Decarbonisation Technology

November 2023

Powering the Transition to Sustainable Fuels & Energy


Decarbonisation Solutions

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In September 2023, the IEA announced an updated Net Zero Roadmap (available at https://bit.ly/3F6Abse), which shows that due to record growth in clean energy technologies, it is still possible to limit global warming to 1.5°C.

This seems somewhat contrary to earlier reports from the IPCC and others, which project that we are likely to hit 1.5°C in the next five years. The IEA itself reports that many of the required actions to meet net zero are not on track. Credible commentators talk about a 1.5°C overshoot and consider massive amounts of carbon dioxide (CO_2) drawdowns will be essential if we are to ultimately stabilise our climate. The difference between the IEA's Roadmap and its tracking reports is that the Roadmap lays out what is needed to achieve the desired 'possible' outcome, whereas the tracking reports monitor actual progress and then assess what is probable.

In a sense, the IEA has laid out a new challenge: to turn the possible into the probable. To paraphrase the IEA, it will take 'strong international co-operation' and 'Governments need to separate climate from geopolitics'. Politicians must stay the course and recognise that investment in the energy transition and clean energy infrastructure is essential for social stability and economically prudent. Acting now will avoid much higher costs in the longer term.

Decarbonisation Technology magazine brings together the global community working to deliver the energy transition by sharing the progress in developing and deploying clean energy technologies and implementing policies that drive and support the transition.

This edition has a focus on maritime transport, with articles on the International Maritime Organization's revised GHG strategy and developments in new marine engines designed for flexibility to use a range of low-carbon fuels. The importance of regulatory support for the emerging hydrogen economy is discussed, with a call for alignment on global standards. The importance of hydrogen hubs within industrial clusters is also highlighted. This last point is exemplified in the article on the Andalusian Green Hydrogen Valley and the hydrogen corridor between South and North Europe.

As the IEA stresses, there is little point in the drawdown of CO_2 unless we also minimise CO_2 emissions by transitioning to renewable energy sources and capturing the carbon from residual fossil fuel combustion during the transition. In this context, research into minimising carbon emissions from concrete production is also valuable.

Returning to the IEA Net Zero Roadmap, we need to accelerate investments in renewable energy production, drive for energy efficiency, and minimise methane emissions as well as CO_2 during the transition.

Decarbonisation of transport fuels to reduce emissions

With transportation responsible for almost one-third of global CO_2 emissions, the priority is to be able to meet future demands while moving towards net zero

Yvon Bernard
Axens

Transport emits nearly 8 Gt of carbon dioxide (CO_2) each year, or 30% of global CO_2 emissions (IEA, 2023). Urgent actions are required to meet future demand while lowering the carbon intensity of transport fuels and chemicals. The use of renewable and alternative feedstocks (such as municipal waste, second-generation vegetable oil, and forestry residues) will play an increasing role in this transition. Axens is actively contributing to the energy transition in the industry and society by providing technologies for the production of gasoline and middle distillates (jet fuel and diesel) that meet the most stringent standards.

The decarbonisation of transport fuels and the reduction of greenhouse gas (GHG) emissions, with the relevant Axens technologies, will be discussed in this article. Together, these form part of the solution along with a range of complementary measures (not all of which need technological solutions) for reducing emissions across different transport modes:

- Avoid unnecessary journeys for the movement of people or goods.
- Incorporate energy efficiency across the transport system value chain. Obvious examples are refinery processing efficiency, including carbon capture, and using energy efficiency indices for new ship design (maritime) and retrofitting existing ships.
- Encourage more sustainable use of transport. In cities, this includes behavioural measures such as switching from cars to forms of transport with lower emissions, including electrified public transport and cycling (one of the most economical ways of commuting).
- Government policies that drive and support the transition, include mandates such as ReFuelEU, tax incentives such as the US IRA, project funding from research through to first projects, with the Horizon Europe funding a good example, and finally the permitting process to build out renewable capacity and sites for long-term carbon storage.

In the following sections, various technologies will be presented using different inputs and producing different products, addressing the fuel market and other industries that also need to reduce their carbon footprint.

Potential to reduce the carbon intensity of the transportation sector with biofuels

❶ Sustainable/low-carbon road fuels

Emissions from road transport were 5.87 Gt CO_2 in 2022 (IEA, 2023). Major economies, including Australia, China, the EU, India, the UK, and the US, have adopted policies that support the uptake of battery electric vehicles (BEVs) and the decarbonisation of transport. In Europe (EU and UK), mandates banning the sales of internal combustion engines (ICE) in passenger vehicles and vans will become effective from 2035. Even then, it will take another decade or more for the turnover of the light-duty fleet to BEVs. Progress in rural communities is likely to lag that in the bigger cities, where BEVs are also seen as part of the solution for air pollution. Given that in 2023, more than 80% of the existing fleet of cars and vans on the road are powered by internal combustion engines, substituting fossil fuels with renewable/low-carbon fuels is vital for rapid action to reduce emissions from road transport.

❷ Sustainable aviation fuels

Aviation transport emissions totalled 0.89 Gt eqCO_2 per year in 2022 (IEA, 2023). The International Civil Aviation Organisation (ICAO) adopted a long-term aspirational goal of net-zero carbon emissions by 2050. The Air Transport Action Group (ATAG), an industry body, proposed a range of technical, operational, and behavioural solutions to reach the goal of net zero by 2050. The deployment of sustainable aviation fuels (SAFs) is expected to contribute a minimum of 53% towards this goal (ATAG, 2021).

> **“SAFs are drop-in fuels, fully fungible with conventional aviation jet fuels, which do not require equipment change, special infrastructure or modification of the supply chain”**

Seven fuels are qualified under ASTM-D7566 for the production of SAF (CAAFI, 2023). Axens provides mature technologies for the three main pathways:

- The HEFA pathway with the Vegan process for hydrotreatment of lipids to produce hydroprocessed esters and fatty acids (HEFA)
- The Fisher-Tropsch (FT) pathway with the BioTfueL process (gasification and FT) to produce SAF from lignocellulosic biomass (Annex 1)
- The Alcohol-to-jet (ATJ) pathway with the Jetanol process to produce SAF from low-carbon/renewable ethanol.

SAFs are drop-in fuels, fully fungible with conventional aviation jet fuels, that do not require equipment change, special infrastructure or modification of the supply chain. However, SAFs are currently a few factors more expensive than conventional aviation kerosene.

③ Sustainable marine fuels

Marine transport accounted for 0.78 Gt eqCO_2 per year in 2022 (IEA, 2023). In its initial strategy, the International Maritime Organization (IMO) had already adopted the use of energy efficiency and carbon intensity indices for new ship designs and retrofitting existing ships. In July 2023, the IMO adopted a revised strategy with the goal of reaching net zero emissions by 2050, which will require the uptake of alternative zero and net-zero GHG emission fuels (covered in more detail elsewhere in this issue).

In contrast to SAF, a wider range of fuel types are under consideration for the decarbonisation of marine fuels, from gases such as hydrogen, ammonia, and bio-methane to lighter liquids, such as methanol and heavier bio-diesels. In common with SAF, these lower-carbon intensity alternative marine fuels are more expensive than conventional marine diesel.

Reducing the carbon intensity of fuels is possible, and some plants are already producing biodiesel, SAF, and bioethanol. The following section will discuss available technologies from Axens to support the effort of GHG emission reduction.

Integrating technologies for the production of renewable/low-carbon transport fuels

Renewable or waste-derived feedstocks can be divided into three categories – renewable oils and fats, lignocellulosic biomass residues, and captured CO_2 with renewable hydrogen – each of which then determines which technology options can be used for conversion into sustainable fuels and chemicals, as shown in **Figure 1**.

Integrating renewable technologies within existing refinery processes may represent one of the quickest, most efficient, and economically viable transition pathways. Hydrogenation,

Hydrogenation processes

Hydrogenation processes use substantial amounts of hydrogen. As already discussed, hydrogen from electrolysis relies on the availability of electricity from fully renewable sources. Retrofitting carbon capture technology to steam methane reformers can represent the most cost-effective way of producing low carbon-intensity hydrogen in the refinery, providing there is regulatory support for this route and that CO_2 is sequestrated (in depleted wells). Axens can provide such decarbonisation technologies with DMX and Advamine.

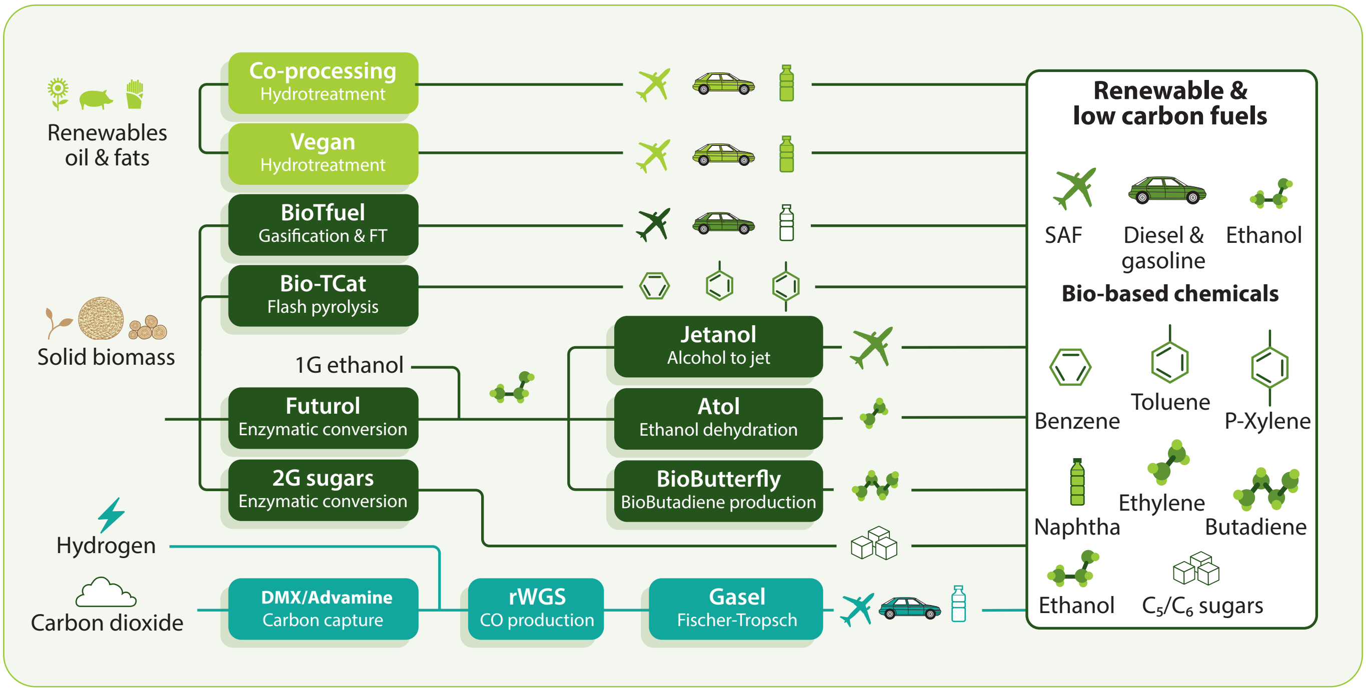

Figure 1 Axens technologies for renewable/low-carbon fuels and bio-based chemicals

hydrocracking, and fluid catalytic cracking are all mature, established technologies that can be readily adapted to co-process varying amounts of renewable feedstocks.

As an increasing diversity of renewable and waste-derived feedstocks are considered, additional investments in technologies not widely used in conventional refineries, such as gasification, pyrolysis, and Fischer-Tropsch synthesis, will be required.

We will now detail the production schemes depending on the feedstock:

❶ Renewable vegetable oils and animal fats

Vegetable oils and animal fats (lipids) can be hydrotreated to produce HEFA suitable for use as renewable diesel and renewable kerosene for SAF.

Over the last 10 years, many new hydrotreating plants have been built, and 10 operating units (some operating, some under construction, and some starting up soon) use the Vegan hydrotreating process licensed by Axens (see **Figure 2**).

The lipids are hydrotreated to remove oxygen and other contaminants, followed by a hydroisomerisation step to upgrade the linear paraffins. Vegan technology can be easily tuned to match the required boiling range and cold flow properties of the desired product, allowing operators to balance the production of renewable diesel and/or SAF according to market demand.

Hydrotreatment is a mature technology in widespread commercial use in refineries. Some refiners have opted to co-process renewable feedstocks in their existing hydroprocessing unit as an economically viable short-term solution with only minor modifications, but still with the expertise needed from a licensing company to properly assess the quality and quantity of feedstock to be processed with the associated impact on unit performance. Others have retrofitted those hydroprocessing units or invested in a new unit to process only renewable feedstocks.

Interest in hydrotreatment may have plateaued in Europe, mainly due to the cap on

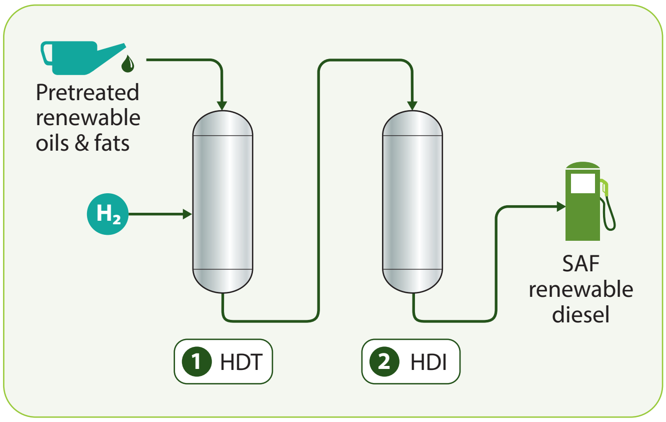

Figure 2 Vegan hydrotreatment to produce HEFA for renewable fuels

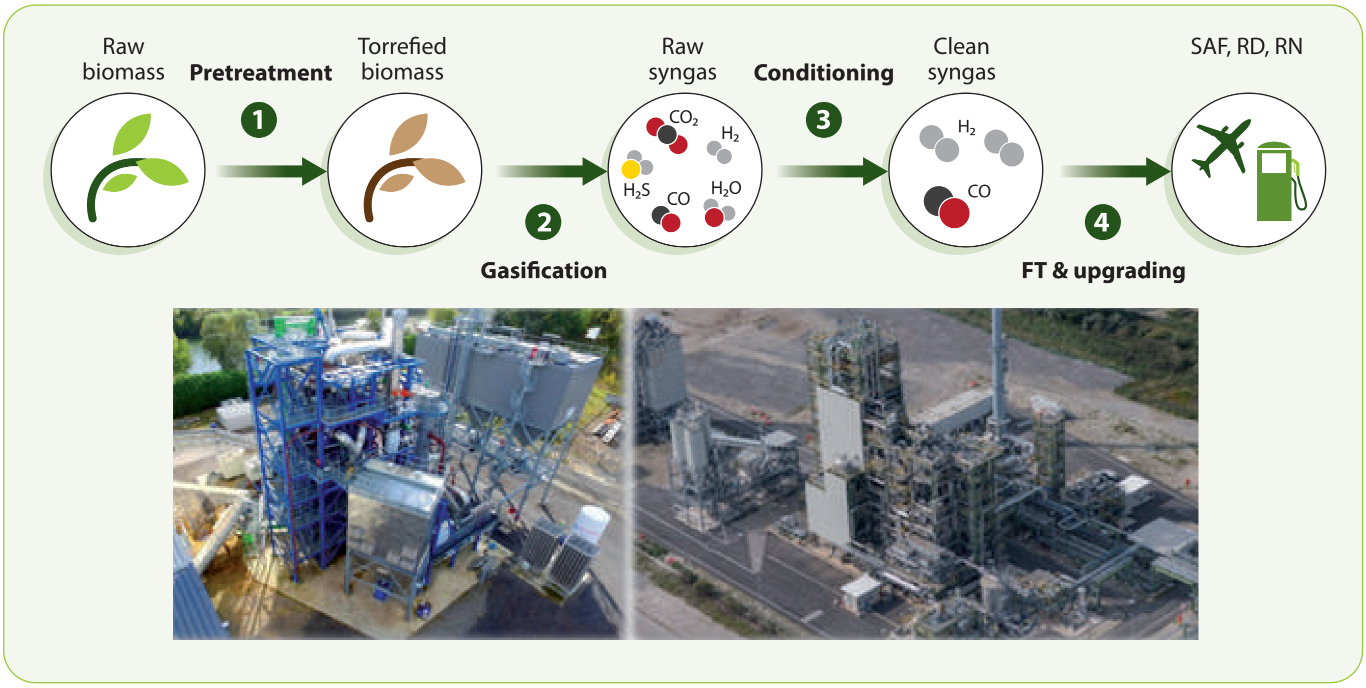

Figure 3 BioTfueL process from biomass to renewable fuels

first-generation biofuels and concerns about the availability of second-generation biofuels, such as used cooking oil, animal fats, and low indirect land use change (ILUC) crops. Elsewhere, the US have a different approach to calculating carbon intensity, resulting in continued interest and investments. In India, jatropha is gaining interest as an oil crop that can be grown on marginal land, which presents a low ILUC risk.

② Solid biomass

Lignocellulosic residues from forestry and agriculture are favoured biomass feedstocks that do not compete with food production. These can be converted to fuels using thermal (gasification or pyrolysis) or biological processes.

BioTfueL: biomass gasification with Fischer-Tropsch synthesis to aviation jet

Axens worked since 2010 as a member of the Bionext partnership (Avril, Axens, CEA, IFPEN, thyssenkrupp Industrial Solutions, and TotalEnergies), with funding from the French Government and the Hauts-de-France region to develop the BioTfueL technology for the production of SAF for aviation from biomass residues. Paraffinic naphtha is also produced and can be used in a steam cracker, the entry gate to the plastic world and its need to reduce fossil usage.

BioTfueL (see **Figure 3**) is a four-step process: torrefaction of biomass, gasification to produce syngas, syngas conditioning (cleaning, acid gas removal, and purification), and then Fischer-Tropsch synthesis to convert the syngas into advanced bio-jet. Following success with the demonstration units in France, this technology is now ready for commercialisation with a first licence sold to Elyse Energy for a project in the South of France.

The BioTfueL process is flexible and can be used to produce kerosene for SAF as well as naphtha to be used in steam crackers for the plastic industry.

Bio-TCat flash pyrolysis

Axens has partnered with Anellotech, which has developed a fast pyrolysis process to produce bio-based aromatics, including benzene, toluene and xylenes (BTX) and paraxylene, to offer a competitive decarbonisation pathway for the production of polyesters, PET, and other chemicals.

Bio-TCat (see **Figure 4**) is a three-step process: a feed pretreatment section (MinFree) which removes minerals in the feed; a one-step reaction section (biomass-to-aromatics conversion through the thermocatalytic process); and a section for upgrading and separation of the aromatic mix obtained. Following success with the demonstration units in the US, this

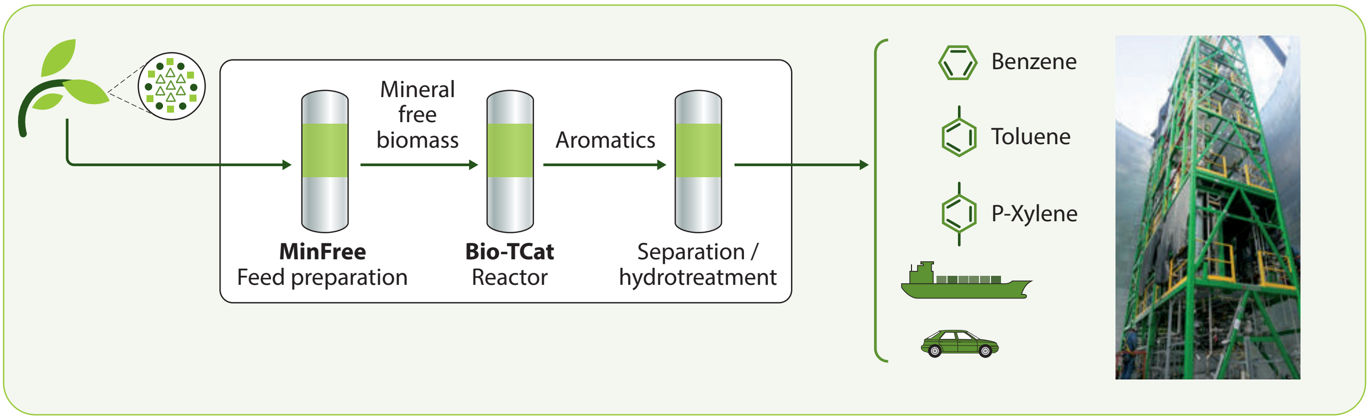

Figure 4 Bio-TCat process to produce renewable biofuels and bio-based chemicals as alternatives to petro-based products (Anellotech, 2023)

technology is now ready for commercialisation.

Futurol and Jetanol: from enzymatic conversion of lignocellulosic biomass and catalytic conversion to advanced biofuels

Today, the main substitute for fossil gasoline is bio-ethanol produced from first-generation food crops (sugar cane, sugar beet, and starchy crops) via the fermentation of sugars to ethanol. In the EU, the updated Renewable Energy Directive (RED II) capped the use of first-generation biofuels for road and rail transport at 7%, with a reduction to 3.8% by 2030. At the same time, RED II introduced targets to increase the use of advanced biofuels to at least 6.8% by 2030. Some new targets have been proposed at the European Commission level, and an awaited version III of the RED should be voted on and agreed before the end of 2023.

Futurol technology, developed by Procethol 2G, a company composed of different partners (R&D, industrial, and financial partners) produces advanced bio-ethanol from lignocellulosic residues (for example, wood chips, straw from cereal crops, bagasses, rice straw, and bamboo). As shown in **Figure 5**, the Futurol process involves four steps

① **Biomass pretreatment:** Lignocellulosic biomass is broken down into three major components: cellulose, hemicellulose, and lignin. Hemicellulose is then converted into monomeric sugars.

② **Biocatalysts production:** Enzymes as well as yeasts are produced on-site for economical reasons, avoiding external supplies.

③ **Hydrolysis and fermentation:** The enzymes are used for enzymatic hydrolysis of the cellulose into sugar monomers and, simultaneously, the fermentation of these sugars into ethanol by yeasts.

④ **Products recovery:** Fermented mash from the hydrolysis and fermentation step is treated to separate and recover the different products:

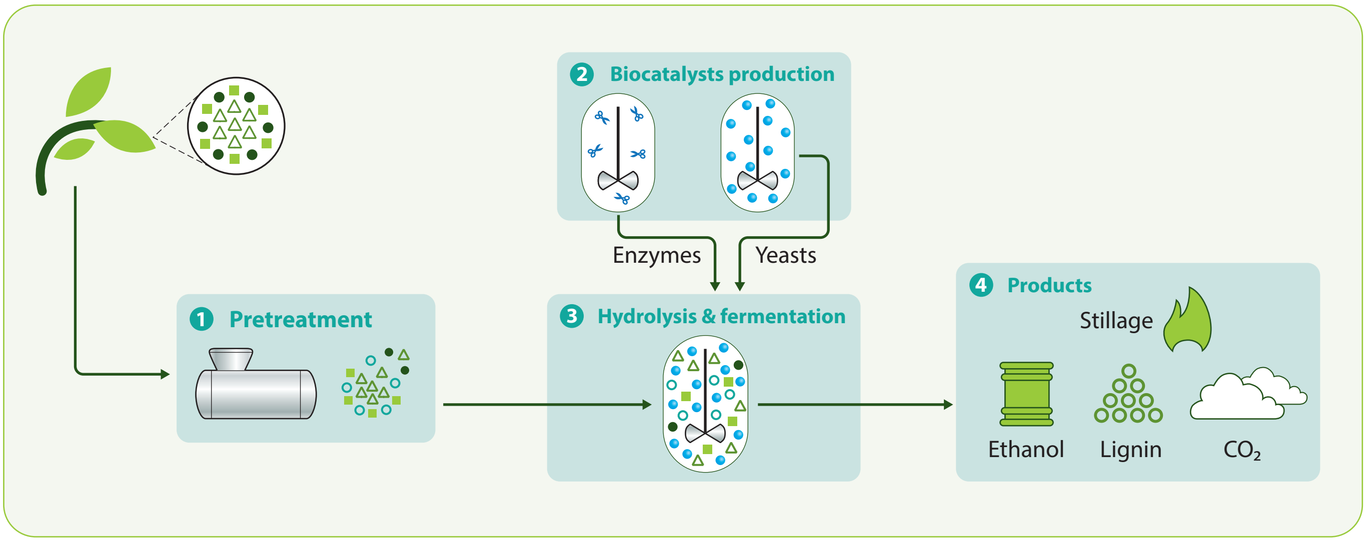

Figure 5 Axens Futurol technology for bio-ethanol production

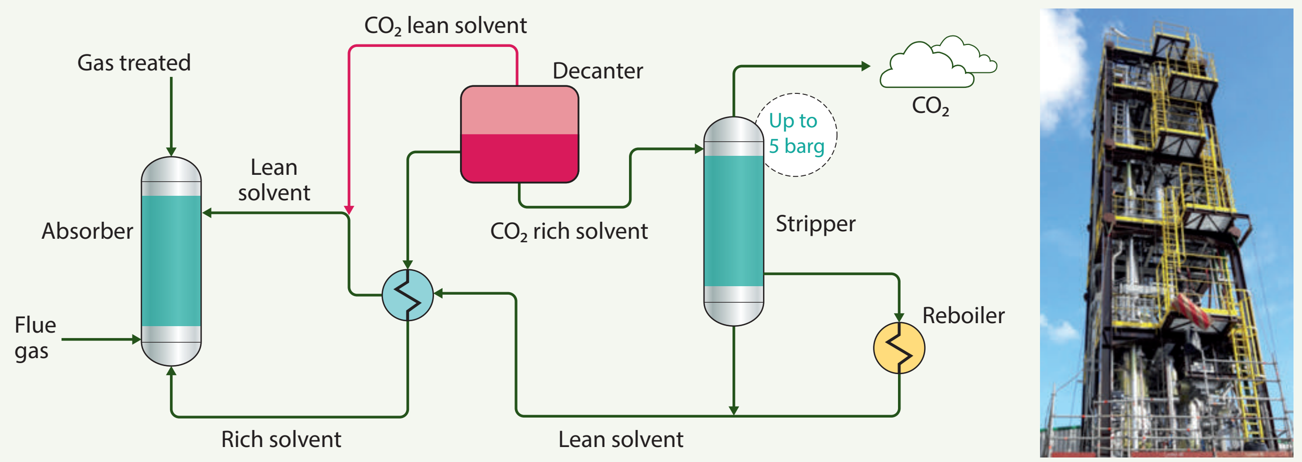

Figure 6 Axens carbon capture technology DMX process scheme and demonstration plant

fuel-grade ethanol, lignin, clarified stillage, and CO_2.

Captured CO_2 and renewable hydrogen for synthetic fuels

❶ DMX: Capturing CO_2 with advanced demixing solvent

Axens has a strong track record in the application of pre- and post-combustion carbon capture technologies for a range of industrial flue gases (steam methane reforming, naphtha cracking, steel and cement manufacture, power plants and waste incinerators). The DMX CO_2 capture absorption process (see **Figure 6**) uses a solvent that reduces the energy intensity for carbon capture by nearly 30% compared with the industry standard MEA (monoethanolamine). A DMX demonstration plant is currently in operation at the ArcelorMittal Steel mill plant in Dunkirk, with a process to be commercialised in the coming months.

❷ Reverse water gas shift: Gasel: a complete integrated suite of technologies

E-fuels are classified as synthetic fuels (if the CO_2 is biogenic or from direct air capture) or recycled carbon fuels (if the CO_2 comes from fossil origin) which use captured CO_2 and transformed into carbon monoxide via a reverse water gas shift (RWGS) reaction (see **Figure 7**). It is then mixed with hydrogen from the electrolysis of water using renewable electricity to make a syngas.

The syngas is then processed into an Axens Gasel Fischer-Tropsch process used to synthesise longer chain hydrocarbons, followed by hydrocracking/isomerisation to produce fuels with a suitable boiling range for e-kerosene and e-diesels. This process produces e-kerosene that qualifies as synthetic aviation fuel under the new ReFuelEU regulation, as well as paraffinic naphtha.

Alternatively, the syngas can be combined with hydrogen for the production of e-methanol with existing processes such as Haber-Bosch.

Conclusion

The challenges ahead are to rapidly expand the availability and to improve the economics of sustainable transport fuels and renewable

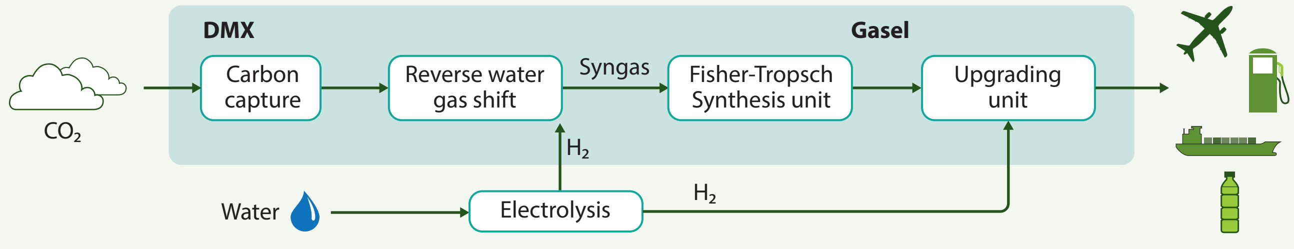

Figure 7 E-fuels: from CO_2 and H_2 to low-carbon fuels

Catalytic conversion of advanced/bioethanol to ethylene Advanced bioethanol or bioethanol (1G ethanol) can be processed and dehydrated using the energy-efficient Atol process for the production of bio-ethylene, an effective route for the decarbonisation of ethylene-based chemicals, such as plastics.

Alcohol-to-jet process The alcohol-to-jet process is one of seven pathways certified under ASTM D-7566 for the production of SAF. Earlier in 2023, Axens announced a project pipeline approaching 1.4 million tonnes per annum of SAF production using its Jetanol alcohol-to-jet technology in different countries. The bio-ethylene is dimerised to butenes and hexenes, which in turn are oligomerised to the kerosene range, followed by a hydrogenation step to saturate the olefins and meet ASTM D7566 specifications (Bernard, et al., 2022).

chemicals. Government support in setting long-term objectives, providing funding for the scale-up of emerging technologies, potentially giving guarantees to investors for the first plants, and setting production and blending mandates or tax credits is welcome and necessary in creating a positive environment for the uptake of these fuels.

Axens, together with it parent company, IFP Energies nouvelle, can support customers and investors with proven technologies for sustainable fuels to meet growing demand from the different transport sectors.

Advamine, BioTfueL, DMX, Futurol, Gasel, Jetanol, and Vegan are trademarks of Axens. Bio-TCat and MinFree are trademarks of Anellotech.

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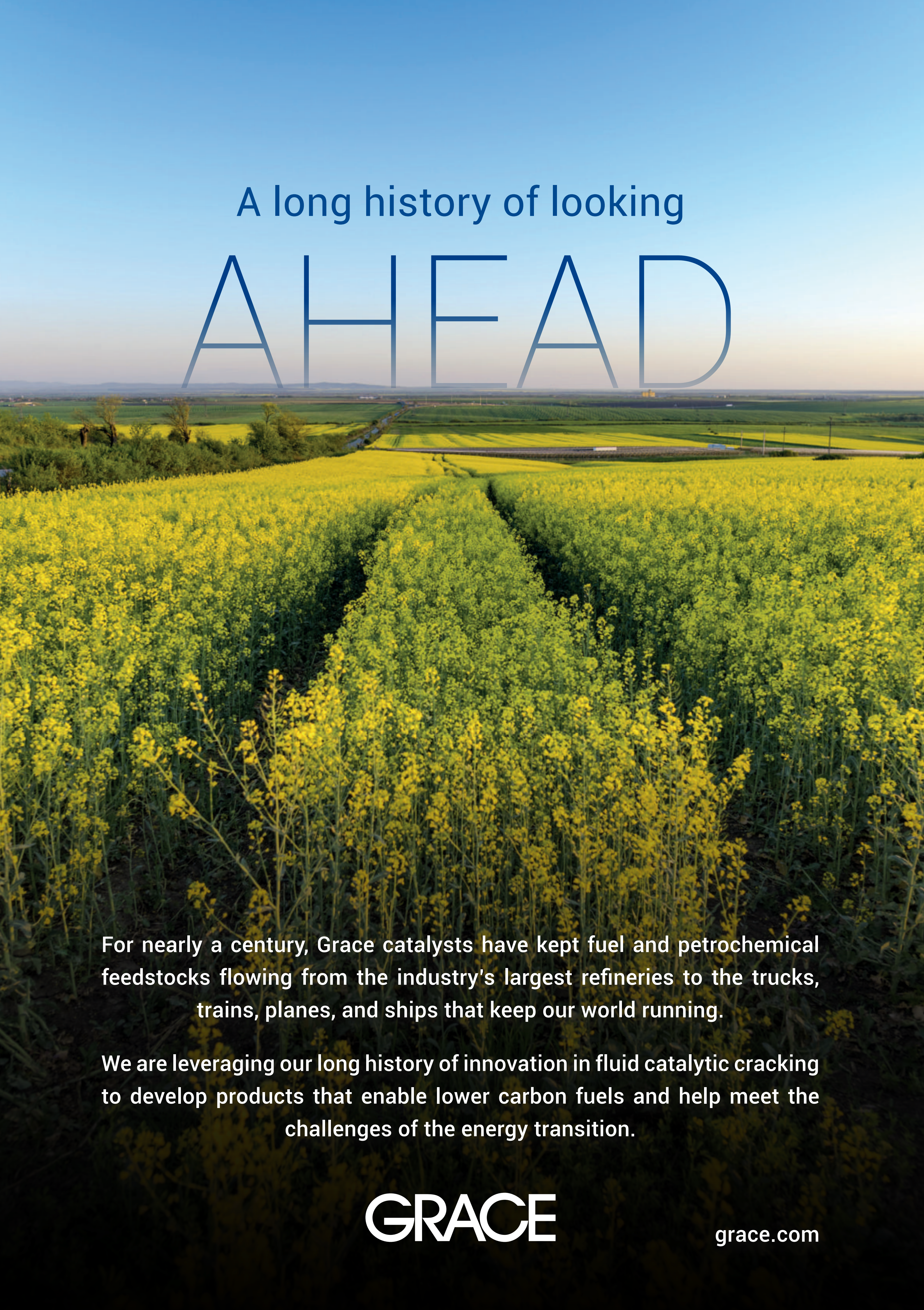
A long history of looking
AHEAD

Reducing GHG emissions from international shipping

The International Maritime Organization's revised strategy and future plans

Eddy Van Bouwel
EvBo Consult

The International Maritime Organization (IMO) holds responsibility for regulating emissions from international shipping. The IMO is a United Nations agency headquartered in London, and brings together 175 Member States (IMO, 2023). IMO established GHG reduction ambitions for the first time in 2018, when an initial GHG strategy was adopted (IMO, 2018). The initial strategy included the ambition to 'reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely'. Importantly, the initial strategy included a commitment to review the strategy every five years. IMO's Marine Environment Protection Committee (MEPC) was given a timeline to adopt a revised GHG strategy in 2023.

Revised IMO GHG Strategy

A revised strategy was adopted at the 80th session of the Committee in July 2023, significantly raising the level of ambition and the speed to reach net zero GHG emissions (IMO, 2023). The most significant change is the adoption of a net zero GHG target by or around 2050. In addition, indicative checkpoints have been added for 2030 and 2040, including the ambition to have at least 5% of the energy used to be from near-zero GHG technologies by 2030. The initial and revised strategies are summarised in **Table 1**.

Current emission levels and outlook to 2050

As all targets are expressed as percentage reductions vs 2008, it is interesting to look at the most recent emissions data vs 2008. IMO's Fourth GHG study, published in 2020, provides an authoritative reference (IMO, 2021). Over time, different methodologies have been used to estimate GHG emissions from international

Timeline	Initial IMO GHG Strategy (2018)	Revised IMO GHG Strategy (2023)
As soon as possible		Peak GHG emissions as soon as possible
By 2030	Reduce carbon intensity by at least 40%	Reduce carbon intensity by at least 40% Uptake of zero or near-zero GHG emissions technology: at least 5%, striving for 10% of the energy used Indicative checkpoint: reach at least 20% total annual GHG emissions, striving for 30% reduction
By 2040		Indicative checkpoint: reach at least 70% total annual GHG emissions, striving for 80% reduction
By 2050	Pursuing efforts towards 70% carbon intensity reduction	By or around, i.e. close to 2050: reach net-zero GHG emissions
2050+	Phase out emissions as soon as possible in this century	

Table 1 IMO 2018 and 2023 GHG Strategies (all % reduction targets are relative to 2008)

	Total GHG emissions Mton CO_2eq, (% change vs 2008)	
	Voyage based	**Vessel based**
2008	794	940
2012	701 (-11.7%)	848 (-9.8%)
2018	740 (-6.8%)	919 (-2.2%)

Table 2 Evolution of emissions from international shipping

shipping; two such methodologies were used in the Fourth IMO GHG report: vessel-based allocation and voyage-based allocation.

Vessel-based estimation uses vessel characteristics combined with assumptions of typical operations by vessel type to estimate total emissions. This methodology was used in earlier IMO GHG assessments.

Voyage-based estimation uses actual voyage data combined with vessel characteristics. This obviously requires a lot more data and data processing but should yield a more accurate estimate of total emissions.

While there is a significant difference in the results of both methods in terms of assessing progress towards the new IMO GHG targets, the most important point is to look at the numbers on a consistent basis. To that purpose, the 4th IMO GHG report includes a reassessment of the 2008 emissions based on the new estimation methods. **Table 2** summarises the main GHG emissions estimate numbers reported by the 4th IMO GHG study.

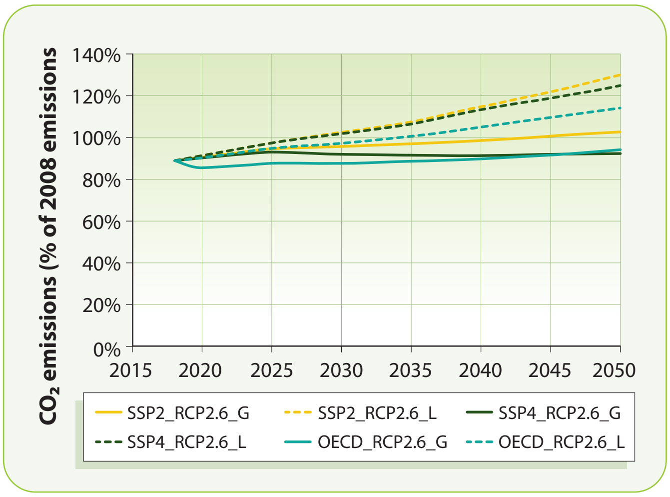

Figure 1 Projections of maritime ship emissions as a percentage of 2008 emissions (IMO, 2021)

Credit: Reproduced with the permission of the International Maritime Organization (IMO), which does not accept responsibility for the correctness of the material as reproduced: in case of doubt, IMO's authentic text shall prevail. Readers should check with their national maritime Administration for any further amendments or latest advice. International Maritime Organization, 4 Albert Embankment, London, SE1 7SR, United Kingdom.

In the absence of further regulations, emissions are projected to increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 for a range of plausible long-term economic and energy scenarios (see **Figure 1**). The current projections are significantly lower than earlier 'Business As Usual (BAU)' estimates. For example, the BAU scenarios considered in the Third IMO GHG study (IMO, 2015) projected an increase in emissions by 50% to 250% in the period to 2050.

As historically different methodologies have been used to estimate total GHG emissions from international shipping, measuring progress towards IMO's targets will be less straightforward than one would expect.

IMO's ability to assess global emissions, however, should further improve through the implementation of the Data Collection System (DCS) (IMO, 2016). Starting from January 1, 2019, ships of 5,000 gross tonnes (GT) and above are required to collect and report fuel consumption data for each type of fuel oil they use. The reporting process includes a third-party verification step. This should allow IMO to produce more accurate estimates of emissions. Obviously, the 2008 reference emissions will need to be reassessed to ensure a consistent basis for measuring progress towards IMO's GHG strategy targets.

Carbon Intensity

Carbon intensity (CI) is a measure of ship efficiency in relation to the cargo carried, assessing GHG emissions per ton-mile of transport work. It can be measured in two ways: relative to the ship's cargo carrying capacity, referred to as the Annual Efficiency Ratio (AER) and measured in gram CO_2/Dwt/nm (where Dwt = dead weight tonnage), or, relative to actual cargo carried, referred to as the Energy Efficiency Operational Indicator (EEOI) and measured in gram CO_2/ton cargo/nm.

The IMO Fourth GHG report has estimated CI improvements relative to 2008 for both CI indicators and based on the two emission

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	AER		EEOI	
	Vessel based ($g\ CO_2$/Dwt/nm)	Voyage based ($g\ CO_2$/Dwt/nm)	Vessel based ($g\ CO_2$/Dwt/nm)	Voyage based ($g\ CO_2$/Dwt/nm)
2008	8.08	7.40	17.10	15.16
2012	7.06 (-12.7%)	6.61 (-10.7%)	13.16 (-23.1%)	12.19 (-19.6%)
2015	6.64 (-17.8%)	6.15 (-16.9%)	12.33 (-27.9%)	11.30 (-25.5%)
2018	6.31 (-22.0%)	5.84 (-21.0%)	11.67 (-31.8%)	10.70 (-29.4%)

Table 3 Estimates of carbon intensity as reported by the IMO Fourth GHG study with percentage improvement vs 2008

inventory methodologies discussed above. The results are summarised in **Table 3**.

CI has clearly improved quite substantially since 2008. It is interesting to note that the largest improvements apparently happened between 2008 and 2012. This was when the first energy efficiency measures were being discussed at IMO. From 2012 onwards, annual improvements appear to settle in the 1-2% per year range. The difference between vessel-based and voyage-based CI numbers is directionally consistent with the observed differences in total emissions estimates between the two methods. The difference between AER and EEOI numbers is striking. This undoubtedly reflects the effect of so-called ballast voyages, when ships travel empty between ports while pursuing new cargo, and partial load voyages.

EEOI should be the preferred indicator, as it reflects actual transport work. However, using EEOI requires the collection of more data, including data that is sometimes seen as commercially sensitive. As a result, IMO's recent energy efficiency regulations, such as the Carbon Intensity Indicator (CII), are based on AER. Regardless of which CI indicator is considered, the 2030 target of 40% improvement vs 2008 appears to be realistically achievable if the current annual improvement trend can be maintained.

Coherence of 2030 targets

Table 1 shows three distinct targets for 2030, raising the question of which is more ambitious. The target regarding the uptake of zero or near-zero GHG emissions technology is a subset of the CI target, as any use of such fuels will obviously lead to reduced CI. We will look at that in more detail later in this article. The absolute emissions target and CI are linked through the demand for shipping services. In case of a higher demand for shipping services in 2030, CI will need to improve further to reach the same level of total emissions from international shipping. This relationship is illustrated in the waterfall charts of **Figure 2**.

Figure 2(a) illustrates the relationship for the 2018 voyage-based AER data shown in Table 3. The data imply that demand for shipping services has grown by 18% in the 2008-2018 period. With an estimated CI improvement of 21%, the resulting 2018 emissions are 6.8% below the 2008 emissions.

Figure 2 Scenario 1 looks at what it would take to reach the 30% emission reduction, assuming that the CI target of 40% reduction is achieved. The graph shows that demand for shipping services would only be allowed to grow by 16.7% between 2008 and 2030. This means we would need to see a small reduction in demand between 2018 and 2030.

Figure 2 Scenario 2 shows that demand can grow by 33.3% between 2008 and 2030 to reach the minimum emissions reduction target of 20% while achieving the CI reduction target of 40%.

Figure 2 Scenario 3 shows what further reduction in CI would be needed to reach the more ambitious target of -30% emissions reduction in case demand grows by the same 33.3% as in Scenario 2. That would require a CI reduction of 46.7%, which implies a faster reduction than we have seen in the 2012-2018 period. This is where the introduction of near-zero carbon emission fuels may play a role.

Pathway towards net zero

Two elements must work together to guide the industry towards net-zero emissions: reducing the amount of energy needed to move ships as much as reasonably possible and introducing zero and near-zero GHG emission technologies.

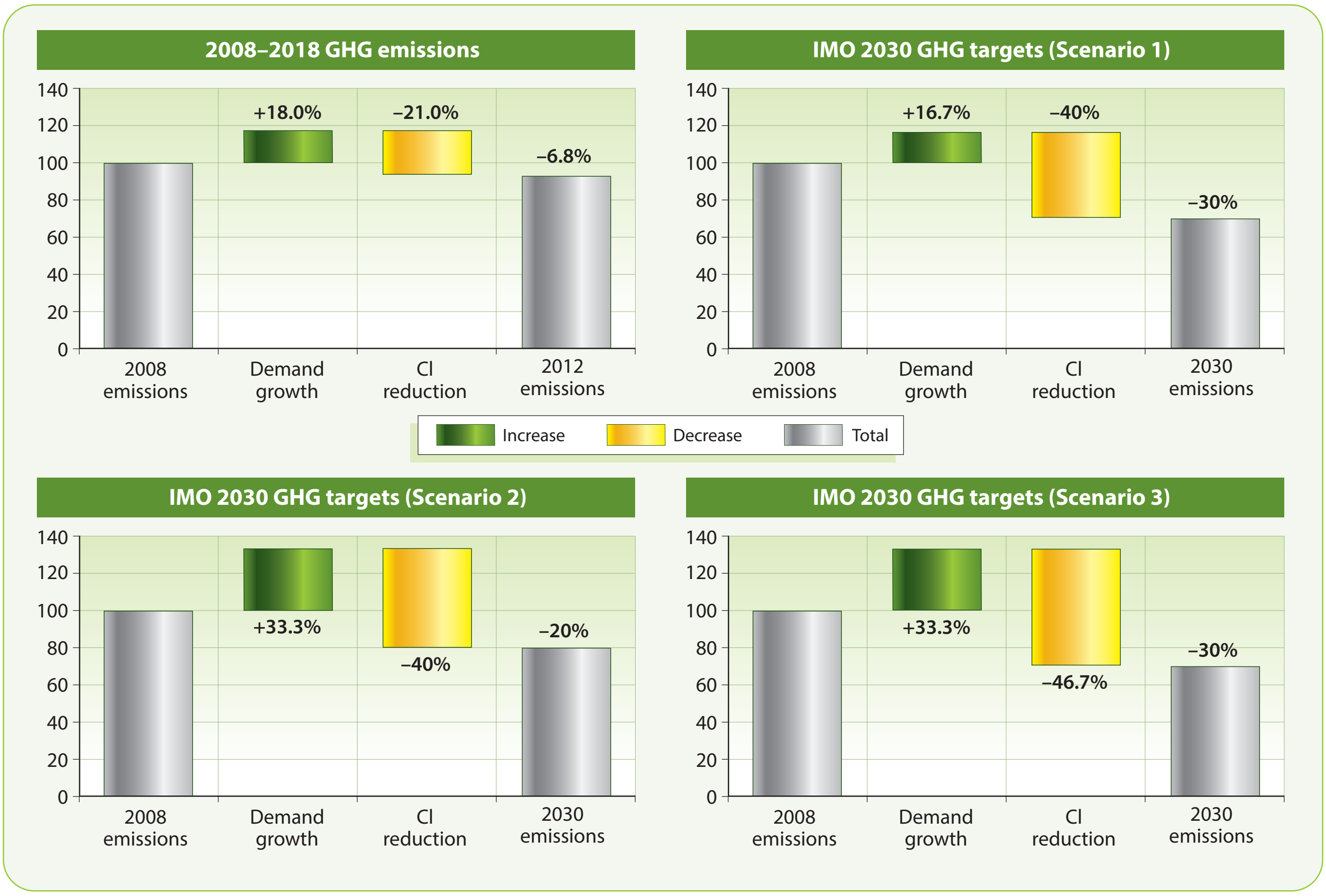

Figure 2 Relationship between demand for shipping services, carbon intensity, and total GHG emissions: (a) 2008-2018 – voyage-based AER data, (b) 2008-2030 Scenario 1, (c) 2008-2030 Scenario 2, (d) 2008-2030 Scenario 3

IMO started introducing measures to improve energy efficiency in 2011 with the adoption of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) regulations. In 2021, further regulations were adopted: the Energy Efficiency Existing ship Index (EEXI) and CII rating. These regulations steer the first element of the net zero pathway. They have been identified as short-term measures in the IMO strategy and have steered the continuous improvement in carbon intensity observed to date.

Role of low- or zero-carbon fuels

So far, there are no IMO regulations in place to address the second element of the net zero pathway. The introduction of near zero-carbon fuels into the mix should lead to an acceleration of the CI reduction trend. The industry has not been waiting on the regulations to start the development and piloting of zero-emission ships and fuels. The Global Maritime Forum (GMF) is tracking these developments on a regular basis. The fourth edition of the GMF report includes 373 registered projects, a significant increase vs the 203 projects identified in the third edition (Anna Rosenberg and Ana Madalena Leitão, 2023).

However, surely, the full transition from conventional fossil fuels to zero and near-zero GHG fuels will not happen on a voluntary basis as long as the alternatives are significantly more expensive than conventional fuels. Therefore, the IMO strategy has identified so-called mid-term measures that will be aimed at stimulating the use of low- and zero-carbon fuels. Two candidate measures have been put forward (IMO, 2023): a technical element, namely a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG intensity, and an economic element on the basis of a maritime GHG emissions pricing mechanism.

As guidance for the development of the so-called mid-term measures that should steer the initial introduction of zero and near-zero fuels, the revised IMO GHG strategy mentions some key principles and criteria that should be considered:

- The measures should effectively promote the energy transition of shipping and provide the world fleet with the necessary incentive
- The measures should contribute to a level playing field and a just and equitable transition
- They need to consider the impacts of measures on states, including developing countries, in particular the least developed countries (LDCs) and small island developing states (SIDS).

Considering these principles and criteria, we can put forward a number of more concrete considerations that can be used to arrive at an optimised basket of measures as defined in the strategy. The measures should steer the energy transition, and the word transition is very relevant. It describes a process over a period of time and not a sudden step change. This is logical, as the transition requires the introduction of new fuel production and new engine technologies. This process that takes time, with a need to develop experience before going into the large-scale roll-out of the new technologies. The introduction of new technologies typically follows an S-curve with relatively slow initial growth in the application of the new technology, followed by a ramp-up period. To foster this process, a combination of measures can and should be put in place that gradually disincentivises the use of conventional technology and incentivises the application of the new technologies.

It is rather important that the disincentivising of conventional technologies does not happen in a brutal, sudden way, as that would have an immediate important effect on the cost of shipping and may lead to an unacceptable impact on states. Rather, a modest initial disincentive with a pre-announced timeline for increasing the disincentive would do the job. It would provide a clear signal that conventional technology will be phased out while leaving sufficient time for the industry to adjust and avoid a major increase in shipping cost, for example by further focus on energy efficiency measures. Incentives for the new technologies, on the other hand, will need to be substantial initially. The need for incentives should decrease over time as experience is gained, technologies are improved, and economy of scale helps to bring down the cost of alternative fuels.

To maintain a level playing field, measures will be needed that effectively close the cost gap between conventional fuels and zero and near-zero GHG fuels. While there may be ways to do this through a combination of levies and subsidies, a strong business case could also be created by allowing compliance with the GHG standard within a pool of ships. In this way, the higher cost of an alternative fuel used in one vessel could be covered by the pool, effectively spreading the cost over a number of vessels that continue to use conventional fuels while meeting the GHG standard on a pool basis. The EU's recently adopted FuelEU Maritime regulation includes such a mechanism (Council of the EU, 2023).

Availability of near-zero carbon fuels

A further critical question concerns the availability of alternative fuels in sufficient quantities to allow the shipping industry to meet the IMO targets. A study commissioned by IMO to look into the feasibility of different decarbonisation pathways concluded that full decarbonisation by 2050 is feasible through a realistic sustained annual fuel production growth rate, provided measures to create the demand are put in place promptly (Michael Campbell, 2023).

On the other hand, a recent study by DNV has looked into this question and concluded, based on a comprehensive mapping of currently announced projects, that demand for shipping could amount to 30 to 40% of global carbon-neutral fuel production in 2030 (DNV, 2023). Other industry sectors will be competing for these fuels as part of their decarbonisation efforts. This means that a supply shortage could occur, leading to high market prices. It may, therefore, be desirable to consider a mechanism that caps the maximum fuel cost, at a level that is high enough to encourage the switch to low- and zero-carbon fuels, but such that the impact on shipping costs and, consequently, the impact on states remains acceptable. Again, the EU's recently adopted FuelEU Maritime regulation includes such a mechanism. European countries have developed a proposal that would introduce similar concepts at a global level to IMO.

Focusing on the technical element of the proposed IMO mid-term measures should hold the key to stimulating the initial deployment of low- and zero-carbon fuels that is needed. The objective to reach 5% of energy demand by 2030 will be challenging. The sooner IMO can provide clarity on how the envisioned technical fuel GHG standard will be introduced, the higher the probability that the 5% target can be achieved. It should be noted that ships will need compliance options, as not all existing ships will be able to accommodate alternative fuels, and they may not be able to access low- or zero-carbon fuels.

Finally, a critical factor in the development of IMO's mid-term measures is the finalisation of the well-to-wake (WtW) GHG footprint methodology, the so-called LCA guidelines. The framework for this tool was agreed at MEPC 80 (IMO, 2023), but significant work remains to develop default GHG footprint values for the alternative fuels that are being developed. Due attention will need to be given to the verification and certification processes needed to guarantee that fuels on the market realise actual GHG savings and that fraud is detected and sanctioned. However, clarity on how WtW footprints will be calculated is needed to provide certainty to investors in near-zero carbon fuel production facilities.

Conclusion

IMO has taken a major step forward with the adoption of its revised GHG strategy in July 2023. The energy efficiency measures rolled out since 2011 have contributed to an improvement in CI of at least 20% since 2008. Further measures to be adopted will now need to focus on the transition to near-zero carbon fuels.
To achieve the objectives of the 2030 GHG strategy, the development of IMO's mid-term measures needs to proceed swiftly according to the timetable included in the revised strategy. That is critical to provide the certainty of demand needed to attract the vast amount of capital to speed up the production of alternative fuels.

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Hydrogen economy Part 2: Converting strategy into reality

An in-depth look at the supporting elements of the hydrogen supply chain: economics and regulations and how to operate within the infrastructure

Robert Ohmes, Nathan Barkley, Mike Annon, Greg Zoll and Jessica Hofmann
Becht

The pursuit of the hydrogen economy continues to evolve as energy providers, energy consumers, and logistics firms examine the economic and technical viability of hydrogen as a pathway to meet decarbonisation goals. As highlighted in Part One of this series, many challenges and opportunities exist within the production, distribution, and consumption sections of the hydrogen supply chain. Though not insurmountable, these items require close examination and analysis to drive the hydrogen economy. Within Part Two, we will take a deeper look at the supporting elements of the hydrogen economy: economics and regulations. As is often the case, the regulatory framework will provide the context, rules, and optionality to operate within the hydrogen economy, and the economic incentives, both positive and negative, will provide the cash flow and returns to fund investments in hydrogen infrastructure.

Economic and regulatory drivers

As highlighted in Part One, for the hydrogen supply chain to function and grow, consumers need to see value in using low-carbon hydrogen, while hydrogen producers and midstream operators need positive economics to justify their investments (see **Figure 1**). Currently, only about 10% of announced hydrogen projects have reached Final Investment Decision (FID). Besides some of the technical concerns discussed in Part One, the main reasons for the lack of further progress are clear financial incentives and regulatory signals.

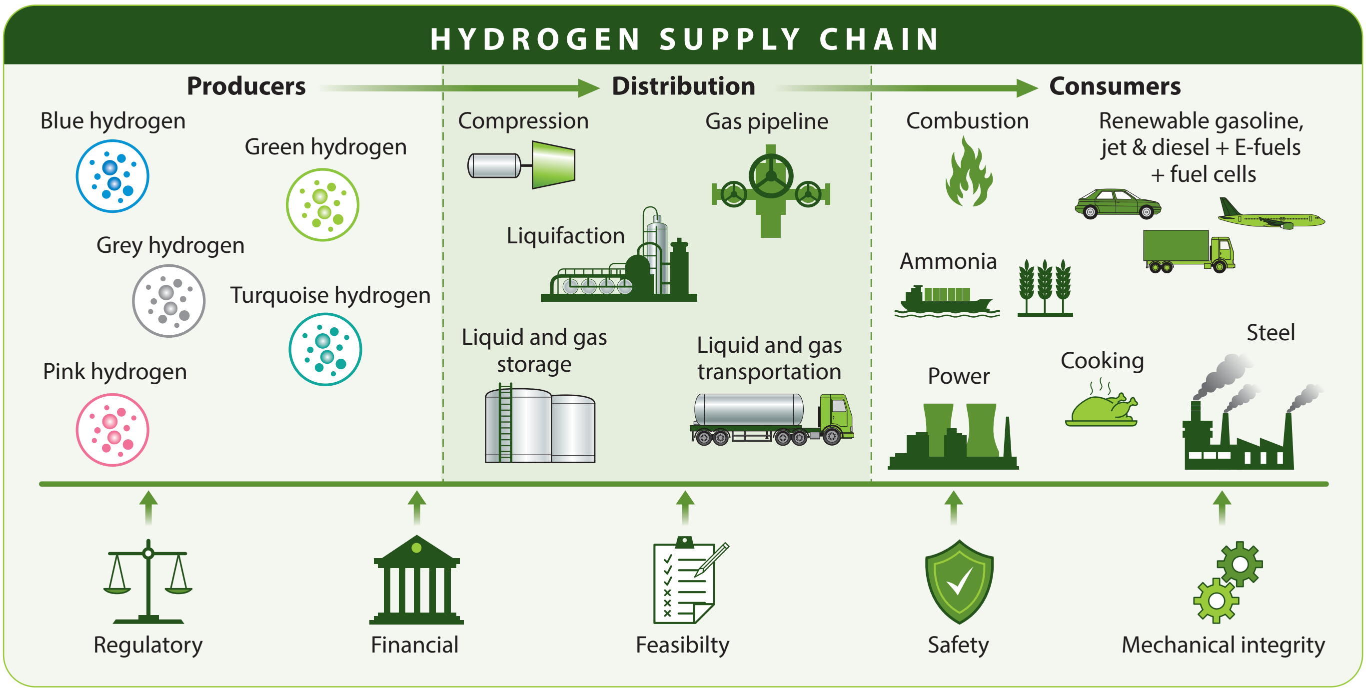

Figure 1 Hydrogen economy supply chain overview

One mechanism governments and regions are using to help bring together producers and consumers is the development of industrial clusters or hubs. The driver behind this approach is that by closely locating and integrating producers and consumers, economies of scale can be realised, distribution infrastructure can be optimised, and investors can have increased confidence in the long-term economic viability of the investments and operability of the assets. The following are some examples of these concepts:

- **HyVelocity Hub**: This hub plans to leverage existing infrastructure within the US Gulf Coast, as this region of the US has more than 1,000 miles of hydrogen pipelines and around 50 production plants. The group is a collection of two non-profit entities (GTI Energy and Center for Houston's Future), along with major industrial players, such as Air Liquide, ExxonMobil, Mitsubishi Power, Shell, Chevron, Sempra Infrastructure, Energy Transfer, Ørsted, and the University of Texas.
- **Teeside Industrial Cluster**: Within the UK, a consortium has been created to put together a fully integrated power generation and CO_2 capture and storage (CCS) system to help create a decarbonised industrial cluster. As part of this initiative, several entities are looking to construct hydrogen generation and transportation assets to make Teeside one of the largest low-carbon hydrogen hubs.
- **Rotterdam Hydrogen Hub**: Given Rotterdam's existing industrial infrastructure and port facilities, this location was selected as one of Europe's largest hydrogen hubs. Entities such as Shell, Eneco, BP, and HyCC are developing green hydrogen projects, and the Port Authority is working with multiple entities to develop several pipelines to supply the Netherlands and connect to other parts of Europe. In the long term, the Port Authority is exploring the supply chain requirements to export hydrogen globally.
- **HALO Hydrogen Hub**: This particular hub is intriguing, as it leverages production, distribution, and consumer assets across Louisiana, Oklahoma, and Arkansas to bring forward low-carbon hydrogen. These regions have significant pipeline and industrial infrastructure to use as part of the initiative, and existing as well as new consumers within industrial, commercial, and manufacturing segments and optionality for clean energy sources.

In reviewing the global standards for the definition of 'low-carbon' hydrogen, as well as the certification of hydrogen as decarbonised and the criteria for government-driven incentives, no single standard, certification, or economic incentive exists on a global basis. Each of these areas is being defined, refined, and issued on a country or regional basis and is behind the time progression of feasibility analysis, capital project activities, and investment decisions.

Here are a few terms for clarification of this discussion:

- **Standard:** A universally developed and agreed methodology for measuring quality
- **Regulation/Normative**: Rule or directive made and maintained by an authority to set limits based on standards
- **Certification**: Action or process of providing an official document confirming the status or level of achievement by an independent certification body based on standards and regulations.

Figure 2 provides a summary of progress by governments or international agencies to bring structure and specificity to the issue of a global hydrogen definition and demonstrates the complexity, variability, and status of these standards, regulations, and certifications.

A few interesting points about these regulatory elements are:

❶ Though a single definition of low carbon or decarbonised hydrogen has not been set, the leading definition involves a carbon intensity of 15-35 $gCO_2eq/MJLHV$ or 2-4 $kgCO_2eq/kgH_2$, is 99.9% pure hydrogen, and the hydrogen is delivered at 3 MPa pressure.

❷ Green hydrogen requires a consistent supply of renewable power, but only a few countries globally have a fully renewable electricity mix. Definitions vary of which forms of biomass or biogas can be considered 'green'.

❸ Nuclear power is not universally accepted as a green energy source, which impacts its use for the electrolysis of water to hydrogen.

❹ Many European regulations focus on four criteria to ensure low-carbon intensity hydrogen meets long-term emission reduction goals: additionality, temporal correlation, geographic correlation, and GHG savings.

- **Additionality**: The simple principle behind

EU (+ European Economic Area) certification

- CertiHy – EU Consortium funded by European Commission Issues
- Guarantee of Origin (GO) electronic certificate based on certification process
- Covers both green hydrogen and low-carbon hydrogen
- Compliant with EU EECS (European Energy Certificate System) and CEN EN16325 standard
- Latest published CertiHy scheme Apr 2022
- Certificates expire as soon as hydrogen is used
- TUV HUD is an auditor
- CertiHy low-carbon hydrogen has carbon footprint <36.4g CO$_2$e/MJ
- CertiHy green hydrogen is low-carbon hydrogen that is from renewable energy, including biomass and biogas
- Well-to-Gate and uses ISO 14044 and 14067
- 99.9% purity and 3 MPa pressure

International

- International Partnership for Hydrogen and Fuel Cells in Economy (IPHE)
- Published Rev2 Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen Nov 2022
- Point of production + transportation, but not use. Scope 3 for raw material and transportation
- 99% purity and 3 MPa pressure
- On-site verification + documentation approval
- Also issued discussion paper on trade rules

UK

- Dept Business Energy & Industry Strategy (BEIS)
- Published guidance document Jul 2022 – UK Low Carbon Hydrogen Standard
- Provides detailed methodology for emission calculation
- Must be 20g CO$_2$e/MJLHV emission intensity to be considered low carbon +99.9% pure and 3 MPa pressure
- Includes point of production, but not downstream use
- Interestingly, excludes H$_2$ fugitive emissions

France

- AFHYPAC (French Association for Hydrogen and Fuel Cells) – France Hydrogène – 450 members
- Currently publishing position papers and strategy documents
- Calling for clarity on RED II, RED III, and Fit for 55
- Concerned about additionality principle, temporal correlation, geographical correlation, exclusion of nuclear power, and setting correct average electricity grid emission factor

California + Other N. A.

- LCFS (Low Carbon Fuel Standard) in place since 2011. Has provision for hydrogen used for FCEV (Fuel Cell Electric Vehicles) and renewable fuel production
- Two pathways for calculating carbon intensity – Lookup Tables and Tier 2 application
- More than 30 accredited certification entities available
- Book and claim approach used
- Hydrogen from electrolysis and bio-based allowed

EU RED

- RED (Renewable Energy Directive) regulatory framework, latest RED II in 2018
- RED III included elements on hydrogen and derived fuels
- Use 50% of hydrogen for RFNBO (Renewable Fuel of Non Biological Origin) by 2030
- RFNBO must be at least 2.6% by 2030 (may increase to 5.7%)
- RED III not ratified yet – now in trialogue

China

- Governed by China Hydrogen Alliance's Standard – released 2021
- Defines low-carbon hydrogen as 14.51 kgCO$_2$/kgH$_2$ and renewable hydrogen as 4.9 kgCO$_2$/kgH$_2$
- Annual certification and third parties provide on-site audits
- No chain of custody methodology is defined

EU ISCC

- ISCC (International Sustainability and Carbon Certification) Plus is a voluntary market-based scheme for bio-based recycled material
- Scheme can be used to certify renewable hydrogen for biofuels, recycled carbon fuels, and RFNBOs
- Other entities oversee audits and ISCC issues certificates

Figure 2 Examples of standards, regulations, and certification across the world

additionality is that the power for electrolysis of water to hydrogen should come from new renewable sources rather than taking existing renewable power away from existing electricity users. Hence, the hydrogen will have to be generated by direct physical connection with the power source or through confirmed purchased power agreements, as well as being generated from new renewable facilities and sources.

- **Temporal correlation**: A specification of the time between power generation and use by the electrolysers to generate hydrogen. Most of these time frames involve calendar hours and do allow for power storage for use by the asset. However, the time frame is purposely condensed to ensure the use of renewable power directly for low-carbon hydrogen.
- **Geographic correlation**: The electricity generation assets and electrolysis system must be within the same geographical region, often defined by bid zones within a given country or groups of countries.
- **GHG savings**: the GHG savings must be accounted for and included to demonstrate that

the amount of decarbonisation of the hydrogen has been achieved. To be considered renewable or low-carbon hydrogen, a 70% or higher emission reduction must be achieved compared to fossil fuel-based hydrogen.

⑤ Two accounting methods are typically used, allowed, or specified for tracking the chain of custody of low-carbon hydrogen: mass balancing and book-and-claim. Some regulatory or standard organisations allow one or the other, while some allow the application of both methods.

- Mass balancing relies on the physical delivery of the hydrogen along with a matching certificate that describes the energy sources used to produce the hydrogen. The primary advantage of this approach is that the accounting follows with the point-of-sale and allows tracing of said hydrogen in downstream uses that mix with fossil-based hydrogen. The downside is that this physical delivery requirement reduces the market potential for that produced hydrogen.
- Book-and-claim separates the physical delivery from the certificate. Hence, the hydrogen can be physically delivered into the marketplace, and the certificates can be traded for those who need to buy obligations. The advantage of this method is that there is more flexibility in the marketplace. However, the downside is that the loss of the physical delivery tied to the certificate means the resultant hydrogen cannot be easily tracked through the supply chain.

⑥ **Carbon accounting boundary**: Conceptually, the boundary for emissions accounting for low carbon hydrogen production and usage should be consistent among all governing entities. However, two primary boundaries exist – Well-to-Gate and Well-to-Wheel. The Well-to-Gate approach includes the power generation, transportation of that power, and subsequent hydrogen production, but excludes the downstream transportation and final usage. Well-to-Wheel extends the Well-to-Gate elements to the final point of use. Understanding the boundary of each emissions standard and regulation will ensure the balances are properly addressed.

The final focal area is the economic incentives for low-carbon hydrogen production. Comparing current costs for renewable power generation as well as the scale of production and the additional costs of CO_2 capture within blue hydrogen with that of conventional grey hydrogen, the cost of green hydrogen is four to 10 times higher than grey hydrogen, while blue hydrogen is two to four times higher than grey hydrogen. To close these gaps, several options and mechanisms exist or are becoming available.

Carbon taxes and emission trading systems (ETS)

Several options exist within these trading systems. In essence, the regulators either define a specific carbon tax based on emission values using a standard accounting system or allow for trading of credits among producers and consumers of those credits in order to create an economic incentive to reduce emissions. Within the ETS systems, either a Cap-and-Trade or Baseline-and-Credit system are used, as well as offset options, where third parties guarantee to complete projects and operations to meet an obligation. One of the main challenges with these methods from a hydrogen economy perspective is that, though they create an economic benefit or penalty to drive a given policy, the markets for these systems are often slow to meet the targets and these systems do not always effectively bring together producers and consumers in an efficient market. For credits to be traded, they have to be certified by one of the national certification or voluntary schemes that comply with the methodology and sustainability criteria such as that defined in the Delegated Acts of the Renewable Energy Directive (RED) for 'renewable liquid and gaseous fuels of non-biological origin' (RFNBO). Government entities are striving to drive the right economic behaviors, but the shift will take time and effective refinement to achieve the desired outcome. Continued and more integrated collaboration between the private sector and governments is needed to improve the effectiveness of these systems.

California LCFS

One regulatory and market-maker scheme that has seen success is the California Air Resources (CARB) Low Carbon Fuel Standard (LCFS). Though known more commonly in the arenas of incentivising energy efficiency within industrial sites and driving the adoption of renewable

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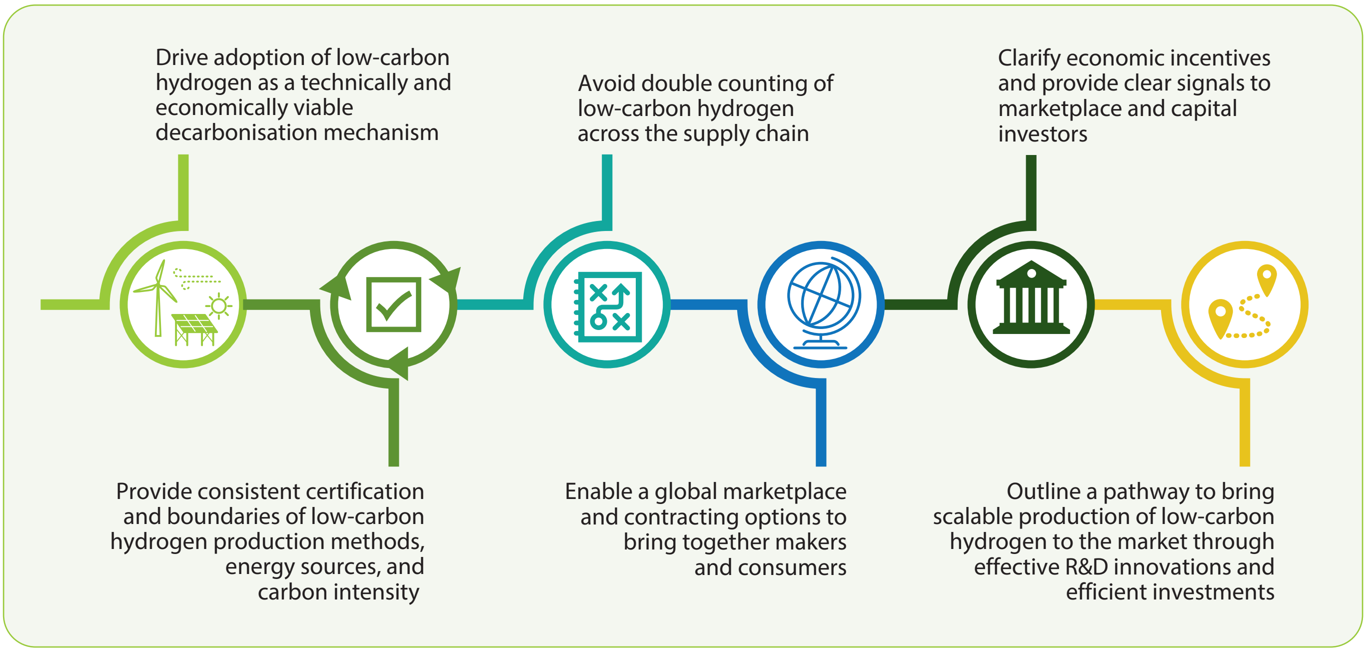

Figure 3 Why do we need standards, regulations, and certification?

fuels, a mechanism exists within the LCFS framework to generate credits from low-carbon hydrogen generation. One positive element of this mechanism is that the achievement of credit generation is technology-neutral, such that the marketplace can find the most efficient way to decarbonise a given product and maximise credit generation. The carbon intensity of various production methods is clearly defined within the scheme, either through the use of a Lookup Table method or Tier 2 method, and more than 30 entities are accredited verification bodies to certify adherence, thereby providing transparency within the marketplace. The approach is helping to drive the production of low-carbon hydrogen for use in transportation sectors, either through the use of low-carbon hydrogen in fuel cells or the use of renewable hydrogen for the production of renewable transportation fuels. However, the system has a long way to go to achieve the strategy targets.

Life cycle emissions ($kgCO_2eq/kg\ H_2$)	ITC percentage	PTC value ($2022\$/kgH_2$)
2.5 to 4.0	6.0%	0.50
1.5 to 2.5	7.5%	0.75
0.45 to 1.5	10%	1.00
0 to 0.45	30%	3.00

Table 1 Life cycle emissions determine the level for Investment Tax Credits (ITC) and Production Tax Credits (PTC) under the Inflation Reduction Act

Other states within the US and other parts of North America are looking to adopt similar mechanisms to drive hydrogen adoption.

Inflation Reduction Act (IRA) and production credits

To further drive the adoption of low-carbon hydrogen within the US, the Inflation Reduction Act (IRA) of 2022 introduced two new/expanded tax credits on top of the $8 billion in provisions for hydrogen hubs introduced in 2021 with the Infrastructure, Investment, and Jobs Act (IIJA). The Section 45V credit involves a sliding scale to provide Production Tax Credits (PTC) for 10 years or Investment Tax Credits (ITC), both based on the life cycle emissions. The Section 45Q credit takes an existing credit for carbon sequestration and increases the value. Producers can take one of the credits but not both.

As shown in **Table 1**, producers that can make green hydrogen or highly decarbonised blue hydrogen will get the largest credit.

Based on typical emissions, conventional hydrogen production from natural gas without carbon sequestration will not be eligible for the credits. Therefore, the only production methods that will be eligible will be partial or full carbon capture on steam methane reforming using natural gas or renewable gas and electrolysis hydrogen from renewable power. Both of these incentives drive the cost of production for blue and green hydrogen closer to that of conventional grey hydrogen, thereby incentivising production and, hopefully, consumption.

One challenge of this scheme is that the focus is on the production side, and there is limited incentive to spark investment in distribution infrastructure, which is sorely needed to connect producers and consumers on a broader scale. In addition, at the time of the writing, the US Internal Revenue Service (IRS) is just issuing the rules associated with claiming these credits, including clarification of the domestic content requirements (DCR). Making the recovery of these credits clear to investors will help drive the right capital flows and avoid further delays in progressing project engineering and construction.

Auctions and other novel schemes

Within Europe, one novel approach to help bring producers and consumers together while also closing the gap between production costs and consumers' willingness to pay is the use of government-backed auctions. Essentially the way these double auctions work is that a government entity agrees to buy a certain amount of low- carbon hydrogen over a given period (typically 10 years) for a predefined pricing arrangement, and then the government entity auctions shorter-term supply contracts under individual tenders. The gap between the cost of hydrogen purchased from producers and sold to suppliers is covered by the government, thereby using taxpayer funds to solve one of the critical limits in expanding the hydrogen economy – providing supply and demand side investors with firm production and supply contracts. This approach also helps to provide supply to those entities with a more significant economic desire to secure low-carbon hydrogen and are willing to pay more for that material.

For the longer term, other schemes are being considered to further drive decarbonisation. An example is a carbon take-back obligation, where the carbon generation entities (crude oil producers, refiners, and importers) would be obligated to capture and store a portion of the CO_2 generated by their activities, including the final use of their products. Over time, the emission capture requirement would grow and help drive decarbonisation from a supply side. The challenges with this approach are the ability of the producers to capture and store CO_2 from final usage as well as the practicality of certification and confirmation when compared to more demand-side options. That said, other novel incentives are needed to inspire R&D, investment, and both supply and demand-side low-carbon production and usage.

Takeaways and conclusions

In summary, to drive hydrogen adoption beyond the supply, demand, and distribution aspects, further clarification of standards, regulations, certification, and economic incentives is critical. As energy firms, governments, and research entities look at converting their hydrogen strategy into reality, the following five critical questions should be asked and answered, risks identified and mitigations developed, and supply chain elements reviewed:

- What markets are available, and what points of view exist for that market, both from a supply/demand and economic perspective?
- What are the technology pathways and optionality that should be used?
- How are capital costs, economics, and risks being accounted for and mitigated?
- What are the critical early impacts and decisions that must be made to increase the probability of a positive outcome on the investment?
- Which components of the overall hydrogen supply chain production, distribution, and consumption require further expansion or efficiency improvement to meet technical and economic feasibility?

Those hydrogen economy players that can most effectively address these areas will be in the best position to expand the hydrogen economy and meet the overall decarbonisation goals.

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Andalusian Green Hydrogen Valley

The industry is focused on decarbonisation and the energy transition, with emission reduction targets to hit in 2030 and 2050

H_2 Business Unit
Cepsa

Cepsa is working to deliver its 'Positive Motion' pledge to decarbonise all its businesses, reduce Scope 1 and 2 emissions by 55%, reduce the carbon intensity of its products (Scope 3) by 15-20% by 2030, and achieve net zero CO_2 emissions by 2050. We will help our industrial partners and transport customers decarbonise internationally, making us an industry leader in the energy transition.

Since the 1990s, the European Union (EU) has promoted the development of renewable energies through legislative acts such as Directive 2018/2001/EU (RED II), which defines the objectives of the Union's energy policies in the field of renewable energies and decarbonisation of various sectors (such as industry and transport). Subsequently, a range of related policies and legislative instruments have been proposed, revised, and approved.

The European Green Deal, a package of initiatives to achieve net zero greenhouse gas (GHG) emissions by 2050, puts the emphasis on the adoption of renewable fuels such as hydrogen in industry and transport, with the objective of mitigating the effects of climate change. A year later, despite the tremendous impact of the COVID-19 pandemic, where the EU had to take important measures in energy matters, it launched the Hydrogen Roadmap, making hydrogen a central axis of the European decarbonisation plan. With the aim of further strengthening energy policies, the Commission published a new energy legislative package, Fit For 55, setting ambitious targets and tools to reduce GHG emissions to at least 55% below 1990 levels by 2030. The Commission also introduced national targets for renewable energy and mandatory targets to decarbonise and diversify the transport sector, with the aim of reducing the GHG intensity of carbon fuels by using quotas for renewable fuels such as biofuels and renewable fuels of non-biological origin (RFNBO) by 2030.

After Russia's invasion of Ukraine, the EU decided to accelerate the energy transition, increasing the targets for the share of renewable energy in the EU mix, including the production of 10 million tons of domestic hydrogen, with imports of another 10 million tons by 2030, and targets for production and supply of RFNBOs in industry and transport under the RePower EU strategy.

> "The petrochemical industry's linear product life-cycle model, characterised by extraction, production, consumption, and disposal, is riddled with environmental consequences"

The increase in the production of renewable hydrogen in member countries represents a unique opportunity to begin the design of a European environment characterised by the security of energy supply and, in particular its application in sectors that are difficult to electrify.

Since then, regulatory development at the European level has increased exponentially, resulting in a regulatory network with clear objectives in each sector, such as aviation (ReFuel Aviation), maritime (FuelEU Maritime),

Figure 1 Andalusian Green Hydrogen Valley

Alternative Fuel Infrastructures (AFIR) Regulations, and an improved ETS (Emission Trading System).

At the national level, the percentages and minimums required in the regulation are mandatory, so EU Member States must implement the regulations within the established timelines.

Cepsa is an integrated energy company active in all phases of the oil and energy value chain, with a worldwide presence. It is the second largest consumer of hydrogen in Spain due to its internal demand in the refinery and chemicals activities. It is located in the Energy Parks (EP) of La Rábida (Huelva) and San Roque (Algeciras), where the main objective is to produce fuel for all transportation sectors. In addition, the company has extensive experience in projects and the operation of small- and medium-scale hydrogen technologies in safe industrial environments and the development of sustainable fuels:

- Cepsa has been producing biofuels in its refineries for more than 10 years and is carrying out pioneering studies worldwide to convert waste and used oils into renewable fuels.
- Cepsa is now using the experience gained in the production of biofuels to take the first steps towards the implementation of the Andalusian Green Hydrogen Valley in an environment with a high potential for the consumption of renewable hydrogen.

Spain is well-placed to be a leader in the production of renewable hydrogen, as it is blessed with abundant solar and wind energy. Cepsa's two Energy Parks are in southern Spain, where truly competitive renewable energy prices can be achieved.

Andalusian Green Hydrogen Valley

In December 2022, Cepsa announced its commitment to develop a 2GW electrolysis project in the Andalusian Green Hydrogen Valley, with two clusters in the highly industrialised areas of southern Spain: Huelva and Algeciras (see **Figure 1**). This situation will allow the development of a knowledge axis around renewable hydrogen, which will benefit from economies of scale through the construction of high-capacity renewable hydrogen electrolysers and the development of an integrated value chain, culminating in supply to various industries (fertilisers and others) and other economic sectors such as transport (maritime, aviation, and road transport).

- Huelva's Onuba Project seeks to decarbonise the facilities within the La Rábida Energy Park together with neighbouring industries, starting with the installation of 400 MW of electrolyser capacity (with a plan to increase up to 1GW as alliances with new partners are materialised). As well as decarbonising our operations by reducing our Scope 1 and 2 GHG emissions, we are reducing Scope 3 emissions for our clients via the decarbonisation of transport fuels and fertilisers.

The project has already resulted in a collaboration between Cepsa and important partners such as Enagás Renovable, Alter Enersun, and Fertiberia. Together with Fertiberia, a leader in the development of sustainable and high-added solutions for agriculture, green ammonia will be produced from the implementation of renewable hydrogen by electrolysis. The Onuba Project will also meet other emerging demands, including:

- Decarbonisation of our Energy Park and new internal projects, including a new hydrogenated vegetable oil (HVO) plant, to be developed together with Bio-Oils (an Apical company) for the production of decarbonised diesel-like fuels.
- Road passenger transport through an agreement with Damas, a national road transport company, to promote sustainable mobility using renewable hydrogen as a fuel. The agreement aspires to contribute to the necessary technological development to promote the introduction of renewable

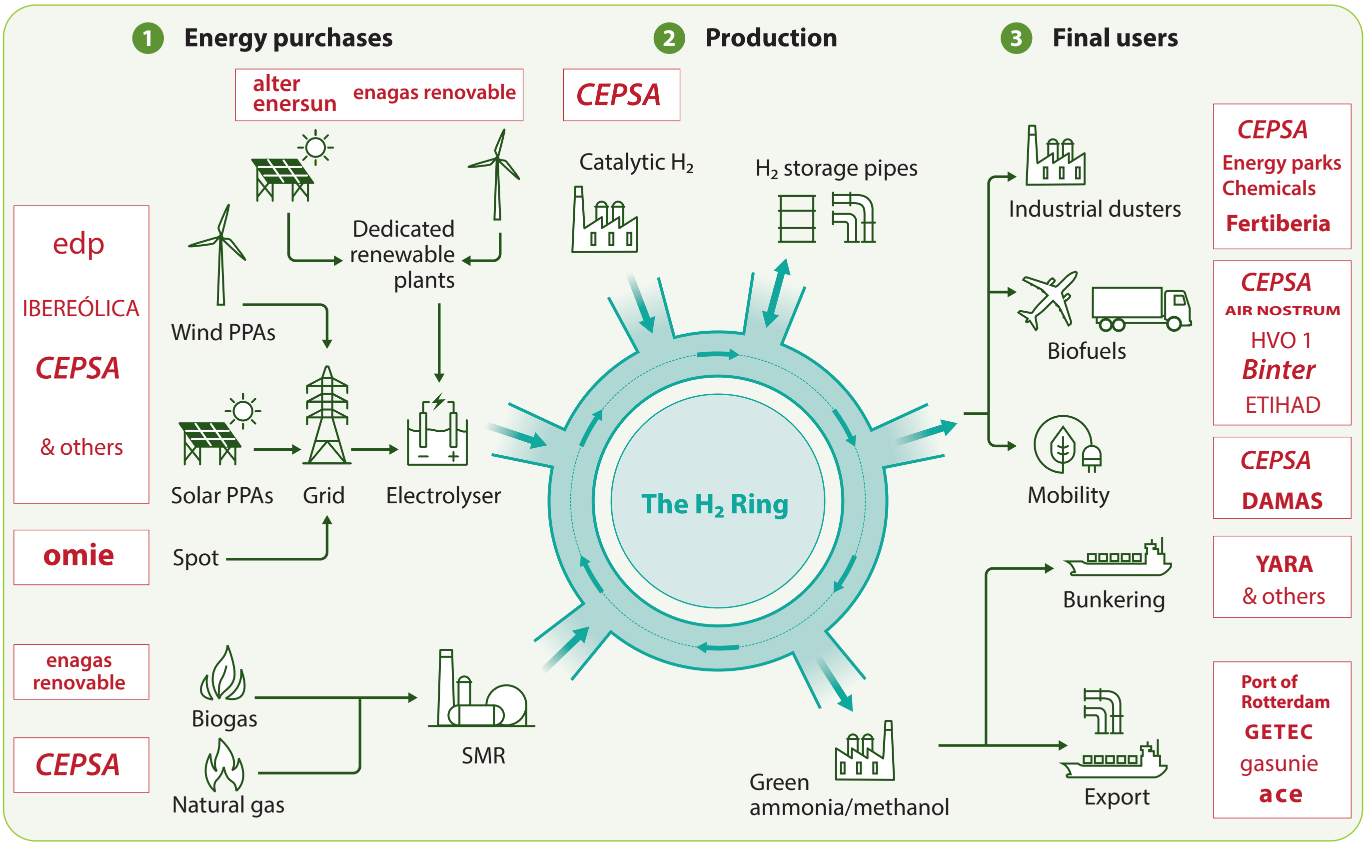

Figure 2 The H2 ring

hydrogen for use in public transport and heavy-duty vehicles.

- Conversations to develop e-methanol are also ongoing.

In summary, two key products will be at the core of the current project: green ammonia and HVO fuels (biodiesel and biojet) for heavy road transport and aviation.

These HVO fuels, known as sustainable aviation fuel (SAF), are key for the decarbonisation of the aviation sector, where agreements have already been signed with airlines, including Air Nostrum, Binter, Ryanair, TUI, and Vueling.

- Algeciras' CARTEIA Project seeks the construction of a 1 GW capacity electrolysis plant for the decarbonisation of the EP and the production of renewable hydrogen to be used to decarbonise hard-to-abate sectors, specifically, the maritime transport and fertiliser sectors. An agreement with EDP Renewables was signed in 2022 to collaborate in the development of the electrolysis capacity.

The renewable hydrogen produced will feed the new green ammonia plant to be built jointly by Yara Clean Ammonia and Cepsa. This ammonia plant will have an annual production capacity of up to 600,000 tons.

As Cepsa is the first bunkering services provider in Spain, the ambition is to supply maritime shipping using the Strait of Gibraltar (more than 100,000 vessels per year, 10% of the international traffic). While this demand emerges, the agreement with Yara Clean Ammonia will also allow the export of this green ammonia.

H2Med

The Onuba and CARTEIA Projects will be connected to H2Med, a multinational project supported by Portugal, Spain, France, and Germany. H2Med will interconnect via pipeline hydrogen production projects and demand in the Iberian Peninsula with Central Europe. This infrastructure is expected to be operational by 2030.

European Hydrogen Corridor

As part of the CARTEIA project, the first European corridor linking North and South Europe between two of its most important European ports, Rotterdam and Algeciras, will be developed. To this end, agreements are in place with ACE Terminal, an initiative from Gasunie, HES International, and Vopak to develop a hydrogen import terminal in the Port of Rotterdam. The terminal will have the capacity to be used as a storage of ammonia to be finally used as fuel, feedstock for fertilisers, or hydrogen carrier for customers in central Europe.

The terminal will also offer the conversion of the ammonia into hydrogen and facilitate the transshipment and onward transit. Another agreement has been signed with GETEC, which provides heating, cooling, and electrical services to industrial customers in various sectors (chemical, automotive, and food) in Germany, the Netherlands, Switzerland, and Italy. This alliance will enable the supply of green hydrogen and its derivatives, which GETEC will distribute to industrial customers in different European countries. Conversations are ongoing with other potential partners.

H2 ring

The main strength of both projects is the possibility of using different assets from different partners to take advantage of every single component within the 'H2 ring' (see **Figure 2**). Each site will produce and mix various types of hydrogen (electrolytic, biogenic, and catalytic).

The industrial hubs will provide the flexibility to meet the demand for different products over time, considering external factors such as the availability of renewable energy and the growing demand for sustainable fuels. Given the uncertainty in the emerging demand for the different fuels, this will enable Cepsa to focus on the development of RFNBOs (hydrogen, ammonia, and methanol) with the flexibility to adapt to emerging demand. Potentially, this flexibility will also allow the provision of ancillary services to the power sector.

Innovation and knowledge sharing

Cepsa brings its experience in managing different technological, finance, and environmental aspects to support an innovative and clear energy transition commitment while searching for new solutions that work efficiently across different sectors and with people from the society to meet these challenges.

As an example, Cepsa will promote the circular economy by using residual water from public pretreatment plants in its processes, thus encouraging the development of public/private collaboration.

In addition, it is important for all society to embrace this new paradigm. One way Cepsa is doing this is through training courses organised together with the International University of Andalusia (UNIA) to share experiences with professionals from the different sectors based on the development of Cepsa's strategy and the risks associated with them.

Challenges

Several challenges are hindering the growth of this new market. Despite all the efforts made so far, regulatory uncertainty remains, particularly with regards to meeting the requirements for RFNBO production and reducing energy supply costs, certification of the final product, and permitting. A supportive regulatory environment is key to the expansion of this market.

Considering the current gap between the cost of grey and green products, appropriate subsidies are essential. Formulas combining Capex and Opex support should be investigated.

Lastly, it is also crucial to establish a robust power distribution network to meet the new demand resulting from the electrification of the economy.

Final remarks/commitment

Cepsa is committed to taking the necessary actions to accelerate the energy transition and the move towards a low-carbon economy, constantly seeking new energy solutions and more efficient technologies that allow us to reduce our emissions.

We strive to minimise the impact of our activities and give the highest priority to protecting the environment.

We work for the coexistence of industry and the environment in a sustainable manner through actions to conserve biodiversity, protect the marine environment, and manage water responsibly.

H_2 Business Unit, Cepsa
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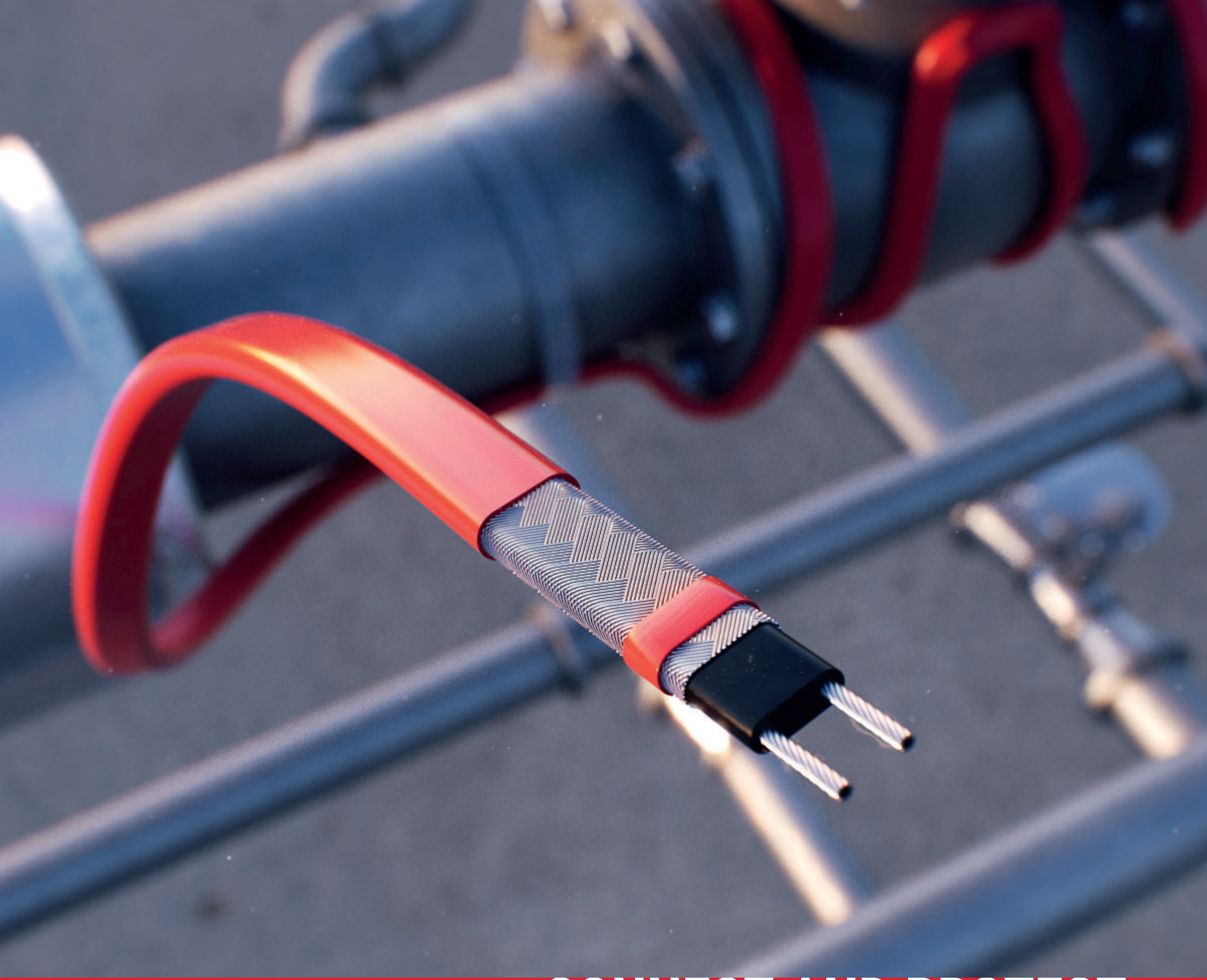


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Hydrogen through methane pyrolysis

Methane pyrolysis is an important emerging technology that presents an economically attractive hydrogen production process with zero CO_2 emissions

MP Sukumaran Nair
Centre for Green Technology & Management, India

The message is clear. Greenhouse gases, especially carbon dioxide (CO_2), emitted from human activities using fossil fuels and feedstocks, currently and over the past 150 years, significantly contribute to global warming. Therefore, a global consensus has been reached that we must reduce greenhouse gas emissions and foster a sustainable, low-carbon economy.

The potential for hydrogen to play a significant role in the transition from carbonaceous fuels to clean energy resources without CO_2 emissions is widely recognised. Hydrogen can serve directly as a fuel in fuel cells, internal combustion engines, or furnaces for industrial processes that are difficult to electrify. Hydrogen can also be used as a building block in decarbonised chemicals and transport fuels where a higher energy density is required.

Hydrogen is abundant in nature, but only in the combined form (with oxygen as water and carbon as hydrocarbons), which requires the intervention of high-order energy reactions for its liberation to the free molecular form. Hitherto, most manufacturing processes involving hydrogen – ammonia, methanol, power, and chemicals – used the energy from fossil fuels for its separation and downstream uses, which invariably resulted in emissions of large quantities of CO_2. Around 90% of the hydrogen produced today is from steam methane reforming (SMR), autothermal reforming (ATR), or gasification processes using methane, naphtha, fuel oil, petroleum coke, or coal as feedstock – all of fossil origin.

The production of hydrogen from the electrolysis of water (WE) is a known technology and was the main industrial source of hydrogen during the 1960s. In present times, the term ‘green hydrogen’ has been coined to denote hydrogen produced using electricity generated from renewable sources. As such, a prerequisite for the use of the term green hydrogen is either an uninterrupted supply of renewable electricity from the grid or a dedicated supply of renewable electricity (from wind, solar, geothermal, hydropower, or biomass) as part of the project.

While water electrolysis processes are in early commercialisation, further research and development are needed to design larger capacity plants with improved economies of scale.

During the energy transition period, hydrogen production from fossil sources can support the growing hydrogen economy, providing the carbon intensity of the process is comparable with that of water electrolysis. Many existing

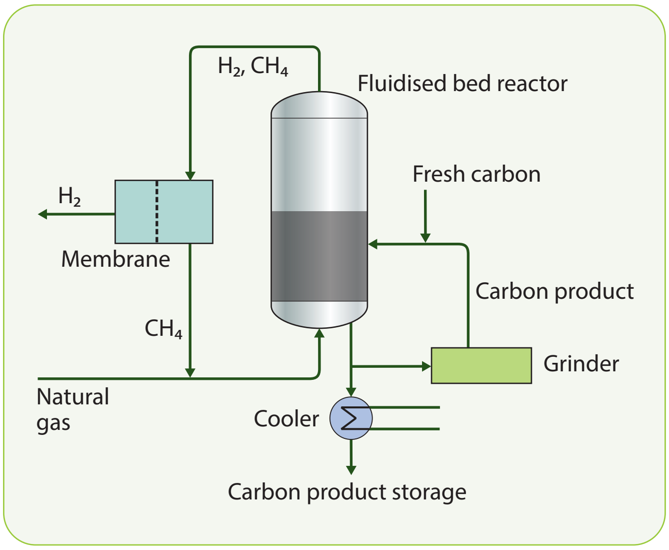


Figure 1 Methane pyrolysis schematic
Courtesy: Wiley Online Library

Figure 2 The world's first commercial-scale methane pyrolysis plant *Courtesy: Monolith*

SMRs are being revamped to add carbon capture equipment. The captured carbon can then be used for the synthesis of chemicals or fuels or sent to certified sites for sequestration and permanent storage, thus avoiding emissions to the atmosphere. This requires additional facilities with the consequential investment for the management of the CO_2. Hydrogen produced using fossil fuel feed to an SMR with carbon capture is termed 'blue hydrogen'.

Critical challenges developing green hydrogen technologies include the development of cost-effective and efficient electrolysers and building the necessary infrastructure for handling, storage, and distribution of hydrogen. The Green Hydrogen Catapult (GHC), formed in 2020, is a coalition of industry leaders organised with the support of the UN High Level Champions for Global Climate Action. The GHC has targeted the deployment of 25 GW electrolysers with the aim of reducing the cost of green hydrogen below $2/kg, which will allow the clean fuel to be cost-effective in the short term (Climate Champions, 2030).

Pyrolysis technologies for methane

An emerging technology for generating clean hydrogen is the pyrolysis of methane to produce hydrogen and solid carbon (char). Compared with SMR with CCUS, the methane pyrolysis process has a major advantage: the carbon produced is in the elemental solid form. As the methane pyrolysis process does not produce CO_2, it avoids the need for carbon capture and sequestration infrastructure. Compared with water electrolysis, the methane pyrolysis process does not need renewable electricity or water as a feedstock.

Currently, methane pyrolysis is at a lower technology maturity level than electrolysis or SMR with CCUS. Development is focused on improving the reliability of the pyrolysis process and attaining economy of scale operations. Several companies are commercialising methane pyrolysis technology, moving from the pilot plant (200kg H_2 per day) and demonstration unit levels (200kg H_2 per day) through to the first commercial-scale plants (>5kt p.a. H_2) (see **Figure 2**)(Monolith, 2021) (BASF, 2023), (Ekona, 2023), (Monolith hydrogen, 2023).

The methane source can be in the form of conventional natural gas or as bio-methane from anaerobic digestion of manure and other forms of biomass waste. The hydrogen so produced is termed ‘turquoise’, on the colour spectrum between blue and green.

The main developmental challenges include the cost of hydrogen produced, energy efficiency, and operational reliability. Uses for the solid carbon by-product are also an important consideration. In the interim, while capital costs will be higher, the cost of hydrogen production will likely be lower than that of SMR with CCS or water electrolysis.

As the technology matures with larger commercial plants providing economies of scale, methane pyrolysis will have an edge over other competing technologies. Methane pyrolysis is an active area of research that is now attracting interest from some of the leading engineering technology companies, including BASF, Ekona, Baker Hughes, and Mitsui. The pyrolytic decomposition of methane can be affected in three ways: thermal, plasma, and catalytic.

Thermal pyrolysis

Pyrolysis of methane in the absence of oxygen yields carbon (solid) and hydrogen (gas) as per the reaction below:

CH_4 (gas) → C (solid)+ $2H_2$ (gas) ΔH -76KJ/Mole

The reaction is highly endothermic with an equilibrium that shifts toward hydrogen and carbon around 300°C and goes to completion around 1,300°C.

It is similar to the reduction of iron oxide (ore) to metallic iron with methane. Here, the molten metal helps to split the carbon hydrogen bond in methane to free up both elements. In the industrial process, gaseous methane is fed to the bottom of a high-temperature reactor filled with molten metal as lead (Pb) or a molten metal alloy of nickel and bismuth (NiBi) and heated to 1,300°C. The molten metal promotes the formation of solid carbon and gaseous hydrogen. The carbon so formed rises through the molten medium and floats at the top, from where it is skimmed off and transferred to a carbon tank. A one-third mole of the hydrogen produced is used to heat the reactor and maintain the temperature, while the rest is cooled and stored.

The Karlsruhe Institute of Technology (KIT) in Germany has developed a process that uses a liquid-metal bubble column reactor. The column is filled with liquid metal and heated to 1,000°C. Fine methane bubbles enter the column through a porous filling at the bottom. These bubbles rise to the surface, and at such high temperatures, the ascending methane bubbles are increasingly decomposed into hydrogen and carbon.

Catalytic pyrolysis

The thermal decomposition of methane requires a high temperature in the order of 1,300°C. Metals such as nickel, iron, copper, and cobalt have demonstrated catalytic activity for methane decomposition at lower temperatures, between 500-800°C.

The reaction is carried out in nanostructures like nanotubes, nanofibres, or graphene. Metal catalysts exhibit fast deactivation and are difficult to separate from the carbon produced. To overcome these limitations, carbonaceous catalysts in the form of amorphous high surface area carbons active in the range of 800-900°C are employed. Such carbon catalysts will likely have a slower deactivation rate than metal catalysts. Strategies for continuous regeneration of catalytically active carbons are an active area of research.

Plasma pyrolysis

In this process, plasma torches are used to crack the methane molecule into hydrogen and solid carbon powder. It is similar to water electrolysis but uses only one-fifth of the electricity, resulting in operational costs more than 50% cheaper than water electrolysis. The methane is introduced to a tubular plasma reactor. Part of the length of the reactor tube lies in a horizontal rectangular waveguide through which microwave power is supplied to excite the methane to the plasma state.

Currently, the decomposition of methane is accompanied by a combination of cracking, oligomerisation, and aromatisation reactions, which tend to minimise the formation of elemental carbon. Research is underway to limit these side reactions to attain better carbon and hydrogen yield. Plasma pyrolysis is considerably more expensive than thermal and catalytic pyrolysis due to the high power intensity needed.

Industry outlook

Natural gas has a 24% share of global primary energy consumption in 2022, growing at around 5.3% per annum (BP, 2023). Production in 2021 was 4,037 billion cubic metres (BCM), of which 1,022 BCM are traded globally.

Given that conventional natural gas is a fossil fuel, it is not sustainable in the long-term, but it is an important transition fuel, with lower GHG emissions than coal (providing energy companies deliver their commitments to minimise methane emissions from natural gas operations) (OGCI, 2022).

Biogas, or renewable natural gas (RNG), produced via anaerobic digestion from renewable biomass, is a source of renewable energy that can reduce net greenhouse gas emissions. Methane separated from biogas is called bio-methane. Since methane is a potent GHG gas, reducing methane emissions from municipal waste treatment sites or from agricultural manure and biomass is an important climate mitigation goal. Hence, bio-methane can be considered a sustainable feedstock for methane pyrolysis.

Catalysed pyrolysis uses only non-toxic metals; therefore, the disposal of spent catalyst is not a concern. Moreover, the ongoing innovation and research concerning the thermodynamics and kinetics of the pyrolysis reaction may open up new vistas with higher activity catalysts. Co-product carbon may be used in the manufacture of a variety of products – carbon black, fibres and nanotubes – as well as a soil improver and for pollution control applications and environmental remediation.

Methane pyrolysis and SMR with carbon capture are both promising processes for the production of renewable hydrogen production. They should be seen as complementary to rather than competitive with hydrogen from water electrolysis, with a ‘carbon-intensity’ metric used to drive sustainability for all three processes.

Comparison of clean hydrogen production technologies

Electrolyser capacity accounted for only 0.1% of global hydrogen capacity but is growing rapidly, reaching 510 MW by the end of 2021, with announced projects under construction leading to an estimated 170-365 GW by 2030 (IEA, 2023). However, the current pace of green hydrogen capacity expansion is not on track to meet the net zero goal by 2050. In 2023, the bulk of hydrogen production continues to be from unabated SMR within the oil refining, gas and chemical (fertiliser, methanol and petrochemical) industries.

Hydrogen is seen as key to the decarbonisation of energy-intensive industries, including steel and cement (see **Figure 3**). While all technologies available for the production of green hydrogen are optimised through research and innovation, it is expected that by 2025,

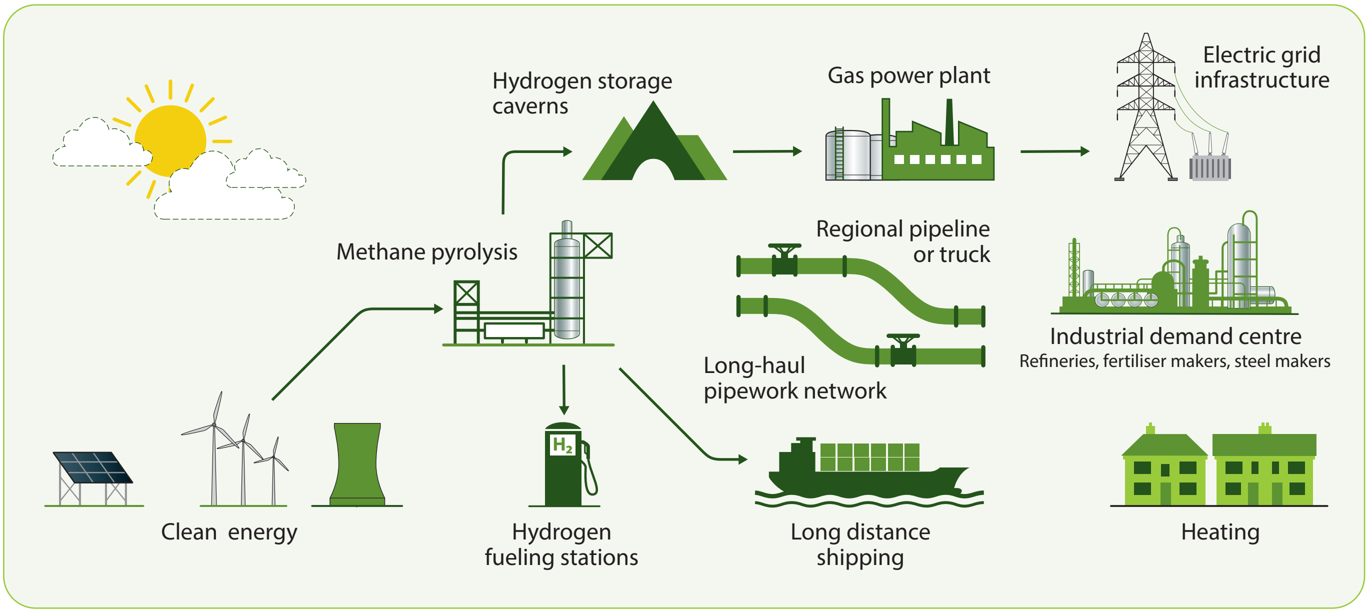
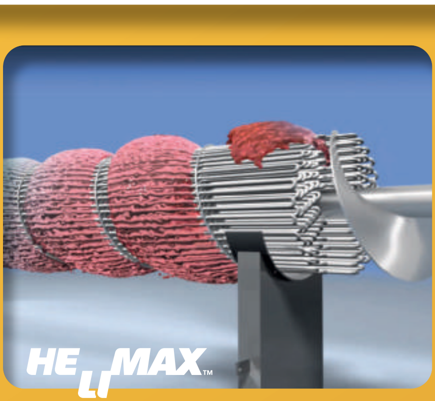


Figure 3 Clean hydrogen economy *Courtesy: Monolith and S&P Global Market Intelligence*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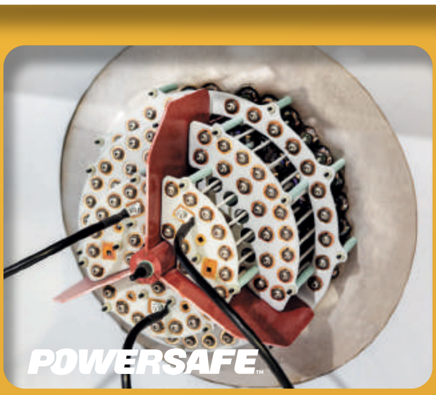
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Project	Process	Location	Capacity MT of H_2	Investment	Date of commissioning	Remarks
Aqua Aerem Desert Boom Hydrogen	Aqua Aerem WE	Northern Territory, Australia	410,000 (annual)	$10.75 billion	2027	Modular hydrogen production units. H_2 price: $2/kg
Shell Hydrogen	WE by TUCE	Rotterdam, Netherlands	200 MW, 20MW Alkaline WE 50-60 TPD H_2/day	–	2025	2.4 MMT of CO_2 will be saved
GreenHyScale project by GreenLab Skive	WE P2X multi MW range alkaline electrolyser	Denmark, consortium of 11 entities*	6 MW 100 MW 30 TPD H_2	30 million Euros	2022 2024	–
Shell Zhangjiakou Green Hydrogen JV	WE by Shell Power to H_2	Zhangjiakou Hubei, China	20 MW in Ph 1 60 MW in Ph 2	–	2023 2025	–
NEOM Green Hydrogen - Air Products, ACWA Power, NEOM	WE by TUCE	S. Arabia	2 GW 20 MW AWE	–	2026	1.2 MMT of green NH_3 annually

* GreenLab Skive A/S, Green Hydrogen Systems A/S, Energy Cluster Denmark, Lhyfe, Siemens Gamesa Renewable Energy, Equinor Energy A/S, Technical University of Denmark, Imperial College London, Everfuel, Quantafuel, and Euroquality

WE - Water electrolysers, MT - Metric tonnes , MMT - Million MT, TUCE - thyssenkrupp Uhde Chlorine Engineers

Table 1 Major green hydrogen projects under implementation

major sectors will witness an accelerated shift towards green hydrogen (see **Table 1**).

Process economics

Even though capital costs for methane pyrolysis are high, operating costs are certainly lower. Additionally, the elemental carbon by-product represents a secondary income stream. The availability of water and the outlets for oxygen co-produced pose challenges for the economics of water electrolysis, while the added capital and operating cost incurred towards building CCS infrastructure are disadvantages for SMR (see **Table 2**).

The cost of clean hydrogen production varies as each of the processes uses different designs, technologies, feedstock, and utilities. The economics of various hydrogen production processes avoiding GHG emissions is also better understood through the levelised cost of hydrogen (LCOH). LCOH considers the costs to produce one kilogram of clean hydrogen, including Capex and Opex components. The Capex for blue hydrogen includes the complete SMR/ATR unit with an associated CCS facility, and that for green hydrogen includes the electrolyser unit with the essential ancillaries. Storage and transport are excluded.

Researchers, technology providers, and process operators have studied the economics of blue, green, and turquoise hydrogen production. Today, the average LCOH is $2-3kg for an SMR with CCS, $5-6/kg for water electrolysis (WE), and $2.8-3/kg for methane pyrolysis (see **Table 3**). If a credit is given to the carbon by-product, the LCOH for methane pyrolysis may be as low as $1.8/kg. These figures are based on an average gas price of $9 per MMBTU and renewable power at $45/MWh.

The levelised cost of blue hydrogen will vary in line with oil and gas prices but will likely fall as independent CCS facilities come on stream. Similarly, the LCOH of green hydrogen is expected to fall by 2030 due to a reduction in the cost of renewable power, as well as

Project	Developer	Project components	Capacity	Scheduled date	CO_2 saving	Investment
Hydrogen Hub Edmonton Western Canada	Air Products Ltd	ATR + CCS Power from H_2 by Baker Hughes	1,500 metric tonnes per day	2024	–	$1.1 billion
H2H Saltend project Humber, UK	Equinor, Norway	ATR + CCS by Linde	600 MW to expand to 1,200 MW H_2 production to produce 125,000 MT of H_2 for power	2026	8 million tonnes per year	–
Ascension Parish, Blue H_2 Energy Complex, Louisiana US	Air Products	SMR + CCS	750 million SCFD of H_2	2026	5 million tonnes per year	$4.5 billion
H2morrow Pilot Project, Germany	Equinor, Open Grid Europe	ATR + CCS	8.6 million MWH equivalent H_2	–	–	1.9 million

SMR – Steam methane reforming, ATR – Auto thermal reforming, CCS – Carbon capture and storage, SCFD – Standard cubic feet per day

Table 2 Large SMR hydrogen with CCS projects under development

Criteria ↓	Process →	Steam methane reforming (SMR)	Water electrolysis (WE)	Methane pyrolysis (MP)
Energy required/MT of H_2, MWH		6	55	10
CO_2 produced/MT of H_2, MT[1]		9-10	0	0
By-products/MT of H_2, MT		CO_2	Oxygen - 8	Carbon - 3
Energy efficiency, %[2]		75	55-70	58
Levelised cost of hydrogen, $		2	5	2.8 (1.6 with credit for by-product carbon)

Sources: BASF (BASF, 2023); 1 Using electricity sourced from renewables; 2 (Sanchez-Bastardo, et al., 2021)

Table 3 Comparison of broad parameters

increases in the efficiency of electrolysers and future reductions in the unit cost. A full-scale offtake of char or carbon black co-produced in the pyrolysis process will invariably reduce the cost of turquoise hydrogen.

Progress with research on reactor design, modularisation, catalyst development, and process control will lead to improvements in process reliability with a consequential reduction in the cost of hydrogen.

Methane pyrolysis is an important emerging technology that presents an economically attractive hydrogen production process with zero CO_2 emissions. When bio-methane is used as the feedstock, it can result in a negative carbon intensity (Monolith hydrogen, 2023). Given the forecast future demand for hydrogen, it should be seen as complementary to blue and green hydrogen production and an important contributor in building the hydrogen economy.

VIEW REFERENCES

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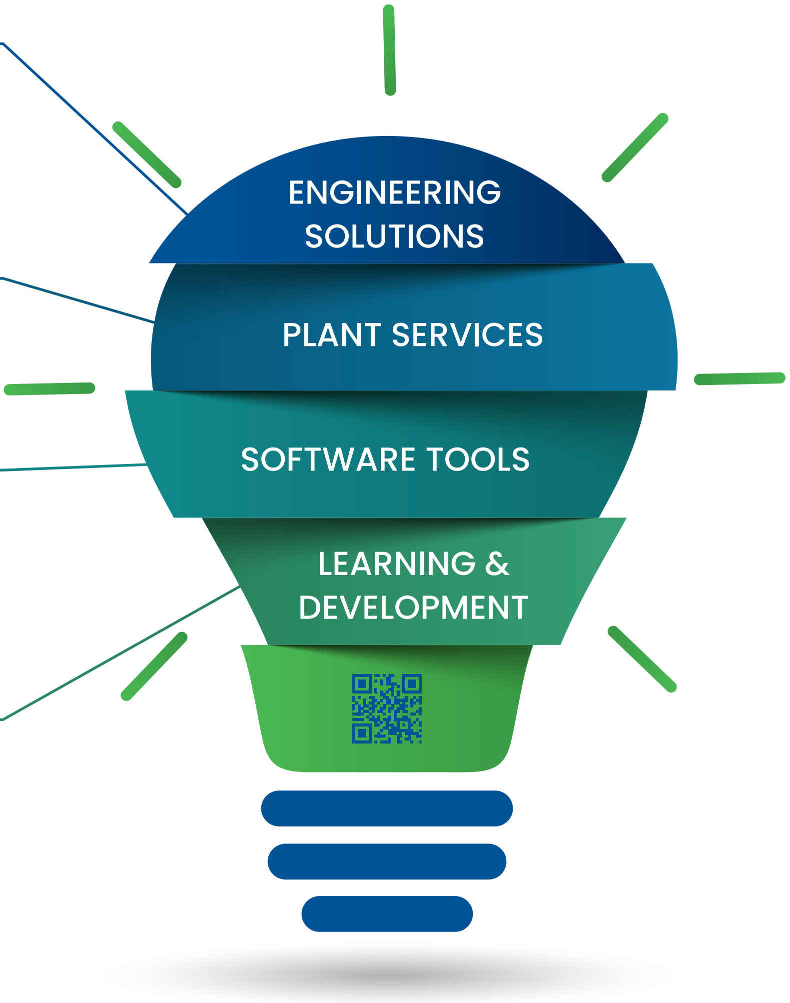
WHATEVER THE QUESTION, BECHT IS THE ANSWER.



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Technological challenges facing the current carbon market

Carbon capture technology could significantly reduce emissions. But what issues need to be addressed before these processes can be utilised?

Charles L Kimtantas and Joe Selby
Bechtel Energy Technologies and Solutions

As the world continues to grapple with the impacts of climate change, the need for innovative solutions to reduce carbon emissions has become increasingly pressing. One such solution that has gained significant attention in recent years is carbon capture technology, which holds the potential to significantly reduce emissions from industrial processes and power generation.

However, with new technologies and the application to new or different sources of carbon dioxide (CO_2) come questions about their readiness and feasibility. This article explores the current state of technology readiness for carbon capture and what challenges must still be addressed before widespread adoption can occur.

CO_2 and other greenhouse gases (GHG) accumulate in the atmosphere and act like a greenhouse to trap the sun's heat. Excessive GHG are causing the atmosphere to trap more heat (see **Figure 1**), and this can cause:

- The atmospheric temperature to increase, deserts to form, and natural ice sources to melt, thereby leading to increasing ocean levels and flooding of low-lying coastal areas of the world.
- An intensification of weather events such as hurricanes, tornadoes, thunderstorms, and rainstorms, and the resulting increase in risk to life and damage to property.

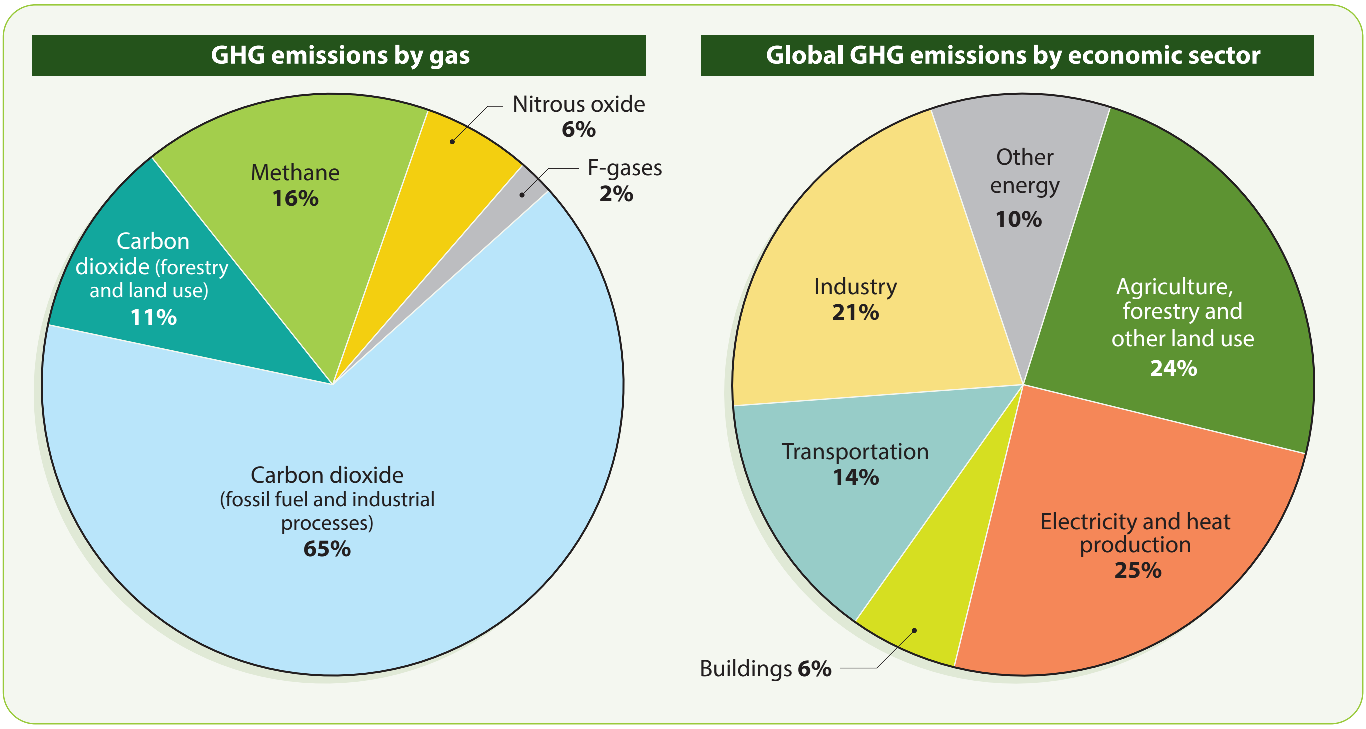
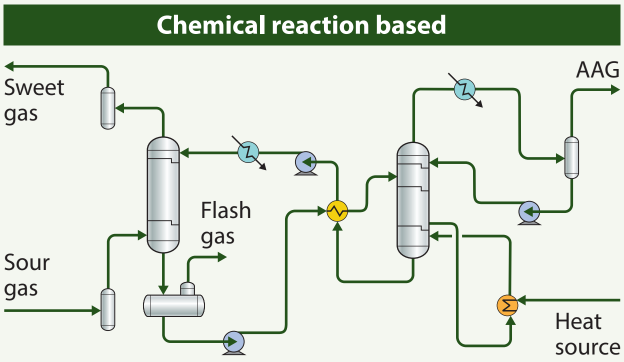
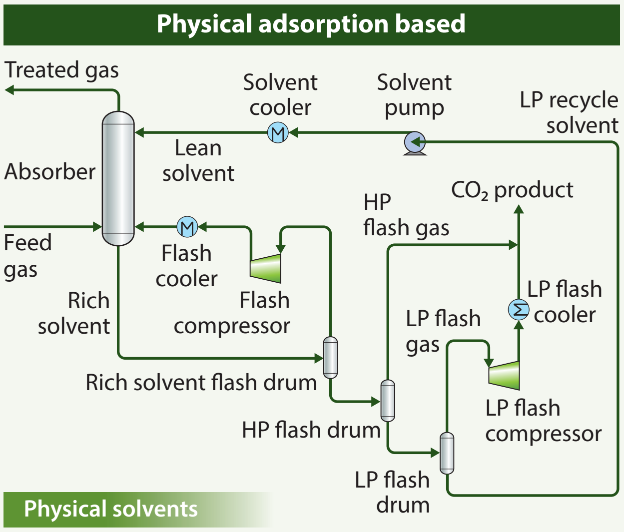


Figure 1 Total US greenhouse gas emissions by economic sector in 2021
Source: *Sources of Greenhouse Gas Emissions* (EPA 2021)





Amine types

Primary Amines:
- Monoethanolamine (MEA)
- 2-amino-2-methyl-1-propanol (AMP)
- Diglycolamine (DGA)

Secondary Amines:
- Diethanolamine (DEA)
- Methyldiethanolamine (MDEA)
- Diisopropanolamine (DIPA)

Tertiary Amines:
- Triethanolamine (TEA)

Cyclic Amines:
- Piperazine (PZ)
- Morpholine

Physical solvents
- Propylene carbonate (Fluor process)
- N-methyl-2-pyrrolidone (Purisol process)
- Dimethyl ethers of polyethylene glycol (Selexol)
- N-formyl-morpholine and N-acetylmorpholine (Morphysorb)
- Rectisol

Figure 2 Chemical reaction and physical adsorption-based carbon capture

CO_2 emission reduction targets

Scientists from around the world have determined target requirements to reduce the impact of CO_2 on the environment of the world, as listed below:
- "To keep global warming to no more than 1.5°C – as called for in the Paris Agreement – emissions need to be reduced by 45% by 2030 and reach net zero by 2050." (UN, 2022)
- "The United States has set a goal to reach 100% carbon pollution-free electricity by 2035, which can be achieved through multiple cost-effective pathways, each resulting in meaningful emissions reductions in this decade." (The White House, 2021)
- "The NDC (Nationally Determined Contribution) sets an economy-wide target for the US to reduce its net greenhouse gas (GHG) emissions by 50-52% below 2005 levels in 2030." (SDG Knowledge Hub, 2021)

Understanding carbon capture technology

Carbon capture is the removal of CO_2 from a stream, usually a vapour stream, by various technologies with the potential to recover the CO_2 in a usable form or to sequester the CO_2 for long-term storage. The primary CO_2 capture systems are categorised as:
- Solvent based
- Chemical reaction: amine, ammonia, sodium hydroxide (NaOH) or potassium hydroxide (KOH)
- Physical adsorption
- Solid adsorption
- Membrane
- Distillation – cryogenic or high pressure
- Solid generation – refinery coker

Solvent-based carbon capture

Solvent-based carbon capture technologies are divided into chemical reaction and physical solvent systems.

Chemical reaction-based systems employ a chemical to react with the CO_2. The reacted solvent is then regenerated, the CO_2 is released, and the regenerated solvent is reused.

Physical solvent-based systems use a solvent that can physically adsorb the CO_2. The rich solvent is then regenerated, typically with pressure reduction and heat, to release the CO_2, and the regenerated solvent is reused. A simplified flow diagram of the two systems and a list of the typically used solvents are presented in **Figure 2**.

Solid adsorption-based carbon capture

Solid adsorption carbon capture systems use a solid adsorbent to capture the CO_2 within the solid adsorbent. The solid adsorbent

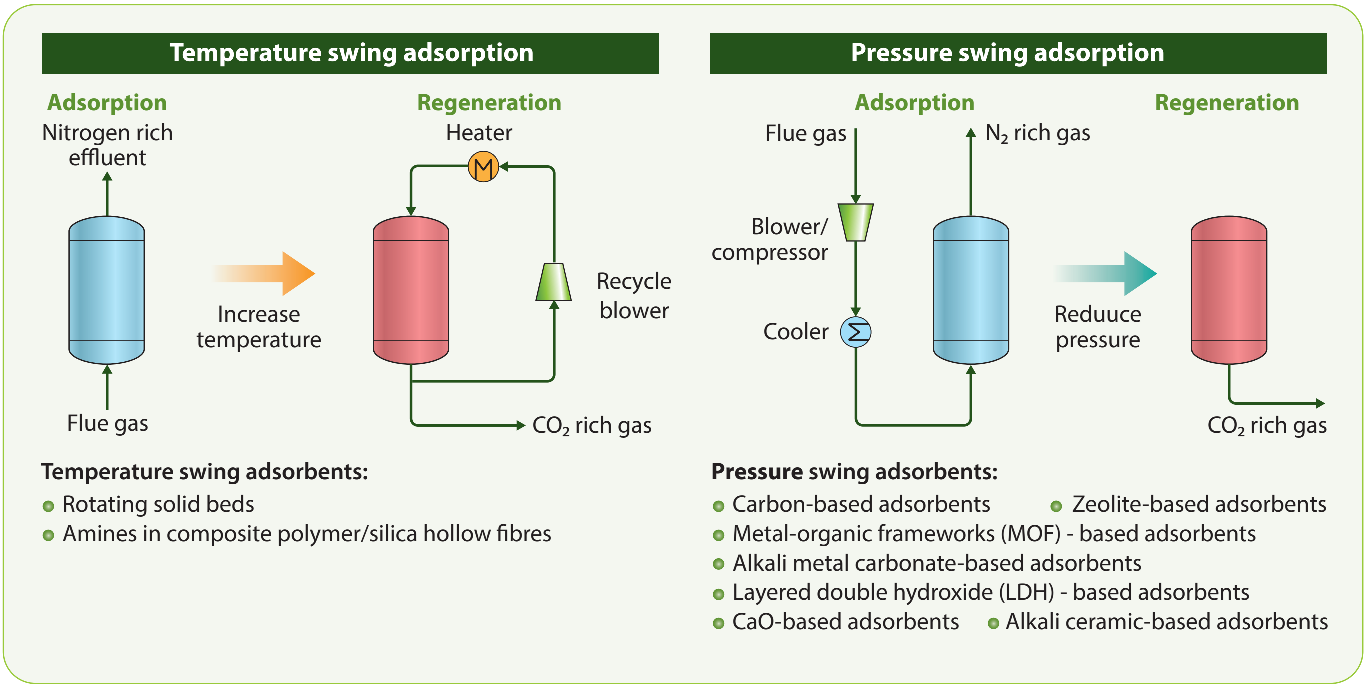


Figure 3 Temperature and pressure swing adsorption systems

contains many small pores that allow the CO_2 to accumulate in the adsorbent. Most solid adsorbent systems use multiple adsorbent beds that can be switched from adsorbing the CO_2 to regenerating the CO_2 out of the adsorbent. This regeneration can be done using a temperature or pressure change, depending on the type of adsorbent being used (see **Figure 3**).

Membrane-based carbon capture

Membrane-based carbon capture uses semi-permeable membranes to selectively separate the CO_2 from the other gases that are present. Depending on what the other gases are, the CO_2 may pass through the membrane, or the other gases might pass through the membrane, leaving the CO_2 behind. A wide variety of membranes are available, and a few of these

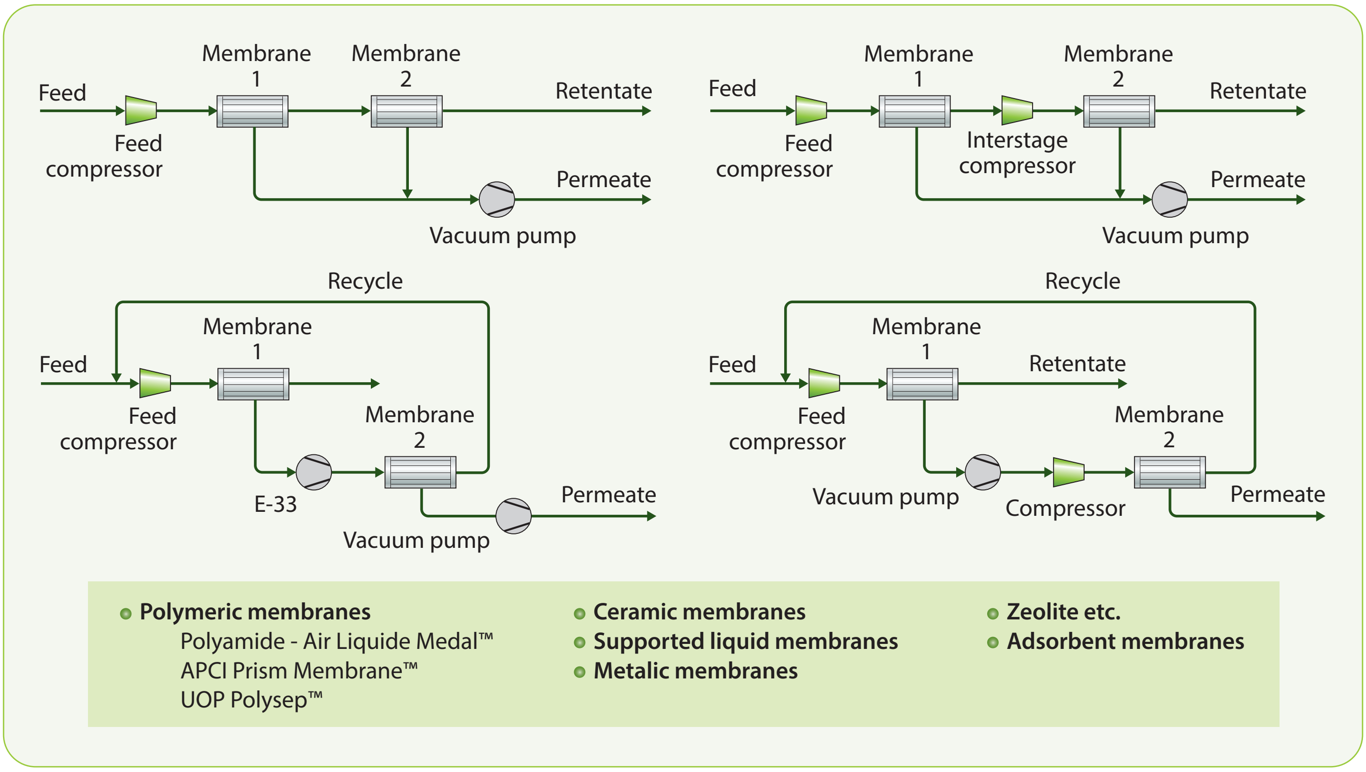


Figure 4 Types of membranes and four typical membrane configurations

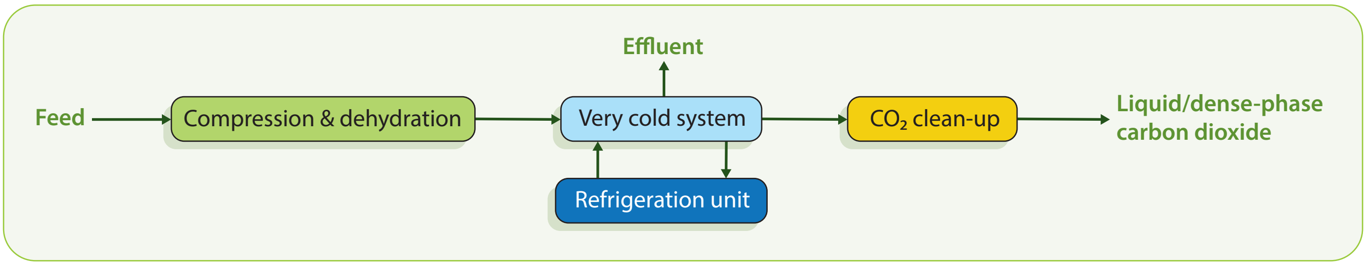


Figure 5 Cryogenic carbon capture

are listed in **Figure 4**, along with some typical membrane configurations used to maximise the CO_2 recovery and purity.

Distillation – cryogenic or high-pressure-based carbon capture

Distillation of CO_2 from various streams, such as flue gas from combustion power plants, process heaters, and combustion generator turbines, is accomplished using a combination of compression to medium to high pressures (500-3,000 psig) and cooling of the fluid to very low temperatures, possibly even to cryogenic temperatures near -50°F. A simplified block diagram of a system is presented in **Figure 5**.

> “As DAC technologies mature and sources of low-cost energy becomes available, DAC may become comparable to point source CO_2 capture”

Direct air capture

Rather than capturing higher concentrations of CO_2 directly from emission point sources, direct air capture (DAC) is an interesting option that can allow emitters of CO_2 to offset their emissions by removing the CO_2 using DAC. This may allow some facilities to continue to emit CO_2 emissions as regulations tighten by capturing an equivalent amount of CO_2 directly from the atmosphere. DAC today captures less than 1 Mt CO_2/year, but carbon drawdown from the atmosphere is considered to be critical to address the 1.5C outlined in the Paris agreement.

The liquid solvent DAC system consists of the contactor and the calciner. In the contactor, air is pushed or pulled through packing material. The packing material is soaked with a KOH solution, which reacts with CO_2 in the air to form potassium carbonate (K_2CO_3) in the solution. The solution then goes to a regeneration reactor, where anionic exchange with calcium hydroxide ($Ca(OH)_2$) produces calcium carbonate ($CaCO_3$) and regenerates the KOH solution. The regenerated solution is then pumped back to the contactors.

The solid DAC system with adsorption cycles can use temperature, pressure, humidity, or a combination of these factors to regenerate and saturate the sorbent. Temperature swing adsorption involves adsorbing CO_2 at a given temperature until the target capacity is reached and then regenerating the bed with heat (such as steam). Pressure swing adsorption uses elevated pressure to adsorb CO_2 and then reduces pressure to release it. These systems are fast, but have increased capital costs due to generating and handling pressurising gases. Vacuum swing adsorption adsorbs CO_2 at atmospheric pressure and then reduces pressure to release it. These systems reduce cost and hazards but require industrial vacuum use. Humidity or moisture swing adsorption favours the adsorption of water over CO_2 and regenerates the sorbent by introducing water to the system. These various approaches offer flexibility in controlling the regeneration and saturation phases and can be adapted to different environments and conditions.

As DAC continues to evolve, new technologies are being developed that do not fit neatly into the categories of solid or liquid systems. DAC is currently very energy intensive, which can impact the economics drastically. As DAC technologies mature and sources of low-cost energy becomes available, DAC may become comparable to point source CO_2 capture.

“There are currently 18 DAC plants operating worldwide, capturing almost 0.01 Mt CO_2/year, and a 1 Mt CO_2/year DAC plant is in advanced development in the United States. In the Net Zero Emissions by 2050 Scenario, direct air capture is scaled up to capture almost 60 Mt CO_2/year

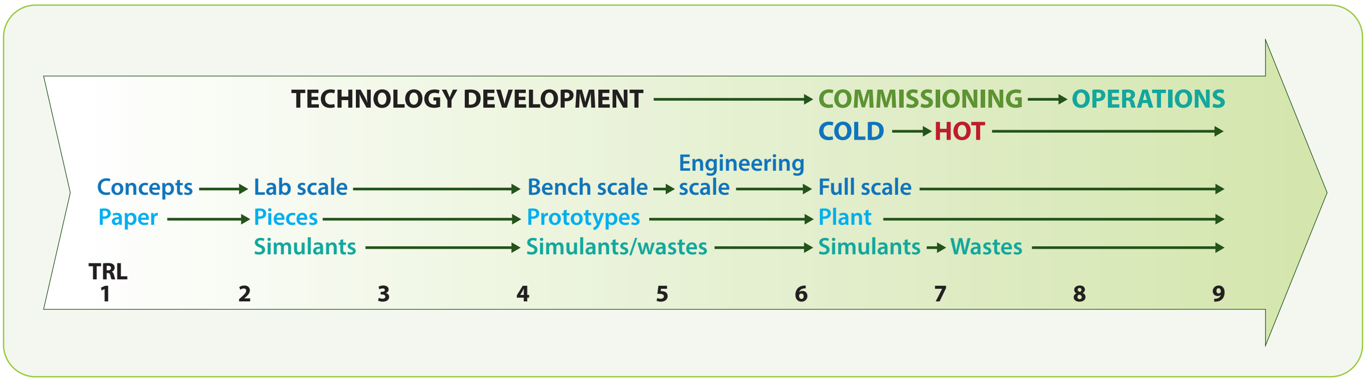


Figure 6 Technology Readiness Levels for different CCS technologies

by 2030. This level of deployment is within reach but will require several more large-scale demonstration plants to refine the technology and reduce capture costs." (IEA, 2023)

Assessing Technology Readiness

The phrase 'Technology Readiness Level' or 'TRL' is used to classify the suitability of a technology for implementation. The TRL scale ranges from 1 (basic principles observed) to 9 (total system used successfully in multiple project operations).

TRLs shown in **Figure 6** should be considered as only estimates for the technologies described, which are not fully commercialised (TRL<9). Figure 6 is our interpretation of the TRL criteria for the various carbon capture technologies (Global CCS Institute, 2021)

Economic considerations for carbon capture

Relative cost of CO_2 capture

The relative cost for CO_2 capture varies by industrial sector because of the CO_2 concentration of the targeted CO_2 source (see **Figure 7**). A range of relative costs are provided below for 12 different CO_2 sources. Hydrogen (SMR) high cost was selected as the base of 1.0 (100%).

CO_2 emission reduction efforts by the US government

- In August (2022), the President signed the Inflation Reduction Act (IRA) that included provisions related to taxes and credits to reduce carbon emissions. The IRA increased the current tax credit for CO_2 within Internal Revenue Code section 45Q and delineated between DAC and other capturing methods (The White House, 2022).
- In August 2022, the U.S. Department of Energy's (DOE) Office of Fossil Energy and Carbon Management (FECM) announced more than $31 million in funding for 10 projects to develop carbon capture technologies capable of capturing at least 95% of CO_2 (Jenkins, 2022).

Industrial sector relative costs

SEC	Low concentration	Low cost	High cost
1	Direct air capture	200%	563%
2	Power generation	63%	175%
3	Cement	75%	163%
4	Iron & steel	50%	150%
	High concentration		
6	Hydrogen (SMR)	63%	100%
7	Ethylene oxide	31%	44%
8	Bioethanol	31%	44%
9	Ammonia	31%	44%
10	Natural gas processing	31%	44%

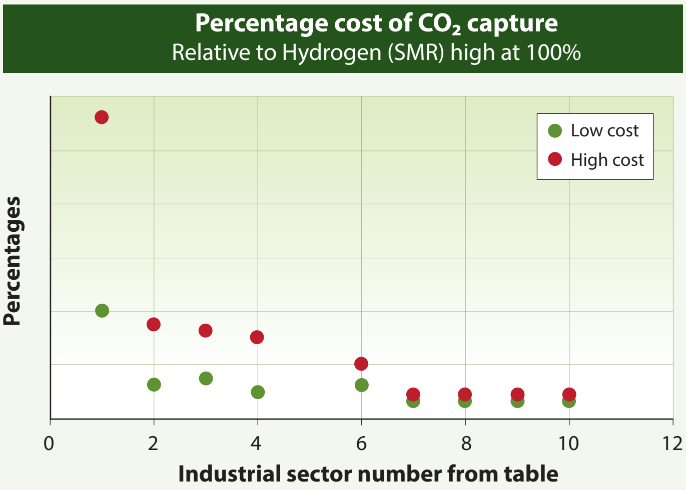


Figure 7 Relative cost for carbon capture by sector

Source: 2019 IEA data (IEA, 2020) – some have adjusted to incorporate Bechtel's internal opinions

Technologies	TRL 2023	Comments
Amine solvents		
Pre-combustion using generic amines/blends	9	LNG (100% CO_2 capture); RetroFit SMR (65% CO_2 capture); refining (CO_2 capture varies); natural gas (CO_2 capture varies)
Shell Cansolv	8-9	
Fluor Solvent	9	Pre-combustion
MHI KS-1	8-9	
Aker Solutions	8-9	Pre-/post-combustion
Post-combustion using generic MEA	8-9	Generic MEA is the standard by which carbon capture is measured in the power industry
Ammonia solvents		
Chilled ammonia process	7	Post-combustion such as power plants
AC-ABC	6/4	Pre-/post-combustion – pilot plant & demo conceptual studies equipment
Physical solvents		
Selexol	9	Pre-combustion
Rectisol	9	Pre-combustion
Sulfinol	9	Pre-combustion
Other solvent technologies		
Benfield process	9	Pre-/post-combustion
Sterically hindered amines	6-8	Demo to commercial
Amine/non-amine blended solvent	5	Pilot used at Drax (UK's largest power station)
ION Clean Energy solvent	7	Six-month demo plant operation
Phase change solvents	5-6	Demo plant in Dunkirk under construction – steel mill CO_2 capture
Amino acid-based solvent – precipating solvents	4-5	Lab tests to conceptual studies
Encapsulated solvents	2-3	Lab tests
Ionic liquids	2-3	Lab tests
Direct air capture	7	
Membrane		
Natural gas processing separation membranes	9	
Polymeric membranes	4-8	3 FEEDs with demo in Wyoming – feed studies for large pilots (MTR & Univ of Texas)
Electrochemical membrane integrated with MCFCs	7	Large pilots
Polymeric membranes/cryogenic hybrid	6	Pilot studies
Polymeric membranes solvent hybrid	4	Conceptual studies
SINTEF membranes	6-7	Unclear as SINTEF is a non-commercial research group
Room temperature ionic liquid (RTIL) membranes	2	R&D only
Solid adsorbent/filter		
Direct air capture	7	
Metal-organic framework (MOF) technology	2-4	Lab testing, early design/development
Solid looping		
Calcium looping (CaL)	6-7	Commercial-scale feasibility/cost studies
Chemical looping combustion	5-6	Pilot tests
Other technologies		
Engineered enzymes	7	Pilot/demo at pulp plant
Algae/bacteria	3	Accelergy's TerraSync

Table 1 Carbon capture Technology Readiness Levels

- In 2021, the US re-joined the Paris Agreement.
- In 2022, two US legislative actions "in combination with past actions, are projected to drive 2030 economy wide GHG emissions to 40% below 2005 levels. The clean energy provisions of these two laws, are estimated to reduce emissions by approximately 1,000 MMT CO_2e in 2030." (Approximately 15% reduction) (US Dept of Energy, 2022)

Carbon capture impact on society

- Carbon capture will require an unprecedented amount of new energy investment.
- Fossil fuel infrastructure built over centuries needs to be replaced within the next few decades by clean energy alternatives. The US will need to:
    - Build thousands of square miles of wind and solar farms
    - Deploy battery storage to keep power flowing even on calm, cloudy days
    - Build next-generation nuclear power plants
    - Double the country's transmission line capacity.
- The 'Not In My Back Yard' (NIMBY) groups are using the environmental laws to delay or get cancelled new green projects (Stapp, 2022):
    - Windmills off Cape Cod
    - Geothermal facility in Nevada
    - Largest solar farm in America.
- Increasing the growth rate for electrical generation will be required.
- "Increasing the growth rate of electricity transmission will not happen without comprehensive legislation on permitting reform. Moreover, the magnitude of the task to transform the U.S. economy can only be fully understood in the context of the land required for green energy projects. Consider that researchers say wind and solar expansion would require up to 590,000 square kilometres of land. That amount of land is larger than New England plus Illinois, Indiana, and Ohio. That is big. It will not happen." (Rogan, 2022)
- Electrification of transport and industrial process heat and residential heating.

Public and workplace health and safety

There will be possible impacts on public health and the workplace due to emissions generated by new technologies. These new emissions will need to be evaluated and possibly mitigated to minimise any new health or safety challenges to the public or private sectors.

Considerations after capturing carbon

After the carbon is captured, it needs to be disposed of in an environmentally friendly manner. This will require using the CO_2 to produce hydrocarbons, such as propane, gasoline, diesel, and aviation fuel, to replace existing crude oil-based fuels; for enhanced oil recovery; for long-term below-ground storage after clean-up and compression; or for conversion to environmentally neutral materials, such as elemental carbon, calcium carbonate for road foundations, or other neutral chemical compounds.

Conclusion

There is a large number and variety of carbon capture technologies. Some of these, like generic amines and blended generic amines, have been in use for decades. These technologies are well-proven, with hundreds of commercial plants operating for decades. These have been primarily for pre-combustion applications such as natural gas treating for CO_2 and H_2S removal to meet fundamental specifications, including LNG, pipeline, household natural gas appliances, refinery process heater fuel, and electric power generation.

With the need to reduce the amount of CO_2 that is going into the atmosphere, many new and creative technologies are being developed and tested. As these are proven to be cost-effective, they will move into the arena of commercial carbon capture. These will require site analysis, engineering, and economic studies to determine which technology will be the best for a specific location and application.

VIEW REFERENCES

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Paving the way to low-carbon propylene from the FCC unit

With the demand for propylene expected to increase in the petrochemical industry, new technology is required to process it and reduce CO_2 emissions

Bani H Cipriano, Clint Cooper and Stefan Brandt
W. R. Grace & Co

Propylene plays a critical role in the petrochemical industry. Approximately 70% of propylene produced is used in the manufacture of polypropylene, a widely used polymer in durable goods and packaging, among other uses. The demand for propylene is projected to increase by 36% through 2030 (or 4% annualised) (Wood Mackenzie, 2022). One challenge associated with meeting the increased demand for propylene is the CO_2 emitted during its production. The production of propylene and ethylene is estimated to generate 250-300 million metric tons (MTs) of CO_2 per year. Since the annual demand for propylene and ethylene combined is approximately 295 million MTs per year, the production of ethylene or propylene generates, on average, approximately 1 MT of CO_2 per MT of ethylene or propylene (Dziedziak & Murphy, 2023).

Jurisdictions are continuing to implement CO_2 taxation or increase the magnitude of their CO_2 tax with the aim to reduce emissions. Countries in the Asia Pacific, such as Singapore, are implementing new carbon taxes (Gupta, Tan, Ho, & Hui, 2023). The carbon price in Europe has recently reached values of ~€100/MT (Twidale, Abnett, & Chestney, 2023). Against this backdrop, petrochemical feedstock producers will be challenged to reduce the carbon intensity of their production processes.

Propylene is made via different processes; the three most important are steam cracking, fluid catalytic cracking (FCC), and propane dehydrogenation (PDH). This article compares the carbon emissions of these processes and further examines the carbon intensity of propylene from the FCC unit. ZSM-5 technology is discussed, including its unique ability to increase the yield of propylene from the FCC without increasing CO_2 emissions. Finally, a life cycle analysis (LCA) for producing propylene from the FCC is presented, showing how Scope 3 emissions change when a refinery shifts operation between transportation fuels and propylene modes.

Carbon intensity of different processes

The process to produce propylene (and ethylene) involves either cracking of larger molecules (naphtha, VGO, resid, ethane, propane, butane) in the case of steam cracking and FCC or dehydrogenation of propane in the case of PDH. These reactions are endothermic and require significant amounts of energy. **Table 1** shows ranges for the carbon intensity of different processes. Note that in both steam cracking and FCC, propylene is one of several products produced, so the emissions are expressed as MT of CO_2 per MT of total product produced.

	CO_2/product, MT/MT	Reaction temperature,°C
Refinery/FCC (Concawe, 2022)	0.3-0.4	550
PDH (Environmental Protection Agency)	1.2-1.7	630
Steam cracker (S&P Global, n.d.)	1.0-1.8	840

Table 1 CO_2 emissions generated per unit of product produced and typical reaction temperature for several processes

Operational move	Effect on propylene production	Effect on CO_2 emissions
Increase ZSM-5 additive rate	▲	⇔
Reduce riser severity	▼	▼
Reduce C/O (higher Feed T)	▼	▼
Reduce gasoline/ LCO recycle	▼	▼

Table 2 Summary of the effect of different FCC unit operating variables on CO_2 emissions and propylene yield

Table 1 shows that refinery-based propylene has the lowest carbon intensity. The main reason is that, as a catalytic process, the FCC unit typically operates at the lowest temperature and is a more energy-efficient process for the production of olefins. Further, FCC is not equilibrium-limited: while the dehydrogenation of propane in the PDH process takes place in the presence of a catalyst, the reverse reaction is also possible, and higher reaction temperatures are required to drive the equilibrium towards propylene (Stitt, Jackson, & King, 1999). As a result, the FCC has the lowest reaction temperature. CO_2 emissions generated in propylene production processes stem from heating feedstocks to the required reaction temperatures: the higher the temperature, the larger the energy requirement and CO_2 emissions generated. Some of this energy is provided by burning coke produced in these processes (in the case of the FCC unit, most of the energy is supplied this way; more on this below).

The implication of Table 1 is striking. If lowering emissions were the sole metric in determining the preferred method for producing propylene, it would be preferred to source propylene from the refinery. In practice, it is not so simple since the refinery and the FCC unit are traditionally geared towards producing fuels.

FCC chemistry: Coke generation and propylene production

The FCC unit requires the production and combustion of coke to generate the heat required to vaporise the feedstock and drive the endothermic cracking reactions taking place in the riser. The combustion of this coke in the FCC unit accounts for approximately 15-20% of the CO_2 emissions from the refinery (Gudde, Larive, & Yugo, 2019) (Jing, et al., 2020).

The coke produced in the FCC unit stems from several contributors:

❶ Hydrogen redistribution reactions in the catalytic cracking
❷ Cracking of heavy feed components
❸ Poor feed vaporisation
❹ Dehydrogenation reactions catalysed by contaminant metals in the feed
❺ Unstripped hydrocarbons entrained in the catalyst entering the regenerator.

The coke yield directly contributes to the Scope 1, or direct, CO_2 emissions from the FCC unit. Factors that increase the coke yield (for example, operating at a higher reaction temperature) will increase emissions from the FCC unit. Reducing FCC unit severity (lowering the riser temperature), reducing the catalyst-to-oil ratio (C/O) (for example, by increasing the feed temperature and reducing catalyst cooler duty), or reducing slurry or light cycle oil (LCO) recycle rates will all reduce CO_2 emissions from the FCC unit, accomplishing the objective of reduced Scope 1 CO_2 emissions. However, these moves typically lead to reduced conversion and increased slurry from the FCC unit. While it may be desirable to operate the FCC unit at lower direct emissions by decreasing the coke yield, this is generally not economically attractive.

The yield of propylene from the FCC unit can be increased by:

❶ Increasing reaction temperature
❷ Increasing the C/O ratio
❸ Decreasing the hydrocarbon partial pressure (introducing additional steam into the process)
❹ Improving feed quality,
❺ Reformulating the catalyst to drive propylene yield higher
❻ The use of ZSM-5 technology.

Options 1-3 will either increase coke yield or require additional energy, thereby increasing emissions from the process, whereas ZSM-5 technology usage has a neutral effect on CO_2 emissions (the catalyst itself can be reformulated to minimise changes in coke yields). The effect of changing operational variables and the impact on CO_2 emissions and propylene production is shown in **Table 2**.

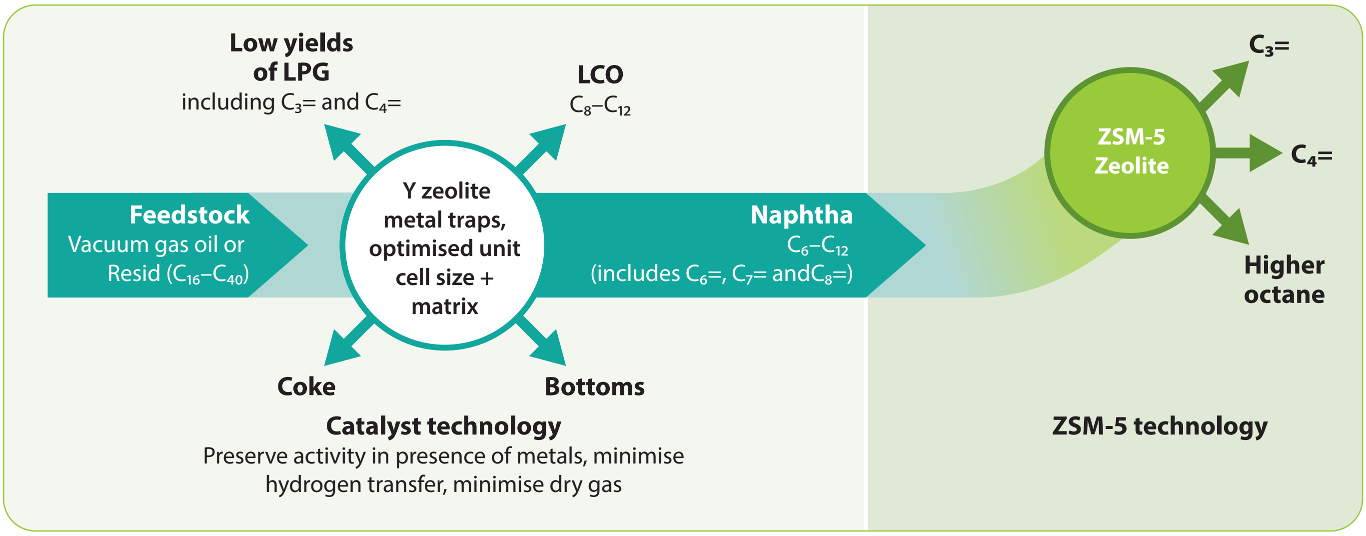

Figure 1 Roles of Y-zeolite-based catalyst and ZSM-5 technology in the generation of propylene and butylene

ZSM-5 technology is key to increasing propylene yield from the FCC. This shape-selective zeolite cracks gasoline-range molecules predominantly into LPG olefins (Dwyer & Degnan, 1993). In general, to maximise propylene and FCC gasoline RON, the preferred base catalyst generates and preserves the maximum yield of gasoline-range olefins so these can be further cracked by the ZSM-5 technology into propylene. The concept is illustrated in **Figure 1**, showing the catalytic approach to maximise LPG olefins from the FCC.

The use of ZSM-5 has two key advantages over operational parameters to increase the yield of propylene from the FCC:

➊ It has no effects on the coke yield in the FCC, so it has a negligible effect on process CO_2 emissions

➋ It has an outsized impact on propylene yields relative to changing operational parameters.

This last point is exemplified by the data in **Figure 2**. For this comparison between a base catalyst with and without a high-activity ZSM-5 additive, the propylene yield is observed to increase ~2 wt% on a fresh feed basis (ff) when the riser temperature is increased by ~20°C, whereas the use of only 2 wt% ZSM-5 additive increases the C_3= yield by nearly this amount at a constant temperature.

Generally, operational shifts that reduce CO_2 emissions from the FCC unit, accomplishing the objective of reduced Scope 1 CO_2 emissions, also reduce the production of LPG olefins from the FCC unit. To regain the lost LPG olefins from these operating moves, ZSM-5 additive rates could be increased until the desired LPG production rates are met. **Figure 3** depicts a commercial example where the adaptability of the FCC was exploited to reduce the riser outlet temperature (ROT) while recovering the valuable C_3= yield using ZSM-5 technology (Brandt, 2010). As shown in Figure 3, the ROT in this commercial example was reduced by ~25°C, which resulted in a decrease in Scope 1 emissions of approximately 35,000 MT of CO_2/year while maintaining the same propylene yield. This example highlights the flexibility of the FCC unit to achieve different yield and CO_2 emission profiles.

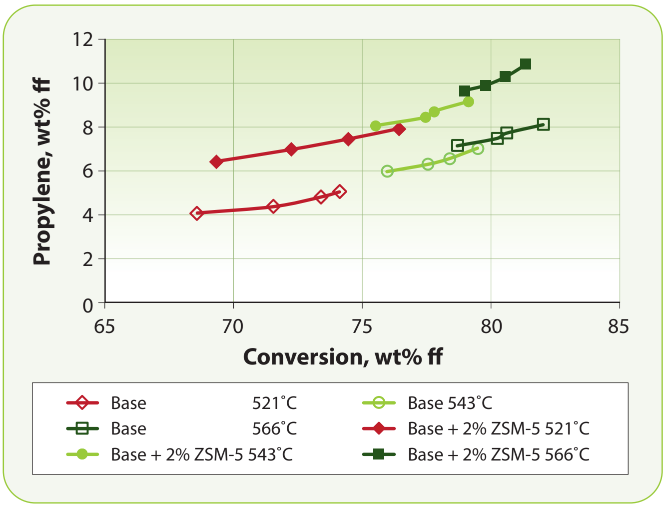

Figure 2 Davison Circulating Riser (DCR) data comparing propylene yields between a base catalyst (open symbols) and the same base catalyst + 2 wt% of a high-activity ZSM-5 additive (filled symbols) at various temperatures between 521°C and 565°C

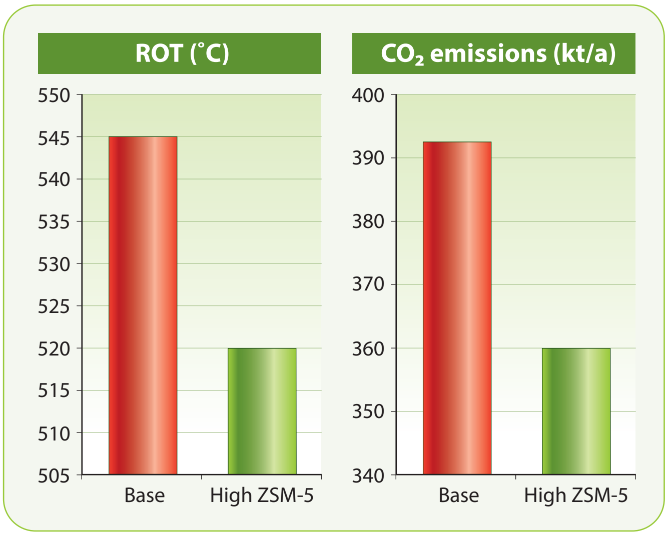

Figure 3 Commercial FCC unit data comparing standard operation at high ROT (red) with a case for low ROT, high ZSM-5 technology (green) *Adapted from (Brandt, 2010)*

ZSM-5 additives are available from many suppliers but range widely in activity. Applications targeting the highest propylene yields benefit greatly from ZSM-5 additives with corresponding activity levels. Higher-activity ZSM-5 additives require lower additive usage, minimising the dilution of base catalyst activity. This affords the refiner with the flexibility to employ catalysts with low hydrogen transfer, boosting propylene yield even further.

W. R. Grace has a long track record in ZSM-5 innovation: the high-activity additives currently in our portfolio include OlefinsUltra MZ technology and the latest Zavanti additive, intended for applications with the highest C_3= yields (Hager, Nate, DeVaney, Payne, Amalraj, & Cipriano, 2023) (Serban, Ekeocha, Singh, & Cipriano, 2021).

LCA: Comparison of Scope 3 emissions from the FCC unit

Grace recently conducted an LCA to better understand how the use of ZSM-5 additive affects Scope 3 CO_2 emissions from the FCC unit. A calculator was developed to quantify the change in emissions that results when an FCC unit focused on gasoline production uses ZSM-5 technology to produce propylene. This comparison is made at constant operating conditions.

Several assumptions were made in this LCA, including:

- The carbon intensity of FCC catalyst and ZSM-5 additive manufacturing is the same. When additive is used, the addition rate of the catalyst decreases by the amount of additive used.
- Propylene generated by the FCC is routed to petrochemical plants for the production of polypropylene. The assumption used in this LCA for emissions generated during the polymerisation of propylene is based on the work of Alsabri, et al. (Alsabri, Tahir, & Al-Ghamdi, 2021). Also, we assume there is capacity in the FCC unit propylene purification train to handle additional propylene produced.
- In addition to generating propylene, the use of ZSM-5 generates other LPG olefins (butenes) and saturates, as well as a small amount of ethylene. We assume all of these components are combusted as fuels since butenes are alkylated and added into the gasoline blending pool, and propane, butane and ethylene are burned as fuel. The assumption used in the LCA for emissions generated in the combustion of fuels is 8.887 kg CO_2 per gallon of fuel consumed (Environmental Protection Agency, n.d.).
- Globally, 19% of all plastics were incinerated in 2019, so it is assumed that eventually the plastics derived from ZSM-5 usage are incinerated at this rate (OECD, n.d.). An estimated emissions rate of ~3 kg CO_2eq per kg of plastic incinerated is assumed for this LCA, in line with the estimates of others (GAIA, n.d.).

Utilising ZSM-5 in the FCC unit has the following primary effects on Scope 3 CO_2 emissions:

- More CO_2 generated from increased rates in petrochemical plants to produce polypropylene
- More CO_2 generated from the combustion of propane, butane, and ethylene
- More CO_2 generated from plastics incineration
- Less CO_2 generated from the combustion of FCC gasoline in vehicles. This is a result of gasoline being converted by ZSM-5 into propylene and other lighter molecules.

The results from the LCA indicate that for a 50 kbpd FCC unit, the use of ZSM-5 additive to convert 1 wt%ff of gasoline-range material translates into a 4,500 MT/year reduction in Scope 3 CO_2 emissions (this is roughly equivalent to the emissions produced by 1,000 passenger vehicles in a year) (Environmental Protection Agency, n.d.). These effects are summarised in **Figure 4**.

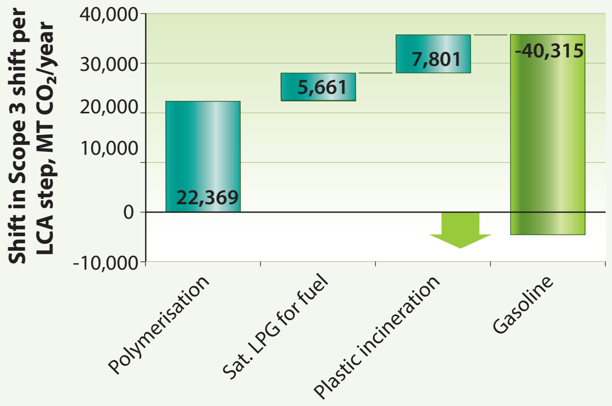

Figure 4 Results of LCA for changes in Scope 3 emissions from an FCC unit when enough ZSM-5 is used to reduce gasoline by 1 wt%ff (assumed throughput of the FCC unit is 50 kbpd). The green arrow indicates that the net effect of ZSM-5 usage is to decrease Scope 3 emissions

Outlook and conclusion

Propylene from the FCC unit features the lowest carbon intensity among the main propylene production routes. The FCC unit also has the most favourable cost position for propylene (Hager, Nate, DeVaney, Payne, Amalraj, & Cipriano, 2023). While the FCC unit can yield significant propylene, it has traditionally targeted maximum gasoline. This is not surprising when considering the historical growth in transportation fuel demand. However, once transportation fuel demand peaks, Grace predicts more FCC units will shift their focus towards propylene. The improved cost position, lower carbon intensity, and growth in demand for propylene will provide tailwinds to refiners who adopt a propylene strategy to maximise profitability in the long term.

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Circular economy strategies for petrochemical sustainability

Sustainability is a journey for the industry, not a destination, and the circular economy is one of the tools to make that journey possible

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In an era where environmental concerns are at the forefront of global discourse, industries are being challenged to rethink their practices and adopt more sustainable approaches. The petrochemical industry, a crucial player in global economic growth, is under particular scrutiny due to its significant environmental impact. As we strive for a more sustainable future, the concept of a circular economy has emerged as a promising solution. This article delves into the world of petrochemicals, unpacks the circular economy framework, and explores how circular economy strategies can revolutionise petrochemical sustainability.

> **“The petrochemical industry’s linear product life-cycle model, characterised by extraction, production, consumption, and disposal, is riddled with environmental consequences”**

Petrochemicals, derived from fossil fuels, play an indispensable role in modern society. They are the building blocks of countless products, from plastics and packaging materials to pharmaceuticals and textiles. However, the petrochemical industry’s linear product life-cycle model, characterised by extraction, production, consumption, and disposal, is riddled with environmental consequences. The greenhouse gas emissions, resource depletion, and plastic waste crisis associated with this linear approach have prompted a re-evaluation of the industry’s practices.

To understand the urgency of adopting circular economy strategies in the petrochemical industry, it is crucial to dissect the emission landscape. This sub-sector’s emissions span a wide range of products, from fertilisers to synthetic fibres, with plastics at the forefront. Additionally, emissions arising from oil refining, which is intricately linked to the petrochemical process, must be considered. Oil refining serves as the precursor to various petrochemical processes and contributes significantly to emissions.

When both the emissions from oil refining and chemical plants are combined, their cumulative impact is staggering. This combined category accounts for approximately 30% of total industrial emissions, a substantial share. To put it in a global perspective, these emissions amount to more than 9% of the total greenhouse gas emissions, showcasing the magnitude of the challenge at hand.

Unveiling the circular economy

The traditional linear product life-cycle model in the chemical and petrochemical industry has undeniably led to environmental degradation, resource depletion, and a plastic waste crisis. This model is no longer tenable, especially when the emissions associated with this industry are both significant and avoidable. Enter the circular economy, a framework that seeks to disrupt the linear status quo and bring about sustainable transformation.

The circular economy presents an alternative paradigm. At its core, this concept envisions a system where resources are used, reused, and regenerated in a closed loop, minimising waste and environmental impact. Instead of the traditional 'take, make, dispose' model, a circular economy promotes a 'reduce, reuse, recycle' ethos.

In the context of the petrochemical industry, a circular economy entails transforming the linear product life cycle into a circular one. This means designing products for longevity, ease of repair, and eventual disassembly to recover valuable materials. It also involves embracing renewable feedstocks, such as bioplastics derived from plant materials, to reduce dependence on fossil fuels.

Extended producer responsibility (EPR)

One of the foundational principles of a circular economy is extended producer responsibility. This concept mandates that producers take responsibility for the entire life-cycle of their products, including their eventual disposal. The goal is to internalise the costs of environmental management within the production process, incentivising more sustainable practices (see **Figure 1**).

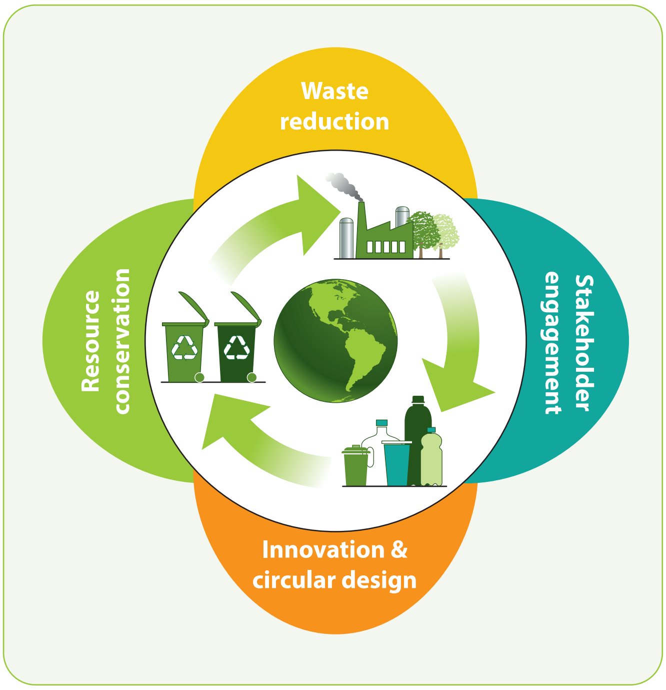

Figure 1 Benefits of extended producer responsibility

In the petrochemical realm, this translates to manufacturers designing products that can be easily dismantled and recycled at the end of their useful life. This strategy not only reduces waste but also drives innovation in product design and materials selection.

Producers are tasked with establishing efficient collection and recycling infrastructure for their products. In the petrochemical sector, this involves creating systems that enable the proper collection and processing of plastics, chemicals, and other products. This infrastructure may include dedicated collection points, partnerships with recycling facilities, and innovative technologies for material recovery.

EPR often involves financial mechanisms that compel producers to cover the costs associated with the collection, recycling, and proper disposal of their products. This financial responsibility can drive producers to design products with fewer hazardous materials, reduced environmental impact, and increased recyclability, thereby minimising the costs associated with end-of-life management.

To align with EPR principles, producers are encouraged to adopt sustainable materials in their products. In the petrochemical industry, this might involve transitioning from conventional plastics derived from fossil fuels to biodegradable plastics or bio-based feedstocks. Such a shift not only reduces the environmental impact of products but also contributes to the development of a circular economy.

By encouraging producers to design products with longevity and recyclability in mind, EPR helps conserve valuable resources. The petrochemical industry relies heavily on fossil fuels and raw materials; EPR-driven practices can lead to reduced consumption of these resources by promoting recycling and material recovery.

EPR's emphasis on product recovery and recycling contributes to a significant reduction in waste generation. With proper collection and recycling infrastructure in place, fewer products end up in landfills or incineration facilities, reducing the environmental burden associated with waste disposal.

EPR stimulates innovation in product design and manufacturing processes. Producers are incentivised to develop products that are not only environmentally responsible but also economically viable. This drive toward circular design can lead to the creation of new markets and business models centred around resource efficiency and sustainability.

EPR encourages collaboration between industry, government, and consumers. It

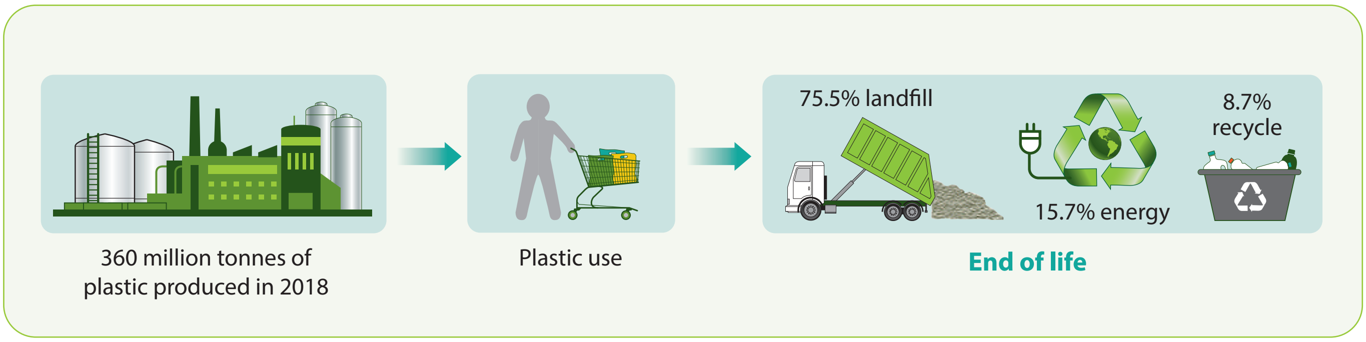

Figure 2 Life cycle of plastics (according to US EPA data for 2018)

fosters a sense of shared responsibility for environmental stewardship and creates a platform for dialogue and partnership among stakeholders. This collaboration can lead to more effective policies, streamlined waste management systems, and increased public awareness.

Plastic recycling and upcycling

Plastic waste has emerged as a significant environmental challenge, necessitating innovative solutions to minimise its impact. The manufacturing of plastic has risen with a yearly expansion of 8.4% since 1950. By 2018, the yearly plastic production had reached 360 million tons, and it is projected to escalate to 500 million tons by 2025 (TCGR report). Research into various choices for handling plastic waste indicated that the majority of discarded plastic waste is managed by depositing it in landfills. As per data provided by the US Environmental Protection Agency (EPA), in 2018, 75.5% of all generated plastic waste was disposed of in landfills, 15.7% was used for energy retrieval, and only 8.7% of plastic underwent recycling (US; EPA, 2021) (see **Figure 2**). This underscores the notably high proportion of plastics that are directed to landfills. However, the circular economy offers a glimmer of hope through advanced recycling techniques. Innovations like chemical recycling break down plastic polymers into their constituent monomers, allowing them to be reprocessed into new plastics with virgin-like quality. Additionally, upcycling methods can transform plastic waste into higher-value products, such as textiles or construction materials, giving discarded plastics a new lease of life.

Advanced recycling technologies, such as chemical and mechanical recycling, offer promising avenues to tackle plastic waste and enable the recovery of valuable materials for integration into new product life cycles. These technologies play a vital role in promoting a circular economy in the petrochemical industry.

Chemical recycling is a process that involves breaking down plastic waste into its molecular components through various methods, such as pyrolysis, gasification, hydrogenolysis, depolymerisation, and liquefaction (see **Figure 3**). Pyrolysis, gasification, hydrogenolysis, and hydrothermal treatment are thermochemical methods to convert plastic wastes into naphtha-like feedstocks for the production of petrochemicals. The use of catalysts in these methods might give some control over the product distribution and process conditions. Depolymerisation involves the conversion of complex polymers back into their monomeric units, which can then be used as building blocks for the production of new plastics or

Figure 3 Plastic recycling methods

other chemical products. Liquefaction, on the other hand, uses heat and solvents to transform plastic waste into a liquid form that can be further processed into valuable materials.

Chemical recycling offers several advantages over traditional mechanical recycling. It allows for the treatment of mixed or contaminated plastic waste, which is challenging to process through mechanical recycling.

Mechanical recycling typically includes sorting, shredding, and reprocessing plastic waste into granules or pellets, which can be used as feedstocks for various applications. This process is particularly effective for plastics that have not undergone significant degradation and contamination.

While mechanical recycling has been widely adopted in the industry, it has limitations. The process is often restricted to certain plastic types and requires careful sorting and separation of different polymers to maintain product quality. Mechanical recycling also faces challenges when dealing with heavily contaminated or degraded plastics, leading to a reduction in the quality of the recycled materials.

The implementation of advanced recycling technologies requires collaboration among various stakeholders. Petrochemical companies, waste management entities, and recycling facilities need to invest in research and development to scale up these technologies and optimise their processes. Government support through policies and regulations can incentivise the adoption of advanced recycling technologies and promote the creation of a robust circular economy for plastics.

By harnessing chemical and mechanical recycling technologies, the petrochemical industry can recover valuable materials from plastic waste and integrate them into new product life cycles. These technologies not only contribute to waste reduction but also reduce reliance on virgin fossil fuel feedstocks, promoting resource efficiency and environmental sustainability. Embracing advanced recycling technologies enables the petrochemical industry to be at the forefront of the circular economy movement, driving innovation, creating new business opportunities, and fostering a sustainable future.

Carbon capture and utilisation (CCU)

Addressing the carbon footprint of the petrochemical industry is paramount for its sustainability. Circular economy strategies introduce the concept of carbon capture and utilisation. The petrochemical industry is a substantial contributor to CO_2 emissions, often originating from fossil fuel combustion and industrial processes. Rather than releasing this CO_2 into the atmosphere, innovative technologies are being developed to capture and utilise it as a feedstock. Waste CO_2, when combined with renewable energy sources, can be transformed into a range of valuable products, thereby closing the carbon loop and promoting circularity.

Synthesising alternative fuels

One of the most promising applications of waste CO_2 lies in the synthesis of alternative fuels. CO_2 can be chemically converted into hydrocarbons through processes like Fischer-Tropsch synthesis. By using renewable energy sources such as solar or wind power, these hydrocarbons can be generated in a carbon-neutral or even carbon-negative manner.

Synthetic hydrocarbons produced from waste CO_2 can serve as clean and sustainable alternatives to conventional fossil fuels. These fuels can be seamlessly integrated into existing infrastructure and used in transportation, aviation, and other sectors that rely heavily on fossil fuels. There are several ongoing researches, projects, and investments in the synthesis of alternative fuels such as dimethyl ether (DME), synthetic natural gas (SNG), and sustainable aviation fuel (SAF) using CO_2 as a feedstock. The development of innovative catalysts and reactors is the key factor for these processes.

The process of converting waste CO_2 into alternative fuels involves several key steps:

❶ **CO_2 capture:** Industrial emissions containing CO_2 are captured using innovative technologies such as absorption, adsorption, or membrane separation. Material development plays an important role in CO_2 capture. This step prevents the release of CO_2 into the atmosphere.

❷ **Hydrogen production:** Green hydrogen is a pivotal element in this process. Electrolysis, powered by renewable energy sources such as solar or wind, generates hydrogen from water. Green hydrogen not only serves as a reducing agent for CO_2 conversion but also addresses another critical environmental challenge: the decarbonisation of hydrogen production itself. By utilising renewable energy sources for electrolysis, the entire process becomes carbon-neutral or even carbon-negative.

❸ **CO_2 conversion:** In the presence of green hydrogen, captured CO_2 is chemically converted through processes like Fischer-Tropsch synthesis or methanol synthesis. These reactions yield hydrocarbons or liquid fuels, which serve as alternative energy sources.

> **“Through advanced chemical processes, CO_2 can be transformed into a variety of building blocks that serve as raw materials for producing plastics, polymers, and other essential petrochemical products”**

❹ **Fuel refining:** The synthesised hydrocarbons undergo further refining and treatment to meet specific fuel standards. This ensures compatibility with existing infrastructure and engines.

Petrochemical applications

In addition to alternative fuels, waste CO_2 can be utilised to synthesise various petrochemicals. Through advanced chemical processes, CO_2 can be transformed into a variety of building blocks that serve as raw materials for producing plastics, polymers, and other essential petrochemical products. This approach reduces the reliance on traditional fossil feedstocks while reducing carbon emissions.

For instance, waste CO_2 can be converted into ethylene, a critical precursor for manufacturing a wide range of plastics. By utilising CO_2 as a feedstock, the industry can decrease its dependence on fossil fuel-derived ethylene and mitigate its environmental impact. Furthermore, this process contributes to the circular economy by reusing carbon resources and minimising waste generation.

Benefits and challenges

The use of waste CO_2 to synthesise alternative fuels and petrochemicals offers several benefits, such as emission reduction, resource efficiency, diversification, and technological innovation. However, challenges such as technological scalability, cost-effectiveness, and the need for sustainable energy sources must be overcome to fully realise the potential of waste CO_2 utilisation.

Collaborative ecosystems

Transitioning to a circular economy requires collaborative efforts across the entire value chain. Industries, governments, and academia must work together to create an ecosystem that fosters innovation and knowledge sharing.

- **Industries as enablers:** Collaborative cross-sector partnerships dissolve silos, allowing industries to exchange expertise and adopt circular practices collectively. This synergy ensures the real-world application of circular principles and collaborative innovation.
- **Government support and alignment:** Government bodies, working hand-in-hand with industries, can establish regulatory frameworks that provide a clear direction and incentivise sustainable practices. A supportive regulatory environment can thus catalyse the transformation to a circular economy.
- **Academia’s research contribution:** Collaborating with academia infuses research insights and technical knowledge into circular initiatives. Joint research projects and technology transfer foster the development of cutting-edge solutions that bridge theory and practical implementation.
- **Nurturing innovation ecosystems:** Collaborative platforms cultivate innovation, enabling ongoing idea exchange, refinement, and improvement. This dynamic environment accelerates innovation while aligning strategies with real-world challenges.
- **Accelerated sustainable technology development:** Collaborative efforts enable pooled resources for research and development, expediting the creation of advanced recycling technologies and optimised bio-based feedstock production. These technologies underpin circular practices.

Challenges and roadblocks

While the promise of a circular economy for petrochemicals is undeniable, it is not without its challenges. Implementing circular economy strategies demands significant investments in research, technology, and infrastructure. The transition may also require regulatory reforms to incentivise sustainable practices and discourage linear product life-cycle models.

Furthermore, consumer behaviour plays a pivotal role. Shifting mindsets from disposable to durable products necessitates education and awareness campaigns. Consumers must be empowered to make informed choices that align with the circular economy's principles.

Conclusion

The petrochemical industry stands at a crossroads, poised to either perpetuate its linear, resource-depleting trajectory or embrace a circular approach that harmonises economic growth with environmental preservation. The circular economy offers a blueprint for petrochemical sustainability by re-imagining production, consumption, and waste management. By adopting strategies like extended producer responsibility, advanced recycling, carbon capture, and collaborative ecosystems, the industry can forge a path toward a regenerative and responsible future.

As we embark on this transformative journey, it is crucial to recognise that closing the loop in the petrochemical sector is not just an ecological imperative – it is an economic opportunity. By aligning profit motives with sustainability goals, stakeholders can drive innovation, enhance competitiveness, and contribute to a world where petrochemicals no longer deplete our planet's resources but rather enrich its circular rhythm of life.

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Heat trace solutions for the energy transition

Mission-critical heat trace solutions for the energy transition industries are essential as more industrial facilities convert to clean fuels and CO_2 reduction

Jim Dawson and Pele Myers
nVent

Every country has the responsibility to shift the world away from coal and reduce or eliminate carbon emissions to build a more sustainable world. This shift to cleaner energy brings new challenges and requires innovative heat-trace solutions in many industries to ensure reliable operation and uptime in the safest and energy-efficient way.

Liquefied natural gas (LNG) is essential in the energy transition as it plays an instrumental role in shifting away from coal and reducing carbon emissions. There is a global race to provide natural gas to the world for industry, power, and heating. Countries with excess natural gas (methane) are currently building LNG liquefaction plants to prepare LNG for export, while countries that need natural gas are building LNG regasification plants. The entire LNG supply chain – from liquefaction and gasification plants to terminals, jetties, and storage tanks – requires specific process temperature maintenance or freeze protection.

Biofuels and clean fuels are essential in the energy transition towards attaining carbon neutrality. Biofuels are derived from renewable sources such as plants, used cooking oils, algae, or biowaste. Biodiesel production, fuel terminal retrofits, renewable diesel refinery conversions, and sustainable aviation fuel (SAF) production are in progress around the world. In biofuel plants, each step of the refining process – from the handling and storage of feedstock and final products, over the pretreatment and refining processes, to the blending and transport facilities – requires specific process temperature maintenance or freeze protection.

Carbon capture and storage (CCS) is essential in the energy transition as it plays a critical role in CO_2 removal from the atmosphere. CCS technologies aim to store the CO_2 underground, and CCU technologies aim to utilise CO_2 as feedstock in other industrial processes such as enhanced oil recovery or e-fuels production. CO_2 can be captured from fuel gas (pre-combustion) or flue gas (post-combustion) in many industrial sectors (such as oil and gas, LNG, biofuels, steel, and cement) or even by direct air carbon capture (DAC) in the atmosphere. In CCS plants, the capture, utilisation or storage stages require specific process temperature maintenance or freeze protection.

Hydrogen (H_2) is essential in the energy transition towards attaining a carbon-neutral world. In traditional sectors, H_2 has been used for decades in refineries (for hydrotreatment), petrochemicals, and fertilisers (ammonia). However, new sectors are emerging fast.

- Grey H_2 generation is typically done through steam methane reforming (SMR) from natural gas, where large volumes of CO_2 are vented.
- Blue H_2 has stricter regulations to capture the CO_2 emissions with CCS technologies.
- Green H_2 uses emerging technologies based on a water electrolysis process driven by renewable electricity. This way, H_2 is generated with zero CO_2 emissions and can be used as a clean energy carrier or building block for clean transport fuels.

In H_2 plants, the generation, conversion, transport or storage stages require specific process temperature maintenance or freeze protection.

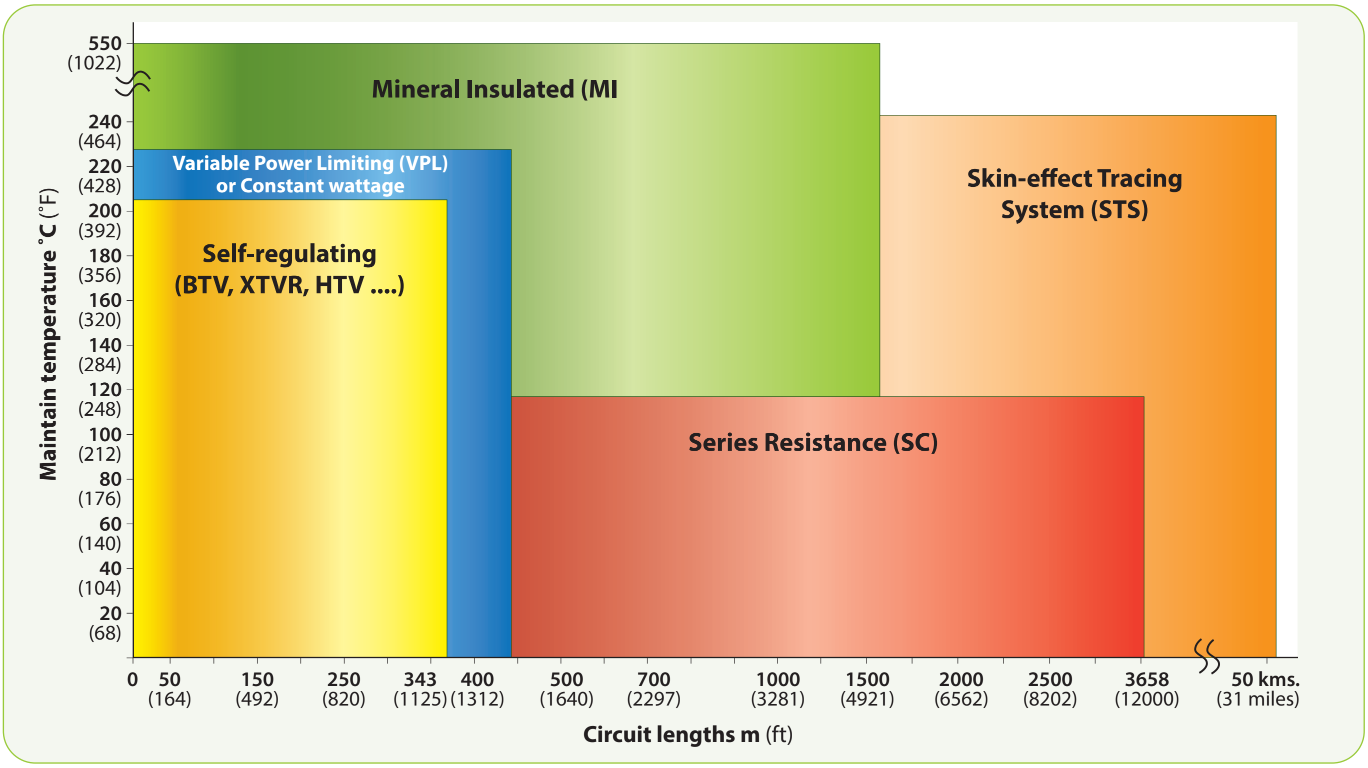

Figure 1 Cable technology portfolio: solutions that cover a wide range of temperature and circuit length requirements for any application

Managing process temperatures requires an integrated heat management system

Plants and refineries require pre-determined temperature management from pipe freeze protection to high-temperature process maintenance in piping, equipment, tanks, and instruments. Consequently, they need to rely on heat trace cables capable of meeting a broad range of precise design criteria.

nVent offers a portfolio of Raychem cable technologies that cover a wide range of temperature and circuit length requirements, as shown in **Figure 1**. Moreover, a complete heat management system must also include:

- An engineered design using proprietary TracerLynx 3D HMS software to optimise process maintenance piping, equipment, tanks, and instrument temperatures for precise design criteria and conditions.
- Power distribution system that provides the most efficient power management and electric heat tracing (EHT) designs.
- Control and monitoring system with supervisory software that confirms the system is working properly, offers useful diagnostic information to optimise maintenance and operation, manages alarms, and saves energy.
- Instrument winterisation to protect and ensure reliable operation of instruments.

The following case studies exemplify how a complete system using the right technology can solve comprehensive temperature maintenance requirements. In many cases, a combination of heating cable technologies proves most optimum.

Case study 1: Constant wattage heating cable technology in LNG industry

A major LNG facility in Corpus Christi has access to abundant natural gas and premier marine access with two loading berths large enough to receive the largest LNG carriers. The customer's mission-critical objective is operational reliability and an optimal frost heave prevention system for three 160,000 cubic metres LNG storage tanks. The project required detailed control and monitoring capabilities to minimise operational risk and maximise productivity.

nVent engineers designed a redundant frost heave prevention system using Raychem constant wattage heaters, connection kits, resistance temperature detectors (RTD), and a 277V/480V power distribution combined with a Raychem NGC-30 heat trace control and monitoring unit to save energy, minimise risk, and maximise productivity.

Case study 2: Variable power limiting heating cable technology in biofuels industry

One of the largest midstream infrastructure and logistic solution providers in the US is shifting its terminal facilities from petroleum-based to biofuels production. This conversion requires multi-million-dollar terminal retrofits to enable the aggregation, storage, blending, and distribution of biofuels, mainly biodiesel, all totalling up to 5,000 miles of pipeline and 130 liquid petroleum terminals.

Since typical terminal storage and distribution for petroleum-based products, like diesel and gasoline, do not require supplemental heat tracing, areas such as piers, jetties, tankage, blending, and interconnecting piping had limited power distribution capacity. However, biodiesel, ethanol, and SAF storage and distribution do require heat tracing to maintain the right viscosity levels. For example, biodiesel (B100) requires a process temperature maintenance of 110°F (43°C). The customer's mission-critical objectives for the heat management solution include finding the optimal yet cost-effective system design for this project that would keep critical processes running and manage the additional demands for power distribution in the terminal areas such as piers, jetties, tankage, blending and interconnecting piping.

nVent engineers designed a system using Raychem Variable Power Limiting technology (VPL-4) powered at 480V for longline heating, interconnecting piping, and vessel heating. VPL heating cables offer great features like ease of design and cut-to-length installation. However, most important to the customer was that the long circuit length capability of VPL-4 at 480V reduced the circuit count and addressed the challenge of limited power distribution in piping and vessels in areas of the terminal.

To manage the higher temperature lines that required process temperature maintenance or freeze protection, the engineers selected Raychem HTV high-temperature self-regulating heating cables with High Power Retention (HPR) technology that have a minimum of 95% power retention after 10 years and a design life of 30 years or more. The design was completed with a heat trace control and monitoring unit to save energy, minimise risk, and maximise productivity.

Case study 3: Series resistance heating cable technology in biofuels industry

A Newfoundland refinery is undergoing a major retrofit to manufacture renewable diesel and SAF. The main feedstock will be animal fats and plant oils, which will arrive via ships from the Northeast USA. Since the previous petroleum feedstock loading dock and distribution system did not require heat tracing, the dock area had limited power distribution available. However, because animal fats and plant oil feedstocks and some finished goods become waxy and solidify at ambient temperatures, they require heat tracing to maintain temperatures in the 120°F (50°C) range to keep them in liquid form. The customer's objective was to find an efficient and budget-friendly heat management solution to sustain mission-critical processes and handle increased power needs at the dock and distribution areas.

nVent engineers designed a system using Raychem series heating (SC) cables for the longlines due to their ability to meet the process temperature maintenance needs, heat the long distribution lines, and manage the limited power distribution reliably, safely, and with the lowest installed cost. The design was completed with a heat trace control and monitoring unit to save energy, minimise risk, and maximise productivity.

Case study 4: Skin-effect tracing system technology in biofuels industry

Two major renewable producers in Port Arthur, Texas, have partnered on a challenging project to deliver chicken fat as feedstock to a rail unloading facility, then through an underground line into the refinery. The underground line would be buried at depths ranging from 6 to 100 feet. Chicken fat and used cooking oil are two of the feedstocks being utilised in the refinery to produce renewable diesel. Routing this feedstock into the refinery involves the design of a one-mile-long heated underground pipeline.

The chicken fat and oil have to be maintained at a process temperature of 120°F (50°C) to keep them in liquid form. The customer's mission-critical objectives for the heat management solution included protecting critical processes and managing the engineering and contractor challenges for construction, installation, and future reliable operation of this underground heated line.

nVent engineers designed a system using

the Raychem Skin-effect Tracing System (STS) because the bundled longline technologies would optimise the heat management system performance:

- Pre-insulated/pre-fabricated piping systems that offer superior thermal insulation reliability and underground integrity by providing a homogeneous temperature profile for the entire length of the pipeline.
- Fiber-optic Distributed Temperature Sensing (DTS) systems to measure the temperature of the underground pipeline every metre along its underground routing.
- Raychem Pipeline Supervisor (RPS) predictive analytics software for comprehensive control and to safely manage temperature-critical pipelines.
- Power distribution solution at one end of the pipeline.

Process temperature maintenance of this key feedstock line was completed using directional drilling to install a one-mile-long, pre-insulated, STS-heated, underground pipeline with the temperature being maintained at 120°F (50°C). The pipeline temperature is being monitored every metre along this pipeline using DTS-Fiber Optic. RPS ensures feedstock flow assurance by monitoring the entire pipeline and providing the data required by operations to ensure this underground line is functioning as designed.

Case study 5: Self-regulating heating cable technology in CCS industry

Ethanol plants in the Midwest USA produce significant CO_2 as a result of fermentation. With an overall goal of protecting the long-term viability of the ethanol and agricultural industry, a Midwest customer is partnering with more than 30 ethanol plants across five states on a project to reduce the carbon emissions at each location through a CCS process.

At each ethanol facility, CO_2 will be captured, dehydrated, and compressed, and then CO_2 will be gathered and transported through pipelines to the deep geological formation injection point in North Dakota. The customer's mission-critical objectives for the heat management solution include ensuring operational reliability for managing northern climate freeze protection and process temperature maintenance and optimising energy efficiency across all the plants. This CCS project is currently the largest in the world and upon completion will safely capture 18 million metric tons of CO_2 per year.

nVent engineers designed a system using Raychem XTVR high-temperature self-regulating heating cables with High Power Retention (HPR) technology for both the process temperature maintenance and freeze protection applications. The design was completed with the advanced Raychem NGC-30 heat trace control and monitoring unit to save energy, minimise risk, and maximise productivity.

Case study 6: Self-regulating heating cable technology in hydrogen industry

A leading global producer of industrial gases in Alabama is constructing a new SMR hydrogen plant to support the long-term viability of the chemical industries in the area. The facility design and construction include all the infrastructure and utilities required for an industrial project. The customer's mission-critical objectives for the heat management solution include finding the optimal system design that would keep critical process maintenance and freeze protection applications running, prevent condensation in large bore piping that transports process gases and nitrogen gas, protect/winterise instruments, and provide an energy-efficient control and monitoring solution that verifies the operational reliability of the heat management system.

nVent engineers designed a system using Raychem XTVR high-temperature self-regulating heating cables with HPR technology for both the process temperature maintenance and freeze protection applications. The design was completed with the NGC-40 heat trace control and monitoring unit to save energy, minimise risk, and maximise productivity.

Summary

Critical heat trace solutions for the energy transition industries will remain vital as more industrial facilities convert to clean fuels and CO_2 reduction. Securing reliable operation and uptime in plants and refineries, especially with the high-temperature maintain demands of new biofuel feedstocks, will require well-designed solutions to manage pipe, tank, and equipment temperatures.

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Carbon storage in concrete through accelerated carbonation

With 88.5% of GHG emissions created from concrete during cement production, there is an urgency to develop technology for the industry to hit net zero targets

Gareth Davies and Luan Ho
Tunley Environmental

Concrete is the most widely used man-made material in the world by both weight and volume (Miller, et al., 2020). An estimated 30 Gt of concrete is produced annually, equating to more than 3.5 tonnes of concrete per person annually. The only material competing with concrete for production is fresh water, which is essential to human life. This should exemplify our reliance on concrete globally as a society.

Concrete is produced from a binder material (cement), non-porous minerals varying in size (aggregate), water, and low concentrations of admixtures (pigments, superplasticisers, and accelerating agents). It is estimated that concrete production alone contributes to 8% of anthropogenic greenhouse gas (GHG) emissions and 3% of global energy demand.

Figure 1 shows that an estimated 88.5% of the GHG emissions from concrete can be attributed to cement production, with the majority of the remainder coming from mining of aggregates (10.1%). Approximately half of these carbon emissions are from the combustion of fossil fuels to provide the energy to convert raw materials into cement (Gursel, et al., 2014). While challenging to develop and implement, there is a clear roadmap to eliminate this half of the emissions through the implementation of electrical kilns and the use of renewable energy.

However, the remaining 44.25% of the CO_2 emissions are from the calcination of limestone, which is intrinsic to cement production and currently unavoidable. Consequently, novel and innovative GHG mitigation strategies must be investigated, developed, and implemented quickly to mitigate the GHG emissions caused by the production of concrete. Only once technologies are developed can a true plan to net zero concrete be cemented into place.

Portland cement is the most widely used cement composition. It is made by heating limestone and clay materials in a kiln to form clinker, followed by grinding with gypsum (Aitcin, 2016). The most common version of Portland cement is a grey cement, appropriately referred to as ordinary Portland cement. In 2011, ~3 Gt of Portland cement was produced globally (Gursel, et al., 2014).

CO_2 emissions from the production of Portland cement totalled 2.6 Gt, of which 0.435 tonnes of CO_2 per tonne of Portland cement produced was emitted through calcination. Portland cement was developed in the early 1900s, so the chemistry and chemical nomenclature are old and mostly understood within the realm of civil engineering. It is primarily composed of calcium silicates, calcium aluminates, calcium sulphate, and calcium aluminoferrites. The composition of ordinary Portland cement (CPA 32.5) is shown

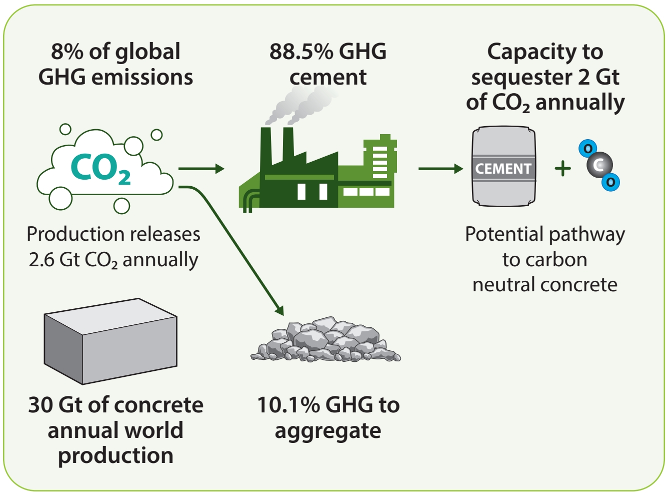

Figure 1 GHG emissions from concrete production

Civil acronym	Full chemical name	Chemical formula	Percentage composition
C3S	Tricalcium silicate	$3CaO{\cdot}SiO_2$	61%
CS2	Dicalcium silicate	$2CaO{\cdot}SiO_2$	13%
C3A	Tricalcium aluminate	$3CaO{\cdot}Al_2O_3$	8.9%
C4AF	Tetracalcium aluminoferrite	$4CaO.Al_2O_3$	8.9%
Gypsum	Calcium sulphate	$CaSO_4$	8.2%

Table 1 Composition of ordinary Portland cement (CPA 32.5)

in **Table 1** alongside the traditional nomenclature and full chemical name.

It is fair to say that for most people who have laid concrete, water is added to the initial ready mix of cement, followed by the addition of aggregate to make a 'wet' cement, which then 'dries' to form solid concrete.

This is a misnomer as the water does not evaporate from the mixture at all; if significant evaporation were allowed to occur, this would lead to weak, undesirable concrete. Instead, there is a chemical reaction between the compounds in the cement (see Table 1) and the water.

This hydration reaction transforms dicalcium silicate and tricalcium silicate into calcium silicate hydrate and hydrated lime (also known as portlandite), as shown in **Equation 1**. The hydration reaction is the essential process that enables cement to harden, and hence concrete to transform from a liquid paste into a hardened product suitable for construction:

$$2[2CaO \cdot SiO_2] + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2 \qquad \text{(Eq 1)}$$

Carbonation of concrete and cement

Carbon sequestration directly into concrete or cementitious material is one of the potential mitigation pathways to offset (and reduce) the total GHG emissions of concrete production. While other pathways exist targeting the manufacturing stage (for example, carbon capture at the kiln and replacement of cement composition), this article focuses on carbon sequestration within concrete and cementitious materials. Essentially, the carbon sequestration process reverses the initial cement production process where CO_2 is split from calcium carbonate (limestone), and is referred to as carbonation or mineralisation (Stefanoni, et al., 2018). Controlled carbonation of cementitious material was first proposed in the 1970s. However, it has recently gained attention due to the potential to mitigate against the significant GHG emissions from concrete production (Qin, et al., 2019).

Between 1950 and 1990, carbonation of steel-reinforced concrete was an area of major concern. The carbonation neutralised the alkalinity of the concrete and caused the steel to corrode. Hence, a qualitative method of analysing carbonation was developed by applying a phenolphthalein indicator to the concrete, which provides a measure of the pH of the concrete.

It was identified that increasing the density of the concrete reduced the porosity and prevented significant carbonation. This change in the production of reinforced concrete was advised with the introduction of European standard EN 206-1 in 2000, enabling structures to have an expected service life of 50-100 years. However, the process of carbonation actually increases the strength of the concrete due to the formed calcium carbonate having a larger crystal size and occupying the unfilled porosity of the concrete (Hussain, et al., 2017).

Calcium hydroxide ($Ca(OH)_2$) is the hydrate most readily reactive with CO_2 within hardened cement (Savija, et al., 2016). This readily reacts with CO_2 in the atmosphere to reform calcium carbonate ($CaCO_3$), as shown in **Equation 2**. Other hydrated salts in the concrete can also uptake CO_2. If produced from calcium hydroxide or other calcium families, the produced calcium carbonate is air and temperature-stable and, therefore, will not release the trapped CO_2 back into the atmosphere. Cement has a theoretical maximum carbonation capacity of 50% (Lippiatt, et al., 2020). If the cement within concrete could be carbonated to this maximum capacity, this would sequester 2 Gt of CO_2 annually.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \qquad \text{(Eq 2)}$$

Carbonation of concrete, as a naturally occurring process, is slow and problematic when not controlled. As previously highlighted, natural carbonation of steel-reinforced concrete

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can cause rusting of steel. In addition, natural carbonation can also cause the cracking of concrete and build-up of harmful chloride-based compounds (Xu, et al., 2022). Therefore, different processes for controlled carbonation to sequester CO_2 into the cementitious material and improve the properties of the concrete are being researched. A key advantage of controlled carbonation is that once the concrete is sufficiently carbonated, further natural carbonation is limited.

Consequently, the existing issues occurring from natural carbonation are also mitigated. Concrete quality is typically assessed in terms of compressive strength, curing time, workability, tensile strength, and modulus of elasticity.

Research on the carbonation of cement also aims to identify the rate of carbonation and the amount of carbonation (often measured by depth of carbonation). The depth of carbonation is the distance (mm) from the surface to the concrete that the CO_2 has penetrated and been mineralised to form calcium carbonate.

One of the controlled carbonation methodologies involves utilising a carbonation chamber to carbonate pre-cast materials (Hussain, et al., 2017). These accelerated carbonation chambers can be fitted to allow control over CO_2 concentration, humidity, and temperature. Notably, commercial carbonation chambers typically do not utilise pressurised CO_2 and only use a percentage concentration of CO_2 at atmospheric concentration.

The main parameters affecting the rate and depth of carbonation and structure of final carbonised concrete are permeability (porosity), pozzolanic content (beyond the scope of this article), moisture (humidity), CO_2 concentration, temperature, and duration of exposure (Hussain, et al., 2017). Control over these parameters is essential as accelerated carbonation chambers aim to maximise carbonation depth. However, the formation of calcium carbonate in the exterior pores blocks further carbonation in the rest of the concrete. For example, the temperature of the carbonation chamber affects solubility and transport as well as the hydration of the cement phases (Xu, et al., 2022).

Higher temperatures decrease the solubility of both calcium ion and CO_2, which retards the carbonation reaction. However, the transport of substances and the amount of available calcium hydrates for carbonation increases at higher temperatures. Therefore, there is an optimal temperature for carbonation to give a high carbonation rate and large carbonation depth.

This optimum temperature depends on the cement composition, with temperatures varying between 0°C and 100°C. One significant observed advantage of this is that carbonation causes the accelerated curing of concrete. One study found that concrete bricks, which originally required 20 hours of steam curing, only needed two hours of carbonation curing to have comparable compressive strength (Liu, et al., 2022). Li et al. investigated the carbonation of cured concrete blocks in an accelerated carbonation chamber (Li, et al., 2019). They identified CO_2 uptake after 28 days at 15.8%. Additionally, the carbonated concrete blocks had a 10% higher compressive strength than the control moisture-cured concrete. Beyond this, the carbonated concrete blocks also had higher abrasion resistance and chloride ion permeability.

Another emerging method of carbon sequestration in concrete is embedding CO_2-rich materials within the concrete mixture (Stefaniuk, et al., 2023). These materials can then release the CO_2 during the curing of the concrete, which can react with calcium hydrate salts to form calcium carbonate immediately. This process avoids the challenge of achieving the required CO_2 penetration depth in the concrete for sufficient mineralisation. However, it introduces many new challenges. One recent investigation by MIT incorporated sodium bicarbonate, which dissolved in the water and released the CO_2 slowly over time. This CO_2 then readily reacted with the calcium silicate hydrates in situ to create an extended structure of calcium carbonate with reduced porosity (see **Figure 2**).

Another advantage of this process is that it mitigates the harmful consequences of late-stage carbonation, such as shrinkage and cracking. Early results demonstrate this method of carbonation to be very effective at carbon sequestration, with CO_2 incorporation listed at 15 wt%. This is based on TGA decomposition profiles of the cured cementitious material.

Cement is typically used at 10-15 wt% in concrete, depending on the final properties required. If sodium hydroxide or a similar

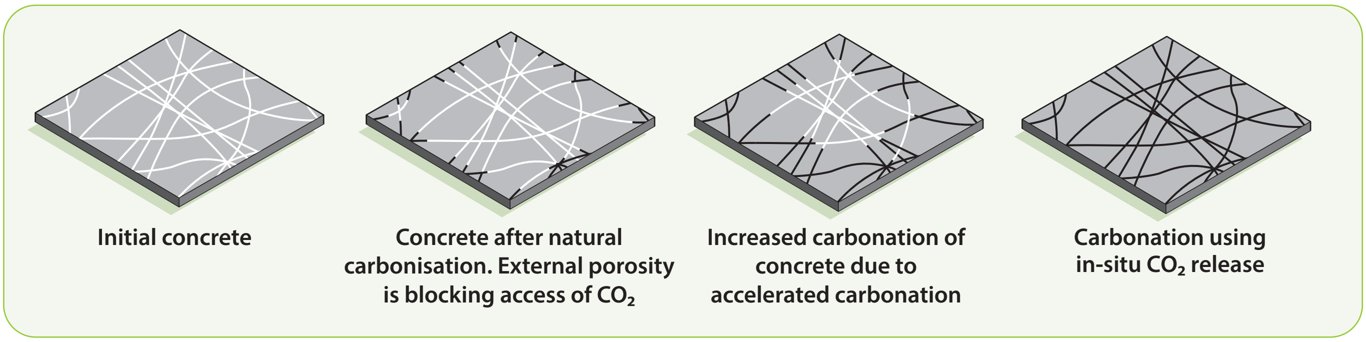

Figure 2 Representation of changes in the porosity of concrete with different types of carbonation, natural, accelerated chamber, and in-situ carbonation

CO_2 releasing material was implemented in concrete with 10 wt% cement, this could enable the sequestration of 15 kg of CO_2 per tonne of concrete. If all the 30 Gt of concrete produced yearly were replaced with a mixture able to accomplish this, 0.45 Gt of CO_2 could be sequestered annually. Even if modest sequestration like this were achieved, it would reduce cement-related emissions by 17.3%. Combined with the predicted 50% reduction from electrification, this would reduce GHG emissions by 67.3%.

It is estimated that 3 billion tonnes of construction and demolition waste is produced annually (Pu, et al., 2021). It is possible to recover a portion of the cementitious material from this waste and reuse it in the production of fresh concrete. When this is performed, the materials are widely referred to as recycled concrete aggregate (RCA). However, when RCA is used in concrete production, significant issues are often present, such as high energy and cost, micro-cracking, and production of waste solutions/fine aggregates. This is where controlled carbonation comes into play. This RCA has the same chemical composition as fresh concrete, meaning the RCA can permanently sequester CO_2 through mineralisation following the same reaction pathway.

Furthermore, carbonated RCA can mitigate some of the existing problems when used in fresh concrete due to reduced water absorption and increased stability to leaching. In terms of carbon sequestration, plain crushed concrete was reported to absorb ~11 kg CO_2 per tonne, and RCA (5-20 mm) sequestered 7.9 kg of CO_2 per tonne (Xuan, et al., 2016), (Kikuchi, et al., 2011). However, using carbonated RCA also avoids the emissions from the displaced aggregate.

One study produced 1 m^3 concrete blocks with reportedly 5.53% lower GHG emissions due to the 43% RCA content (Guo, et al., 2018). If the carbon sequestration was also considered for carbonated RCA in this instance, it would have reduced the GHG emissions by a further 2.28%. When the quality of RCA is not good enough, it can still be used as down-cycled material in floor slap applications.

Conclusion

Concrete is a fundamental material in the construction industry. Concrete production poses many environmental challenges, with direct carbon emissions arising from not only extracting raw materials but also the calcination of limestone.

In this article, carbon sequestration by concrete is discussed as a potential mitigation pathway to reduce emissions from concrete production. Carbon sequestration in concrete by controlled carbonation using controlled carbonation chambers and/or carbon-rich materials to produce concrete may be a viable strategy.

It is reasonable to state that by acting as a carbon sink during the use stage, concrete can partially self-offset the carbon emissions generated during the manufacturing stage. There are also potential applications in carbonating end-of-life concrete and reusing it as a filler material to further increase carbon sequestration.

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Fuelling the decarbonisation of international shipping

The shipping industry's transition to net zero is a sizeable challenge, but major progress is being made on the main driver: legislation

Sebastiaan Bleuanus
Wärtsilä Netherlands BV

It has been an eventful year for those working on the decarbonisation of international shipping. Besides a flurry of technology developments and the world's first demonstrations, we have seen significant progress on the main driver of shipping's transition to net zero: legislation. The recently increased ambition level of the IMO (described elsewhere in this issue of *Decarbonisation Technology*) can be interpreted as a solid call to action for the industry. Besides progress at the IMO, the European Union's council adopted the FuelEU Maritime package on July 25, 2023. This package includes a raft of measures but critically also focuses on the carbon intensity of the fuels used in shipping and incentivising the uptake of renewable fuels of non-biological origin (RFNBOs).

Though the legislative fog on the decarbonisation of shipping has started to lift, a one-size-fits-all solution has not yet emerged, nor is one expected to materialise. With so many different ship types, operational profiles and regional differences, different solutions will be needed.

So how do we get this done as an industry, and what are some of the ways Wärtsilä is supporting the industry with decarbonisation?

Efficiency will be critical, both upstream and downstream

While shipping is already the world's most efficient mode of large-scale transportation, further increases in the shipping system are still possible. Here, we need to distinguish between five steps for further increasing efficiency:

❶ **Transport needs optimisation.** The inevitable cost increase for transporting items over long distances will lead to a rethink of the need for transport. Tied in with global tensions, we may see an increase in re-shoring, which brings about changes in the need for raw materials and finished products.

❷ **Transport system optimisation.** Because a ship's energy consumption per mile is highly dependent on her speed, being able to go slower and avoid waiting at anchorage before docking pays off. Every year, more than 2 million port calls are co-ordinated individually, and more than $18 billion worth of excess fuel is unnecessarily burned, with 160 million tonnes of CO_2 emissions. To help avoid this, port call optimisation techniques have been developed and introduced.

❸ **Ship optimisation.** Having established the need and optimum speed to sail, a close look at the ship itself reveals that a large part of today's global fleet is not being used in an optimum way. Often designed and sea-trialled for higher speeds than those used in practice (especially when taking a holistic approach to transport system optimisation), real-world vessel efficiency can be increased through hydrodynamic improvements by adding so-called energy saving devices, by lowering ship resistance through hull air lubrication, and even by adding sails to take advantage of the free fuel: wind. A notable example of this is the Pyxis Ocean bulk carrier that recently completed her maiden voyage from Shanghai to Paranagua in Brazil after being retrofitted with two wing sails, one of which was co-funded by the CHEK project (see opposite) developed

Figure 1 Pyxis Ocean bulk carrier fitted with two rigid wing sails to reduce fuel consumption (*©CHEK project/Cargill*)

Figure 2 M/S Aurora Botnia photographed in the Vasa archipelago

by BAR Technologies (see **Figure 1**). Each sail is predicted to save 1.5 tonnes of fuel per day at sea.

④ **Engine optimisation**. Medium-speed four-stroke internal combustion engines used either as main or auxiliary engines are already reaching 50% efficiency, but further improvements are still to be had. Special attention should be paid to combustion efficiency in low-pressure gas-fuelled engines, as an increase in combustion efficiency directly translates into lower methane emissions. An example of technology development to reduce methane emissions and increase engine efficiency was recently demonstrated on board the Aurora Botnia RoPax ferry as part of the SeaTech project (see **Figure 2**). Aurora Botnia is a state-of-the-art ferry powered by four Wärtsilä 31DF dual fuel gas engines as part of a hybrid propulsion system. One of the installed engines was upgraded to reach sizeable emission reductions and ultra-high energy conversion efficiency by precisely controlling the fuel mixture at every operating point of the engine. The VTT Technical Research Centre of Finland conducted a measurement campaign on board to verify the results. Measurements were conducted on the upgraded engine and one of the non-modified Wärtsilä 31DF engines. **Figure 3** illustrates the main results on measured methane emissions from both the non-modified engine (Main Engine #4, or ME4) and modified engine (Main Engine #3 or ME3) (Lehtoranta, Kuittinen, Vesala, & Koponen, 2023). The achieved emission reduction is quite clear and sizeable, ranging from a 50% reduction at the highest loads to up to 75% at lower loads.

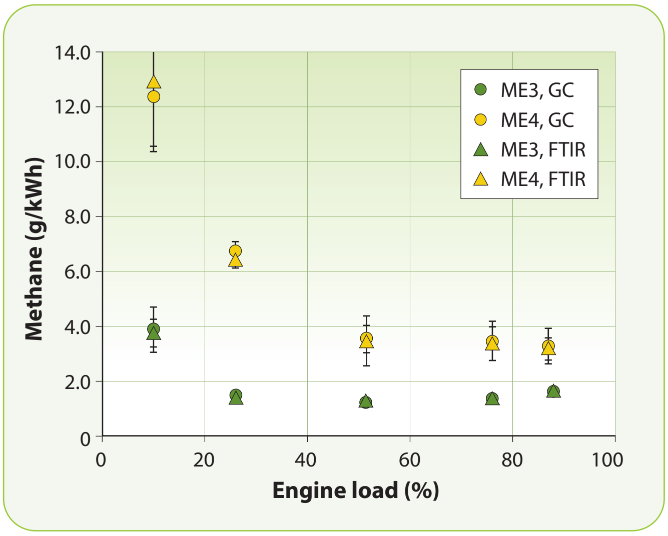

Figure 3 Methane emissions measured on board Aurora Botnia for Main Engine 4 (non-modified W31DF) and Main Engine 3 (equipped with the technology developed in the SeaTech project) *©Lehtoranta, Kuittinen, Vesala, & Koponen*

⑤ **Engine and fuel optimisation**. Having gone through the first four optimisation steps, the remaining gap for the required emission level will have to be tackled by optimising the carbon intensity of the fuel burned on board. Where the preceding steps often result in increased vessel profitability, this last step will increase the operational cost of the vessel. However, this is about to change. With legislation under development that includes so-called 'market-based measures' – such as carbon taxes, fuel levies or subsidies on renewable fuels – the playing field starts to tilt towards the utilisation of renewable fuels. With this in mind, Wärtsilä is developing a portfolio of engines able to run on methanol, ammonia, and hydrogen. Working to a compressed timeline, the market

About CHEK project

The CHEK (deCarbonising sHipping by Enabling Key technology symbiosis on real vessel concept designs) project proposes to reach zero emission shipping by disrupting the way ships are designed and operated today.

The project is developing and will demonstrate two bespoke vessel designs – a wind energy-optimised bulk carrier and a hydrogen-powered cruise ship – equipped with an interdisciplinary combination of innovative technologies working in symbiosis to reduce greenhouse gas emissions by 99%, achieve at least 50% energy savings, and reduce black carbon emissions by more than 95%.

Rather than ‘stacking’ novel technologies onto existing vessel designs, the consortium is developing a unique Furure-Proof Vessel (FPV) Design Platform to ensure maximised symbiosis between the novel technologies proposed and taking into consideration the vessels’ real operational profiles rather than just sea-trial performance. The FPV Platform also serves as a basis for replicating the CHEK approach towards other vessel types, such as tankers, container ships, general cargo ships, and ferries. These jointly cover more than 93% of the global shipping tonnage and are responsible for 85% of global GHG emissions from shipping.

introduction of these engines is scheduled for 2026. For ammonia, the market introduction is planned for this year, with first deliveries (to the marine market) next year, while our first methanol engines have already been released and delivered.

Which fuels will be available to the shipping industry where and at what cost remains shrouded in uncertainty, so our focus at Wärtsilä is on providing fuel flexibility to shipowners. This allows them to not only safeguard themselves against ending up with stranded assets but also to use the fuel that best fits their circumstances at the time to maintain profitability.

Taking a step back from shipping and looking at the global energy transition in a more holistic way, scarce resources, such as biomass and RFNBOs, should be used where they have the biggest impact and where there is no viable path towards direct electrification. At this point, another major transport modality comes into play: aviation.

With both using about 300 million tonnes of fossil fuel per year, shipping and aviation have a lot of similarities. Both need to be as safe as possible, and both will still rely on fuels to meet the bulk of their energy needs, primarily because liquid (or liquified) fuels provide superior energy densities. That means both air and sea transport need to have sufficient access to large volumes of renewable fuels at a reasonable cost. What that cost is, the market will decide, of course. However, intense collaboration between shipping, aviation, and the fuel supply industry is needed to arrive at an optimum cost solution for both.

Jointly, our focus should be on providing the best solutions from a systemic point of view – a view, for instance, that takes into account the fuel flexibility advantage that shipping has over aviation. Not only will shipping have many different fuels that can be used, but the composition of these fuels can also (as evidenced by shipping’s long experience of operating on residual fuels) be more variable versus shipping. So let us leverage that as an industry together as we move towards decarbonised air and sea transport.

Acknowledgement of external funding

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Decarbonisation through innovation

Explore some of the latest available sustainable technologies

Flue gas analyser identifies leaking burner during normal operation

A number of years ago, a refiner in the US Gulf Coast had a vertical, cylindrical fired heater with a Thermox combustion gas analyser to measure excess oxygen and methane/hydrocarbons (using a catalytic detector).

In one anomalous instance, the plant operators started seeing an alarmingly high methane/hydrocarbon reading (of approximately 0.6-0.7% by volume) in their firebox during normal operation, even though process was online and the heater was operating at high temperatures.

A high reading of this type is unusual during the normal operation, which raised suspicion, leading the technicians to contact their local AMETEK representative for support. The representative visited the site and began diagnosing the analyser and performing multiple calibrations. They ran span gas to validate the measurement further, only to find that the readings were spot on – and all tests showed the measurement was solid. Something in the process was causing the high methane/hydrocarbon spike and affecting the reading.

The refinery technicians investigated the process further and did not find any visible issues that day. However, about a week later, the refinery was informed that plant operators had found a leaking burner on that heater, which was causing the very high methane readings.

The Thermox WDG-V combustion analyser

Once that burner was taken out of service, the high methane readings went away. Thankfully, the plant and the team were safe after this uncommon instance, although unwelcome methane emissions and process risk had occurred.

Example of horizontal, natural gas-fired burners in operation

Most operators do not expect unburnt fuel to be in the firebox because fired heaters typically operate at high temperatures – well above the auto-ignition temperature of methane. However, as this case study suggests, there are instances where pockets of unburnt fuel can exist, flow through the system, and become detected downstream by the flue gas analyser.

Beyond a leaking burner, a high methane/hydrocarbon reading can also occur from a loss of flame at the burner or a process tube leak during normal operation – in addition to an accumulation of fuel during start-up and light-off after insufficient purging between ignition cycles. In these instances, there may not be sufficient oxygen, turbulent mixing of the flue gases, or temperature to fully oxidise the pockets of methane and hydrocarbon within the firebox, prompting these high methane/hydrocarbon readings and fuel-rich conditions.

The use of a flue gas analyser to monitor for unburnt fuel, methane, hydrocarbons, and even hydrogen fuels in the firebox can ensure safe combustion control and reduced emissions even in the most unexpected of cases.

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nVent RAYCHEM: Supporting high-temperature mission-critical applications in the energy transition

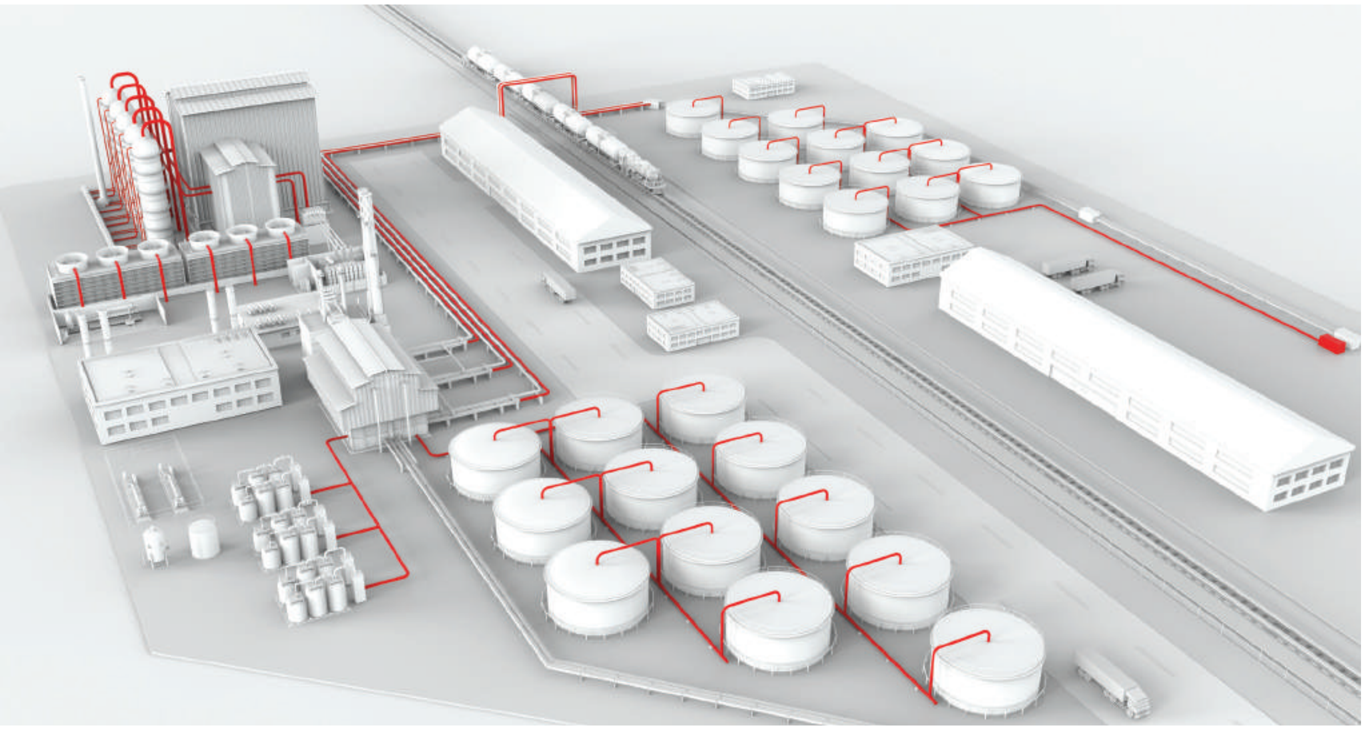
Reliable heat management with self-regulating cables, including high-power retention technology

The energy transition mainly focuses on four main industries: LNG, biofuels, hydrogen, and carbon capture and storage (CCS). Each of these industries brings unique challenges from a heat management system perspective. These applications range from conventional utility system freeze protect heat tracing applications to critical process maintenance applications associated with very interesting feedstocks being utilised in biofuel facilities.

The LNG industry requires a lot of freeze protection and process maintenance designs. In many applications, very cold temperatures can be more of an operational than a heat issue due to the fact that LNG is refrigerated and compressed to a temperature of -162°C/-260°F. At nVent, a lot of research and testing has gone into the development of heating cable technology and components that can be installed at these cryogenic temperatures. Raychem self-regulating (SR) heating cables are used in applications associated with utilities, fire water systems, gas condensation, and frost heave prevention under LNG storage tanks. High-temperature SR applications are mainly associated with the site-based power plant steam system, including designs for steam lines, boiler feedwater, blowdown lines, and condensate.

The hydrogen generation industry is still largely steam methane reformer (SMR) technology-driven. This is called grey hydrogen. When the CO_2 generated in SMR is captured and stored, the resultant hydrogen is called blue hydrogen. The latest technology to produce what is classified as green hydrogen is based on the electrolytic splitting of the water molecule using green power, resulting in hydrogen and oxygen with no CO_2. High-temperature SR applications in the hydrogen industry are similar to those described for LNG because an SMR plant in many ways is like a power plant producing waste heat steam. Thus, high-temperature applications include steam lines, boiler feedwater, blowdown lines, condensate, and some process maintenance applications associated with fuel gas and the pressure swing adsorption (PSA) units.

The CCS industry is growing rapidly and is typically associated with the refining, hydrogen, ammonia, power, steel, and cement industries, which all generate a significant amount of the greenhouse gas CO_2. CO_2 is removed from the flue gas of the



Biofuels and clean fuels are essential in the energy transition towards attaining carbon neutrality but their production is more complex and comes with extra challenges processes in these facilities through a few different technologies, with the most common one today being regenerant amine absorption. The CO_2 is then dehydrated, compressed, and typically piped to an underground storage facility. Higher temperature SR heat management applications are typically associated with the steam system, the regenerant amine system, the dehy unit, and the lube oil systems in these facilities.

nVent's high-temperature SR heating cables with innovative High Power Retention (HPR) technology

The biofuels industry includes ethanol, biodiesel, renewable diesel and sustainable aviation fuel (SAF). The feedstocks include plant oils, animal fats, and used cooking oils, which often require process maintenance temperatures in the 50°C/122°F range. Biodiesel as an end product requires a similar process temperature maintenance. This requirement impacts the (un)loading and storage facilities of feedstock and the end product.

nVent recently developed high-temperature SR heating cables with innovative High Power Retention (HPR) technology:

- Raychem XTVR heating cables are designed for continuous operating temperatures up to 302°F (150°C) and withstand temperatures up to 482°F (250°C).
- Raychem HTV heating cables are designed for high continuous operating temperatures of 205°C/400°F and withstand temperatures up to 260°C/500°F.

The power retention levels for both XTVR and HTV cables surpass previous self-regulating heating cables in performance and design life. These cables guarantee a minimum of 95% of rated performance even after 10 years of operation at continuous exposure to maximum temperatures, and a heating cable design life of 30+ years. Plus, with more available power variants (XTVR has seven at 200-277V and four at 100-130V; HTV has eight at 200-277V), a more efficient heat-trace design that closely matches the heat loss of industrial process pipes is now possible. This, in turn, helps with cost savings on energy consumption and power infrastructure, and reduces downtime risk and maintenance costs for decades.

High-temperature self-regulating cables with HPR are a perfect solution for energy transition industries. Not only is this novel technology ready to keep critical processes operational, protect pipes, tanks, and equipment from freezing, and meet the maintenance demands of new biofuel feedstocks, but it also helps us create a more sustainable future.

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