Breaking boundaries to decarbonise plant emissions

How refineries are thinking outside the box to curb emissions and build a clear but flexible path through the energy transition

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The petroleum refining industry is under immense pressure to reduce emissions. Collectively, they play a major role in producing atmospheric greenhouse gasses (GHG). Based on KBC's internal model, a facility processing 150 thousand barrels of crude oil per day emits more than 2 million tonnes of Scopes 1 and 2 carbon dioxide (CO_2) from its processes, heaters, and boilers every year.

Further, the E10 gasoline, which contains 10% renewable ethanol and is produced from the facility's gasoline blendstocks, releases more than four times the amount of CO_2 in use compared to the emissions generated during its production, blending, and distribution process. This example highlights the need to consider the product's entire lifecycle when assessing its carbon footprint.

Researchers show that refineries worldwide emitted about 34.1 gigatons (Gt) of GHGs, with a 0.7% annual increase between 2000 and 2021 (Ma, et al., 2023). According to the International Energy Agency, oil and gas operations contribute about 5.1 Gt of carbon dioxide-equivalent (CO_2-eq) each year in total indirect GHG emissions (IEA, 2023). This accounts for 15% of the total GHG emissions in the energy sector.

The impact of human-produced climate change is undeniable. Global oil refineries and petrochemical plants are increasingly addressing their role in this crisis. Their aggressive goals are aimed at reducing their emissions and those of their products. A comprehensive and practical way to achieve these goals and reach net zero is to build a viable roadmap, such as the example in **Figure 1**.

As Figure 1 shows, a one-size-fits-all solution does not exist. Furthermore, finding a solution, or the most effective combination of solutions

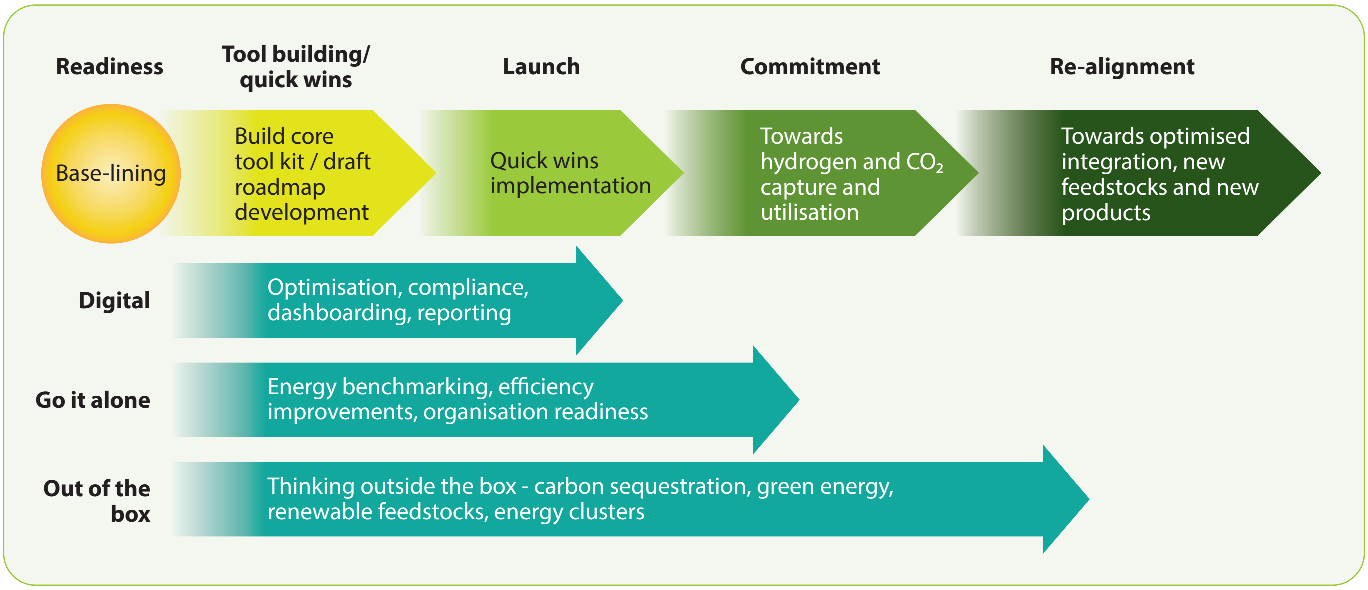

Figure 1 Roadmap to net zero

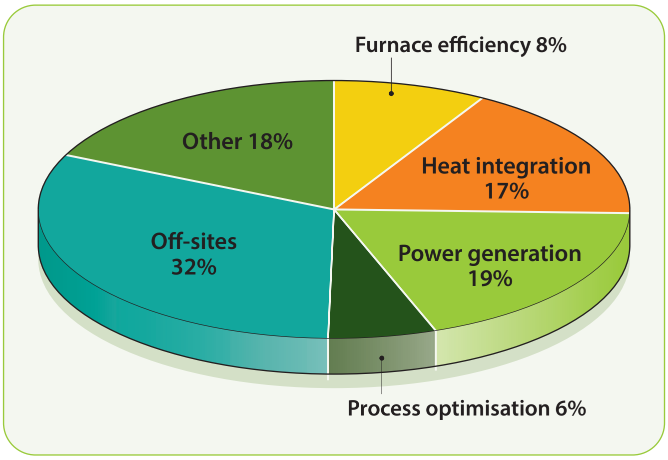

Figure 2 Energy efficiency strategies

can be daunting. It demands a substantial investment of capital, time, and co-ordinated efforts to ensure the solution is profitable and sustainable. Most agree that the answers can be found both inside and outside the facility's boundaries. However, the latter option offers the best chance of significant reductions.

To address this rising concern, governments and regulatory bodies worldwide are responding by applying increased pressure for change. They are implementing carbon taxes and offering incentives for low-carbon product credits, among other approaches. These strategies encourage traditional refiners, who prioritise profits in competitive markets, to invest in new technologies, feedstocks, and products.

This article delves into innovative techniques and technologies that go beyond the norm to decarbonise process plant emissions. In other words, operators will need to consider investing in solutions that lie beyond their usual boundaries; they must think outside the box.

Standard emission reductions

Since 1979, KBC has been a reliable partner for clients in the refining and petrochemical industries. The emphasis has been to help its clients improve yields and profits while cutting energy costs. As ever, these industries face constant market pressures due to fierce international competition and the demands for higher returns on capital.

Historically, energy efficiency has proven to be a relatively low-risk, low-capital way to boost margins. As a fortunate side-effect, this approach also lowers energy use per unit of production to reduce GHG emissions. KBC has assisted hundreds of global facilities to decrease their energy consumption. KBC estimates the results from those projects have removed more than 400 million tonnes of CO_2 emissions. To put this into perspective, it is equal to the annual CO_2 emissions of Australia.

Energy management strategies

Most energy efficiency opportunities fall into a few major categories, including:

1. Furnace efficiency
2. Heat integration (pinch analysis)
3. Process optimisation
4. Power generation system optimisation, as illustrated in **Figure 2**.

Energy efficiency

Continuous improvements in energy efficiency often yield diminishing returns as larger benchmarking gaps close. Based on KBC's global energy benchmarks, even the most wasteful energy users would only achieve a 20-30% reduction in their Scope 1 and 2 emissions if they became top-quartile facilities. This course of action remains the quickest and often least expensive way to start the journey toward eliminating all GHG emissions. As the past few decades have shown, cutting costs and improving margins are sound business objectives. Thus, digging into a detailed review of energy with a 'how low can you go' attitude is always the recommended first step. It is a classic no-regrets move.

However, many refiners are setting targets beyond 30% reductions in their own Scope 1 and 2 emissions by 2030. Achieving these goals requires thinking beyond standard energy efficiency improvements and embracing innovative solutions.

Integrating novel energy efficiency solutions

Energy efficiency is an effective first step along the roadmap to eliminate Scopes 1 and 2 emissions. Refineries and petrochemical systems consume large amounts of energy for chemical reactions, resulting in substantial emissions. Put simply, energy is fundamental to producing fuels and petrochemicals. Once energy consumption is minimised through the energy efficiency benchmarking described above, the remaining challenge is to eliminate GHGs

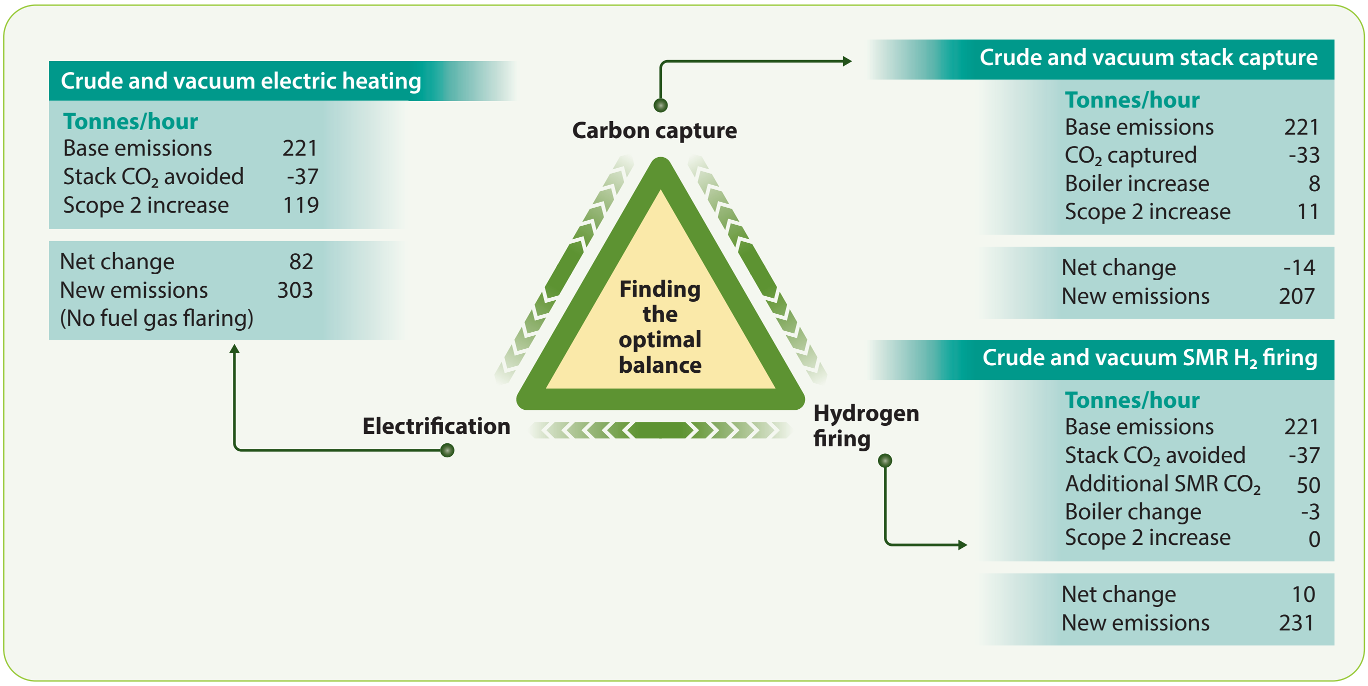

Figure 3 Balancing Scopes 1 and 2 emissions

from the facility. This can be achieved by either providing emission-free energy sources such as zero-carbon intensity hydrogen and electricity or capturing the resulting emissions before they are released into the air via carbon capture.

Misleading internal approaches

Here is the catch. By purchasing more electricity from the grid to energise modified fired heaters, the increase in Scope 2 emissions outweighs the decrease in Scope 1 emissions, as shown in **Figure 3**. This scenario leads to higher product carbon intensities. Using hydrogen-fired

> **By purchasing more electricity from the grid to energise modified fired heaters, the increase in Scope 2 emissions outweighs the decrease in Scope 1 emissions**

heaters and boilers also raises CO_2 emissions due to the fossil energy required to operate the steam methane reformer (SMR) combined with the CO_2 emissions produced by the reaction. If natural gas is purchased and the SMR is used to produce the necessary hydrogen, CO_2 emissions will increase. Even with systems such as amine absorption in place, only half of the expected CO_2 may be captured. This is due to the extra boiler load required for amine regeneration steam and the electricity needed for compressing the captured CO_2.

After energy efficiency improvements are completed, the ‘going-it-alone’ strategy faces fast-diminishing returns. To further reduce emissions, solutions from outside the facility gates must be sought. This approach incorporates new low-carbon energy sources like wind and solar power and uses low-carbon hydrogen produced from electrolysers that employ ‘green’ electricity. Another option includes capturing CO_2 emissions and either using them as chemical process feedstocks or sequestering them in the earth’s crust. Solutions must be explored outside the facility’s boundary.

Outside-the-box approaches

Carbon capture (CC) is a mature technology that carries low risk and reliable operations. The downside of the approach is that these units can require large areas of plot space near the emissions source because of the size and cost of the towers and ducting. Often, that plot space is unavailable. Furthermore, they are capital intensive. For instance, recent projects aiming to capture 1 million tonnes of CO_2 per year cost about USD 500 million, and that is only the beginning. Finding a destination for the captured CO_2 is equally as important to prevent its re-entry into the atmosphere.

An obvious solution is to use the compressed CO_2 as a chemical feedstock (CCU). Several existing and emerging technologies could fit this purpose, as illustrated in **Figure 4**. KBC has modelled nine of the most promising technologies and continues to explore more pathways. To date, no single solution has been implemented on a large scale, largely due to the high cost related to the hydrogen consumed, as the proposed routes often use large amounts of low-carbon intensity hydrogen. This hydrogen is estimated to be at least four times more expensive than SMR hydrogen. It is also projected to remain more expensive unless subsidised by regulatory initiatives such as the US Inflation Reduction Act (IRA) of 2022. The most attractive economic destinations are those that require less hydrogen due to the high cost of green hydrogen, and some of these, such as polycarbonates, have limited global demand. Therefore, introducing market incentives, either through government mandates or commercial branding, will be required to achieve large-scale deployment of these e-fuels and e-chemicals. Note that such mechanisms are already in place to produce sustainable aviation fuels from CO_2 pathways in the EU and the US.

Carbon capture and storage initiatives

Carbon sequestration (CCS) and enhanced oil recovery (EOR) involve capturing and storing CO_2 in a place where it cannot be released back into the air. The compressed emissions are piped to an injection point and stored in underground spaces, such as depleted oil and gas fields. To encourage adoption, the US IRA offers attractive incentives reaching USD 80 for every tonne of CO_2 removed this way. Access to the pipelines that transport CO_2 to the injection point is key. Shipping CO_2 to injection points is another option, but those solutions pose more challenges, given the costs. According to KBC, CCS and EOR projects serve as cost-effective solutions to reduce emissions, particularly if regulators continue incentivising their development.

Electrification only makes sense from an emissions reduction standpoint if the source of the electrons is low- or zero-carbon

Electrification

Another viable energy source is electrification. Electrification only makes sense from an emissions reduction standpoint if the source of the electrons is low- or zero-carbon. Solar, wind, hydro, tidal, and nuclear power all meet these criteria and are under consideration. The variable nature of some non-nuclear sources is a challenging match with an operating facility's critical and constant electricity demand. Technologies to use electric heating to replace fired heaters and boilers are being improved for safety, reliability, and scale. Electric olefin crackers are being built, and KBC expects the use of electrical heat to expand throughout the refinery and petrochemical industries.

#	Name	Main product	Non CO_2 feeds
1	Methanation	Methane	H_2
2	Methanol	Methanol	H_2
3	Fischer-Tropsch	Syncrude / SAF	H_2
4	Oxo synthesis	Butanal	Propylene, H_2
5	Carbonation	Building material	Steel slag
6	Xylenes	Mixed xylenes	H_2
7	Urea	Urea	Ammonia (NH_3)
8	Polyols	Polyether carbonate polyol	Propylene oxide (PO)
9	Polymeric carbonates	Polypropylene carbonate (PPC)	Propylene oxide

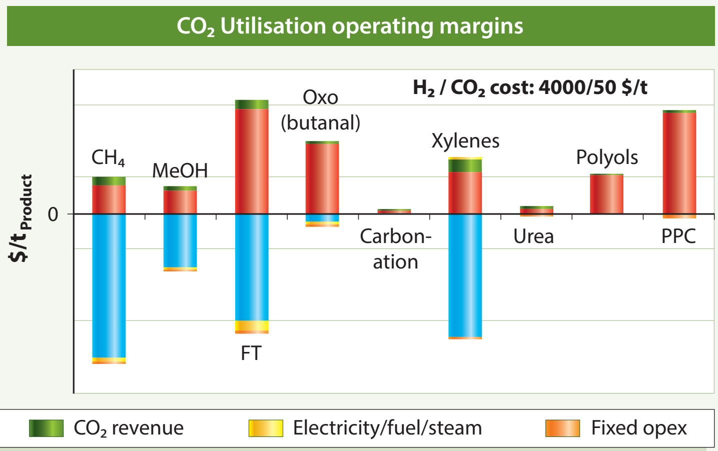

Figure 4 Nine promising technologies to compress CO_2 and CCU operating margins

Electrolyser technologies
Electrolyser technologies are being developed and deployed on a greater scale, resulting in an increased availability of electrolytic ('green') hydrogen. By using capacitors and storing and deploying electrolytic hydrogen, the challenges caused by the inherent variability of environmentally derived electricity can be more effectively managed in refineries and petrochemical facilities. One promising approach involves using electrolysers to convert green electricity into green hydrogen, which can be used as a cleaner alternative to carbon-fuel gas. Additionally, the oxygen produced from this process can replace air in traditional fired heaters. This method offers the added benefit of producing pure CO_2 in the dried flue gas, making it easier and less costly to capture.

Low-carbon hydrogen
Using low-carbon intensity hydrogen as an energy source presents an attractive pathway to reduce Scope 1 emissions. Retrofitting fired heaters with modified burners allows up to 60% of the fuel to be replaced with hydrogen, resulting in a direct reduction of carbon emissions. However, transitioning to 100% hydrogen would require redesigning and rebuilding the heaters, leading to higher capital costs. As mentioned, low- or zero-carbon intensity hydrogen is still more expensive than hydrogen derived from an SMR and the cost gap is expected to persist. To offset this cost, facilities might benefit from generating carbon emissions credits needed for regulatory compliance. In the US, the IRA offers strong incentives to produce low-carbon intensity hydrogen, which should further reduce switching costs.

Embracing system-wide collaboration
These solutions require substantial activity beyond the facility, as shown in **Figure 5**. This technique includes having access to pipelines, low-carbon fuels, and being well-versed in regulatory requirements and incentives. Any proposed solutions must be seamlessly integrated into the facility's current and future operations and flow schemes, and align with the external environment in which the facility operates.

Vision into reality
Due to their interconnected nature, it is crucial to have an integrated picture of the problem and possible solutions. The use of electric heaters, for example, can increase overall emissions on site. Furthermore, capturing emissions in

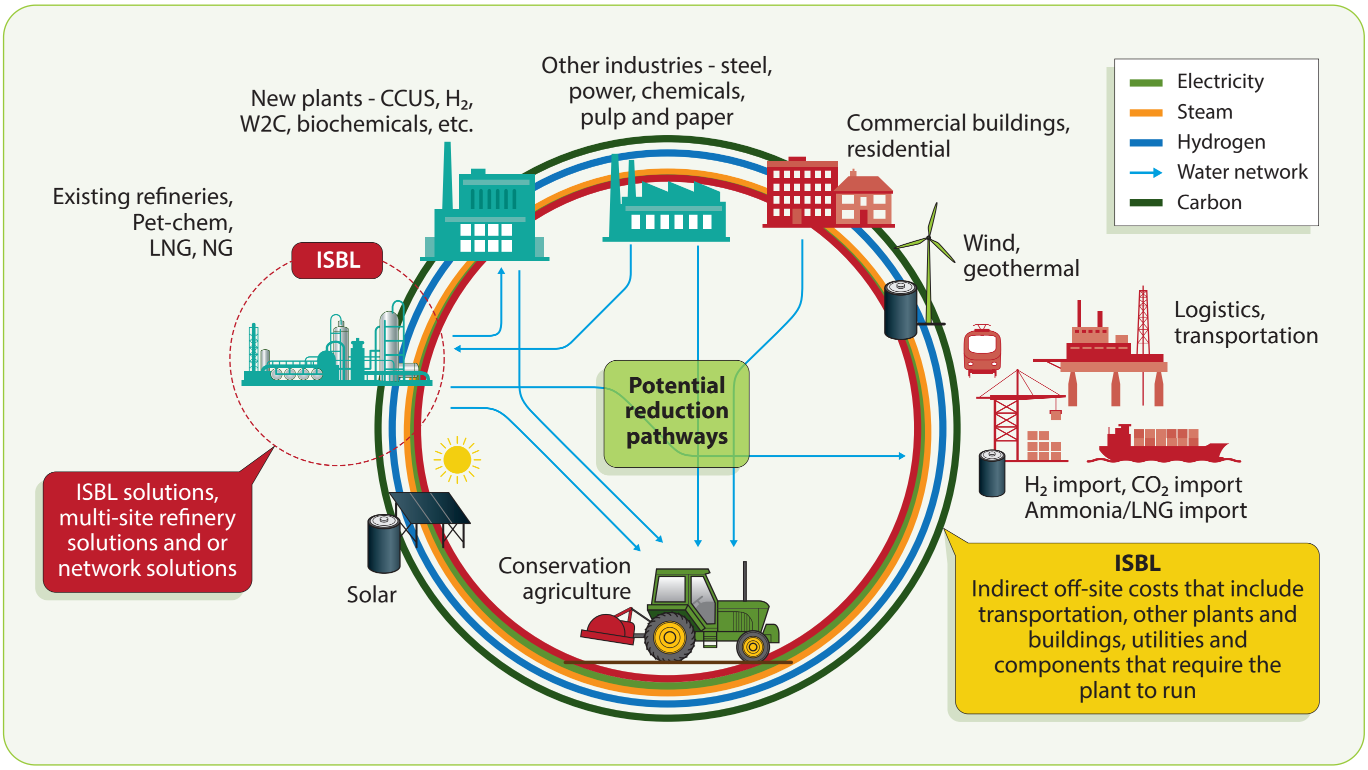

Figure 5 System-wide collaboration for potential emission reduction pathways

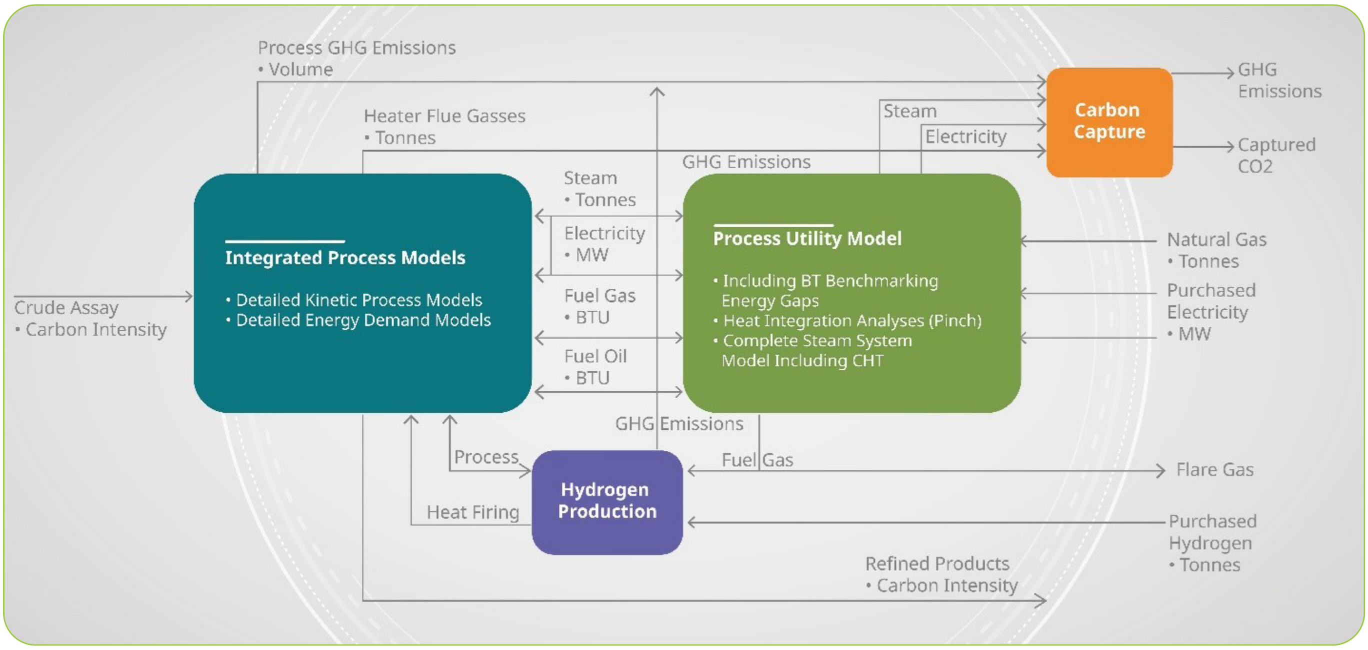

Figure 6 Integrated Process, Energy, Emissions, and Economics Model (IP3EM)

an amine absorption process also increases emissions in the steam boilers. If excess fuel gas must be flared, displacing fuel gas with low-carbon intensity hydrogen is not a viable emissions reduction strategy.

Integrated Process, Energy, Emissions, and Economics Model

To explore ways to reduce emissions within the plant, KBC uses an integrated simulation model called the Integrated Process, Energy, Emissions, and Economics Model (IP3EM). As shown in **Figure 6**, this model considers the energy requirements of the process, the utility system that satisfies that demand, and the emissions that result. By adapting the IP3EM to match a facility's processes and utility systems, KBC simulates the location and characteristics of facility emissions.

Success story

A large European refinery uses the IP3EM approach adapted to its own operations to understand and map the opportunities for reducing emissions. The process starts with energy efficiency improvements and moves towards adopting electrification, green hydrogen solutions, and CCU opportunities. The model is accurate and credible, allowing it to simulate a range of reduction solutions and impact on the whole facility. Furthermore, it is adaptable to suit different scenarios, such as the use of electrolysers, incorporating renewable feedstocks, and the use of low-carbon products. This approach serves as a fundamental and evolving tool for building the refiner's decarbonisation roadmap.

Similarly, this IP3EM approach is being used alongside lifecycle analysis tools, such as the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model, to simulate the impact of incorporating renewable feedstock and product pathways into a refiner's business model. This analysis helps determine the impact on product carbon intensities and compliance with Scope 3 fuel emissions incentives and mandates. Ongoing improvements to the approach involve simulating emerging technology solutions, such as renewable diesel and sustainable aviation fuel processes, plastic pyrolysis, woody biomass gasification, and Fisher–Tropsch processes.

The potential to reduce emissions collectively, between neighbouring plants, shows promising routes towards achieving net zero emissions. KBC applies its IP3EM and energy optimisation tools to analyse complex networks like those found in large ports or industrial hubs. By simulating large-scale systems involving diverse facilities such as gas separation plants, oil refineries, petrochemical plants, and power stations, we gain a deep understanding of approaches to avoid, capture and sequester GHG emissions. These models support collective action among companies around ports and industrial hubs. They also help build wider networks and establish connections with external stakeholders, including regulatory agencies, that are crucial to the success of such projects.

KBC is engaged in two such projects, one in Europe and one in Japan, aimed at building these larger networks. Additional projects are under discussion.

Outside-the-box thinking leads the way

Refiners and petrochemical producers are leading the way with their efforts. How? They are adopting energy efficiency solutions that reduce energy use and boost energy productivity while decreasing GHG emissions. They are also using outside-the-box thinking to capture and sequester carbon emissions from their operations, particularly as more stringent regulations on GHG emissions are being enacted around the globe.

Roadmapping paths to net zero, guided by a robust analytical set of tools, such as IP3EM, is critical to build a clear but flexible path through the energy transition. The route is uncertain, and many factors, from consumer demand and new technologies to changing regulatory pressures and incentives, will change each company's optimum path. While these paths begin within the plant's traditional fence line, they will involve solutions that lie outside it. Exploring and evaluating those external solutions early will lead to a comprehensive picture of the best way forward. Using credible and robust models to evaluate new solutions in ever-changing markets and regulatory environments is the best way to remain flexible and assured of a successful journey.

> **Roadmapping paths to net zero, guided by a robust analytical set of tools is critical to build a clear but flexible path through the energy transition**

References

IEA. 2023. Emissions from Oil and Gas Operations in Net Zero Transitions. IEA. [Online] May 2023. https://iea.blob.core.windows.net/assets/743af33c-b2f5-4a93-a925-1b08f6438e61/

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