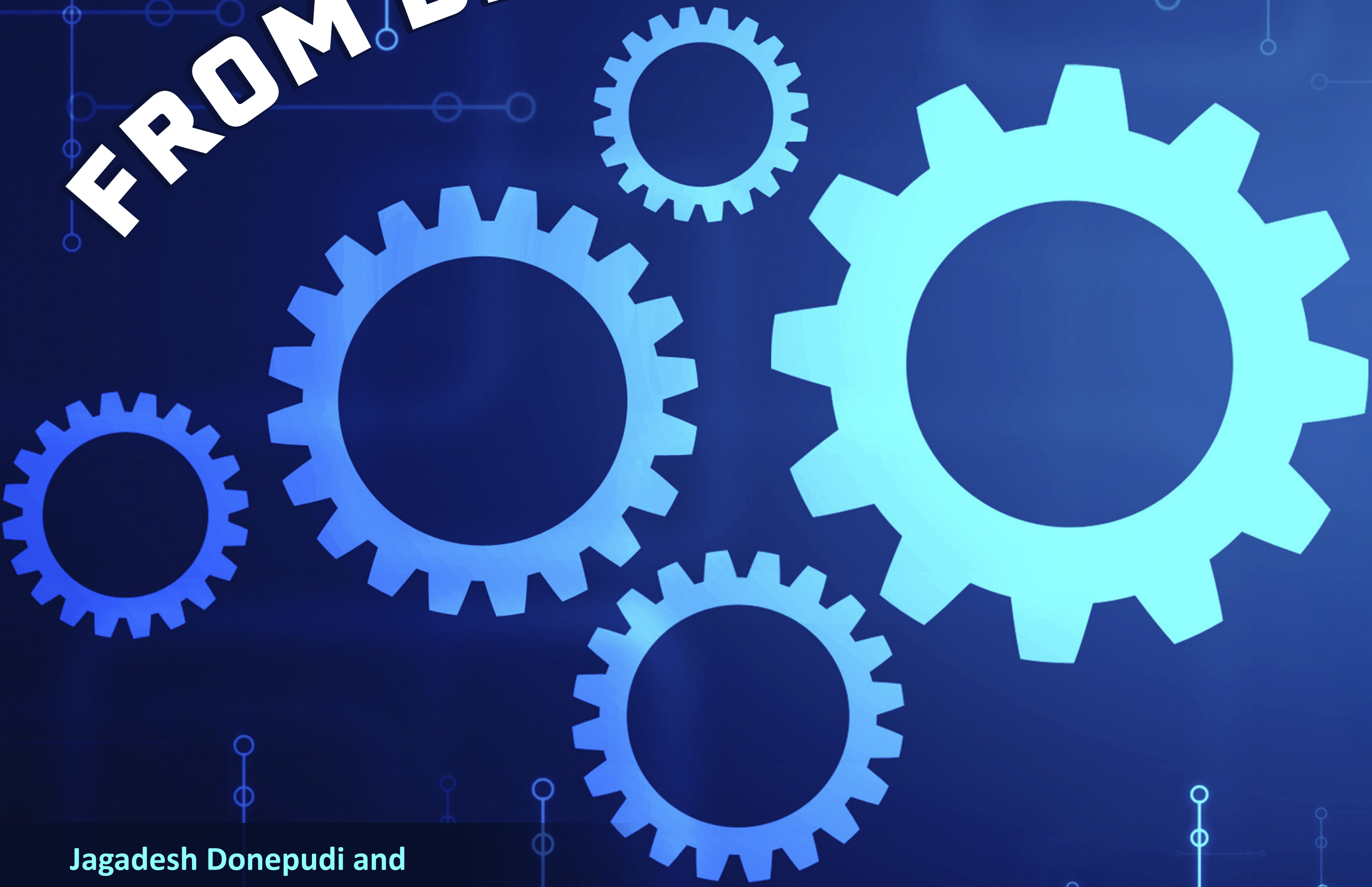
FROM DESIGN TO



Jagadesh Donepudi and Michelle Wicmandy, KBC (A Yokogawa Company), discuss how digital twins can be used to improve operations in green hydrogen projects.

Hydrogen has become one of the most ambitious pillars of the global energy transition. Electrolyser capacity is scaling, renewable power is expanding, and investment accelerates across green, blue, and hybrid hydrogen projects. On paper, the formula appears straightforward: connect renewable electricity to electrolysers, produce hydrogen, store it, and deliver it to industry, mobility, or power markets. In practice, many projects encounter material execution challenges. What looks viable in spreadsheets often proves difficult to operate reliably in the real world. Further, this gap is leading to regret capital.

That gap between design and operation has led to rework, schedule pressure, and scope changes as developers contend with cost inflation, uncertain offtake, and operability and delivery risk.[1]

The challenge is compounded by the market's starting point. Global hydrogen demand remains dominated by industrial uses (notably refining and chemicals), while low-emissions hydrogen production remains limited relative to total demand. Meanwhile, the pipeline of announced electrolyser projects is large. The subset that reaches final investment decision (FID) is significantly smaller – illustrating how quickly 'concept' turns into 'constraints.'[2]

Hydrogen is a system, not a technology

Hydrogen is often discussed as a single technology – an electrolyser here, a storage tank there, a pipeline and a buyer. But a green hydrogen asset is a tightly coupled energy and process system that spans renewable power,

OPERATIONAL RELIABILITY

water, electrolysis, compression, purification, storage, blending, and downstream consumption.

Each layer has its own physics and constraints. In hydrogen, they are interdependent:

- A change in wind or solar output alters electrolyser loading.
- Load cycling influences efficiency, thermal behaviour, and degradation.
- Storage constraints affect dispatch choices and operating envelopes.
- Dispatch affects energy cost, emissions, and contractual reliability.

It is a chain of linked dynamics – power, plant, and product – operating on time-varying inputs and constraints, not design-point conditions. As shown in Figure 1, hydrogen systems link renewable power, electrolysers, storage, and downstream users through a tightly coupled energy-and-molecule network.

Static design in a shifting hydrogen world

For decades, industrial plants have been designed using steady-state cases, equipment datasheets, and nameplate capacities. That approach works reasonably well when feedstocks, utilities, and demand are stable.

Green hydrogen systems are fundamentally different. Renewable electricity is variable. Electrolysers operate across a range of loads and do not maintain constant efficiency at all operating points. Research shows that treating electrolyser efficiency as a constant can materially misestimate hydrogen production because electrolysers spend significant time operating away from design conditions (e.g., variable efficiency overestimates hydrogen production by up to ~20% in realistic models).

Operational reality adds another layer of constraints:

- Startup/shutdown and load cycling introduce wear mechanisms and durability implications.
- Operating strategy choices – such as turning down instead of turning off – can change wear and economics.
- Integration with variable renewables requires more demonstrations and better understanding of lifecycle impacts under real cycling profiles.

Yet, many green hydrogen projects are still evaluated using a limited set of static cases: a design case, a minimum load case, and a maximum load case. These cases are used to size electrolysers, storage, compressors, and power systems. In real operation, electrolysers ramp, idle, and cycle. Storage inventories rise and fall. Demand fluctuates. Control systems intervene. Constraints interact between power availability, equipment limits, and delivery requirements. That disconnect between static design and dynamic operation is where hydrogen projects lose reliability and economic performance.

Hydrogen does not change the need for modelling. It changes the kind of modelling required. As project data matures, design must move from concept-level assumptions to 8760-hour supply-demand profiles, electrolyser polarisation curves, and ramp and start-stop constraints. These polarisation-curve and cycling-dependent models allow renewable variability to be translated into both hydrogen output and electrolyser lifetime impacts. They replace the false assumption of constant efficiency or degradation.

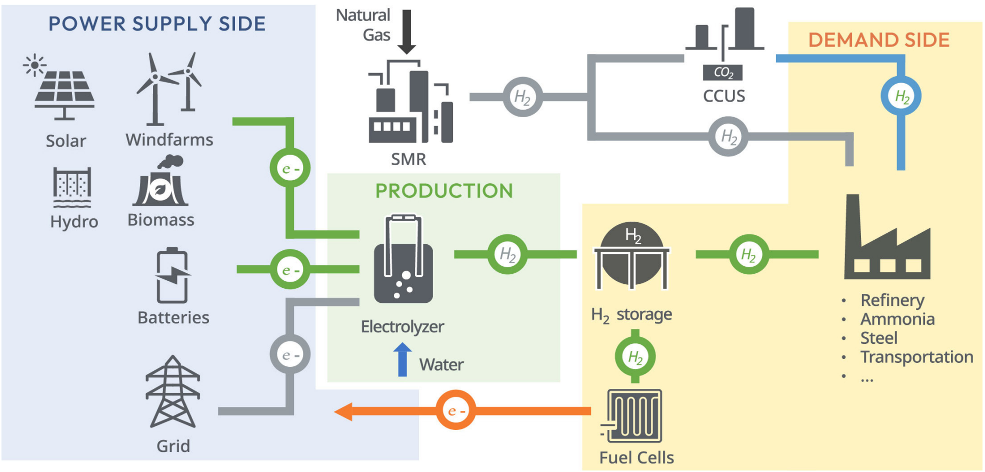


Figure 1. Electrolyser performance and hydrogen output depend on operating conditions.

Uncertain operating data

Once a hydrogen plant is operating, many teams encounter a second challenge: the actual state of the system is often less certain than the data suggests.

Hydrogen is difficult to measure accurately under dynamic, variable conditions:

- Temperature and pressure swings affect density and inferred flow.

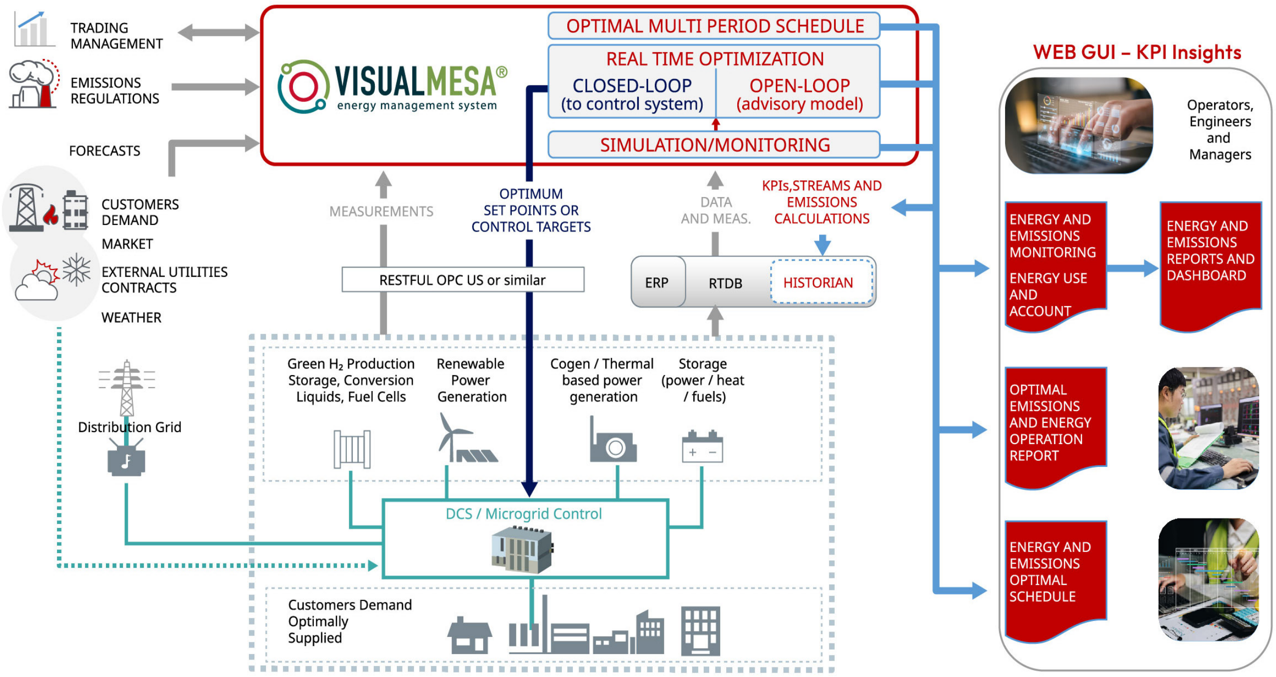


Figure 2. Multi-period optimisation and hydrogen management.

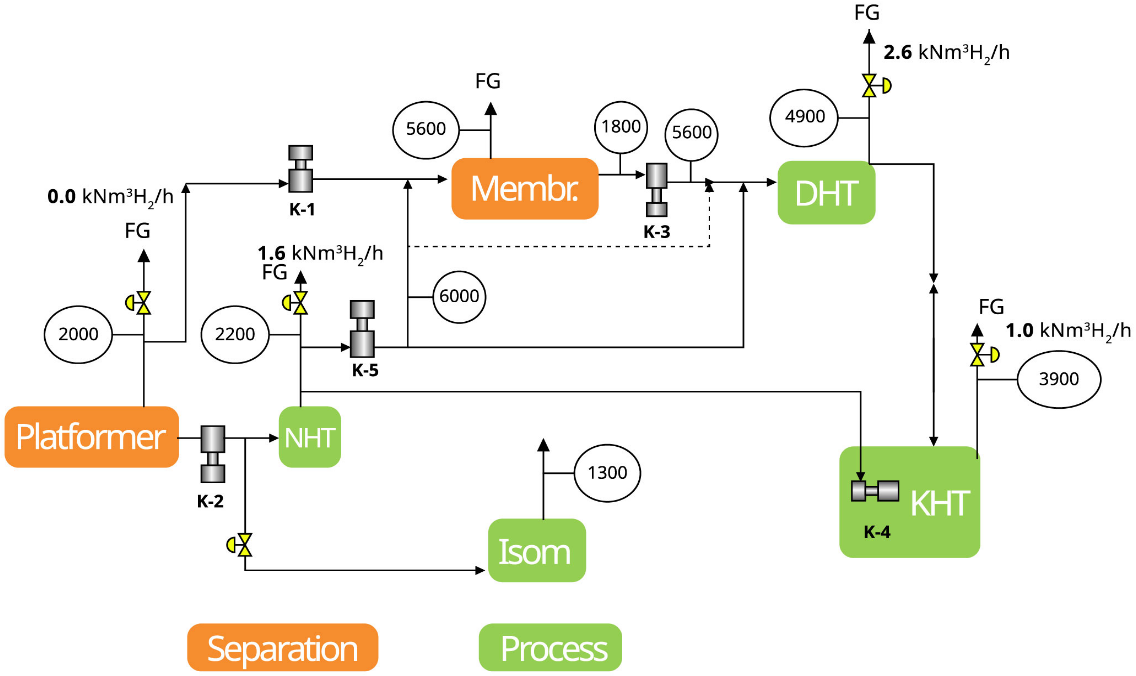


Figure 3. Refinery hydrogen network showing how pressure, flow, and routing constraints govern the physical deliverability of green and conventional hydrogen.

- Composition and impurities affect energy content and quality compliance.
- Meter technologies behave differently under hydrogen blends and changing conditions.
- Calibration becomes harder when the plant rarely operates at a stable 'normal.'

This produces unreconciled measurements – numbers that look precise but may not reflect physical reality.

Without a continuously validated physical model, teams struggle to answer basic operational questions with confidence:

- Is an electrolyser underperforming or is the instrumentation drifting?
- Is storage filling slowly due to compression constraints – or because flow is misestimated?
- Are offtake requirements being met – or merely assumed based on conflicting tags?

This creates a decision-grade data gap: numbers exist, but confidence lags.

Decision-grade digital twins

In practical terms, a decision-grade digital twin links live plant data to a high-fidelity system model that supports monitoring, forecasting, optimisation, and control. The goal is not visibility, it is confidence.

Such a system enables:

- Tracking electrolyser operating states and performance across time and load.
- Modelling production, compression, storage, and demand as a coupled system, as shown in Figure 2.
- Reconciling measurements against thermodynamics and hydraulics.
- Evaluating operating and economic scenarios using time-based profiles.
- Translating variability into feasible dispatch and operating envelopes.

This is not additional instrumentation; it is measurement anchored to physics. It extends established data-reconciliation discipline into hydrogen systems, where uncertainty is amplified by variability. Physics-based process and network twins validate flows, constraints, and operating envelopes while real-time optimisation and scheduling convert that validated system into dispatch decisions.

In renewable-driven hydrogen systems, real-time optimisation alone is insufficient. Decisions on electrolyser loading, hydrogen storage, and withdrawal must be made against forecasts, not just current conditions.

This requires multi-period optimisation. A rolling, time-horizon scheduling layer coordinates electrolyser power use, hydrogen production, and storage across hours, days, and weeks. All physical, commercial, and emissions constraints are respected. As illustrated in Figure 2, multi-period scheduling integrates forecasts, storage, and real-time optimisation into executable hydrogen operating plans.

Multi-period optimisation integrates:

- Weather and renewable generation forecasts.
- Hydrogen demand and delivery commitments.
- Electricity prices and power purchase agreements (PPAs).
- Storage inventories and ramp-rate limits.
- Electrolyser degradation and minimum-load constraints.

The result: an executable operating schedule that keeps hydrogen production feasible, cost-effective, and compliant as conditions evolve.

Operationally, this means forecast-driven, multi-period optimisation across power supply, electrolysers, hydrogen storage, and downstream demand. Weather and renewable forecasts are used to schedule hydrogen production, storage, and dispatch in a way that maximises renewable utilisation while maintaining delivery and emissions constraints. This turns hydrogen from a static production asset into a continuously optimised energy and emissions system.

Case study: integrating green hydrogen into a refinery network

A refinery sought to integrate approximately 200 MW of green hydrogen production into its existing hydrogen network. The challenge was not simply producing hydrogen – it was managing intermittent, renewable-driven electrolyser supply while maintaining fixed hydrogen delivery requirements to critical refinery units alongside existing SMR-based hydrogen supply. As shown in Figure 3, refinery hydrogen systems consist of multiple interconnected producers, consumers, purification units, and pressure-constrained headers that govern how green and conventional hydrogen can be delivered.

The objective was to determine the minimum combination of electrolyser capacity, storage, and operational flexibility required to maintain hydrogen supply reliability under variable renewable input.

To do this, a hydrogen network digital twin was built to evaluate producers, consumers, constraints, and operating envelopes under time-varying renewable input. The study incorporated 8760-hour renewable production profiles to reflect actual operating behaviour rather than design-point assumptions. The model explicitly resolved mass-flow and pressure constraints across the refinery hydrogen headers, revealing where electrolyser output could not be physically delivered despite available capacity.

The network model was evaluated across multiple scenarios using time-series and probabilistic methods within a scheduling framework to map how constraints interact hour-by-hour across the hydrogen network. These included:

- Electrolyser banks operating under ramp, turndown, and degradation constraints.
- SMR production with fixed and variable availability
- Statistical renewable power profiles driving hydrogen production.
- Dynamic mass-balance and pressure constraints across the refinery hydrogen network.
- Alternative storage types and sizes.
- Multiple demand- and supply-side flexibility levers, including battery systems, including battery energy storage systems (BESS) to buffer renewable variability, electrolyser bank control strategies, and PPAs.

Results: from guesswork to operable design

The study produced an operable hydrogen network roadmap rather than a capacity-only design. Four system opportunities were identified, resulting in an 8 - 10% reduction in net hydrogen demand while maintaining refinery delivery obligations. More importantly, the analysis revealed how the combined green and conventional hydrogen system could be operated within physical and economic constraints, enabling:

- Storage sized for observed variability.
- Electrolyser dispatch based on network and pressure constraints.
- Electrical and molecular buffering through batteries and network flexibility.
- Coordinated operation across SMR, electrolysers, storage, and refinery demand.
- A phased pathway for integrating intermittent green hydrogen.

This allowed the system to operate closer to its true to its design limits to improve utilisation.

Accuracy improves hydrogen economics

Most hydrogen cases rest on assumptions about electricity prices, electrolyser performance, and hydrogen sales. Their validity depends on whether the system can be operated within its physical and operational constraints.

Without validated operational models, projects compensate with conservative design:

- Oversized storage.
- Additional electrolyser capacity.
- Renewable energy curtailment.
- Restricted operating envelopes.

These measures increase capital costs and reduce asset utilisation. When operations are governed by a continuously validated model, systems can be designed and dispatched within their true feasible operating envelopes. This approach reduces both capital and operating inefficiencies.

Conclusion

Hydrogen projects succeed when they are operable. The difference between viable and stranded assets will be the quality of operational insight – how well projects understand system behaviour across time, constraints, and variability.

Decision-grade digital twins shift learning upstream, supporting feasibility, operability, certification, and investor-grade performance metrics across the hydrogen lifecycle. Because the digital twin maintains reconciled mass, energy, and emissions balances across time, it also enables product carbon footprint (PCF), hydrogen certification, and investor-grade key performance indicators (KPIs) to be generated from operational truth rather than post-hoc estimates.

Hydrogen must be designed and operated as a dynamic energy system, not static equipment.

References

1. VIRAH-SAWMY, D., BECK, F. J., and STUMBERG, B., 'Ignore variability, overestimate hydrogen production – Quantifying the effects of electrolyzer efficiency curves on hydrogen production from renewable energy sources', International Journal of Hydrogen Energy, 72, pp. 49- 59, (2024), https://doi.org/10.1016/j.ijhydene.2024.05.360.
2. 'Global Hydrogen Review 2024', International Energy Agency (IEA), (2024), https://www.iea.org/reports/global-hydrogen-review-2024, Licence: CC BY 4.0.