THE DOWNSTREAM DEBATE: DECARBONISING HYDROCARBON PROCESSING

Andrew McMullan and Michelle Wicmandy, KBC, a Yokogawa Company, provide details for how to deploy a comprehensive decarbonisation toolset.

The global refinery industry is a cornerstone of the world economy, with a capacity exceeding 100 million bpd in 2023, nearly doubling since 1970. Despite its significance, the industry faces challenges in maintaining profitability due to capital-intensive operations, narrowing margins, and stringent environmental regulations. These factors are requiring refiners to adopt new technologies, especially those aimed at decarbonisation and the energy transition.

The push for net zero

The global push for decarbonisation has put significant pressure on the downstream hydrocarbon industry worldwide. According to the International Energy Agency (IEA), oil and gas operations account for approximately 15% of total energy-related emissions, equivalent to 5.1 billion t of greenhouse gas (GHG) emissions.

The IEA's Net Zero Emissions by 2050 scenario calls for a reduction in the emissions intensity of oil and gas operations by over 50% by 2030. This emphasises the critical role the oil and gas industry must play in driving down emissions as nations continue to pursue their energy transition and decarbonisation goals. However, achieving these targets requires a comprehensive strategy that aligns facility operations with decarbonisation objectives.

To address these challenges, refiners must take a coordinated, two-pronged approach that integrates strategy with operations, as shown in Figure 1. This approach involves improving the performance of today's facilities while planning for the sustainable development of future operations. By intergrating decarbonisation strategies with facility goals, refiners can achieve measurable progress toward sustainability. Note that the text in the green discs in Figure 1 (Energy Mgmt, Report H2, etc.) is for illustrative purposes only.

The decarbonisation journey

For current operations, refineries often focus on energy management and emissions reporting and other operational improvements. Establishing baselines, enhancing visibility, automating processes, and driving continuous improvement are key to achieving short-term gains.

For instance, a recent project exemplifies this balanced approach. By keeping one foot in the present and another in the future, a mid-sized refinery addressed energy costs, asset reliability, and operational inefficiencies. Through targeted workshops, the refinery prioritised initiatives such as quick-win energy efficiency improvements, yield optimisation using digital tools, and decarbonisation planning during turnarounds. This dual-focused strategy illustrates how refiners can align current improvements with long-term decarbonisation goals.

For future facilities, the emphasis shifts to green processes and advanced technologies that support long-term transformation and net zero goals, as highlighted in Figure 1. These innovations are implemented within a structured strategic plan and roadmap.

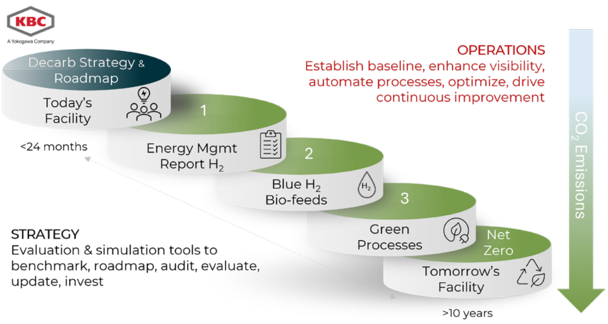

Figure 1. The decarbonisation journey to coordinate strategy with facility operations.

The integrated energy transition toolset

To optimise current facilities and develop an energy transition investment strategy, an integrated toolset is necessary. This toolset must be able to address process and emissions performance of new technologies, their integration with site-wide systems, strategy-driven energy and emissions performance, and process and energy optimisation for both current and future operations.

Proven simulation technologies can be used to develop an Integrated Energy, Emissions, and Economics model (IE3PM). During the initial phases of strategy development, the IE3PM evaluates process configurations, emissions impact, and carbon intensity with consistency across a range of options.

Subsequently, the same models are leveraged and deployed as online digital process and energy system twins to monitor performance, facilitate optimisation, and report improvements.

By employing this comprehensive energy transition toolkit, refiners can align their energy transition strategies with operational goals to drive measurable progress toward sustainability, as depicted in Figure 2.

The role of digitalisation

Use of digital tools, such as IE3PM, provide both a consistent basis for evaluating options during strategy and roadmap development, as well the basis for operationalising digital twins – virtual replicas of physical assets – for monitoring, optimisation, and reporting purposes. They help operators assess decarbonisation strategies, predict their impact, and align operational changes with strategic goals.

They also improve productivity and decision-making across the strategy development and operations lifecycle.

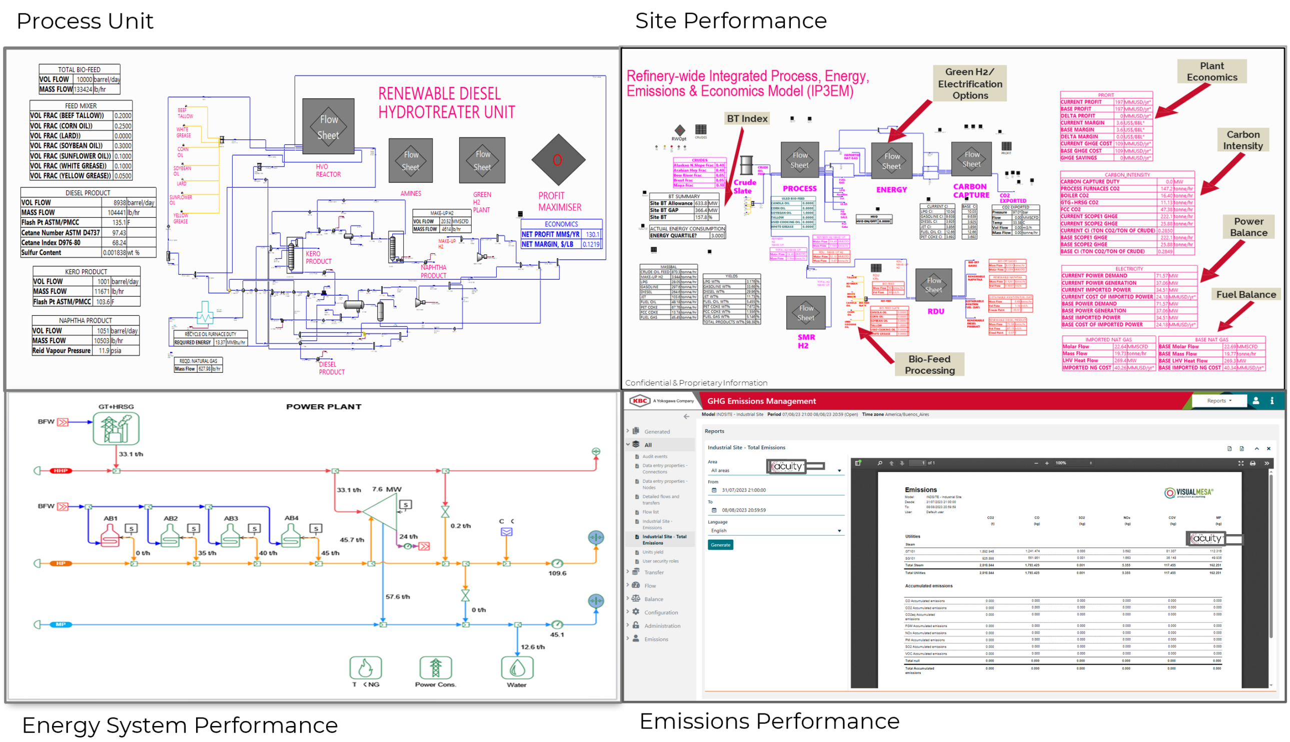

Figure 2. An example of an integrated decarbonisation toolkit for design transformation.

The following sections explore the key components of this toolset, emphasising how these tools can be utilised throughout the journey to net zero.

Process simulation and modelling tools

Advanced process simulation and modelling tools enable engineers to create detailed models of hydrocarbon processing units, including renewables processing. The growing use of digital twins in the industry stems from their ability to identify optimal operating conditions, predict the impact of process changes, and accurately evaluate modifications. They enable continuous performance tracking and immediate identification of deviations to ensure optimal operation. Improvements in operations, asset management, and maintenance lead to savings, making the digital twin an essential tool in oil and gas. By leveraging real-time data collection, analysis, and simulation, digital twins create a rich environment for identifying cost savings. According to the authors' recent research, this technology has been reported to cut unplanned operational downtimes by up to 20%.

Energy management systems

Effective energy management is crucial in the pursuit of decarbonisation. With the IEA estimating that 75% of downstream emissions can be mitigated using existing technologies, the importance of implementing these solutions cannot be overstated. From leak detection to infrastructure upgrades, every step towards optimising energy consumption is a step closer to meeting environmental goals. Advanced energy management systems track and optimise energy consumption across refinery facilities. When integrated into a digital twin framework, real-time energy data use is continuously compared against the optimal model to immediately identify deviations. This approach helps operators take corrective action to improve energy efficiency, thus reducing Scope 1 and 2 emissions.

Carbon capture and storage

Carbon capture and storage (CCS) is a crucial technology in the decarbonisation toolkit. Capturing and storing carbon dioxide (CO_2) emissions from processing units is essential for long-term sequestration. However, the successful integration of CCS into the overall process requires sophisticated modelling to evaluate feasibility and optimise performance. Additionally, the modelling and integration of other low-carbon process technologies enables other decarbonisation strategies to be explored.

Real-time data analytics and monitoring

When integrated into digital twins, real-time data creates a dynamic environment for performance tracking and optimisation. By continuously comparing real-time operational data against the simulated digital twin model, these virtual replicas detect anomalies, predict equipment failures, and identify inefficiencies in the physical assets. This monitoring enables proactive maintenance and optimisation. For example, by analysing sensor data and process parameters in the digital twin, operators anticipate impacts on carbon intensity and take corrective actions.

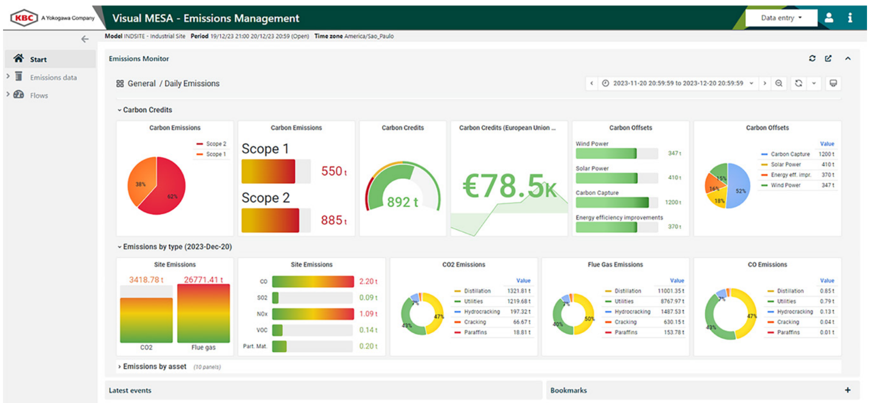

Figure 3. Measuring and reporting emissions across supply chains.

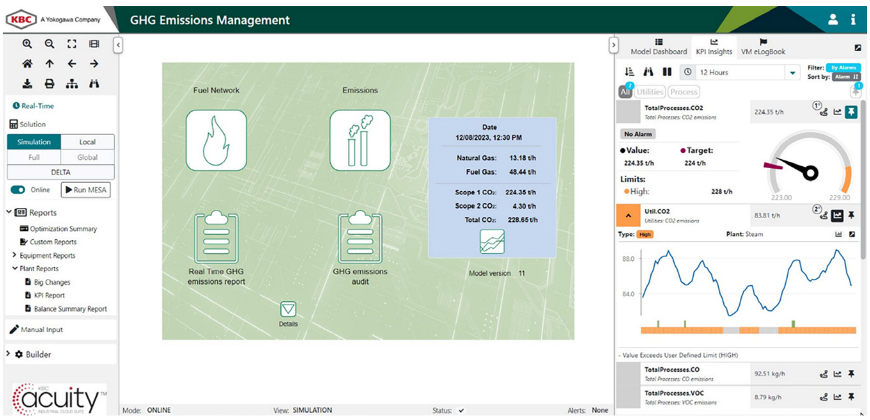

Figure 4. Greenhouse gas (GHG) emissions management software monitors energy use and emissions output.

Regulatory compliance and reporting tools

Maintaining regulatory compliance and accurate emissions reporting are essential components of sustainable refinery operations. According to the World Economic Forum, one of the key drivers for decarbonisation is measuring and reporting emissions across supply chains.

Advanced compliance and reporting tools offer significant support in addressing these challenges, as shown in Figure 3. By integrating these tools within digital twin frameworks, companies can monitor performance in real-time, ensuring alignment with regulatory requirements. This proactive approach allows organisations to identify and address deviations swiftly, demonstrating a commitment to responsible environmental stewardship. Such tools simplify and streamline emissions documentation, aligning with international standards for carbon footprint assessment, life cycle analysis, and GHG accounting.

Bridging strategy and execution

Digitalisation bridges the gap between strategy and execution by providing a consistent view of performance across all phases – from strategy and design to operations. Once in operation, real-time data is integrated into both operations and investment decision making. Advanced tools such as energy management systems and digital twins identify inefficiencies, simulate interventions, and seamlessly implement changes accurately and efficiently.

The following case studies illustrate how digital tools and strategies are applied to achieve measurable decarbonisation outcomes in the hydrocarbon industry.

Case study 1: minimising consumption and emissions

The impact of digital systems is exemplified by a leading refinery with a production capacity of 300 000 bpd. This refinery prioritised decarbonisation and made significant strides in reducing its GHG emissions by leveraging advanced emissions management technologies. Figure 4 shows how the refinery continuously optimises, schedules, and monitors its energy use and emissions output.

Key achievements from these initiatives include:

- Automated, real-time emissions monitoring.
- Comprehensive tracking of Scope 1 and 2 emissions.
- A 6% reduction in electricity consumption.
- A 268 000 t decrease in CO_2 emissions.
- A 41% reduction in sulfur emissions.

These results demonstrate how advanced tools balance productivity with environmental responsibility while preparing refiners for stricter regulations.

Maximising production through digital twin technology

Digital twin technology forms the backbone of effective decarbonisation strategies. In the context of decarbonisation, digital twins simulate the impact of various strategies on plant operations and emissions to provide a dynamic platform for testing different scenarios. By integrating data from sensors and control systems, digital twins optimise process parameters, improve energy efficiency, and reduce emissions without disrupting operations. Real-time data allows for immediate response to deviations from target performance to ensure continuous improvement.

Case study 2: digital twins in action

The impact of digital tools is illustrated by a large European refining complex that is on a decarbonisation journey to reduce its Scope 1 and Scope 2 CO_2 emissions by at least 30% by 2030. The project began in 2017, focusing on over 100 energy efficiency and CO_2 reduction opportunities. An IP3EM was used to evaluate the refinery's configuration and assess the feasibility of technologies such as carbon capture, electrification, and the use of green and blue hydrogen, as shown in Figure 5.

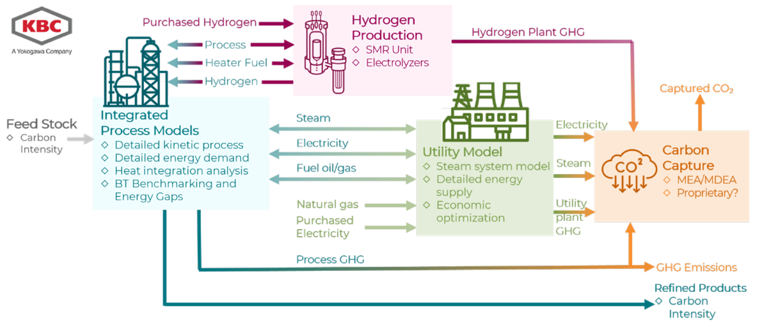

Figure 5. Integrated Process, Energy, Emissions, and Economics Model (IP3EM).

A digital twin framework played a key role in the project, enabling the team to integrate real-time data with the IP3EM model. This advanced simulation tool allowed for a comprehensive analysis of current operations and the predictive assessment of proposed strategies. By simulating various scenarios, the refinery was able to prioritise interventions based on their impact on emissions, energy efficiency, and economic performance.

The following results were achieved:

- A targeted reduction of Scope 1 and Scope 2 CO_2 emissions by at least 30% by 2030 were reported via combining energy efficiency measures and adopting technologies such as carbon capture, green electricity, green and blue hydrogen, and electrification.
- Over 100 energy efficiency and CO_2 reduction opportunities were identified and prioritised to balance quick wins and long-term strategies.
- A comprehensive roadmap was developed to assess the refinery's configuration and provide insights into emissions reduction technologies and their potential impact.

The results demonstrate how advanced modelling and predictive analytics support a structured approach to reduce emissions while maintaining economic viability.

Conclusion

The downstream hydrocarbon industry stands at a pivotal moment where the urgency of decarbonisation and the energy transition aligns with the transformative power of digitalisation. Refineries face mounting pressure to reduce emissions while maintaining operational and economic viability. By adopting integrated tools and strategies, refiners can improve asset performance, prioritise energy efficiency, and align operations with long-term sustainability goals.

The case studies within this article demonstrate the practical impact of digitalisation and how digital tools help refiners optimise processes, reduce emissions, and adapt to changing regulations.

The path forward requires a strategic blend of tailored approaches, effective change management, and continuous technological upgrades. As the case studies and industry trends demonstrate, the benefits of embracing digital transformation are compelling. The refineries that lead in this digital revolution will not only meet their decarbonisation goals but will also set new standards for operational excellence while Bringing Decarbonisation to Life®. HE