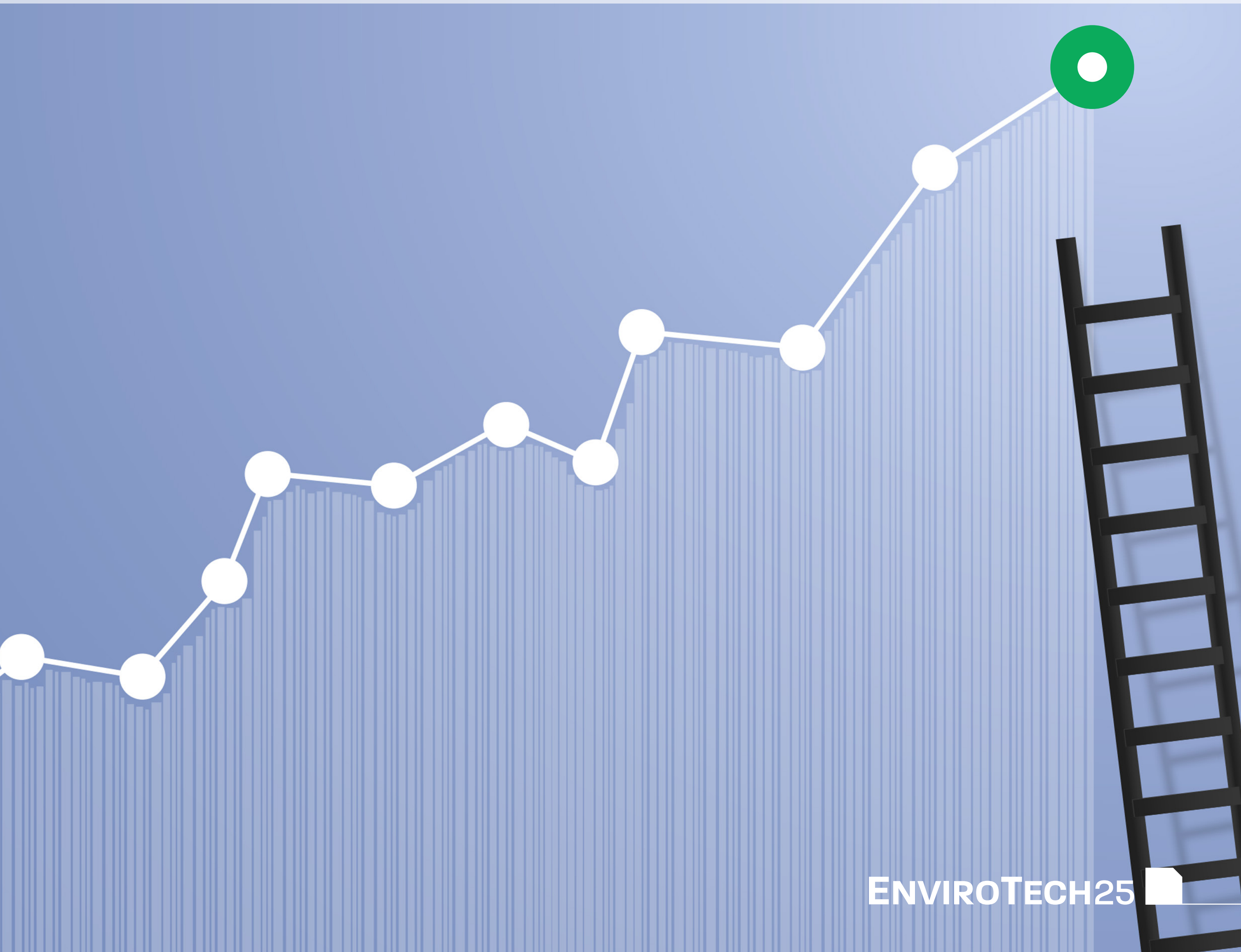
GREEN HYDROGEN AT SCALE

Nicolas Carrara, Juan Ruiz, and Carlos Ruiz, KBC (A Yokogawa Company), explore the challenges of industrial scale deployment of green hydrogen and how advanced technologies can help operators to cross the chasm.

Refineries face growing pressure to decarbonise and reduce their carbon footprint due to both tightening environmental regulations and shifting market economics. In this sector, traditional steam methane reforming (SMR) remains the dominant method of industrial hydrogen (H_2) production. This process emits an estimated 9 - 12 kg of CO_2 for every kg of H_2, which often makes it a major contributor to a facility's overall carbon footprint.[1, 2]



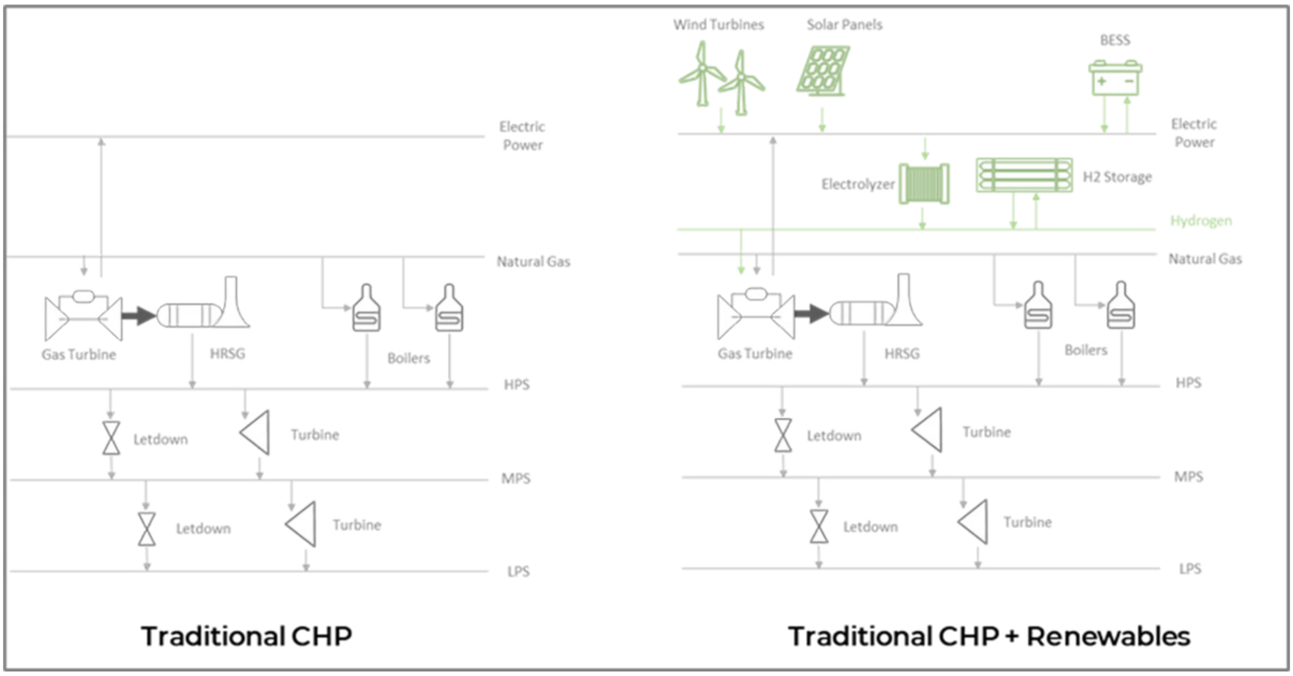


Figure 1. Traditional/renewables utility systems.

Regulatory frameworks are tightening worldwide. In the US, the Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP) requires refineries and other large emitters to measure and disclose facility-level CO_2 emissions, raising scrutiny on H_2 produced through carbon-intensive pathways.[3] At a global level, the International Energy Agency's (IEA) Net Zero by 2050 Roadmap sets out a blueprint with H_2 demand projected to soar.[4] Demand could increase by as much as 105 million t, with more than 200 million t forecast under the IEA's Net-Zero Emissions (NZE) initiative. These projections highlight hydrogen's pivotal role in the energy transition. In Europe, the Fit for 55 legislative package enshrines binding targets to cut greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels.[5]

These frameworks create both regulatory pressure and market momentum, signalling that carbon-intensive H_2 is becoming a liability while green H_2 emerges as both a compliance solution and growth opportunity.

Green H_2, produced via renewable-powered electrolysis, can dramatically reduce lifecycle GHG emissions to about 1 kg CO_2 per kg H_2 from wind and up to 2.5 kg CO_2 per kg H_2 from solar, according to recent lifecycle assessment studies.[6,7,8,9]

Despite these environmental advantages, the shift from pilot scale installations to industrial scale, certifiable green H_2 production faces multiple operational challenges. Operators must contend with the variability of renewable electricity supply, integration with existing combined heat and power (CHP) and grid infrastructures, the capital intensity of electrolyser deployment, the establishment of reliable demand-side contracts, and the implementation of transparent certification and traceability frameworks. Furthermore, production optimisation under dynamic market conditions, and ensuring interoperability across digital platforms, remain critical to achieve economic viability and regulatory compliance.

This article examines those challenges and how they can be addressed through combining digital simulation tools, real-time and multi-period optimisation, certification frameworks, and financial modelling. Together, these capabilities help bridge the gap between design and operation to ensure green H_2 plants remain efficient, flexible, and competitive in rapidly evolving energy markets.

Integrating renewables with CHP systems

Refineries and other industrial sites are increasingly integrating renewable energy sources and lower-carbon H_2 production methods to meet decarbonisation targets. In this way, the typical CHP plants must manage renewable intermittency while ensuring steady H_2 supply to downstream processes. Due to its criticality, these systems require precise energy management to optimise H_2 output while stabilising the broader utility system. Integrating variable renewable energy sources with existing CHP systems requires advanced energy management strategies to maintain process stability and avoid costly shutdowns.

By employing real-time and multi-period optimisation techniques along with appropriate forecasts, operators align CHP output with fluctuating renewable supply, using storage assets or flexible loads to buffer variability while maximising profit. This approach ensures stable production while minimising emissions across the entire energy network.[10] By mid-century almost 90% of global electricity generation will come from renewables, with wind and solar PV together accounting for nearly 70%.[11] This scale of variable generation underscores why holistic optimisation is no longer optional but a necessity.

Real-time optimisation tools help detect inefficiencies and minimise losses, operating in advisory mode or in closed-loop linked to the control layer. Multi-period optimisation in these systems facilitates planning by incorporating price forecasts, equipment availability and maintenance, energy/H_2 demand from the process side, and weather conditions. These tools calculate the optimal operating schedules, estimate monthly natural gas and power use, and support supplier contract negotiations.

Even the best forecasts cannot fully capture market conditions, which is why multi-period planning must be paired with real-time optimisation to keep operations aligned with current market and process conditions.

Grid integration adds another layer of complexity. Renewable variability affects power factors and grid stability, requiring compatibility with power flow simulators to ensure voltage and reactive power stay within feasible limits. Only then can optimisation strategies be reliably implemented in the field.

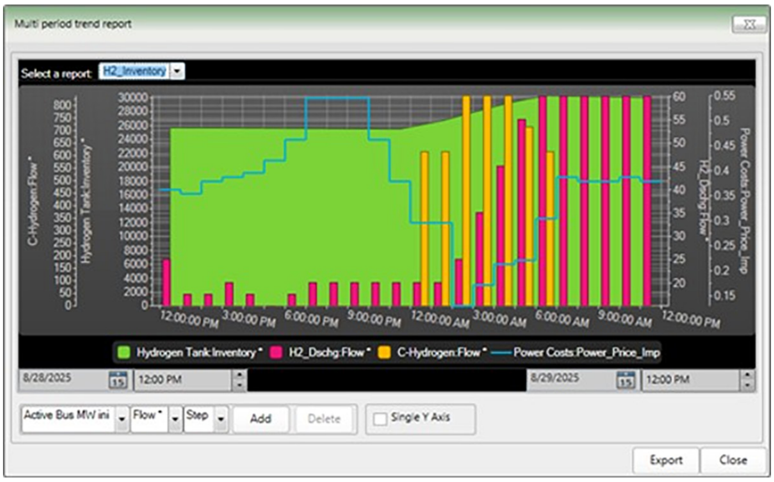


Figure 2. Line-bar chart of the optimal planning for H_2 generation.

As presented in Figure 1, CHP systems are modelled by linking renewables (wind, solar), storage assets (battery energy storage systems [BESS], H_2 tanks), and electrolysers with traditional utilities. Through this approach, operators can combine both multi-period and real-time optimisation to minimise operating costs and/or emissions. The site model must coordinate steam, fuel, and electricity flows across CHP and renewable assets, while also managing H_2 supply from multiple sources to meet process demand.

When grid prices fluctuate or renewable output varies, operators can use storage flexibility (i.e., BESS, H_2 storage tanks, and more) to shift electrolyser loads to off-peak periods. Real-time control reduces operating costs while improving responsiveness to price signals and ancillary service opportunities.

Figure 2 illustrates the optimal planning of H_2 production based on the multi-period optimisation approach. When electricity prices are low, electrolyser output is maximised and H_2 inventories are built up. When prices rise, H_2 is drawn from storage to meet process demand. In this way, optimisation not only maintains reliability but also turns market volatility into a potential source of value.

Figure 3 shows how gas turbine operations interact with solar and wind generation, and how an effective energy management system shapes outcomes. Variability in solar/wind power generation leads to a highly fluctuating break-even price for the operation of gas turbines. Under these conditions, decisions taken solely based on break-even prices, without accounting for multi-period restrictions (such as minimum down times), may lead to less efficient and more costly operations.[12]

Optimal management of multi-commodity contracts

A power and fuel contracts management solution for H_2 plants should enable operators to identify the most advantageous

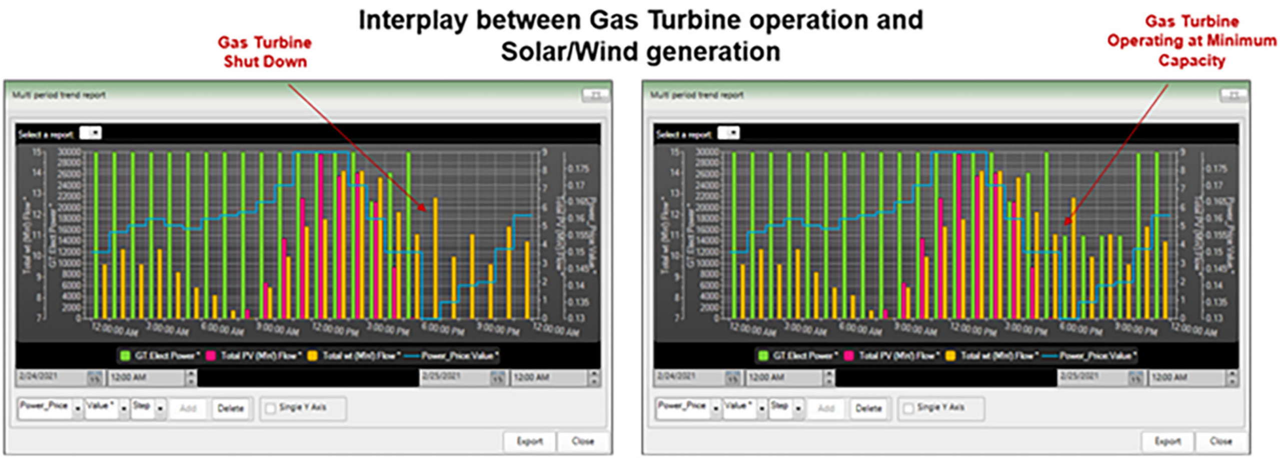


Figure 3. Interplay between gas turbine operation and solar/wind generation.

contracts, incorporate monthly clauses into multi-period optimisation, and test alternatives through what-if scenarios. It must account for electricity and natural gas pricing complexity (such as the split between commodity and transportation costs) and integrate these considerations into production planning. By aligning electrolyser operations with both supply contracts and H_2 offtake agreements, operators can improve cost efficiency, ensure contractual compliance, and maintain a reliable supply.

To achieve this, the system must connect market signals (electricity, natural gas, CO_2, H_2) with a contract database that stores agreements for power purchase, natural gas imports, CO_2 storage, and H_2 offtake. This allows operators to evaluate the most favourable contracts, analyse key clauses such as take-or-pay or penalties, and assess scenarios under varying market conditions.

As shown in Figure 4, multi-period optimisation must cover contract terms, market conditions, and environmental restrictions all together to generate an operations plan for H_2 production. This includes scheduling electrolyser loads, managing H_2 storage and dispatch, coordinating electricity storage and imports/exports, and aligning CO_2 capture and storage activities. The result is a coordinated approach where contracts, markets, and operations are aligned to support economic performance and environmental objectives.

Certification and carbon accountability

Certification anchors the green H_2 value chain. Robust reporting and auditability tools are essential to comply with regulatory frameworks and build market trust. In Europe, the CertifHy[13] scheme provides traceability, transparency, and credibility to the entire green H_2 production chain by certifying both the production method and hydrogen's GHG intensity. This establishes credibility across the supply chain and ensures that emissions calculations are both correct and accurate.

In addition to certification, operators also need tools to monitor performance in real time. Dashboards with detailed analysis capabilities are key to identifying root causes and taking corrective action quickly.[14]

Figure 5 shows how the site's carbon footprint will be affected with (right chart) and without (left chart) management. CO_2 emissions are represented by pink bars, hydrogen export is represented by yellow bars, the carbon intensity of imported electricity is indicated by blue lines, and H_2 storage tank inventories are represented by green areas.

The optimiser/system uses the storage tank capacity to determine over-production of hydrogen during periods of low-carbon intensity of electrical power (i.e., accumulating excess hydrogen in the storage tank) and under-production during periods of high-carbon intensity of electrical power (exporting H_2 from the storage tank). Thus, the net carbon footprint is reduced.

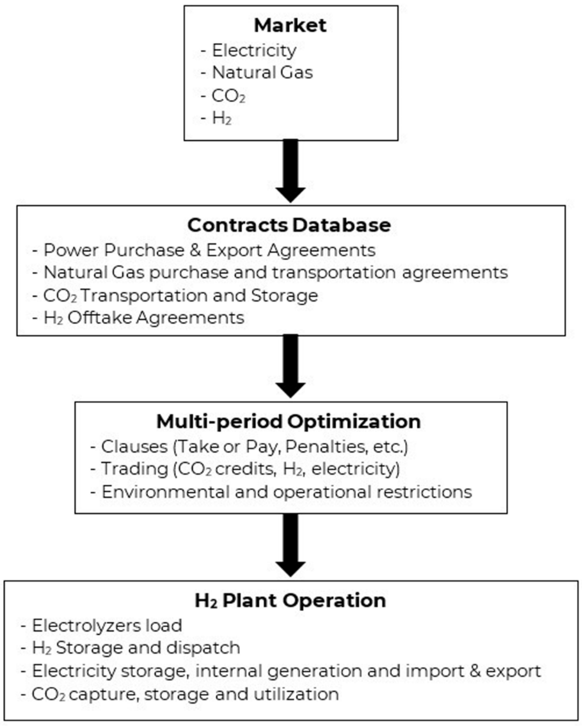


Figure 4. Contract framework and optimisation strategy for H_2 plants.

Figure 5. Hourly carbon footprint in the production of H_2 without and with management.

Ideally, an auditable emissions platform should autonomously calculate cradle-to-gate CO_2 emissions by integrating data from energy systems, electrolysers, and auxiliary units. Emissions reports generated within the system serve as the official records for regulators and certification bodies.

Simulation and training for reliability

At design stage, process simulators enable accurate sizing of electrolysers and storage (BESS, H_2 tanks) and their integration with renewable sources, thereby minimising capital costs and avoiding costly redesigns. Once in operation, advanced monitoring delivers real-time visibility into electrolyser efficiency, degradation rates, and power variability. Process simulators deepen understanding of the physics and chemistry behind H_2 production and support efficient design development.

Dynamic simulation results provide design engineers with insights to improve green H_2 plant engineering. These simulations identify and resolve key challenges to ensure the reliability and safety of the production processes.

The OTS extends this capability by integrating dynamic process models with the actual Distributed Control Systems (DCS) or Supervisory Control and Data Acquisition (SCADA) interface. They provide a safe, realistic platform for operators to practice routine production, start-ups, shutdowns, control tuning, and emergency procedures before plant commissioning. This approach reduces downtime and early operational errors. Operator training with electrolyser banks can improve operational strategies and energy efficiency. For example, including training scenarios covering both safety and optimisation actions, as well as process disturbances, is essential to prepare operators for typical day-to-day operations or to deal with abnormal events.

These tools are particularly critical because practical expertise in green H_2 still remains limited. To achieve meaningful progress toward 2030 energy transition goals, operators must commit to accelerated learning and skill development.

Conclusion

The success of green H_2 relies on more than just installing electrolysers, H_2 storage tanks, renewable sources, and BESS. It demands end-to-end operational excellence, digital integration, and adaptive control strategies. Certification frameworks, advanced optimisation, and operator training are equally critical to ensure that projects move from pilot vision to commercial-scale reality.

Key takeaways for advancing H_2 at scale include:

- Integration matters: combined energy systems must align CHP, renewables, storage, and electrolysers to balance variability while meeting required H_2 demand.
- Optimisation is essential: real-time and multi-period optimisation tools address market and process variability to increase efficiency and save costs.
- Certification builds trust: automated, transparent, auditable emissions accounting ensures compliance and strengthens credibility with regulators and investors.
- Simulation reduces risk: process models and dynamic OTS improve design reliability, operational safety, and workforce readiness.
- Adaptability drives competitiveness: plants that combine technical flexibility with digital intelligence will be best positioned to thrive in evolving energy markets.

Together, these elements support a seamless transition from vision to value. ET

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