, for its Hummingbird ethanol-to-ethylene catalyst for a key application which, when combined with LanzaTech's Alcohol-to-Jet (ATJ) technology, can be used to manufacture SAF using ethanol as raw material.

Atol is the result of a partnership between Total, IFP Energies Nouvelles (IFPEN), and its affiliate Axens that started in 2011. Atol's technology is a 'green' route for bio-ethylene production via catalytic dehydration of 1G and 2G renewable ethanol. The bio-ethylene produced can be fed into existing or new units of, for instance, PE, ethylene oxide/monoethylene glycol (EO/MEG), polyethylene-terephthalate (PET), polyolefins, alpha-olefins production for linear alkylbenzene (LAB) and polyalphaolefins (PAO), benzene alkylation for polystyrene (PS), acrylonitrilebutadiene-styrene (ABS) and polyvinylchloride (PVC). The full-scale market launch of this production method is expected in 2025.

Waste to olefins

Plastic Energy's process uses proprietary patented thermal anaerobic conversion (TAC) technology to convert end-of-life (EOL) mixed plastics waste into a type of pyrolysis oil called TACOIL. The process complements traditional mechanical recycling efforts and energy recovery activities to help build a circular economy for used plastic. TACOIL is used as feedstock for the production of chemical naphtha

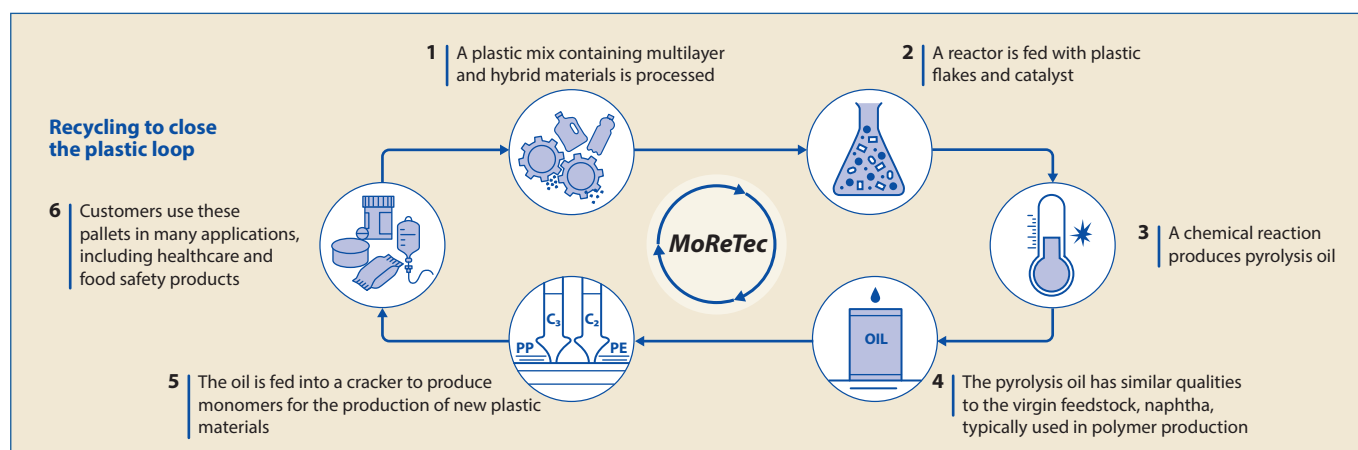


Figure 2 LyondellBasell's MoReTec Process¹²

and diesel, which in turn can be used as feedstocks for polymer production. SABIC and partner Plastic Energy formed a 50-50 joint venture (JV) partnership and, in 2020, started the construction of a circular polymer production unit in Geleen, the Netherlands, which is expected to become operational before the end of 2022.

OMV and Borealis's ReOil pyrolysis process converts post-consumer and post-industrial plastics (mixed plastics) to synthetic crude oil (syncrude) and petrochemical feedstock for virgin plastics production. OMV's process is a pyrolysis process where thermal depolymerisation is performed without adding a catalyst or hydrogen. According to OMV, the plan is to achieve one more scale-up step of the plant by 2022 by increasing the post-consumer plastic feedstock capacity to 16,000 t/y before aiming at building the final industrial-scale 200,000 metric tonnes capacity plant by 2025.

LyondellBasell's proprietary MoReTec recycling technology (see **Figure 2**) aims to return hard-to-recycle post-consumer plastic waste (such as multi-layer films) to its molecular form for use as a feedstock for new plastic materials that can be utilised in food packaging and healthcare items. LyondellBasell and KIT have proven that the use of a catalyst in the pyrolysis process, or the structural breakdown of plastic waste into molecules, is faster and more energy efficient than traditional chemical recycling. The company announced in 2020 that the pilot plant was capable of processing between 5 and 10 kg of household plastic waste per hour. The pilot plant aims to understand the interaction of various waste types in the molecular recycling process, test the various catalysts, and confirm the process temperature and time needed to decompose the plastic waste into molecules. The goal is to complete the tests over the next couple of years and then plan for an industrial-scale unit.

Some other technologies that are further from potential commercialisation include Mourik's BlueAlp Technology, a plastic-to-pyrolysis process and Topsoe's PureStep. BlueAlp and Petrogas (both Mourik subsidiaries) have resolved various bottlenecks and teething problems at their recycling plant in Ostend, Belgium, which is now in full operation. The companies claim that the plant is continuously processing 1.4 tons of plastic waste per hour and

that the gasoil produced is of adequate quality to be used by chemical producers. Topsoe's PureStep process can be run alongside its existing HydroFlex process, used for bio-fuels production. It can take in a range of solid materials, including biomass, plastic, tyres, and municipal solid waste, as well as liquid feeds – tall oil, vegetable oil, and tallow. The PureStep process is still in the development phase with regard to chemicals production.

Bioprocesses

BASF has developed high-performance industrial enzymes, alpha-amylases, uniquely suited for grain processing and bioethanol production. BASF states that its proprietary enzymes improve fermentation by enabling higher yields, which in turn improves efficiency thus lowering CO₂ emissions and more flexible process parameters.

LanzaTech has developed a novel gas fermentation technology that captures CO-rich gases and converts the carbon to fuels and chemicals (see **Figure 3**). The company has developed proprietary microbes that ferment the CO gases in the bioreactor. In essence, the process recycles waste carbon into fuels and chemicals. According to the company, the gas fermentation process is an alternative to the Fischer-Tropsch process.

Houston-based Cemvita Factory is an industrial biotechnology start-up using innovative synthetic biology to decarbonise heavy industry, such as chemical manufacturing, mining, and oil, and gas. Cemvita's process utilises CO₂ stored in a subterranean environment to produce one or more organic compounds useful as fuel and feedstocks for other applications. Cemvita's biomanufacturing platform mitigates emissions from traditionally energy-intensive chemical and catalytic conversion processes by operating under ambient temperature and pressure.

Conclusions

The focus is, as always, to improve the cost/performance of olefins production. The industry will continue towards 'green' and target net-zero GHG emissions. Both regulations and market forces will continue to support R&D aimed at achieving these outcomes. For mature processes like steam cracking and PDH, the most plausible methods for decarbonisation may be the electrification of heat supply

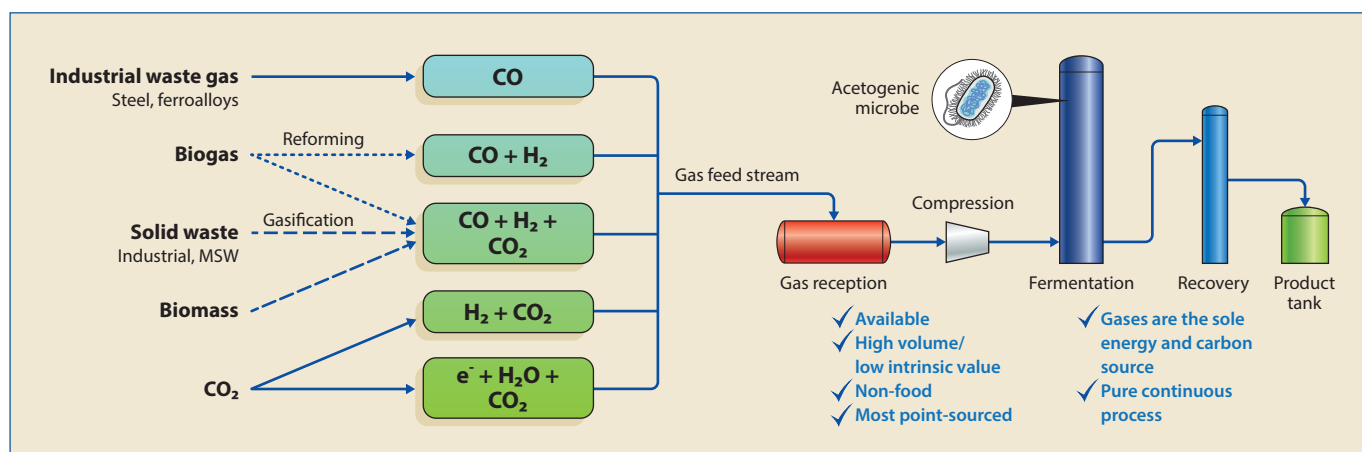


Figure 3 LanzaTech's gas fermentation technology captures CO-rich gases and converts them to fuels and chemicals

or the use of renewable or bio-based feedstocks or ones that supply process heat. Carbon capture technology is another way to lower the carbon footprint of these traditional processes. In addition to reducing overall emissions, making olefins production less dependent on fossil fuels is an important driver going forward.

Electrification is a key energy transition technology in the chemicals industry. Governments and oil and gas majors are clearly buying into the progress of electrified steam crackers and looking seriously to scale them up in the near term. Technip Energies and Siemens announced their joint Rotating Olefins Cracker (ROC) technology, which will be selected by the Cracker of the Future consortium for a demonstration unit. Dow's CEO claimed that e-crackers are more than a decade away from commercialisation, yet the consortium has claimed it will have commercial units ready by 2026.

Coolbrook's concept differs from the others in that it is not just about using electric resistance heated cracker coils. Instead, it relies on a technology that converts kinetic energy to heat produced from an electrically powered rotor. It has shown impressive yields compared to both Lummus and Technip steam cracking technology. It claims it can be a retrofit solution to dramatically lower CO₂ footprints for existing crackers. However, its ability to do so on large scales, as well as mechanical robustness and maintenance issues still need to be proven from pilot demonstration.

Bio-ethylene, like other bio-based chemicals, relies on sources of cheap and plentiful feedstocks. The Braskem process has been successfully scaled up in Brazil, whereas pyrolysis of bio-based waste is likely to result in many small-to-medium-sized plants. Despite Braskem's success, there is a need to consider the 'food vs fuel' argument when considering biomass feedstocks, especially the first-generation ones like corn and sugarcane. The conversion of forestry land for bio-ethylene production can lead to considerable CO₂ emissions that offset environmental benefits.

The use of CO₂ feedstocks via electrocatalytic routes is being developed rapidly and for a good reason. CO₂ is an extremely abundant resource, and locking it into a plastic product is viewed as a win in the eyes of many when compared to geological sequestration. Unfortunately, ethylene is a challenging molecule to make directly from CO₂. Many hurdles must be overcome, including purification of CO₂, low conversions and efficiencies, and a problem of 'CO₂ crossover'. It is likely to remain further behind other conventional olefin technologies.

In summary, changing the emphasis on both energy transition and non-petroleum feedstocks has substantially redirected efforts to produce olefins. This is a continually evolving landscape. Non-fossil approaches are likely to be popular because many downstream chemicals producers wish to remove fossil fuels from their supply chains and have pledged to do so to meet their net zero goals. The need to decarbonise the olefins industry appears to be real, and the electrification of steam crackers is the most near-term technology that can make the biggest impact on lowering emissions. The drive toward chemicals circularity involving

waste plastics is well underway, with major investments announced by polyolefin producers. These will influence the value chain and change the competitive production of olefins in the decades to come.

This article is based on a presentation from the 16th International Conference on Greenhouse Gas Control Technologies (GHGT-16) Conference, Oct 2022.

NEXBTL is a trademark of Neste. PureStep and HydroFlex are trademarks of Topsoe.

References

- 1 The Catalyst Group Resources, *Unconventional Catalytic Olefins Production II: Technological Evaluation and Commercial Assessment – 2021, A Multi-Client Study*, Oct 2021.
- 2 Gholami Z, Gholami F, Tišler Z, Tomas M, Vakili M, A Review on production of light olefins via fluid catalytic cracking, *Energies*, 2021, 14 (4), 1089.
- 3 ISPT. <https://ispt.eu/projects/amazing/>; n.d.
- 4 Amghizar I, Vandewalle L A, Van Geem K M, Marin G B, New Trends in Olefin Production, *Engineering*, 2017, 3 (2), 171-178.
- 5 Cruellas A, Melchiori T, Gallucci F, Van Sint Annaland M, Advanced reactor concepts for oxidative coupling of methane, *Catalysis Reviews* 2017, 59 (3), 234-294.
- 6 Vandewalle L A, Gonzalez-Quiroga A, Perreault P, Van Geem K M, Marin G B, Process Intensification in a gas-solid vortex unit: computational fluid dynamics model based analysis and design, *Industrial & Engineering Chemistry Research*, 2019; 58 (28), 12,751-12,765.
- 7 LanzaTech, 2017.
- 8 Gao J, Zhang H, Guo X, Luo J, Zakeeruddin S M, Ren D, Grätzel M, Selective C-C Coupling in carbon dioxide electroreduction via efficient spillover of intermediates as supported by Operando Raman Spectroscopy, *J. Am. Chem. Soc.*, 2019; 141 (47), 18,704-18,714.
- 9 Theofanidis S A, Galvita V V, Poelman H, Dharanipragada N A, Longo A, Meledina M, Van Tendeloo G, Detavernier C, Marin G B, Fe-containing magnesium aluminate support for stability and carbon control during methane reforming, *ACS Catalysis*, 2018, 8 (7), 5983-5995.
- 10 Theofanidis S A, Galvita V V, Poelman H, Marin G B, Enhanced carbon-resistant dry reforming Fe-Ni catalyst: Role of Fe, *Acs Catalysis*, 2015, 5 (5), 3028-3039.
- 11 Buelens L C, Galvita V V, Poelman H, Detavernier C, Marin G B, Super-dry reforming of methane intensifies CO₂ utilization via Le Chatelier's principle, *Science*, 2016, 354 (6311), 449-452.
- 12 Adapted from Cefic, 2017.

Christopher R Dziedzic is a Senior Sales and Project Manager with The Catalyst Group (TGC) and The Catalyst Group Resources (TCGR), responsible for managing TCGR's Catalytic Advances Program and CO₂ Capture and Conversion Program. He oversees the development of TCGR multi-client studies on industrial topics while supervising market research for multi-client and client-confidential reports. He holds a BSc degree in chemical engineering from Rutgers University.

John J Murphy is CEO of The Catalyst Group (TCG) and The Catalyst Group Resources (TCGR). Having been with TCG/TCGR since 1994, he has expertise in industrial process technologies for decarbonisation, sustainability and circularity as well as refining, petrochemicals, polymerisation and environmental applications. He holds a BA degree from Bowdoin College and an MBA from Lehigh University.