Unlocking hydrogen's potential

The green electron got smart.
The green molecule makes it resilient.



Capgemini

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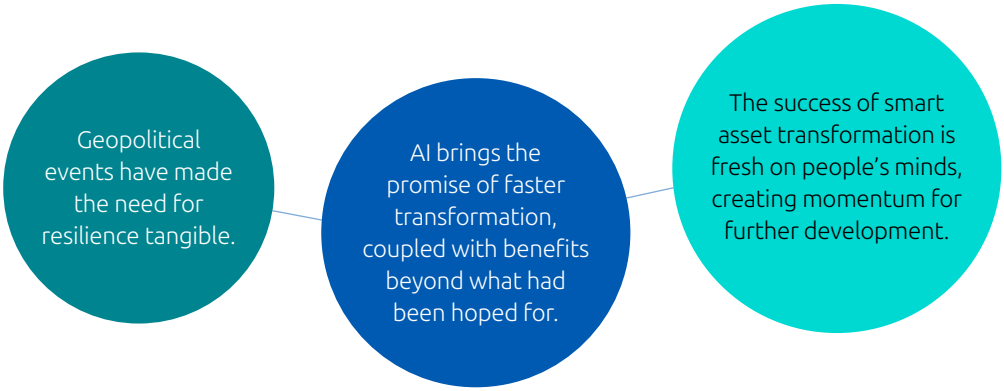
Smart molecules: building resilience in an uncertain world

A window of opportunity

There has never been a greater need to invest in smart molecule infrastructure.

Electrons are more intelligent than ever. Thanks to the adoption of smart asset practices, utilities are better able to track usage, balance loads and react to sudden spikes or troughs. But efficiency is only one requirement of our energy systems. To keep civilization on track, energy providers must balance six requirements simultaneously: cost, efficiency, security, safety, sustainability and resilience. Smart electrons were a great start. Now what we also need are smart molecules.

In recent years, multiple factors have aligned in support of this ambition:



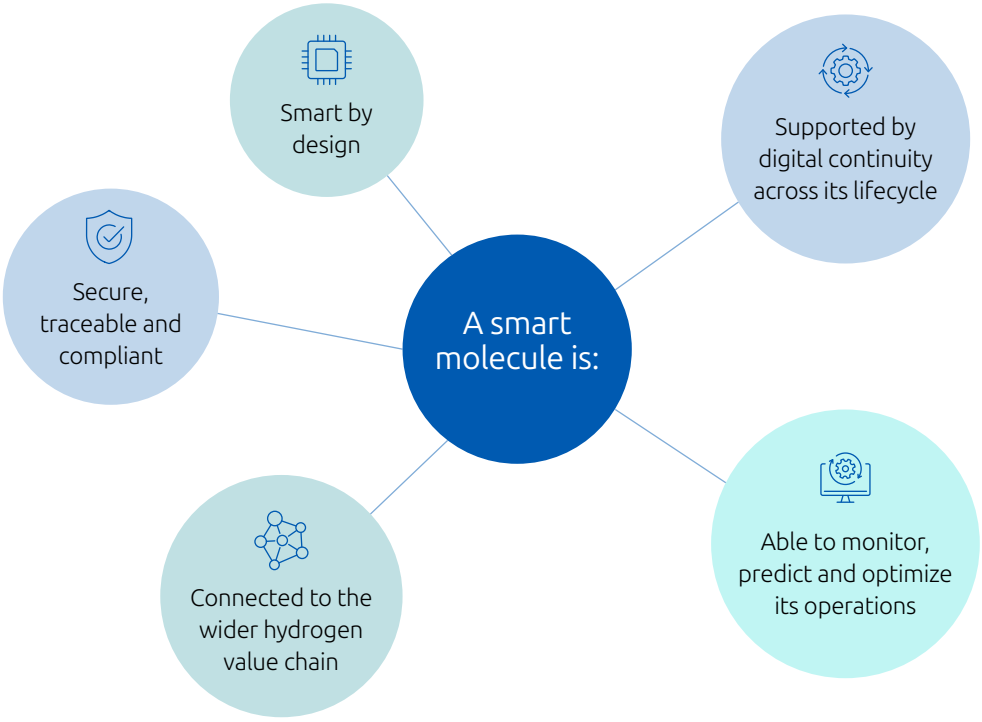


An optimal time

Together, these events make this an optimal time to advance a resilient, smart molecule energy solution. This paper will first review the need, and then explore the benefits that utilities can enjoy from the resilience afforded by smart molecules.

Smart molecules and green molecules

What are "smart molecules?" We use the term to include hydrogen, as well as a whole family of derivatives – ammonia, methanol, synthetic liquid fuels and many others – that provide a variety of unique benefits to our energy infrastructure. In this paper, we'll be focusing on hydrogen that has been manufactured from renewable energy sources – green hydrogen. By extension, molecules derived from green hydrogen via sustainable processes are also green.



Stability in an uncertain world

There are two reasons why resilience is important. One is geopolitical. Beyond storage, green molecules can build resilience into the structure of the energy system itself. They deliver energy through pipelines, shipping and rail, independent of the grid infrastructure. They give hard-to-electrify sectors, such as shipping, aviation and steel, a decarbonization pathway that may not otherwise exist.

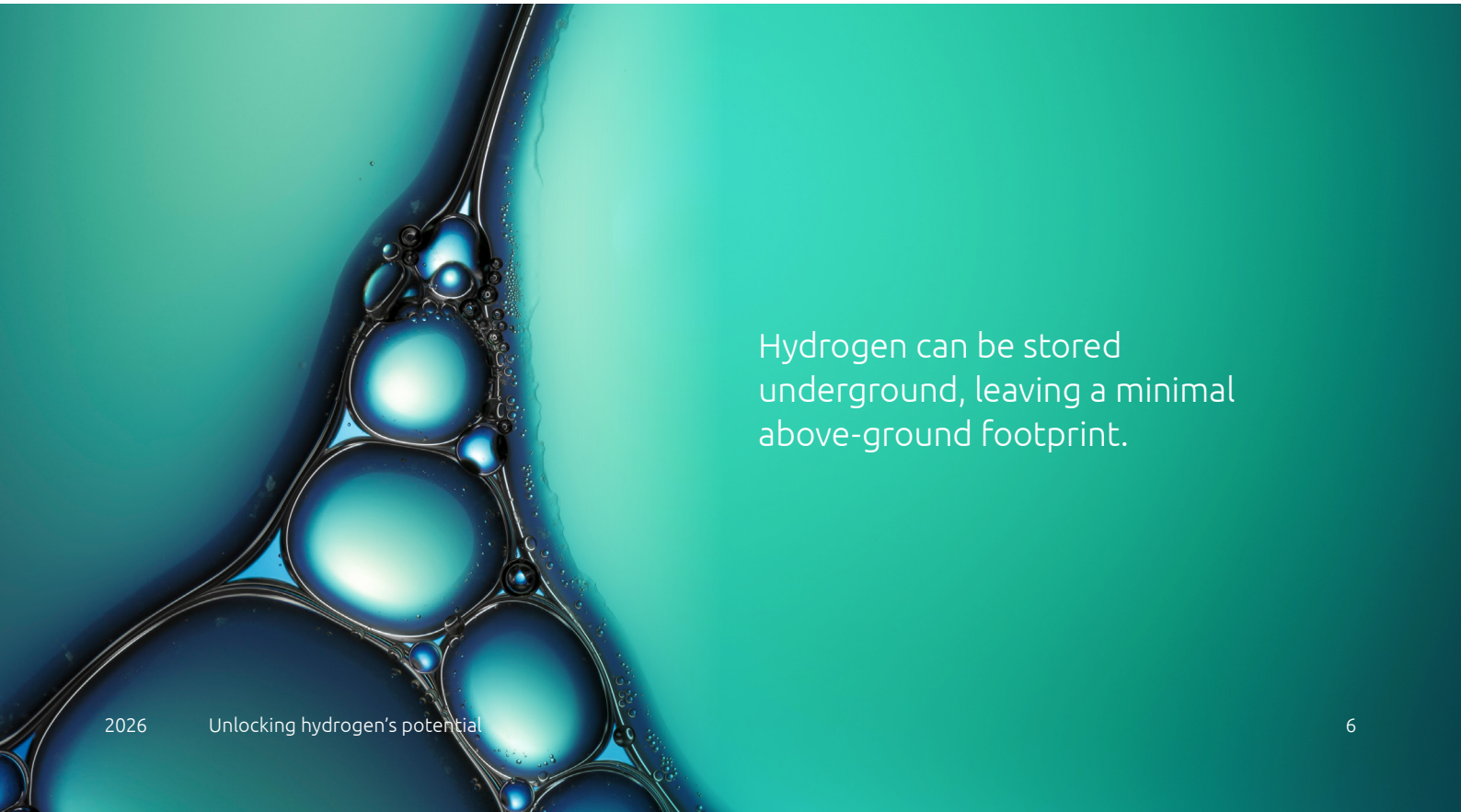
And because hydrogen can be produced domestically or traded internationally, it diversifies supply chains and reduces exposure to geopolitical shocks.

Reliable sustainability

The other reason to prioritize resilience is that it helps transition to sustainable energy sources. By storing surplus electrons in batteries or converted into hydrogen for use in calm, dark periods or during an infamous "dunkelflaute," they decouple energy generation from energy use.

That seasonal flexibility can cut renewable curtailment levels and turn intermittent generation into an asset which, in and of itself, increases resilience. Hydrogen can also be produced using baseload power and then transported to where it is needed at scale, unlike batteries.

The UK Government, for example, is currently looking for 100 hours of continuous discharge from hydrogen or batteries to cover ultra long duration energy storage. One consideration in favor of hydrogen is in the space required for such an energy storage facility. In land-rich countries, the space taken up by batteries may be an acceptable trade. Not so in smaller, denser countries, where every acre given over to energy storage is one less acre of farmland. Confining our energy storage vision to batteries leads us to think small. We sense – even on an intuitive level – that the number of batteries needed to store a nation's energy supply would be unmanageable. Smart molecules allow us to think big. They open the door to large-scale energy storage for long periods of time. Integrated intelligently into the wider energy system, they decouple energy generation from usage, allowing nations to store renewable energy at scale, diversify supply chains, weather disruptions, and deliver clean energy to sectors beyond the reach of electrification.



Hydrogen can be stored underground, leaving a minimal above-ground footprint.

A smart asset framework for hydrogen and green molecule projects



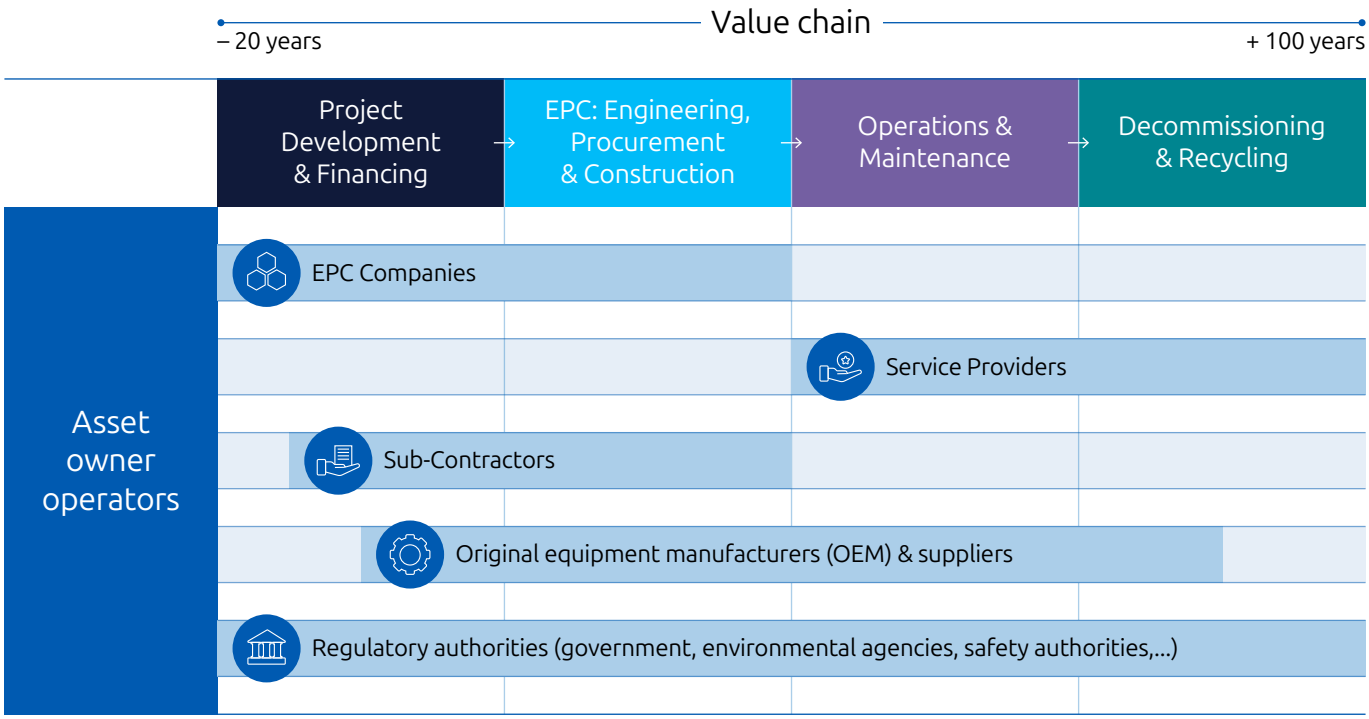
We have the potential to balance out energy production and usage over a scale of months, simply by weaving smart molecules production and use into our infrastructure. But this depends on creating alignment between the different parties involved.

The challenge of coordinating multiple players

Hydrogen production plants, whether green, blue, turquoise or gray, are complex industrial infrastructure assets with extended lifecycles managed by multiple players, including asset owner-operators, Engineering, Procurement and Construction (EPC) contractors, maintenance/service providers, Original Equipment Manufacturers (OEMs) and component suppliers, as well as the regulatory authorities.

However, information flows today are often fragmented across organizational and contractual boundaries. This disconnection creates inefficiencies that cascade through decades of operations, systematically eroding return on investment (ROI) and asset reliability.

For an operation of this complexity to remain aligned, the most important asset is information.



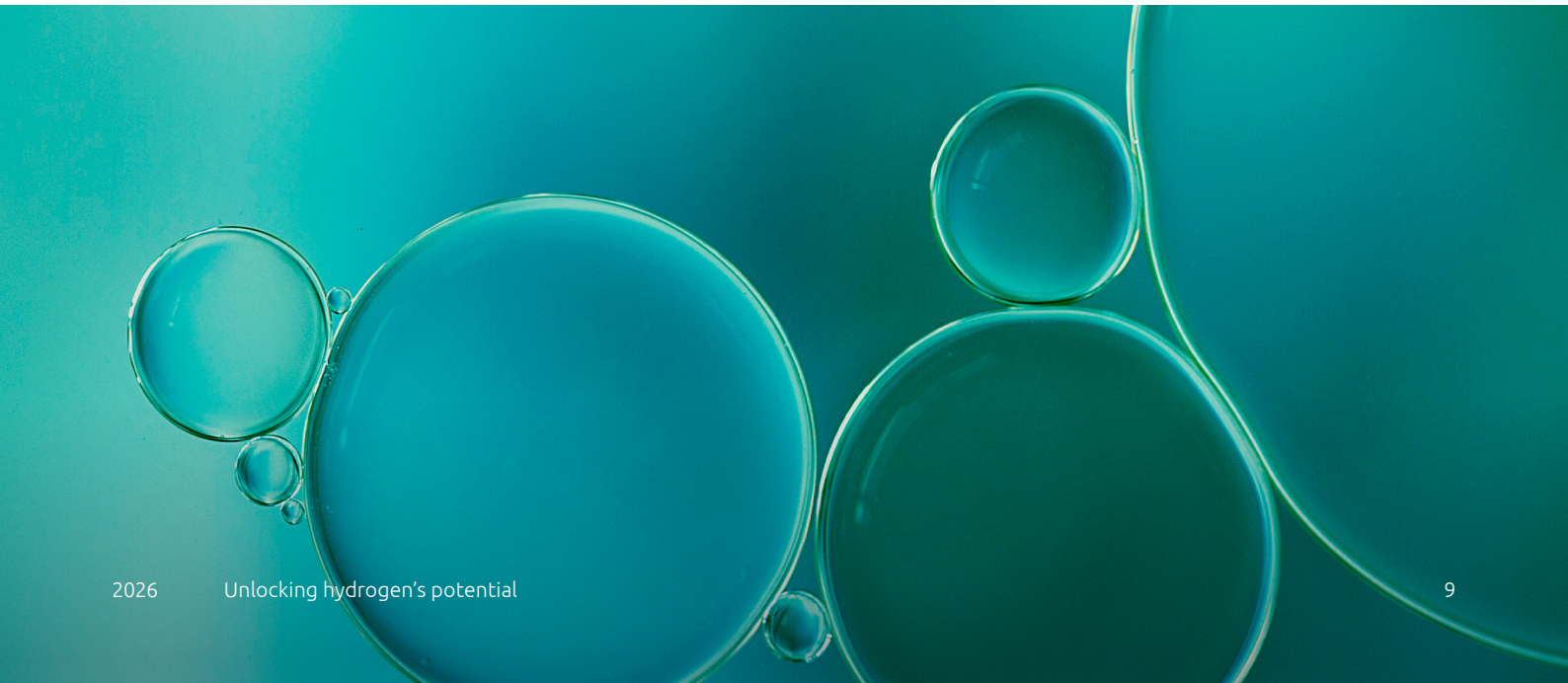
Multiple players are involved in the hydrogen plant lifecycle

The cost of fragmented data

Data discontinuity kills the business case for hydrogen. It raises the cost, creates delays, and increases risk. In fact, some of the greatest barriers to hydrogen asset performance and profitability are the information gaps between design, construction, and operations phases.

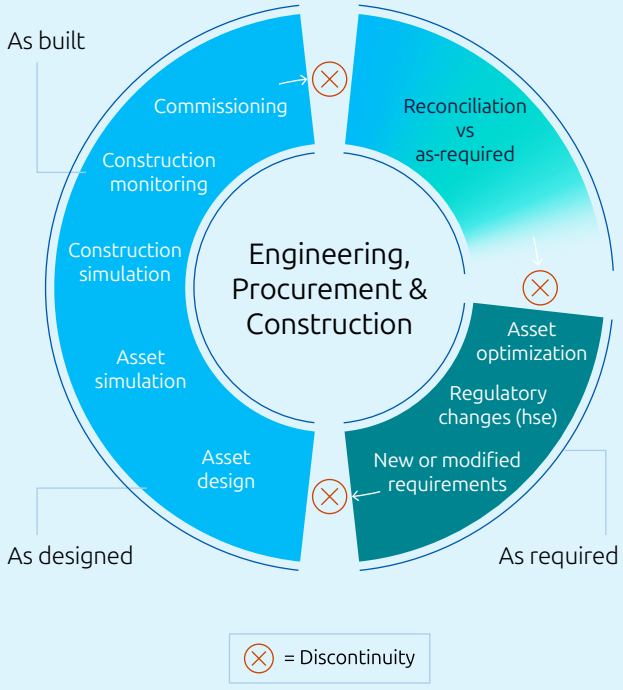
The three most common breakdowns in digital continuity

	Requirements are lost in design	Design diverges from reality	Information is lost in handovers
	↓	↓	↓
1	Traditional contracts lack clarity on operational standards and asset owner expectations	Inadequate clash detection during construction leads to rework and delays	Incomplete documentation and missing asset metadata plague operations teams
2	EPCs design to customer specification, not to operational intent	Poor coordination between design and field teams causes infrastructure validation failures	Outdated drawings and untagged equipment create operational blind spots
Result	Misaligned deliverables and compliance risks that emerge during operations	Cost overruns, schedule slippage, and incomplete documentation	Inefficient maintenance planning, regulatory compliance gaps, and inability to leverage digital capabilities

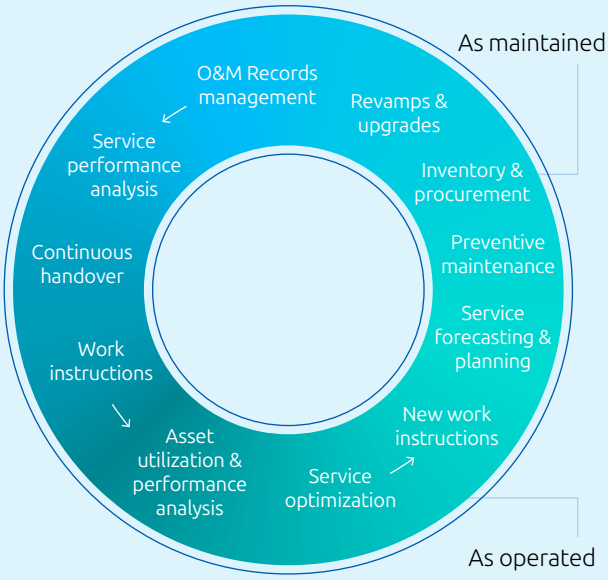


The cost of discontinuity

These information gaps don't just cause friction at transition points, they compound over decades. Operations teams inherit assets they don't fully understand, maintenance becomes reactive rather than predictive, and the hydrogen business case deteriorates through preventable inefficiencies.



Without careful planning, information gaps naturally arise



The solution is digital continuity – keeping data consistent between partners and across time.

Digital continuity – where data meets strategy and engineering

In the rapidly evolving hydrogen landscape – where many assets remain in development phases – a robust asset management strategy must be established from the start.

The three pillars of digital continuity

1

Embed Asset Information Management (AIM) excellence from day one

Define asset operational and maintenance requirements during project development

Contractually obligate EPCs and OEMs to deliver structured, standardized asset data

Create a "single source of truth" for asset metadata, technical specifications, and compliance requirements

2

Align all stakeholders through strategy + engineering + digital

Strategy: Communicate owner-operator requirements clearly upfront

Engineering: Ensure designs are built to operational intent, not just technical specification

Digital: Implement data standards and system integrations that enable information continuity

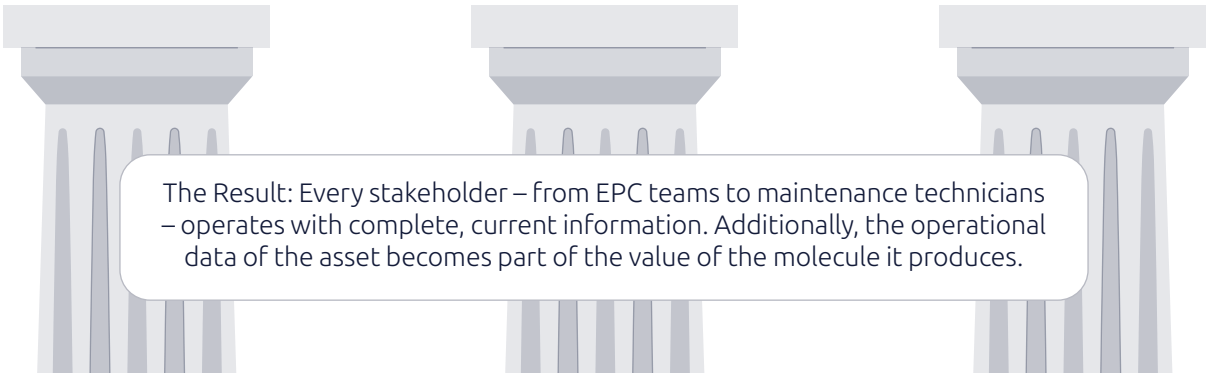
3

Enable seamless transition from Build to Run

As-built documentation delivered with full asset metadata and traceability

Commissioning records tied to operational requirements

O&M handover includes complete asset tagging, regulatory compliance traceability, and digital enablement readiness



The Result: Every stakeholder – from EPC teams to maintenance technicians – operates with complete, current information. Additionally, the operational data of the asset becomes part of the value of the molecule it produces.

This eliminates the inefficiencies, safety blind spots, and lifecycle cost overruns that plague hydrogen infrastructure delivery today.

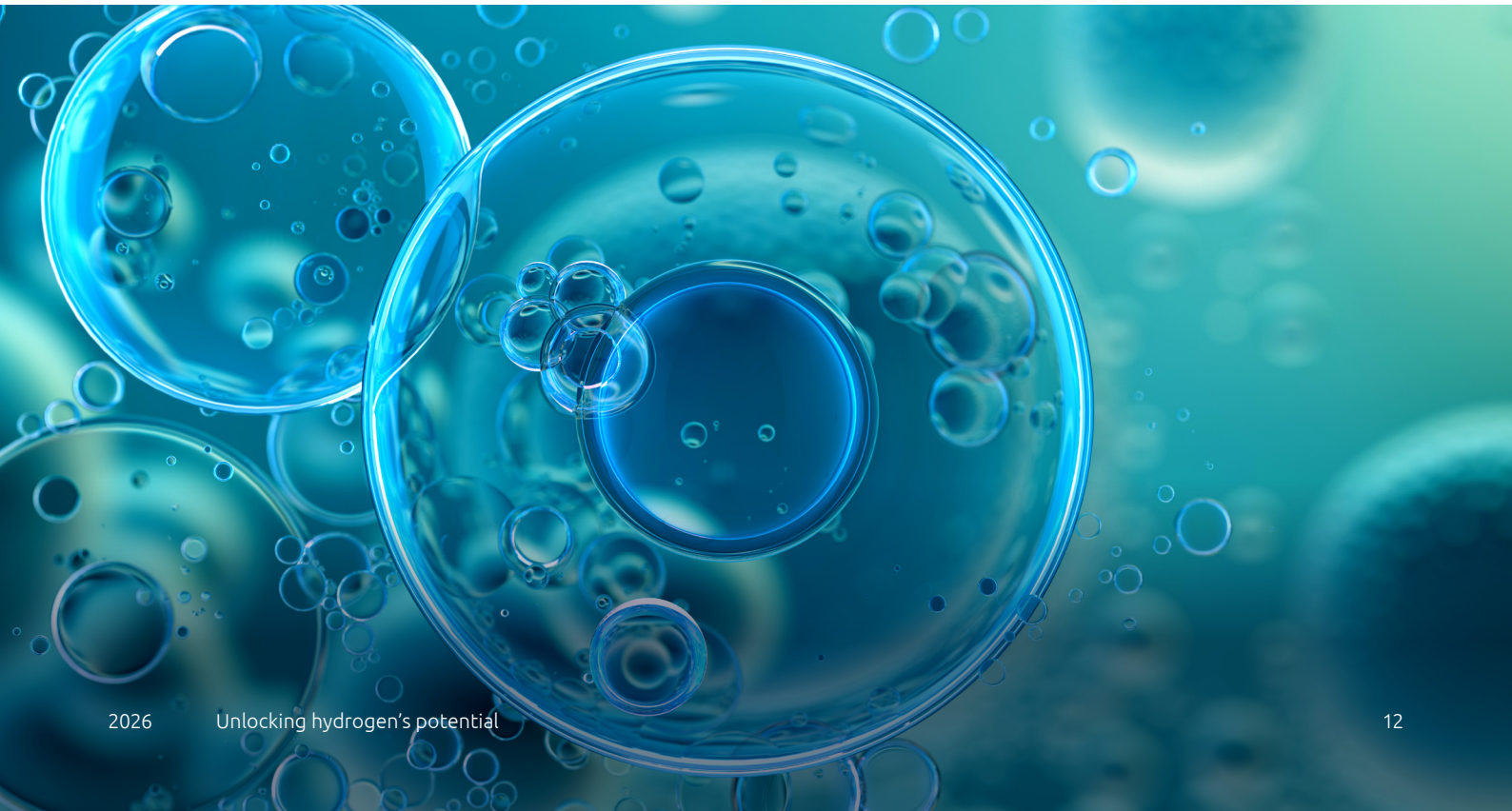
Digital twins across the asset lifecycle

Digital twins are not single static models – they're evolving, interconnected representations of assets across their lifecycle, each serving specific stakeholder needs. As a physical asset moves through its lifecycle, the purpose of a twin changes. In early phases, a requirement twin helps define what form an asset should take, while a design twin informs on how it should be designed.

Construction twins validate design intent against the realities of the field, revealing potential issues before they appear. Finally, operations twins support performance monitoring, and maintenance twins help optimize upkeep.

What makes this approach so powerful is the digital thread – the unbroken connection between all these twins. When a regulatory requirement changes, that requirement is captured in the requirements twin, traced through the design and construction twins, and surfaces as a compliance checkpoint in the operations twin. The result is a continuous flow of trusted information across the asset lifecycle, ensuring that stakeholders always work from current and contextualized data, that risk mitigation is built into every phase, and that critical knowledge and governance are maintained from design through operations.

What makes this approach so powerful is the digital thread – the unbroken connection between all these twins.



Smart assets at scale: from individual assets to fleet management



When each physical asset is linked to a digital asset, the result is a smart asset. While digital twins optimize individual assets, the real strategic value emerges when they are connected across a portfolio of hydrogen infrastructure, from electrolyzers and pipeline networks to storage facilities and distribution hubs. In this way, smart assets drive efficiency, safety, and sustainability across a hydrogen portfolio.

At scale, smart assets create a connected operating environment where compliance, performance, and operational data are continuously monitored and shared. Regulatory requirements can be tracked automatically, creating auditable records of operations and maintenance. This makes it possible for utilities to identify potential compliance gaps early, before they become issues. Early detection by utilities empowers customers to pursue sustainable sourcing with confidence, backed by accurate, reliable upstream tracking that demonstrates accountability to stakeholders.

The same connected data foundation improves economic performance. Leaders gain real-time visibility into asset condition and performance across the fleet, enabling better resource allocation, predictive maintenance, and more informed investment decisions. By connecting strategic objectives with day-to-day operations, utilities can reduce unplanned downtime and optimize asset utilization throughout the lifecycle.

Smart assets also support sustainability goals. They help operators monitor energy consumption, emissions, and resource utilization across the portfolio. This visibility makes it easier to identify inefficiencies, improve processes, and demonstrate progress against ESG objectives.

All of these benefits apply at scale, including for geographically distributed assets. Fleet-level intelligence creates an additional layer of value, enabling real-time oversight of the entire hydrogen ecosystem.

AI opens the door to new possibilities

Securing financing

AI helps from before a project even begins, creating superior risk quantification for financing. AI-driven probabilistic modelling provides confidence intervals around key assumptions: what range of electrolyzer capital costs is realistic, what distribution of hydrogen demand is probable, what regulatory changes are most likely. This enables more accurate cost-of-capital calculations and more intelligent capital allocation decisions.

Engineering, procurement and construction

In hydrogen, EPCs have a hard job. These are projects with little or no standardization, in an environment of changing requirements. To mitigate that risk, client often require risk to be transferred to the EPC firm in the form of a project “wrap.”

AI can play a valuable role here – enabling the asset owner to shift from reactive oversight to predictive governance. It provides early warning of emerging risks long before they become critical path items. This design and build integration moves clients beyond mere oversight to becoming true partners with the EPC firm, driving better outcomes.

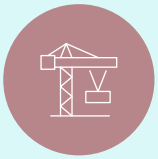
Examples of how AI reduces risk



Risk:
one component out of a hundred has a six-month lead time.

Reduction:
AI flags supply chain issue early, when alternatives still exist.





Risk:
It comes out during construction that design assumptions don't match field conditions

Reduction:
AI predicts likely clashes and coordination issues before they become expensive rework.





Risk:
A new regulation comes into play that requires work to be redone.

Reduction:
AI can flag ongoing discussions in government, before they become law.

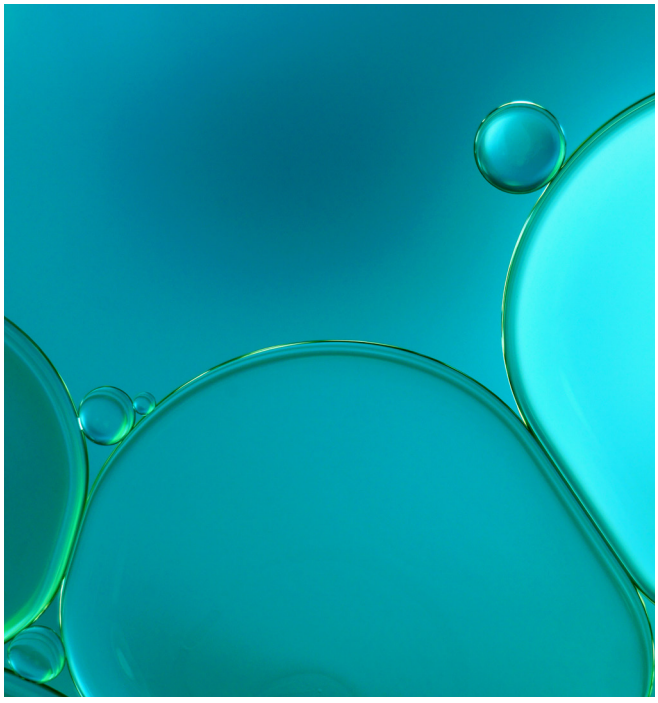


Operations and maintenance

Beyond predictive risk reduction, AI strengthens operational optimization across competing objectives from the business to the regulators.

Hydrogen production operations inherently face trade-offs:

maximize throughput	vs	minimize energy consumption
maximize purity	vs	minimize processing costs
meet demand variability	vs	maintain steady-state efficiency



AI can analyze thousands of possible operating configurations and identify which one optimizes on specific, potentially changing, priorities. This transforms operations from following fixed procedures to continuously optimizing allowing for long term asset performance which adds to a resilient system.

In the short term, we see AI agents that can automatically trade hydrogen colors, ensuring customers across jurisdictions receive regulatory-compliant supply. In the longer term, we see AI agents which will forecast regulatory changes and shifts in long-term weather patterns, dynamically adjusting order volumes and supply contracts accordingly. This supply-demand balancing capability will enable regions like Singapore and Rotterdam to become true trading hubs for future smart molecules.

AI is still very much in the discovery stage. We won't know exactly what an AI-enhanced, smart-molecule-supported energy ecosystem looks like until it's built. But being part of this discovery, along with Capgemini, will be key to creating a sustainable, flexible ecosystem.

While hydrogen for ultra-long duration or intraseasonal storage is in a very early rollout phase, we can make some educated assumptions as to the direction of the market, enabled by AI. Hydrogen (and its family of smart molecules), will be integrated into the energy mix. On sunny days, excess energy will be used to create more hydrogen, and on cloudy days, some of that hydrogen will be converted back into energy. On windy days, the hydrogen store rises, and on still days we make another withdrawal. We may build additional solar and wind installations devoted 100% to hydrogen production. Over time that buffer grows, as an investment. When the next crisis hits, energy will be one factor we don't need to worry about.

Three steps towards smart molecule resilience



We have choices to make. We can continue building infrastructure like legacy projects from the 20th century. Or we can adopt digitally enabled, intelligent, resilient systems into everyday planning, with green molecules playing a key role.

For industry and government leaders who choose resilience, here are three steps we recommend:

1

Reframe resilience as a primary objective.

It's easy to view resilience as a constraint in the short term. Take the long-term view. Cost optimization and efficiency must serve resilience, not the reverse. This requires policy frameworks, procurement standards, and investment criteria that explicitly value redundancy, diversification, and geopolitical hedging.

2

Mandate digital-native infrastructure from project inception.

Asset Information Management (AIM), digital twins, and AI governance frameworks must be contractual requirements, not optional add-ons. This ensures interoperability, eliminates data discontinuity, and reduces lifecycle costs by 10%+ while improving safety and compliance.

3

Build ecosystem collaboration around data standards and governance.

Proprietary systems fragment hydrogen infrastructure. Shared standards and collaborative governance enable fleet-level optimization, predictive maintenance, and systemic resilience that no single actor can achieve alone.



Looking forward

We know how to generate renewable energy. The challenge is ensuring it is available whenever and wherever it is needed. Smart molecules can help create the flexibility and resilience our energy systems need.

At Capgemini, we've helped governments, energy companies, and green technology leaders turn their sustainability ambitions into reality. Together, we can turn strategic intent into resilient, intelligent and distributed energy infrastructure, helping ensure that when the next crisis hits, the lights stay on.

Contact us to learn more

Key contributors



Dr. Kerry-Ann Adamson-Morland
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"For decades, energy systems were optimized around efficiency and cost. In a world shaped by climate volatility, cyber threats and geopolitical uncertainty, resilience must become a design principle in its own right. Smart molecules give us the flexibility and strategic redundancy to make that shift."



Thierry Jourdan
VP Strategy & Transformation
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"Smart Assets without artificial intelligence are merely organized data. AI transforms them into predictive systems that can drive the resilience hydrogen infrastructure demands."



Jasbir Singh
Senior Manager Intelligent Industry,
Capgemini Invent
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"Hydrogen infrastructure must be designed not only to produce and transport a new energy molecule, but to learn, adapt and improve across its lifecycle. Smart assets enabled by digital twins, trusted data and AI will be fundamental to delivering hydrogen projects that are safe, scalable and economically sustainable."



Dr. Jeremy Cure
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"The hydrogen market is entering a decisive phase: the challenge is no longer to demonstrate its potential, but to turn ambition into scalable and competitive industrial solutions. Success will depend on our ability to combine engineering, digital and industrial expertise to reduce costs, mature technologies and accelerate deployment across the entire hydrogen value chain."

About Capgemini

Capgemini is the business transformation partner for enterprises in the age of AI. We help organizations imagine and build an intelligent, sustainable future, combining AI, technology and human ingenuity to transform how they operate, innovate and grow. With unique end-to-end capabilities spanning strategy, technology, engineering and intelligent operations, we bring together deep industry expertise and market-leading capabilities in AI, cloud and data to turn ambition into measurable business outcomes at scale. Supported by a robust ecosystem of partners and nearly 60 years of expertise, Capgemini is a responsible and diverse global organization of over 410,000 team members in more than 50 countries. The Group reported 2025 revenues of €22.5 billion.

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