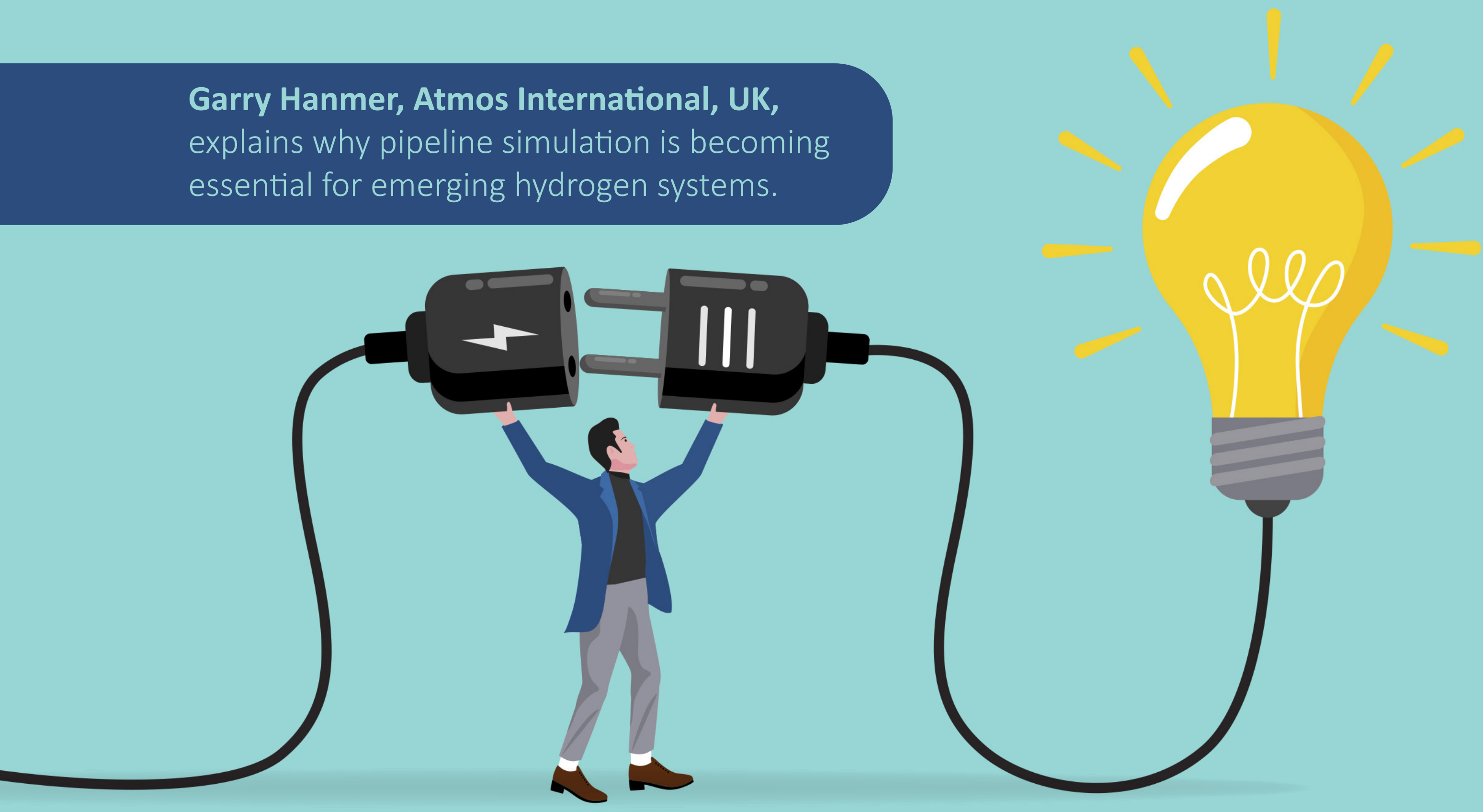
Garry Hanmer, Atmos International, UK,
explains why pipeline simulation is becoming essential for emerging hydrogen systems.



HYDROGEN AMBITION *meets* INFRASTRUCTURE REALITY

Hydrogen infrastructure is entering a phase defined less by uniformity and more by diversity. New production pathways, geographically distributed hubs and cross-border transmission frameworks are placing unprecedented demands on pipeline systems. As hydrogen moves from concept to operation, pipeline simulation is emerging as a critical engineering tool to manage uncertainty, transient behaviour, and system integration across the hydrogen value chain. This article examines recent hydrogen developments across the world and considers how pipeline simulation can support growing hydrogen infrastructure.

Emerging hydrogen colours

Super green hydrogen

In recent years, hydrogen development has expanded across multiple production pathways. More recently, green hydrogen has gained renewed momentum as production efficiency improves and, with it, the potential for cost efficiency.

Researchers in South Korea have developed a new electrochemical catalyst that significantly improves the efficiency of green hydrogen production. This catalyst reduces the energy required for electrolysis and could accelerate the commercial viability of green hydrogen, effectively introducing a new, lower-cost variant of green hydrogen production dubbed 'super green' (see Table 1).[1]

If adopted more widely, such developments are likely to increase both the volume and geographic spread of green hydrogen production. For pipeline systems, this has direct operational implications.

Higher production volumes may increase utilisation of existing pipeline infrastructure, exposing pipelines to operating conditions that influence material integrity, particularly hydrogen embrittlement under cyclic loading. More frequent start-up and shutdown of hydrogen production can intensify pressure cycling, making it essential to understand how operating regimes affect material behaviour.

Pipeline simulation supports this by providing visibility into pressure, flow, and transient behaviour across the system. High-fidelity modelling enables assessment of how operating conditions propagate along a pipeline, helping identify regimes that may contribute to accelerated degradation.

On long-distance hydrogen pipelines, detailed simulation incorporating appropriate equations of state and rigorous model calibration has been shown to closely match measured flow behaviour, supporting reliable definition of operating limits and integrity margins.

As green hydrogen deployment accelerates, simulation provides a practical means of evaluating whether existing infrastructure can continue to operate safely under hydrogen service or whether operational or physical changes are required.

White hydrogen

Alongside advances in engineered hydrogen production, interest is also growing in naturally occurring hydrogen, typically referred to as white hydrogen. Recent exploration activity and reassessment of historical data suggest that geological hydrogen could represent a viable low-carbon energy source in certain regions, with the potential for continuous production instead of energy-intensive manufacturing processes.[2]

Unlike green or blue hydrogen, white hydrogen introduces a different set of infrastructure considerations. Potential geological hydrogen reservoir sites may be located far from established energy infrastructure, increasing reliance on new transmission pipelines rather than repurposed assets.

For pipeline systems, this uncertainty has direct implications for design and operation. Unlike conventional natural gas production, where reservoir performance and decline behaviour are typically well characterised, white hydrogen production profiles remain less predictable. Variability in supply rates and pressure conditions complicates pipeline sizing, compression strategy, and operating envelope definition. Designing infrastructure around a single expected production case may be insufficient where subsurface performance remains uncertain.

Look-ahead pipeline simulation supports this uncertainty by allowing engineers to evaluate how variations in white hydrogen production rates, pressure conditions, and operating strategies affect pipeline pressure, flow, and safety margins over time. By simulating anticipated operating scenarios in advance, operators can test whether proposed strategies remain within acceptable limits and identify constraints before they become operational issues.

Simulation also supports contingency planning by assessing system response to abnormal conditions, such as loss of supply, equipment unavailability, or loss of containment. For emerging white hydrogen projects, this predictive, scenario-based capability provides a practical means of managing uncertainty during both infrastructure design and early operation.

Hydrogen hubs and integrated infrastructure in Morocco

Morocco is pursuing an integrated hydrogen value chain that links renewable generation, production, storage, and export through strategically selected ports as potential nodes within a coordinated hydrogen network, where production, derivative processing, storage and bunkering can be combined to minimise costs and maximise supply chain efficiency.[3]

This vision involves moving hydrogen and its derivatives between multiple assets and functions: from production zones through transmission pipelines to salt cavern storage,

Table 1. Different types of hydrogen and their production methods

Colour code	Brown	Grey	Blue	Turquoise	Pink	Yellow	Green	White
Energy source	Coal or lignite	Natural gas	Any non-renewable energy source	Methane	Nuclear energy	Solar power	Any renewable energy source	Naturally occurring underground
Process of production	Gasification	Steam reformation	Steam reformation and carbon capture and storage (CCS)	Pyrolysis	Electrolysis	Electrolysis	Electrolysis	Extraction
Highest to lowest greenhouse gas emissions	→							
Lowest to highest acceptance level	→							

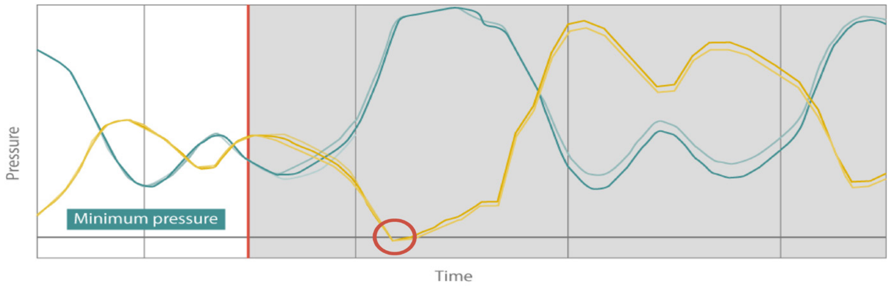


Figure 1. Trending data from a live pipeline's recent activity (light background), along with the look-ahead's prediction of a future scenario. The circled area signposts a potential minimum pressure violation that can be prevented by taking actions early.

onward to heavy industry, and finally to bunkering and export terminals.[4] Such a multi-node system differs from point-to-point transmission in that it exhibits bidirectional flows, frequent transient events and complex interactions between pipelines, storage and downstream facilities. These characteristics introduce several challenges:

- Network topology complexity – multiple injection and offtake points increase the dimensionality of flow interactions compared to linear segments.
- Transient behaviour – storage operations, bunkering schedules and industrial draws can create pressure and flow fluctuations that propagate across the network.
- Operational coordination – maintaining system stability while meeting export windows and industrial demand requires understanding of how changes in one part of the network affect another.

Simulation addresses these challenges by enabling network-wide analysis rather than isolated pipeline assessment. By modelling the full pipeline system, including un-instrumented sections between facilities, simulation provides visibility into how changes at one node propagate through the network. Look-ahead simulation allows operators and planners to evaluate proposed operating schedules, storage injection and withdrawal strategies, and export scenarios in advance, assessing whether the system remains within defined operating limits under varying conditions.

In complex port-led systems, where operational decisions at one location can influence performance elsewhere, this type of integrated, predictive simulation supports both infrastructure planning and coordinated operation. It enables stakeholders to move from conceptual hub designs to technically robust operating strategies that account for transients, interactions, and uncertainty across the entire hydrogen network.

Cross-border hydrogen pipelines and regulatory alignment

The agreement between German and Dutch gas transmission operators to establish a framework for cross-border hydrogen pipelines marks an important step toward international hydrogen transport in Europe. The framework aims to enable hydrogen to move between national systems, supporting industrial demand and broader decarbonisation goals while laying the foundations for a wider European hydrogen network.[5]

While technically feasible, cross-border hydrogen transport introduces challenges that extend beyond pipeline design. Although European standards and codes provide a framework for alignment, individual countries retain responsibility for national regulation, operational practices, and safety requirements. As a result, parameters such as maximum allowable operating pressure (MAOP), lowest allowable operating pressure (LAOP), operating margins, and response procedures can still differ across borders, even within a single physical pipeline system.

From an operational perspective, this creates the need for coordinated system management under non-uniform constraints. Pipeline simulation supports this by enabling a single network model to incorporate country-specific operating limits and regulatory requirements within a shared framework. By modelling pressure, flow and linepack across the entire cross-border system, simulation allows operators to assess whether planned operating strategies remain compliant in each jurisdiction simultaneously, rather than evaluating segments in isolation.

Forecast-based simulation further supports cross-border operation by allowing future operating scenarios to be evaluated in advance. By analysing anticipated changes in supply, demand or equipment availability, operators can identify potential pressure violations before they occur and adjust operating plans accordingly (see Figure 1). This capability is particularly valuable where operational practices or allowable limits differ between countries, as it supports safe, efficient, and compliant operation across borders without relying on overly conservative assumptions.

As hydrogen networks become increasingly interconnected, simulation provides a common technical reference point for cross-border coordination. It enables multiple operators to understand shared system behaviour, manage regulatory differences, and operate complex hydrogen infrastructure as an integrated network rather than a collection of national assets.

From hydrogen ambition to operational reality

Across all these developments, a common theme emerges: hydrogen infrastructure is becoming more dynamic, interconnected, and sensitive to operating conditions. As hydrogen production pathways diversify and networks expand, pipeline simulation provides a consistent engineering foundation for managing uncertainty, ensuring integrity, and supporting coordinated operation. In this context, simulation is not an optional add-on, but a core capability for the next phase of hydrogen infrastructure development.

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