Decarbonisation Technology

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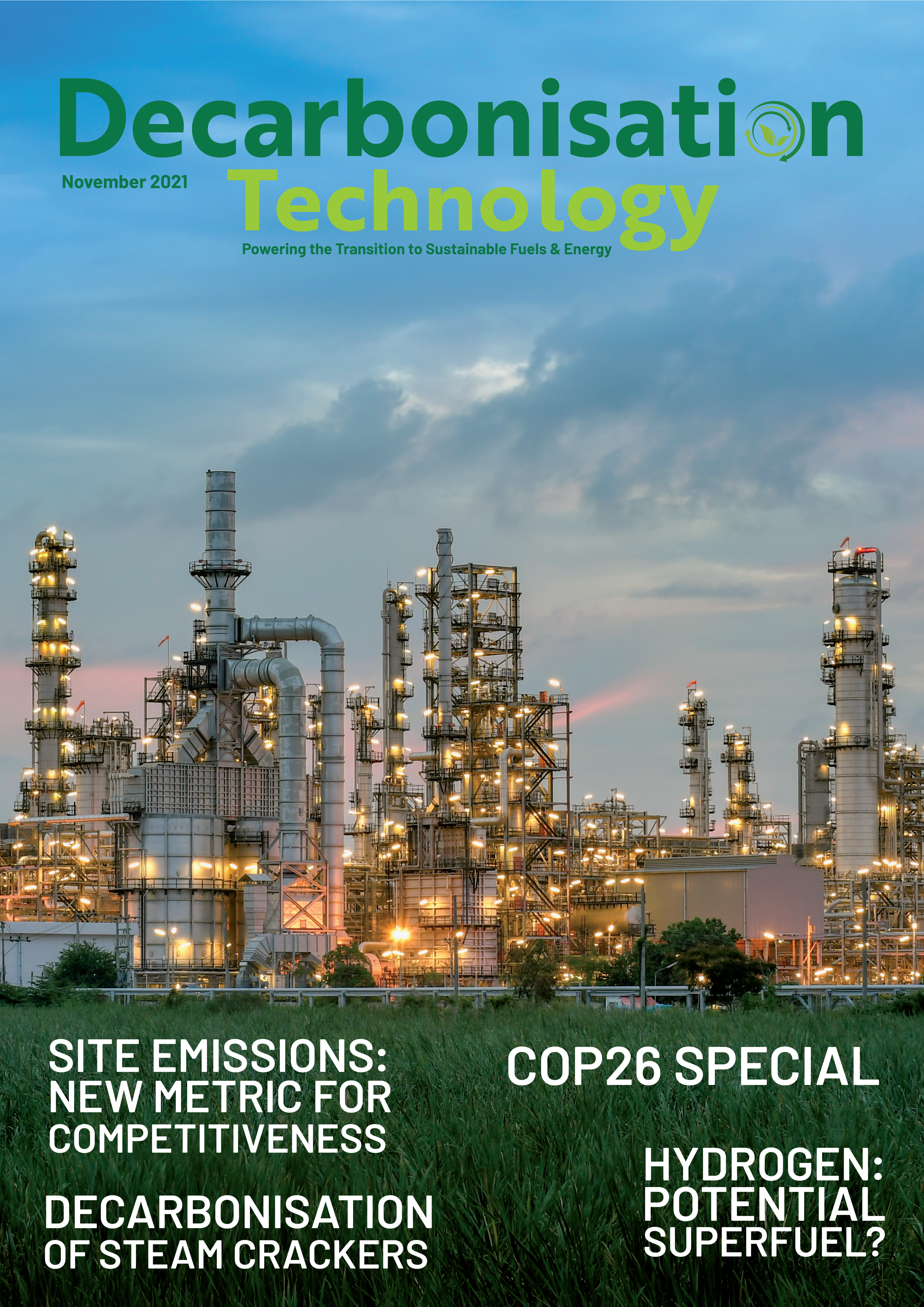
Powering the Transition to Sustainable Fuels & Energy



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DECARBONISATION OF STEAM CRACKERS

Decarbonisation of steam crackers

A number of technologies are available to reduce the CO_2 emissions from steam crackers – from electrification and CCUS to electric furnaces

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Introduction

The majority of the worldwide production of petrochemicals (PCs, e.g. ethylene, propylene, butadiene and aromatics) originates from the steam cracking process. As steam cracking is a thermal process, a significant amount of energy is used to manufacture the products.

Because of this, steam crackers are a significant emitter of CO_2 in the chemical industry, and chemicals represents the third largest direct source of CO_2 emissions in the industrial sector (after iron & steel and cement).[1]

One estimate of worldwide CO_2 emissions from steam crackers[2] shows 198.7 million tonnes of CO_2 in 2015, projected to increase to 264 million tonnes of CO_2 in 2030, or a 33% increase (mid-range of estimate figures are quoted). Clearly, with the global drive to reduce, and then minimise, industrial CO_2 emissions, action is required.

The objectives of the industry are twofold: to reduce or capture CO_2 emissions from the conventional steam cracking process and to seek alternative technologies with lower CO_2 footprints.

Modern steam crackers are well optimised and integrated, such that almost all the fuel gas fired in the furnaces is generated from the process. In addition, high pressure steam is generated from the waste heat from the furnaces, which is used to drive the main compressors and for process heating.

The reduction of CO_2 emissions from the cracker means replacing the methane fuel from the process with alternative lower carbon fuels, such as hydrogen or electrical heating. While the CO_2 emissions from the furnaces can be reduced to zero by using 100% hydrogen or electricity for heating, the CO_2 footprint associated with the generation of the hydrogen or electricity has to be carefully evaluated, as these can exceed the CO_2 footprint from burning the methane fuel.

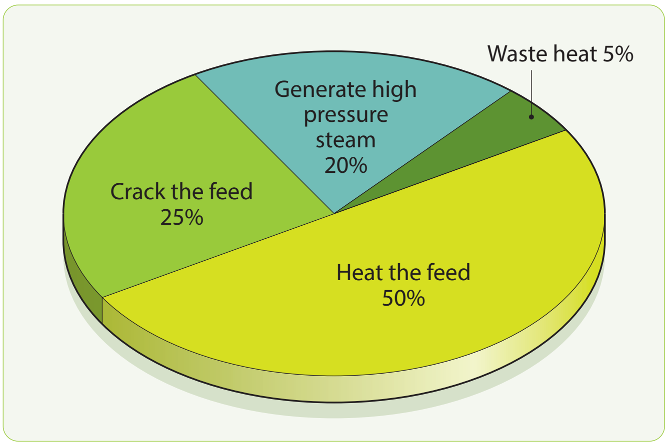

Figure 1 Fired duty splits

When electricity needs to be relied upon for decarbonisation of steam crackers, additional considerations are the availability, reliability and the actual carbon footprint of the power supply, involving many local factors, not all of which may be clear at the time the project final investment decision (FID) is being made.

Reduction of CO_2 from cracking furnaces

The furnace fired duty splits approximately as shown in **Figure 1** in a liquid cracking furnace.

Of this duty, the amount used to crack the feed has to be provided by firing fuel, but the other duties can be reduced by energy optimisation, resulting in minimised fuel firing.

The fired duty, and consequently the CO_2 emissions, can be reduced by 20-40%, the maximum reduction being achieved by Technip Energies' patented[3,4] Low CO_2 Furnace design (see **Figure 2**).

Firing hydrogen

Complementary to the reduction of firing is increasing the hydrogen content of the fuel gas. As the burning of hydrogen does not generate CO_2, this is a relatively easy way of reducing the CO_2 emitted from the cracker. The impact on the furnace burners and performance is being developed and studied (burning hydrogen is likely to result in shorter, hotter, flames, which, combined with a reduced flue gas flow rate, results in reduced steam production from the furnaces and lower radiant section inlet temperatures). Also, some types of burners are not well suited to burning high hydrogen fuels.

Hydrogen can either be generated from the fuel gas generated in the cracker by reforming or imported from outside the cracker. Hydrogen from outside the cracker would normally be generated by electrolysis. Currently, the most mature electrolysis technology is alkaline electrolysis (AE). Taking the AE technology as an example, **Table 1** provides a comparison between hydrogen from electrolysis and hydrogen from SMR reforming the cracker fuel gas. The data is for a 1,500 kTA ethylene liquid cracking plant. The AE estimated figures are based on the data from Reference 8, supplying 100% pure hydrogen to provide the same heat duty as the hydrogen from an SMR reformer converting the fuel gas.

It can be seen from the figures in **Table 1** that:

- By all measures (Opex, Capex, CO_2 emissions, power consumption) reforming provides a better solution than currently available electrolysis technology
- Electrolysis consumes a large amount of electricity, which can represent a considerable operating cost

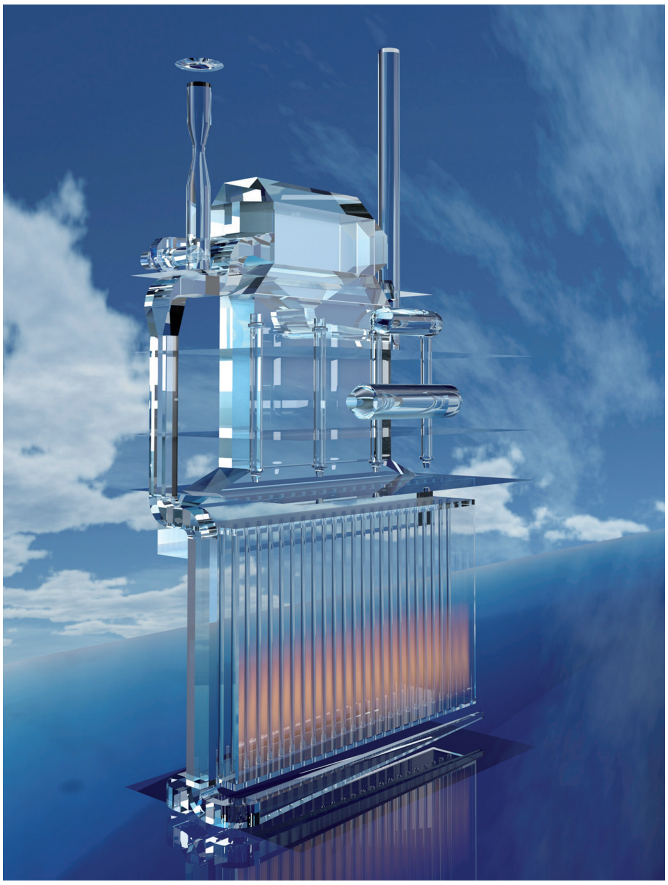

Figure 2 Technip Energies' Low CO_2 Furnace Design

- The Capex for electrolysis is currently very high; however, this is predicted to decrease in the period 2021-2050
- For electrolysis, the CO_2 footprint of the cracker

Parameter	Source of hydrogen	
	Alkaline electrolysis	SMR (blue H_2)
Quantity of hydrogen, t/h (Nm^3/h)	29.9 (332,500)	29.9 (332,500)[a]
Technical cost of hydrogen, $/kg	3.6	0.33
Electrical power, GWh	1.6	0.02
Capex, $bn	1.7	0.4
CO_2 from electricity @ 376 tCO_2e/GWh, MMt/year	4.70	0.11
CO_2 from electricity @ 26 tCO_2e/GWh, MMt/year	0.33	0.04
Parameter	Cracker + AE	Cracker + SMR
Tonnes of CO_2/t HVC @ 376 tCO_2e/GWh electricity[b], tCO_2e/tHVC	1.72	0.24
Tonnes of CO_2/t HVC @ 26 tCO_2e/GWh electricity[c], tCO_2e/tHVC	0.21	0.12

Notes: a. Figure given is for the contained hydrogen in the SMR product. Total heat value of SMR product is the same as that of the hydrogen from electrolysis.

b. 376 tCO_2e/GWh electricity is the basis used for the calculation of cracker CO_2 footprints for comparison with the benchmark in the European Emissions Trading Scheme (ETS)

c. 26 tCO_2e/GWh electricity is the average value for electricity generated from wind or hydroelectric[9]

Table 1 CO_2, Capex and Opex figures for hydrogen from electrolysis and reforming is only reduced if very low CO_2 electricity is available i.e. green hydrogen. As the cracker fuel gas is no longer used in the furnaces, the fuel gas is now surplus

- For 376 tCO_2e/GWh electricity, the CO_2 footprint of the electricity consumed by the electrolyser plus the cracker is greater than the CO_2 emitted by the Source 1 and 2 emissions, when the steam cracker is firing methane fuel (1.72 vs 0.63 tCO_2e/t HVC)
- For 376 tCO_2e/GWh electricity, the CO_2 footprint of the steam cracker with reformer is 62% less than the steam cracker without reforming the fuel gas (0.24 vs 0.63 tCO_2e/t HVC)
- For 26 tCO_2e/GWh electricity, the CO_2 footprint of the steam cracker with reformer is 81% less than the steam cracker without reforming the fuel gas (0.12 vs 0.63 tCO_2e/t HVC)

The amount of hydrogen fired should be minimised, by reducing the firing in the furnaces, as described above. This minimises the hydrogen imported to the plant, or makes more hydrogen available from reformed fuel gas.

Importing hydrogen leaves a surplus of fuel gas generated in the cracker, which is primarily methane. This fuel gas can be used for power generation, but this generates CO_2 and only improves the overall CO_2 footprint of the cracker if imported electricity has a higher CO_2 footprint than the electricity generated from the cracker fuel gas.

	Base	Electrified cracker
Furnace firing duty, MW	1281	995
VHP boiler firing duty, MW	-	-
MP boiler firing duty, MW	-	44
Fuel gas available, t/h	91	91
Natural gas import[a], t/h	~ 2	~ 2
Excess fuel gas, t/h	5.9	25
t of CO_2/t of HVC[b]	0.63	0.55
t of CO_2/t of HVC[c]	0.62	0.48

Notes: a. Natural gas import retained for furnace and flare pilots
b. Based on ISBL firing and electric import at 376 t of CO_2/GWh (Standard EU Emissions Trading Scheme [ETS] figure)
c. Based on ISBL firing and electric import at 26 t of CO_2/GWh (wind/hydroelectric power)

Table 2 Comparison of utility and CO_2 figures for a base and electrified 1500 kTA liquid cracker

Technip Energies believes a better solution than importing hydrogen generated from electrolysis is to convert the cracker fuel gas to a high hydrogen stream, by steam methane reforming (SMR) or auto thermal reforming (ATR). Technip Energies' BlueH2 proprietary technology minimises the energy consumed in the reformer, generates no additional steam, and includes capture of the CO_2. Capture of the CO_2 from the cracker fuel gas is more economical if it is carried out at the outlet of the reformer, rather than from the reforming furnace flue gas, as the pressure at the reformer outlet is higher, and the equipment can be made much smaller, significantly reducing the capital cost.

Electrification

As noted above, when the fired duty of the furnaces is reduced, one of the main consequences is a reduction in the amount of high-pressure steam generated. Consequently, there is unlikely to be sufficient steam to drive the main compressors in the steam cracker. This leads to the use of electric motor drivers for the compressors, or 'electrification' of the cracker.

The use of electric motors as drivers for the main steam cracker compressors is not new. Technip Energies has four reference plants (three grassroots, one revamped) where electric motors are used to drive at least two of the three main compressors. These plants were designed this way to take advantage of the low cost electricity then available in certain countries.

The main challenges with electrifying steam crackers are:

- Experience with electric motors and variable speed drives (VSDs) at the powers required for modern world-scale steam crackers (Technip Energies makes reference to its experience in other industries in which it is a leader, such as LNG)
- Avoidance of harmonic resonance between motor drivers and compressors
- Influence on the electrical supply grid of stopping and starting large motors
- Maintaining compressor efficiencies and speeds when motors are retrofitted
- Accommodating VSD equipment and filters (if required) within plot areas which are close to the motors

Choices need to be made about how many and which compressors to electrify. These depend mainly on the amount of high-pressure steam

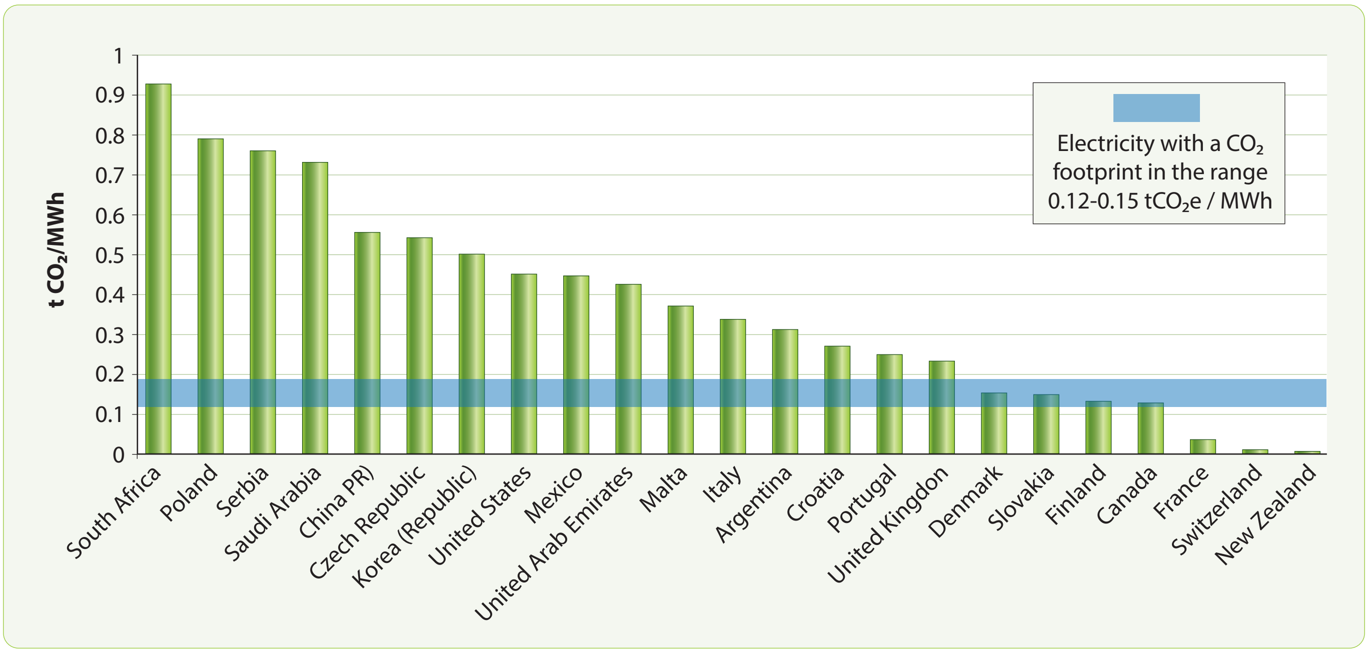

Figure 3 CO_2 footprint for electricity

available and the required compressor speeds and efficiencies.

A key consideration when electrifying crackers is the CO_2 footprint of the electricity available to the plant. The CO_2 reduction benefits of electrification are only fully realised when the electricity available is primarily from renewable sources. **Table 2** gives example figures for a 1500 kTA liquid cracker from a paper presented by Technip Energies at the 2021 Ethylene Producer's Conference.[5]

From **Table 2**, the reduction in CO_2 emissions based on the EU ETS standard CO_2 footprint for imported electricity is 11% and, based on the CO_2 footprint for imported electricity from wind and hydroelectric sources, is 23%. The above figures are not based on Technip Energies' Low CO_2 Furnace, which can provide a further reduction in CO_2 emissions.

The reduction in fuel firing may result in a reduction in fuel gas import or a surplus of fuel gas for export, depending on the feeds cracked and the plant configuration.

Electric furnaces

The use of electricity, instead of firing fuel, to provide the heat for the reactions in the cracking furnaces is being investigated by a number of parties, including Technip Energies. The main issues with the use of electric furnace technology do not concern how the heat is applied to the furnace coils (although these techniques need to be developed and proven), but relate to the amount of electricity required, the CO_2 footprint of the electricity, and the effect on the electricity grid of start-up and shutdown of the cracker.

A simple example of an ethane cracking furnace illustrates the importance of the electricity supply on the use of this technology to reduce CO_2 emissions:

- Flue gas emissions firing 80 mol% hydrogen, 20 mol% methane fuel (typical fuel for an ethane cracking plant without hydrogen extraction) = 10.3 t/h CO_2
- Electrical power required to provide absorbed radiant duty only = 69-86 MW (range depends on electrical conversion efficiency)
- CO_2 emissions required for power supply to give the *same* CO_2 emissions as firing 80 mol% hydrogen fuel gas = 0.15-0.12 TCO_2e/MWh

The required CO_2 footprint for the electricity supply to the site compared to the current CO_2 footprint for grid electricity for various countries is shown in **Figure 3**.[7] Over time, the CO_2 footprint for electricity should decrease, with the phasing out of coal firing and increased use of renewables. Nevertheless, it is clear that to substantially reduce the CO_2 emissions for the complete cracker footprint, it is necessary to source electricity with a very low CO_2 footprint.

Taking the above example of an ethane furnace, for a 1500 kTA ethane cracker, the amount of power required to replace the fired absorbed radiant duty is approximately 560 MW. This does not include the additional 30-90 MWh required for electric motor drives for the compressors, as the steam generation from the cracking furnaces is much reduced. 560 MW is approximately equivalent to the power consumption of 276,000 average EU households. It is clear that start-up and shutdown of the plant represents a significant impact on the power demand local to the site, unless the site is provided with its own dedicated power supply.

As the fuel gas generated in the ethylene plant is not used in the furnaces, another use has to be found for this.

Carbon capture and storage/carbon capture and utilisation (CCS/CCU)

Carbon capture (CC) has been proven in the power industry and can be applied to steam crackers. Apart from the use of high hydrogen content fuels, CC is the only currently commercially proven technology which can achieve very high levels of reduction of CO_2 emissions from steam crackers. Typically, CC can achieve 90-95% CO_2 removal. The CO_2 would be removed from the furnaces and, if required, the auxiliary boilers.

From studies carried out by Technip Energies, it is feasible to operate the steam cracker without the CC plant, therefore the operation and start-up of the steam cracker should not be affected by the addition of the CC plant.

It is straightforward to design a new steam cracker with future provision for installation of CC. The main requirements are:

- Provision of tie-in connections on furnace and boiler stacks
- Provision of plot space for the CC plant, as close as possible to the furnaces and boilers, to minimise the length of the flue gas ducting
- Provision of space for the flue gas ducting and support on furnace and boiler structures

In addition to the above points, the utilities requirements of the CC unit should be considered when the cracker is designed. Whether or not pre-investment is made in the cracker, to allow for the future utilities requirements of the CC unit, needs to be decided on a case-by case basis. Where such investments can be made for relatively low incremental Capex, and future expansion could be very expensive or disruptive to operations (e.g. cooling water intakes and water treatment plants), then pre-investment may be justified.

The conventional routes for captured CO_2 are for oilfield recovery or storage. These routes are only accessible to certain plants, generally those located close to the sea and/or a now unused oil pipeline. An alternative for captured CO_2 is conversion to saleable products,[6] such as methanol and ethanol (which can be converted to olefins) and methane (for export as fuel). Technip Energies anticipates that these routes will be of most interest to cracker operators, as these produce green products which fit with their existing product portfolios, customer base and infrastructure. The technologies are all at early stages of development and only certain parts are currently commercialised.

It should be noted that one of the main Capex and Opex items associated with a conventional CCS plant is the compressor to raise the CO_2 to over 100 bar(g) for discharge to a pipeline for oilfield recovery or storage. When the CO_2 is used to make product, much lower pressures are required and both Capex and Opex can be reduced.

It should be noted that CC does not rely on having low CO_2 electricity available to reduce the CO_2 emissions from the cracker, although the increased utility demand for the CC plant should be met with as low a carbon footprint as possible.

Application of CC does not result in an increase in surplus fuel gas from the cracker.

Associated with CC is oxycombustion, which is the firing of the cracker fuel with oxygen rather than air, in the furnaces and possibly the boilers. The advantage of oxycombustion is that it can eliminate the need for the carbon capture plant, as most of the nitrogen is removed from the flue gas. Some purification of the CO_2 is required to meet typical specifications for CO_2 used for oilfield recovery.

In order to fit oxycombustion into conventional cracking furnace designs, it is necessary to re-circulate flue gas to the furnace burners, to reduce the high flame temperature and provide an adequate volume of flue gas for heat transfer in the furnace convection sections. Consideration also has to be given to the start-up of the furnaces and the cracker, when a transition will need to be made between ambient combustion air and oxygen.

Use of oxycombustion requires an air separation plant to produce the oxygen. The air separation plant has a significant Capex and its own CO_2 footprint. Application of oxycombustion requires the development of burner designs to fire oxygen, and the associated modifications to the furnace design.

Technology	CO_2 reduction achievable	Surplus fuel gas	Estimated date of commercialisation	Remarks
Firing hydrogen from reforming	65-85%	No	Now	Requires a route to use CO_2, CO_2 reduction depends on CO_2 footprint of electricity
Firing hydrogen from electrolysis	0-70%	Yes	Depends on progress in cost reduction and increases in size of electrolysers	CO_2 reduction depends on CO_2 footprint of electricity
Electrification	10-25%	Yes (depending on cracker feed slate/ configuration)	Now	Requires a low CO_2 source of electricity
Low CO_2 furnace	30-40%		2023	
Electric furnaces	0-90%	Yes	2025	CO_2 reduction depends on CO_2 footprint of electricity
Carbon capture and storage/utilisation	90-95%	No	Now	Requires a route to use CO_2

Table 3 Summary of CO_2 reduction techniques

Surplus fuel gas

The ethylene cracking process typically generates most of the fuel required for the furnaces. For gas cracking plants, some imported fuel gas may be required, whereas liquid cracking plants typically export fuel gas. As noted above, for several CO_2 reduction solutions, the reduced fuel gas firing within the cracker results in surplus fuel gas. The fuel gas will typically contain 10-80 mol% hydrogen, depending on the feeds cracked.

The surplus fuel gas can be used for power generation in a combined cycle gas turbine (CCGT), which may generate power with a lower CO_2 footprint than the local power grid and the power could be used to power an electrified cracker. However, CO_2 is still emitted, unless CC is added to the CCGT.

Fuel gas can be converted to products; however, the available technologies are not fully commercialised and/or have a low product yield.

Technip Energies believes the best solution is to convert the fuel gas to a high hydrogen product in a reformer, as described above.

Summary

The above CO_2 reduction techniques are summarised in **Table 3**.

Conclusions

A range of possible solutions to reduce the CO_2 emissions from steam crackers has been discussed. Technip Energies believes that a variety of solutions is appropriate, because of different conditions worldwide, in particular the availability of large quantities of reliable, low CO_2 electricity, different time scales for implementation of projects, the different considerations of new build plants and revamps, and the early stage of development of some technologies.

Both CC and hydrogen firing can be retrofitted to existing crackers with relatively few modifications, as the new plant construction is alongside the cracker. Both technologies can be applied to not only the cracker, but other plants in a complex, such as an adjacent refinery.

VIEW REFERENCES

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