Observatorio Tecnológico del **Hidrógeno**

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Digitalisation of the hydrogen value chain

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EXECUTIVE SUMMARY

Hydrogen is expected to play a central role in the decarbonisation of hard-to-abate sectors, including industry, transport, aviation, maritime applications, and energy systems. **However**, **achieving large-scale deployment will require the digital capabilities necessary to design, operate, optimize, secure and certify increasingly complex hydrogen ecosystems**. Cost competitiveness, operational performance, asset integrity, regulatory compliance and scalability are becoming increasingly dependent on the effective use of digital technologies throughout the asset lifecycle.

This document, prepared by the Hydrogen Technology Observatory, and specifically by its members: **ABB, Cidaut, Emerson, Enagás, Endress+Hauser, Engreen, Inetum, Moeve, NTT Data, Siemens Energy and SLB**, examines how digital technologies can support the development and operation of the hydrogen value chain. **The report objective is not to promote individual technologies, but to provide a practical framework to understand where digital capabilities can address real hydrogen-sector challenges** and where implementation gaps remain.

A key finding of this study is that the **hydrogen sector does not need to develop an entirely new digital paradigm**. The report identifies a set of digital capabilities that are already mature, widely adopted in hydrogen projects across production, transport, storage and downstream applications. These capabilities include cybersecurity, advanced analytics and artificial intelligence, automation and control systems, engineering information management, industrial connectivity, digital twins, digital traceability, and geographic information systems. When deployed as an integrated ecosystem rather than as isolated technologies, they provide the digital infrastructure required to manage complex hydrogen value chain processes, including electrochemical conversion, compression, storage, transport, product quality assurance, interaction with electrical networks, and coordination with industrial demand centres.

The analysis identified multiple hydrogen-specific reference projects where **these technologies are already being deployed, demonstrating that many of the digital capabilities required to support the hydrogen economy are not future concepts but proven industrial solutions.** Examples include large-scale green hydrogen production facilities, integrated green hydrogen and ammonia systems, hydrogen transport infrastructure projects and hydrogen network optimization initiatives already delivering measurable operational benefits.

Furthermore, many of the remaining use cases originate from mature sectors such as Oil & Gas, LNG, power systems, industrial gases and process industries, addressing challenges that are highly analogous to those expected within hydrogen ecosystems. **The combination of hydrogen-native references and directly transferable industrial experience significantly reduces technology adoption risk** and provides project developers with access to a broad portfolio of proven implementation approaches. As a result, **the principal question is no longer whether these technologies can be applied to hydrogen, but** rather **how and when they should be integrated into project development** to maximize long-term value.

At the same time, **hydrogen presents a unique opportunity**. Unlike many mature industrial sectors that must retrofit digital capabilities into decades-old infrastructure, **most large-scale hydrogen projects are currently being designed as greenfield developments**. This allows project developers to establish digital foundations from the outset, incorporating interoperable data architectures, automation platforms, cybersecurity-by-design, engineering information management, and lifecycle digital continuity into the initial project scope. **Decisions made during early design phases will significantly influence future operational flexibility, scalability, integration costs and asset performance**.

An important challenge identified throughout this report is that **digital capabilities are frequently treated as optional project enhancements rather than strategic project enablers**. Under current market conditions, many hydrogen projects face significant CAPEX constraints, creating pressure to focus investments only on assets considered essential for initial operation. As a result, digital capabilities are often reduced, deferred, or excluded during project development. While this approach may reduce upfront expenditure, **experience from mature industries consistently demonstrates that the cost of retrofitting digital capabilities after commissioning is substantially higher than integrating them during design**.

More importantly, many digital capabilities create value across the entire asset lifecycle rather than within a single project phase. Digital twins, for example, can support techno-economic evaluation during Pre-FEED, design optimization during FEED and detailed engineering, virtual commissioning during project execution, operational optimization and predictive maintenance during plant operation, and future debottlenecking, expansion, or retrofitting activities. Similar lifecycle reuse can be achieved through engineering information management, industrial data platforms, cybersecurity architectures and digital traceability frameworks.

Digitalization **must support and enable a full life cycle perspective** of both existing assets and new infrastructure, ensuring more accurate analysis, improved environmental performance, and lower carbon footprints.

Consequently, **digitalization should not be evaluated solely as an upfront project cost, but as a long-term investment whose benefits accumulate throughout the lifecycle of the asset**. Several use cases presented in this report illustrate how **digital technologies can influence asset sizing, production optimization, maintenance planning, operational flexibility, regulatory compliance and lifecycle performance, generating value well beyond their initial implementation costs.**

The report also shows that **technology-adoption risk is generally lower than often perceived**. Many of the capabilities evaluated are already supported by proven industrial implementations and documented operational experience. Their maturity reduces implementation uncertainty while enabling organizations to benefit from established architectures, methodologies and lessons learned. **The challenge for hydrogen projects is therefore not technology availability, but selecting the appropriate capabilities, integrating them effectively, and adopting deployment strategies that align with project objectives and available budgets**.

STRATEGIC HYDROGEN DEPLOYMENT GAPS AND THE ROLE OF DIGITALIZATION

The assessment performed in this report highlights a series of strategic gaps that extend beyond technology deployment and directly influence the long-term scalability, competitiveness and bankability of hydrogen projects. While these gaps represent potential barriers to industrialisation, they also identify areas where early investment in digital capabilities can create significant value.

Digital Foundations Are Not Yet Keeping Pace with Infrastructure Development

Many hydrogen projects are progressing faster in physical infrastructure development than in the implementation of their supporting digital architectures. As projects grow in scale, fragmented data environments, isolated OT and IT systems, and limited interoperability between stakeholders can become structural barriers to growth. Establishing common data environments, interoperable architectures and lifecycle information management from the outset enables future optimization, integration and expansion while avoiding costly rework later in the asset lifecycle.

Key Takeaway: Digital foundations should be treated with the same strategic importance as pipelines, electrolysers or storage assets because they enable future scalability of the entire ecosystem.

Digitization improves project business case accelerating the value realisation

Digitalisation also plays a direct role in improving the business case of hydrogen projects over the full lifecycle of the asset. Early integration of digital capabilities can support more robust techno-economic evaluation, optimise asset sizing, reduce engineering and commissioning risks, improve operational efficiency, enable predictive maintenance, strengthen regulatory compliance and support future expansion or repurposing. These benefits accumulate across project phases, improving lifecycle economics and reducing uncertainty for developers, operators and investors.

Key Takeaway: Digitalisation should be evaluated not only as an implementation cost, but as a strategic value lever that enhances the bankability and long-term competitiveness of hydrogen projects.

The Industry Needs to Accelerate Operational Knowledge Creation

Hydrogen is increasingly valued not only for the molecule itself but also for its certified attributes, including origin, carbon intensity and compliance with sustainability frameworks. This shifts traceability from a compliance activity to a commercial capability.

Digital traceability platforms, digital product passports and integrated data architectures provide the foundation required to support future certification schemes, market access requirements and customer trust.

Key Takeaway: Future hydrogen markets will increasingly reward organizations that can demonstrate the provenance, sustainability and compliance of their products through trusted digital information.

Governance Determines Whether Digitalization Creates Business Value

The report demonstrates that technology alone does not guarantee success. Many digital initiatives fail to deliver expected outcomes because ownership, responsibilities and adoption mechanisms are not clearly defined.

Digitally mature industries have consistently shown that successful transformation requires digital governance to be embedded alongside engineering, operations and business management.

Organizations that establish governance models early are more likely to convert technological capabilities into measurable business outcomes.

Key Takeaway: Digital transformation is ultimately an organisational challenge supported by technology, not a technology project supported by the organisation.

Hydrogen Has a Unique Opportunity to Avoid the Legacy Constraints of Mature Industries

Many mature industries are investing heavily to modernise ageing assets and retrofit digital capabilities into infrastructures that were never designed for digital operation. Hydrogen projects have a unique advantage because most assets are still being designed and constructed.

This creates an opportunity to establish cybersecurity-by-design, lifecycle digital threads, interoperable architectures, engineering information management systems and digital twin environments from the earliest phases of development.

Key Takeaway: Hydrogen can become one of the first energy industries to be digitally native from inception rather than digitally transformed decades after deployment.

Strategic Outlook

Taken together, these gaps suggest that the future **competitiveness of hydrogen projects will depend** not only on access to renewable energy, technology selection or infrastructure deployment, but also **on the ability to establish scalable digital foundations** capable of supporting design, engineering, operations, certification, optimisation and future expansion. **Organizations that address these gaps proactively are likely to benefit from lower lifecycle costs, greater operational flexibility, reduced implementation risk and faster scalability as hydrogen markets mature**.

Key Takeaway: It is essential to ensure that organizations across the hydrogen value chain are aware that digitalization is a key enabler for the sector's future competitiveness.

READER GUIDE

This report is intended to support project developers, infrastructure operators, investors, technology providers, regulators and industrial hydrogen users in understanding how digital technologies can contribute to the development of the hydrogen value chain. It follows a progressive workflow that moves from technologies, to challenges, to lessons learned, and finally to practical implementation examples.

The report has been structured to answer four key questions:

1. **Which digital technologies are relevant to hydrogen projects?**
2. **What challenges do they help address?**
3. **What lessons can be learned from digitally mature sectors?**
4. **How have these technologies been applied in practice and how transferable are they to hydrogen?**

To answer these questions, the report is organised as follows:

Chapter 2 – State of the Art of Digital Technologies Applicable to Hydrogen

This chapter provides an overview of the main digital capabilities relevant to hydrogen infrastructure. The objective is to establish a common understanding of the technologies available and their role within the hydrogen ecosystem.

Chapter 3 – Digital Challenges and Barriers in the Hydrogen Value Chain

This chapter identifies the principal challenges affecting digitalization across the hydrogen value chain. It distinguishes between cross-cutting challenges that affect all stakeholders and challenges specific to upstream, midstream, storage and downstream segments. The objective is to define the operational, technical and business problems that require digital solutions.

Chapter 4 – Lessons Learned from Digitally Mature Industrial Sectors

This chapter reviews experiences from industries that have already undergone significant digital transformation. Rather than focusing on technology features, it captures implementation lessons, success factors and common mistakes to avoid when deploying digital solutions at scale.

Chapter 5 – Application of Digital Solutions Along the Hydrogen Value Chain

This chapter connects challenges and technologies through representative use cases and industrial examples. It demonstrates how specific digital capabilities can address the challenges identified in previous sections and evaluates their transferability and maturity within hydrogen applications. The chapter provides the practical bridge between concept and implementation.

Chapter 6 – Conclusions and Practical Adoption Approach

The final chapter consolidates the findings into a maturity assessment, identifies remaining gaps and presents a practical adoption roadmap. It provides guidance on how organizations can progressively develop digital capabilities while balancing technological ambition, project risks and investment constraints.

1 INTRODUCTION: KEY DIGITAL CONCEPTS

This chapter is intended to establish a common vocabulary for readers from different backgrounds. It provides concise explanations of the main acronyms, technologies, methodologies, and sector-specific terms used throughout this report.

1.1 Acronyms

Table 1. Acronyms of the report

Acronym / Term	Full name	Explanation for this report
ACE	Area Control Error	Power system balancing metric used by transmission operators to measure deviations between scheduled and actual interchanges and frequency performance.
aFRR	Automatic Frequency Restoration Reserve	Ancillary service requiring automated active power response to restore grid frequency; relevant where electrolysers participate in balancing markets.
AHI	Asset Health Index	Composite indicator combining maintenance, inspection, operational and condition-monitoring information to assess equipment health and prioritize interventions.
AI	Artificial Intelligence	Computational methods used to identify patterns, forecast behaviour, recommend actions and support decision-making across design, operations, maintenance and optimization.
API	Application Programming Interface	Interface used to exchange data between software systems; relevant where traceability platforms connect renewable generation, markets, electrolyser operation and commercial systems.
BESS	Battery Energy Storage System	Battery storage asset that can be orchestrated with renewables, controllable loads and hydrogen production assets in energy management or DERMS contexts.
BIM	Building Information Modelling	Structured digital modelling and information-management approach that connects graphical and non-graphical engineering data across design, construction and operation.
BPCS	Basic Process Control System	Core automation layer that controls normal process operation; relevant when integrated with safety systems in hydrogen production plants.
CAPEX	Capital Expenditure	Upfront investment required to develop or implement physical and digital project scope. The report highlights CAPEX pressure as a reason digital scope may be deferred.
CBM	Condition-Based Maintenance	Maintenance performed according to actual equipment condition rather than fixed intervals.
CCGT	Combined Cycle Gas Turbine	Power plant using gas and steam turbine cycles; referenced in relation to stored green hydrogen use in a hybrid power plant.
CCS	Carbon Capture and Storage	Technology chain used to capture and store carbon emissions; referenced in blue-hydrogen network optimization and related cost scenarios.

Acronym / Term	Full name	Explanation for this report
CDE	Common Data Environment	Controlled information management environment where project participants collaborate using consistent and governed data.
CertifHy	CertifHy Certification Scheme	European voluntary certification scheme recognized as a framework to certify the origin and sustainability attributes of renewable and low-carbon hydrogen.
CO_2	Carbon Dioxide	Greenhouse gas used as a key emissions metric in decarbonization and hydrogen sustainability assessments.
DC	Direct Current	Electrical architecture concept; medium-voltage DC bus integration is identified as an upstream challenge for renewable generation, storage and electrolyser systems.
DER	Distributed Energy Resource	Distributed generation, storage or controllable load asset participating in grid or energy-management schemes.
DERM	Distributed Energy Resource Management	Short form used in the report for a distributed energy resource management capability. In practice, the plural/system form DERMS is normally used for the platform.
DERMS	Distributed Energy Resource Management System	Digital platform used to orchestrate distributed energy resources such as renewables, batteries, EV charging, controllable loads and, by adaptation, electrolyser flexibility and hydrogen storage.
DCS	Distributed Control System	Control system architecture used to supervise and control industrial processes; relevant where process orchestration integrates multiple OEM systems.
EIM	Energy Imbalance Market	Market mechanism referenced in DERMS use cases for optimized dispatch and balancing-area participation.
EMS	Energy Management System	Digital system used to optimize energy production, consumption, storage, market participation and grid support services.
EMT	Electromagnetic Transient	High-fidelity electrical modelling domain used to validate protection schemes, controls and dynamic grid interactions.
ERP	Enterprise Resource Planning	Enterprise software systems used to manage business processes and data. Referenced as a source of business information integrated with OT and industrial data platforms.
ETCC	Extract – Transform – Contextualize – Collaborate	Data-management approach proposed in the report as a foundation for data integration, governance and digitalization across the hydrogen value chain.
FID	Final Investment Decision	Decision point at which a project moves from development toward execution; digital economic analysis can reduce uncertainty before FID.
FCR	Frequency Containment Reserve	Ancillary service supporting frequency stabilization; relevant to electrolyser participation in grid balancing and flexibility markets.

Acronym / Term	Full name	Explanation for this report
FEED	Front-End Engineering Design	Engineering phase that defines project technical scope, design basis, cost estimate and execution readiness before detailed design or final approval.
FuelEU	FuelEU Maritime Regulation	European regulatory framework promoting the use of renewable and low-carbon fuels in maritime transport.
GAP	No representative use case documented	Transferability category used in the report when no direct or indirect representative use case has been documented.
GeoAI	Geospatial Artificial Intelligence	Combination of GIS and artificial intelligence techniques used to analyse geospatial data, identify patterns and support decision-making.
GIS	Geographic Information System	Spatial information system that integrates geographically referenced data to support site selection, routing, risk management and operational decision-making.
GO	Guarantee of Origin	Instrument used to disclose the origin of energy supplied to consumers; in hydrogen, it can provide data such as technology, source, location and production period.
GtCO2	Gigatonnes of Carbon Dioxide	Mass unit used for carbon dioxide emissions; the report cites annual emissions at global hydrogen-demand scale.
H_2	Hydrogen	Chemical symbol used throughout the report to refer to hydrogen as a molecule, energy vector, product and industrial feedstock.
HVAC	Heating, Ventilation and Air Conditioning	Building load integrated in DERMS use cases as part of broader demand flexibility and optimization.
ICSS	Integrated Control and Safety System	Integrated platform combining control and safety functions to supervise hydrogen production, storage, emergency shutdown and fire/gas protection.
IEC	International Electrotechnical Commission	International standards body referenced through industrial cybersecurity and functional safety standards such as IEC 62443 and IEC 61511.
IEC 62443	Industrial automation and control systems security standard	Standard framework referenced for robust cybersecurity governance in industrial OT environments.
IEC 61511	Functional safety standard for safety instrumented systems	Standard referenced for safety requirements in hydrogen processing, storage, compression and handling.
IIoT	Industrial Internet of Things	Industrial connectivity technologies used to acquire operational data from field devices and support monitoring, analytics and risk management across hydrogen assets.
IoT	Internet of Things	Network of connected devices and sensors. In the report, IoT is used mainly in the industrial connectivity context for hydrogen monitoring and operational visibility.

Acronym / Term	Full name	Explanation for this report
ISA-95	Enterprise-control system integration standard	Reference architecture concept used to describe layered automation integration from field instrumentation to enterprise systems.
ISCC	International Sustainability and Carbon Certification	Voluntary certification scheme recognised by the European Commission for demonstrating sustainability compliance of renewable fuels, including RFNBOs
ISO	International Organization for Standardization	International standards body referenced through engineering information and hydrogen fuel quality standards.
ISO 14687	Hydrogen fuel quality standard	Standard defining minimum hydrogen fuel quality characteristics for several applications.
ISO 19650	Information management using BIM standard	Governance framework supporting information management, standardization and BIM collaboration practices.
IT	Information Technology	Business and information systems layer. In the report, IT is often discussed together with OT for integration, cybersecurity and data governance.
KTon	Kilotonnes	Unit equal to one thousand tonnes, used in production-capacity figures for hydrogen, ammonia and methanol.
LCOH	Levelized Cost of Hydrogen	Economic metric used to assess hydrogen production cost over the asset lifecycle, including the effect of utilization, power costs, CAPEX and operational performance.
LNG	Liquefied Natural Gas	Mature industrial sector used as a reference for transferable digital practices, including asset management and infrastructure operations.
ML	Machine Learning	AI technique used to identify patterns from data; referenced in leak detection, predictive maintenance and operational analytics contexts.
mFRR	Manual Frequency Restoration Reserve	Ancillary service relevant to power-system balancing where controllable loads such as electrolysers may participate.
Mt	Million tonnes	Mass unit used in hydrogen demand estimates.
MW	Megawatt	Power unit used for renewable, electrolyser, storage and industrial asset capacity figures.
NG	Natural Gas	Fuel and infrastructure system used as a reference or blending context for hydrogen pipeline operations.
NIS2	Network and Information Security Directive 2	EU cybersecurity directive referenced as reinforcing the need for robust cybersecurity governance for critical infrastructure.
OEM	Original Equipment Manufacturer	Equipment supplier. The report highlights multi-OEM integration as a recurring challenge for hydrogen projects.
O&M	Operation and Maintenance	Lifecycle phase where assets are operated, monitored, maintained and optimized.

Acronym / Term	Full name	Explanation for this report
OPC UA	Open Platform Communications Unified Architecture	Open industrial communication standard supporting interoperability between multiple vendors, devices and systems.
OPEX	Operating Expenditure	Ongoing operating cost. The report notes that treating digitalization as OPEX can put digital adoption at risk.
OT	Operational Technology	Industrial systems used to monitor and control physical processes, assets and field equipment.
PEM	Proton Exchange Membrane	Electrolyser technology referenced in a green hydrogen production plant use case.
PLC	Programmable Logic Controller	Industrial controller used to automate equipment and subsystems; referenced for electrolyser package supervision and integration.
PPA	Power Purchase Agreement	Commercial agreement for electricity supply; relevant to RFNBO traceability because renewable electricity sourcing must be linked to hydrogen production.
Pre-FEED	Pre-Front-End Engineering Design	Early project-definition phase used to evaluate options, feasibility, digital foundations, techno-economics and architecture before FEED.
PV	Photovoltaic	Solar photovoltaic generation; referenced in multi-OEM hydrogen production, storage and refuelling use cases.
RED III	Renewable Energy Directive III	EU framework referenced in relation to renewable hydrogen, RFNBO compliance, market access and sustainability requirements.
REDcert	REDcert Certification Scheme	Voluntary certification scheme recognised for demonstrating compliance with renewable energy sustainability requirements and RFNBO certification frameworks.
RFNBO	Renewable Fuel of Non-Biological Origin	EU regulatory category for renewable hydrogen and derivative fuels; compliance requires auditable evidence on renewable electricity sourcing, additionality and temporal/geographical correlation.
ROI	Return on Investment	Metric used to evaluate whether digital investments produce measurable value relative to cost.
RTU	Remote Terminal Unit	Remote control/monitoring device used in distributed infrastructure such as pipelines, utility networks and remote assets.
SCADA	Supervisory Control and Data Acquisition	Supervisory system for monitoring, controlling and acquiring data from distributed assets; central to pipeline, utility and hydrogen operational visibility.
SIL	Safety Integrity Level	Risk-reduction performance level for safety functions, referenced through SIL3 safety systems in hydrogen production plants.
SIS	Safety Instrumented System	Independent safety system executing protective functions such as emergency shutdown when hazardous conditions occur.

Acronym / Term	Full name	Explanation for this report
SLB	SLB	Contributor/company label appearing throughout the document; keep as organizational reference, not as a technical acronym.
SMR	Steam Methane Reformer	Hydrogen production unit referenced in blue-hydrogen facilities and fleet-wide hydrogen plant optimization.
STATCOM	Static Synchronous Compensator	Power-electronics device referenced for high-voltage connection-point voltage control and transmission-system support.
VPP	Virtual Power Plant	Coordinated portfolio of distributed resources operated as an aggregated, market-participating energy asset.

1.2 Key Terms

Table 2. Key Terms of the report

Term	Contextual for this report
Advanced Process Control	Advanced control methodology that optimises industrial processes by simultaneously managing multiple variables and constraints to improve efficiency, stability and operational performance.
Asset Integrity	Capability to ensure that physical assets operate safely, reliably and according to their design requirements throughout their lifecycle. A recurring objective of digital monitoring and predictive maintenance systems.
Book-and-Claim	Chain-of-custody model where environmental attributes are separated from the physical product and traded through certificates.
Chain of Custody	Method used to connect certified production attributes with final consumption across physical or commercial handovers.
Contextualization	Process of enriching raw data with engineering, operational and business meaning so that it can be correctly interpreted.
Cyber-Physical System	Integrated environment where digital systems directly interact with physical industrial assets and processes.
Cybersecurity-by-Design	Approach where cybersecurity requirements are embedded during project design rather than added after commissioning.
Data Analytics	Collection, integration, validation and analysis of data to generate operational, economic or engineering insights.
Data Fabric	Integrated data architecture connecting and contextualizing information from OT and IT systems as a foundation for analytics, AI, digital twins and traceability.
Data Governance	Organizational framework defining data ownership, quality, security, standards and responsibilities to ensure trusted and usable information.
Data Lake	Centralized repository used to store large volumes of structured and unstructured data from multiple operational and business sources.

Term	Contextual for this report
Data Quality	Degree to which information is complete, accurate, consistent and reliable for operational and business decision-making.
Defence in Depth	Layered cybersecurity strategy using multiple independent safeguards to protect critical systems.
Digital Product Passport	Structured digital record carrying certified product attributes such as origin, production period, carbon intensity, certification scheme and custody transfers.
Digital Foundation	Set of digital architectures, information models, governance mechanisms and connectivity capabilities that enable future digital applications and scalability.
Digital Thread	Continuous flow of information linking engineering, construction, commissioning, operations, maintenance and future modifications throughout the asset lifecycle.
Digital Traceability	Digital tracking and verification of hydrogen flows and attributes, including origin, emissions, compliance and chain of custody.
Digital Twin	Digital representation of a physical asset, process or system combining models and operational data to support decisions across the lifecycle.
Downstream	Distribution, refuelling, end-use applications, industrial consumption, mobility, aviation, maritime uses and derivative fuels.
Event-Driven Architecture	Digital architecture where systems exchange information and trigger actions based on operational or business events occurring in real time.
Fleet-Level Optimization	Use of analytics and decision support across multiple similar assets or facilities rather than a single plant.
Greenfield Development	Project developed from inception rather than retrofitted into legacy infrastructure; the report positions hydrogen as an opportunity to be digitally native from the outset.
Interoperability	Ability of systems, devices, applications and organizations to exchange and use information effectively.
Mass Balance	Chain-of-custody model where certified and non-certified products may be physically mixed while certified attributes are tracked through accounting.
Midstream	Transport, storage, pipelines, hydrogen backbone networks and logistics.
Model Predictive Control	Advanced control methodology that uses mathematical models to predict future process behaviour and optimise operational decisions.
Operational Technology Convergence	Progressive integration of OT and IT environments to improve operational visibility, automation and decision-making.
Physical Segregation	Chain-of-custody model where certified hydrogen is physically separated from non-certified hydrogen throughout the value chain.
Predictive Maintenance	Maintenance strategy using condition monitoring, analytics and AI to predict failures before they occur.

Term	Contextual for this report
Predictive Analytics	Analytical techniques that use historical and real-time data to forecast future events, equipment behaviour or operational outcomes.
Prescriptive Maintenance	Advanced maintenance approach that predicts failures and recommends corrective actions.
Semantic Data Model	Structured method used to contextualize and interpret information consistently across systems, applications and stakeholders.
Simulation	Model-based representation of system behaviour used for design, planning, dynamic analysis, virtual commissioning and operator training.
Transferability - Emerging	Non-hydrogen-native references explicitly described as directly transferable or analogous, with none or very low adaptation required.
Transferability - Gap	No representative direct or indirect use case is documented.
Transferability - Strong	Hydrogen-native references or use cases that include hydrogen-specific applications.
Transferability - Weak	Evidence is limited or indirect and requires significant adaptation.
Upstream	Hydrogen production activities, including renewable integration, electrolysis, water treatment and initial compression.
Virtual Commissioning	Testing and validation of automation systems, control strategies and operating procedures using simulation before physical startup.

2 STATE OF THE ART OF DIGITAL TECHNOLOGIES APPLICABLE TO HYDROGEN

Digitalization is becoming a central enabler for the technical, operational and economic deployment of the hydrogen value chain. Hydrogen infrastructures combine process complexity, safety-critical conditions, strong coupling with power systems, fragmented data environments and increasing regulatory scrutiny.

Under these conditions, digital technologies are not simply efficiency levers, but structural components that influence design decisions, operational performance, asset integrity, compliance and scalability. In practice, the digitalization of hydrogen systems is built around the convergence of several technological domains, including cybersecurity, data analytics and artificial intelligence, automation and control, engineering information management, industrial connectivity, digital twins, traceability and geospatial intelligence. Together, these domains create the digital foundation required to move from isolated assets and reactive operations toward integrated, predictive and progressively more autonomous systems. Within the hydrogen context, the relevance of these technologies is amplified by the characteristics of the value chain itself.

Hydrogen production and handling involve electrochemical conversion, thermodynamics, fluid transport, compression, storage, quality assurance and interaction with external infrastructures such as electricity networks, industrial demand centres and transportation systems. These interactions require high-quality data, robust control architectures, interoperable engineering environments and mechanisms to ensure continuity between design, construction and operation.

As a result, the state of the art is not defined by a single technology, but by the structured integration of multiple digital capabilities into a coherent architecture that supports the full lifecycle of assets and infrastructure.

2.1 Cybersecurity

Cybersecurity is a foundational requirement in hydrogen infrastructures because these assets are increasingly treated as critical energy infrastructure and because cyber incidents can translate directly into physical consequences. Hydrogen production, storage, transport and end-use facilities handle high-pressure flammable gases, interact with electricity and gas networks, and increasingly depend on digitally managed certification and reporting schemes. In that setting, cybersecurity cannot be understood as an auxiliary IT concern. It must be treated as an architectural design constraint that shapes system integration, access management, remote operations, communication patterns and even equipment engineering choices from early project phases onward.

In hydrogen systems, cyber risk must be analysed from a process-safety perspective. The relevant question is not only whether information can be stolen or services disrupted, but whether the compromise of digital systems could generate loss of control, loss of view, loss of protection or manipulation of process conditions. This is particularly important in electrolysis environments, where hydrogen and oxygen coexist in the same plant and are separated by membranes or diaphragms. Under these conditions, cyber-enabled deviations in pressure, flow, temperature, current, alarm management, shutdown logic or gas concentration monitoring can become initiating or contributing causes of major accident scenarios.

The hydrogen sector presents vulnerabilities that distinguish it from more mature industrial environments. The technology stack is comparatively novel, the vendor ecosystem is fragmented, and many projects scale up from pilot or first-of-a-kind deployments that do not yet benefit from long operational histories under cyber-adversarial conditions. In addition, the convergence between IT and

OT is often stronger than in conventional industrial plants because hydrogen facilities require close coupling with market signals, renewable generation profiles and remote operations. The state of the art in hydrogen cybersecurity is based on layered protection principles. Defence in depth, strict segmentation between IT and OT, secure remote access and continuous monitoring are essential elements. These measures ensure that access to systems is controlled, detectable and auditable, minimizing the probability of unauthorized interventions. Regulatory frameworks such as the NIS2 Directive and IEC 62443 reinforce the need for robust cybersecurity governance. Compliance is no longer optional but embedded in licensing, insurance and certification processes.

In practical hydrogen operations, cybersecurity also needs to converge with safety engineering. The decisive point is that cybersecurity for hydrogen is not only about protecting digital assets; it is about preserving safe operation, process integrity and trust in digitally managed hydrogen processes.

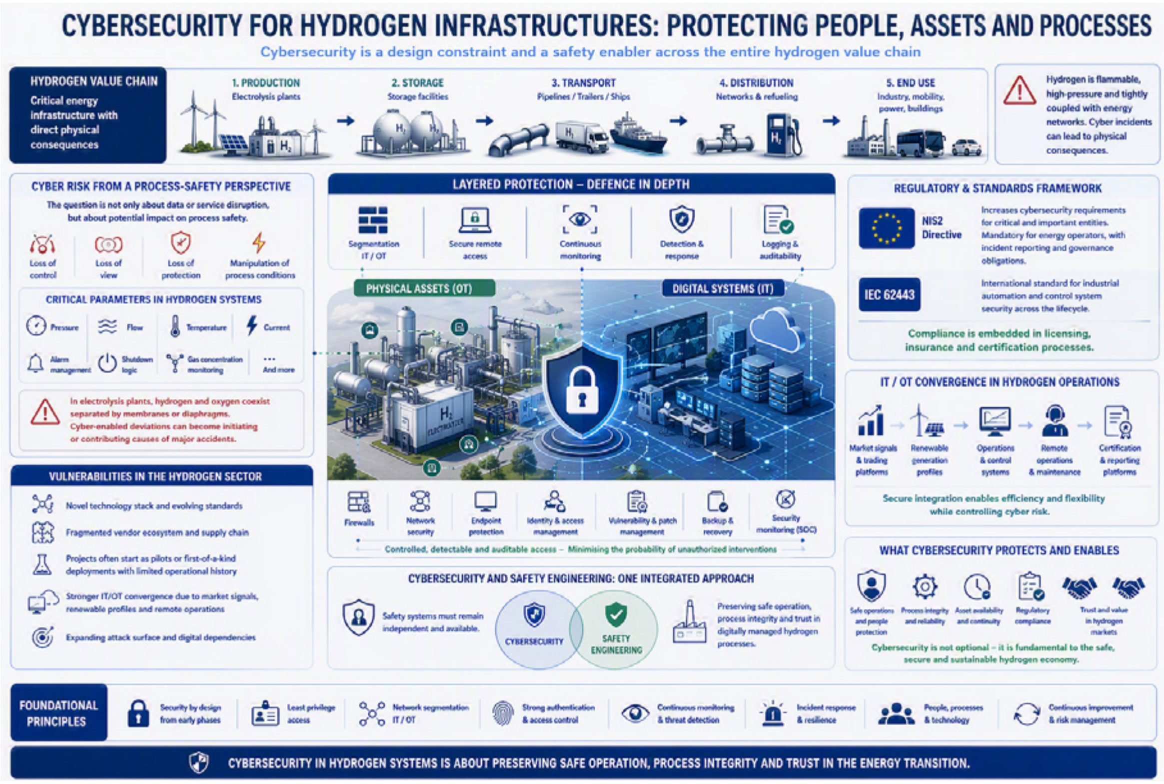


Figure 1. Infographic figure of Cybersecurity for H2 Infrastructures

2.2 Data Analytics and Artificial Intelligence

Data analytics and artificial intelligence constitute the intelligence layer of the hydrogen value chain, enabling organizations to transform large volumes of heterogeneous data into actionable insights. Their value extends across the full lifecycle of assets, from design and planning to operation and optimization.

At the core of data analytics lies the integration of data from multiple sources, including sensors, control systems, engineering tools and enterprise platforms. These data must be structured, validated and contextualized to be usable for decision-making. This process creates a unified data foundation that enables consistency across engineering, operations and business domains.

Once data is properly structured, analytics applications can generate predictive and prescriptive insights. Predictive maintenance, anomaly detection and performance monitoring are among the most relevant use cases in hydrogen systems, where early identification of deviations is critical for safety and reliability. In addition, analytics enables optimization of production processes, particularly in environments characterized by variable renewable energy inputs.

Artificial intelligence enhances these capabilities by applying advanced modelling techniques to identify patterns and correlations that are not evident through traditional methods. Machine learning models can support forecasting of hydrogen production and demand, optimisation of operating conditions, and detection of complex anomalies. When integrated with operational systems, these capabilities enable more responsive and adaptive asset management.

The effectiveness of AI applications depends strongly on data quality and governance. As hydrogen systems are often early-stage deployments, the availability of representative datasets may be limited. This requires a balanced approach that combines data-driven models with engineering knowledge to ensure robustness and interpretability.

Overall, data analytics and AI are key enablers of decision-making, connecting technical operations with strategic and commercial objectives. Their impact increases when embedded into workflows and integrated with other digital technologies such as digital twins and automation systems.

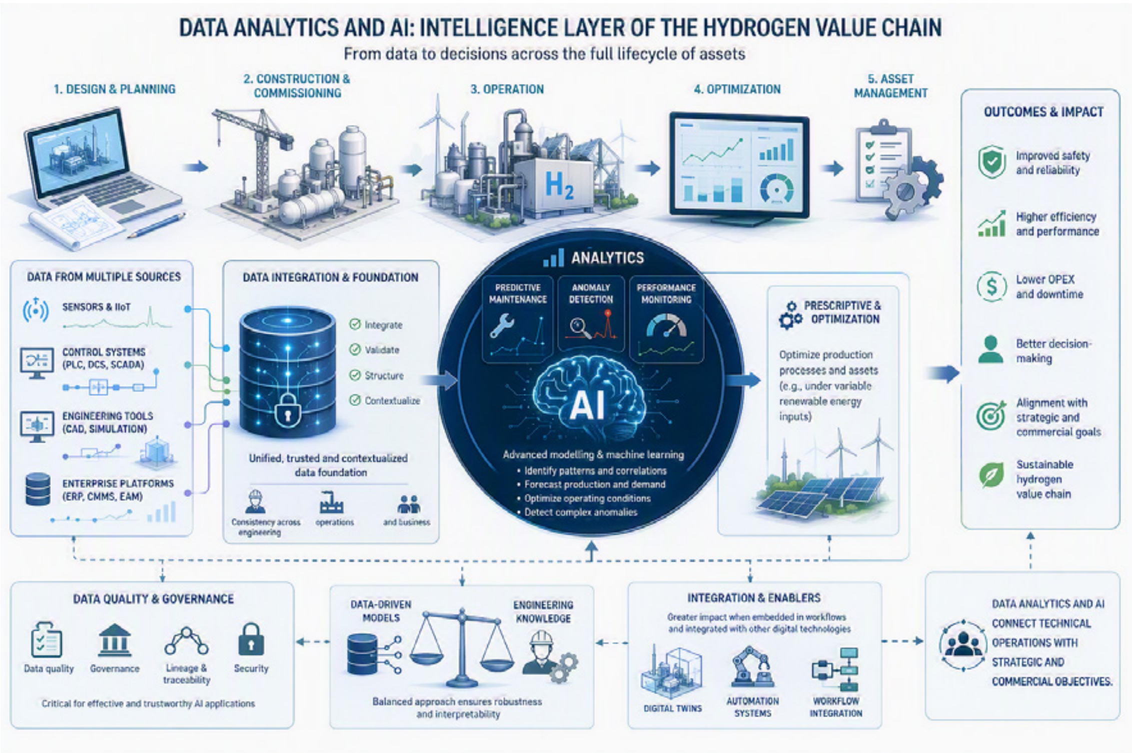


Figure 2. Infographic figure of Data Analytics and Artificial Intelligence for H2 Infrastructures.

2.3 Automation and control systems

Automation and control systems represent the operational core of hydrogen assets, translating engineering design into real-time physical behaviour. These systems ensure that processes operate within safe and efficient limits while responding dynamically to changing conditions.

Modern hydrogen infrastructures follow layered automation architectures aligned with ISA-95 principles. These architectures integrate field instrumentation, control systems, supervisory platforms and enterprise systems into a coherent hierarchy. In parallel, safety instrumented systems operate independently to ensure protection functions under hazardous conditions.

Technological advancements in control systems include the application of advanced process control and model predictive control techniques. These approaches enable multivariable optimization, allowing systems to respond efficiently to variability in inputs such as renewable energy supply. Real-time optimization layers further enhance performance by adjusting operating strategies based on economic and operational conditions.

Interoperability is a key requirement in hydrogen projects, where multiple vendors and modular systems must be integrated. Open standards such as OPC UA and emerging companion specifications for hydrogen equipment enable consistent communication and integration across systems. These standards reduce engineering complexity and support scalability.

Automation systems are particularly critical in hydrogen due to the combination of dynamic operation and stringent safety requirements. The interaction between electrolysis units, power systems, storage and distribution infrastructure requires coordinated control strategies. At the same time, safety systems must be tightly integrated while maintaining independence from operational control layers.

Automation is therefore not only a technical requirement but a strategic enabler of reliability, flexibility and scalability. Early design decisions in automation architecture have long-term implications for system performance and digital readiness.

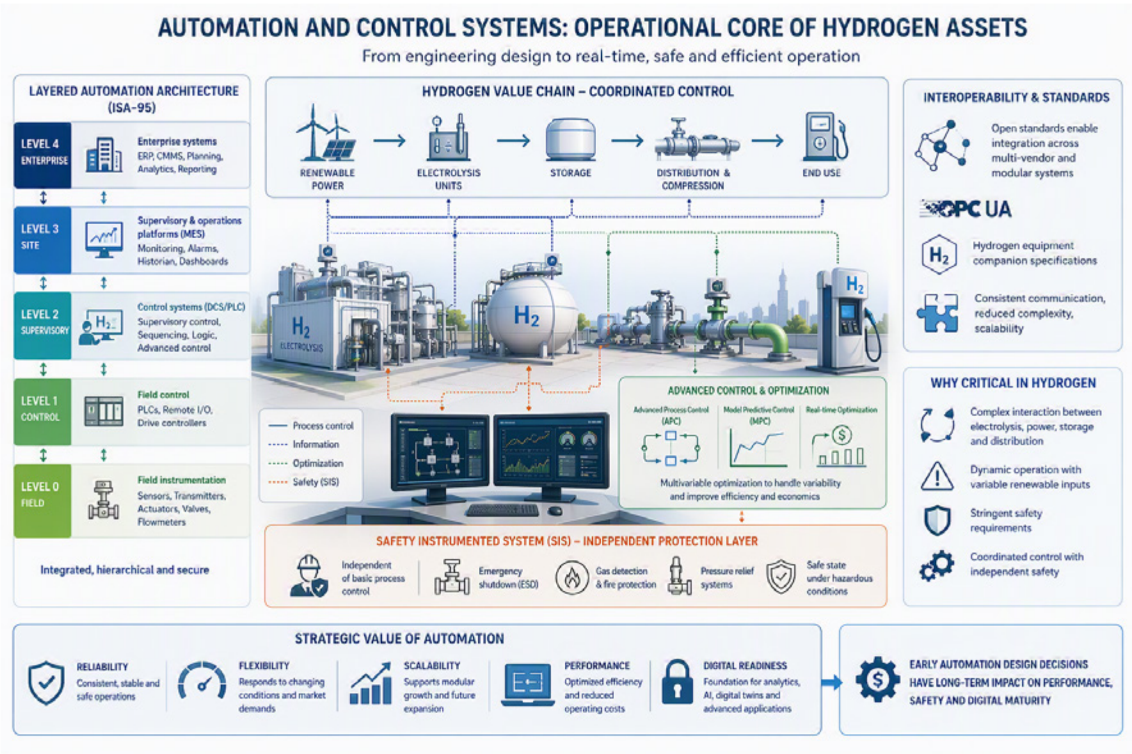


Figure 3. Infographic figure of Automation and Control Systems for H2 Infrastructures.

2.4 BIM and Engineering Information Management

Building Information Modelling and engineering information management technologies provide the structural environments for managing complex hydrogen infrastructure projects. These technologies enable the integration of graphical and non-graphical data into unified digital environments that support collaboration across disciplines and lifecycle stages.

At the core of BIM ecosystems is the concept of a centralized information environment, often implemented through Common Data Environments. These platforms ensure that all project stakeholders work with consistent and controlled information, enabling version management, traceability and secure access to engineering data.

BIM technologies extend beyond 3D modelling to incorporate data management, workflow automation and interoperability capabilities. Open standards enable integration with other digital systems, including IoT platforms, ICSS, SCADA systems and enterprise applications. This interoperability ensures that engineering information remains relevant throughout the lifecycle of the asset.

Engineering information management also focuses on standardization. The definition of data structures, naming conventions and classification systems ensures consistency across projects and facilitates information exchange. Standards such as ISO 19650 provide governance frameworks that support these practices.

The integration of BIM with operational systems is increasingly important in hydrogen projects. Digital continuity between design, construction and operation enables more efficient asset management and reduces information loss across lifecycle stages. This capability is particularly relevant in the hydrogen sector, where assets are complex and require long-term reliability.

Overall, BIM and engineering information management act as the backbone of digital collaboration, ensuring that information is structured, accessible and consistent across all phases of infrastructure development.

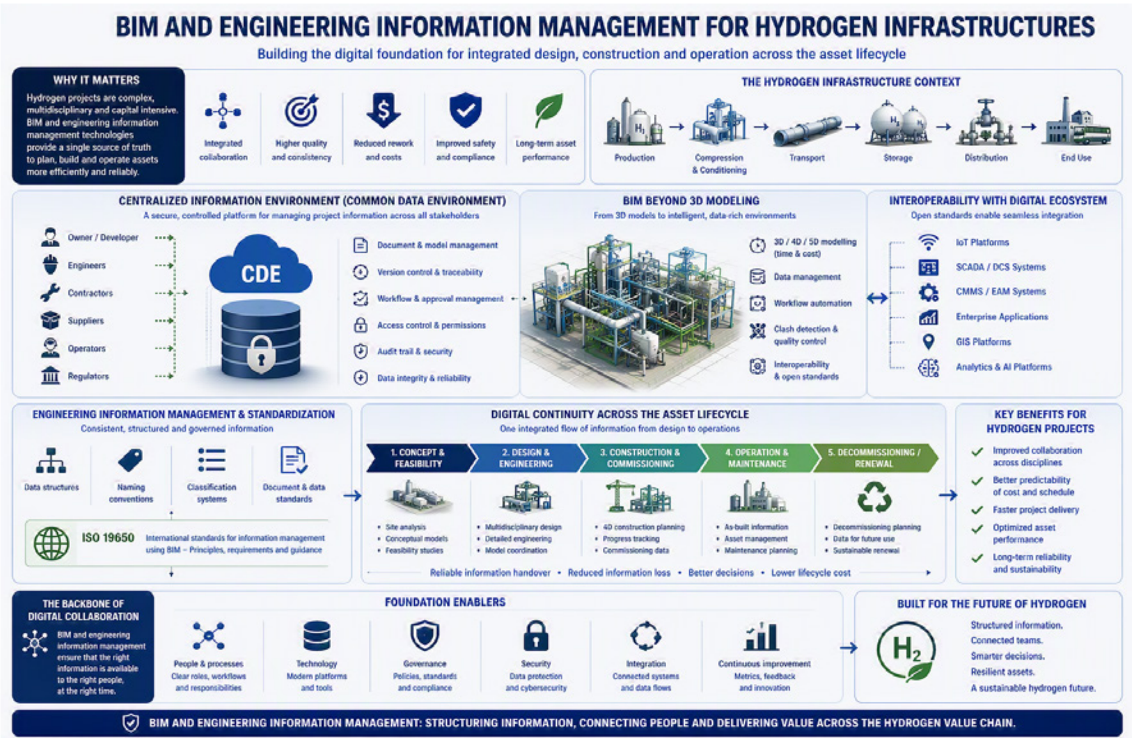


Figure 4. BIM and Engineering Information Management for H2 Infrastructures.

2.5 Internet of Things and Industrial Connectivity

The hydrogen industry relies on complex and geographically distributed infrastructures that encompass production plants, storage facilities, transportation networks and end-use applications. In this context, Industrial Internet of Things (IIoT) and connectivity technologies are becoming essential enablers of safe, efficient and scalable hydrogen operations.

Hydrogen presents unique operational challenges due to its physical properties, including its low molecular weight, high diffusivity and the demanding pressure and temperature conditions associated with production, storage and transport. Addressing these challenges requires continuous visibility of assets and processes through extensive instrumentation and connected monitoring systems.

IIoT technologies provide the capability to acquire operational data from a wide range of field devices, generating real-time information on process variables such as pressure, temperature, flow, vibration, energy consumption and equipment health. This data forms the foundation for operational optimization, predictive maintenance and risk management strategies throughout the hydrogen value chain.

Industrial connectivity enables seamless integration between field devices, control systems and enterprise platforms, facilitating the flow of information across organizational levels. By eliminating data silos and enabling interoperability between systems, organizations can achieve greater operational transparency and improve decision-making processes based on reliable and timely information.

In hydrogen transportation and distribution networks, connected monitoring solutions enhance the ability to detect deviations, identify potential leaks and monitor asset integrity across large distances. Combining sensor data with advanced analytics and digital models allows operators to move from reactive maintenance approaches towards condition-based and predictive maintenance strategies, improving both safety and asset availability.

At production facilities, digital connectivity supports the optimization of electrolyzers and other critical process units by enabling continuous performance monitoring and energy efficiency analysis. Given that electricity represents a significant portion of hydrogen production costs, access to high-quality operational data is critical for maximizing efficiency and reducing overall production costs.

The importance of connectivity extends beyond individual assets. As hydrogen ecosystems evolve, the integration of producers, transport operators, storage facilities and end users will require secure and standardized data exchange. Digital connectivity therefore becomes a key enabler for coordinating complex hydrogen networks, improving system flexibility and supporting future energy market integration.

Furthermore, the vast amount of data generated by connected assets creates the foundation for advanced digital applications such as digital twins, artificial intelligence and asset performance management systems. These technologies have the potential to accelerate operational excellence, reduce lifecycle costs and improve the overall reliability of hydrogen infrastructures.

As the hydrogen economy expands, IIoT and industrial connectivity will play a critical role in transforming data into actionable insights, enabling safer operations, greater efficiency and more sustainable management of hydrogen assets across the entire value chain.

Adoption of IoT technologies must be aligned with cybersecurity and data governance requirements. Secure connectivity and reliable data management are essential to ensure that the benefits of digitalization are realized without introducing additional risks.

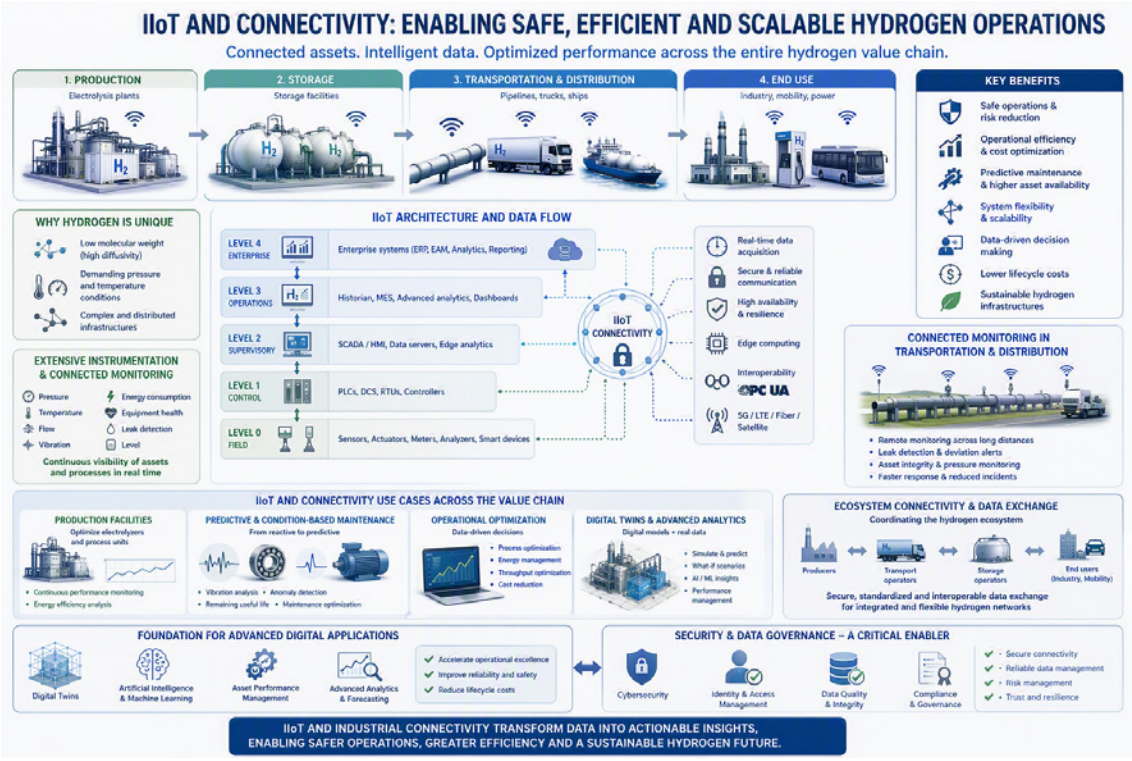


Figure 5. Internet of Things and Industrial Connectivity for H2 Infrastructures.

2.6 Digital Twin and Simulation Technologies

Digital twin and simulation technologies provide virtual representations of hydrogen systems, enabling analysis, prediction and optimization across the asset lifecycle. These technologies integrate models, data and analytics into coherent environments that support decision-making.

Digital twins differ from traditional simulation models by incorporating real or near-real-time data from physical systems. This integration enables continuous monitoring and dynamic analysis, allowing operators to anticipate system behaviour and evaluate alternative scenarios.

Different modelling approaches contribute to digital twin capabilities. Physics-based models provide accurate representation of system behaviour, particularly in safety-critical and engineering-intensive applications. Data-driven models complement these approaches by identifying patterns and correlations from operational data. Hybrid models combine both approaches, balancing accuracy and computational efficiency.

Simulation technologies also operate across different temporal scales. Steady-state models support design and planning, while dynamic models capture transient behaviour and operational variability. The integration of these models enables comprehensive analysis of system performance.

In hydrogen systems, digital twins are particularly valuable due to the complexity of the value chain and the interaction between multiple physical phenomena. They support design optimization, operational planning, risk analysis and investment decision-making. By reducing uncertainty and enabling scenario analysis, digital twins contribute to more robust and efficient project execution.

The effectiveness of digital twins depends on model quality, data integration and governance. As projects evolve, these systems must be continuously updated to reflect changes in assets and operating conditions.

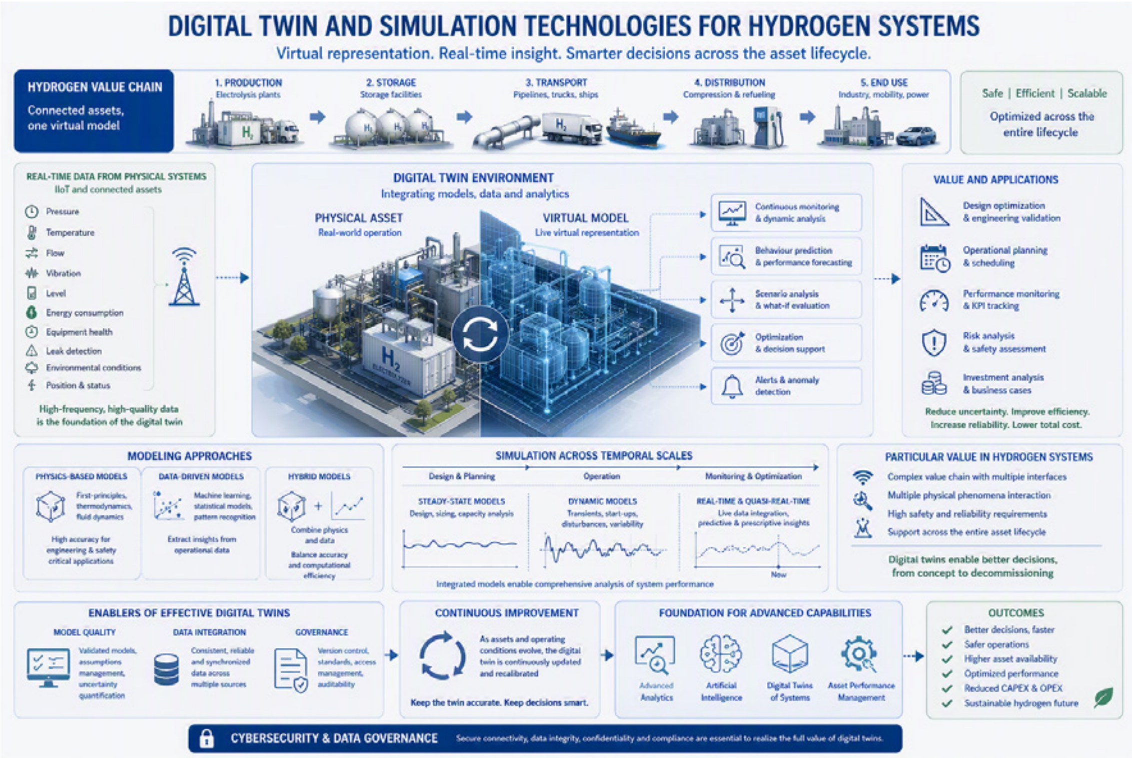


Figure 6. Digital Twin and Simulation Technologies for H2 Infrastructures.

2.7 Digital Traceability

Digital traceability technologies enable the tracking and verification of hydrogen across the value chain, ensuring transparency and compliance with regulatory and certification requirements. In emerging hydrogen markets, where the origin and sustainability of hydrogen are critical, traceability becomes a key value driver.

These systems rely on the integration of data from production, transport and consumption processes, creating a digital record of hydrogen flows and attributes. This includes information related to energy sources, emissions, production methods and operational parameters.

Traceability is particularly relevant for certification schemes such as renewable hydrogen, where compliance depends on accurate and auditable data. Digital platforms must therefore ensure data integrity, security and interoperability across different stakeholders.

Technological solutions often combine data management systems with blockchain or distributed ledger technologies to enhance transparency and trust. These approaches enable verification of data without central authority and support cross-border certification processes.

Beyond compliance, traceability can also support operational optimization and commercial strategies by providing visibility into supply chains and enabling more informed decision-making. As hydrogen markets mature, digital traceability will be a critical enabler of trust, efficiency and market development.

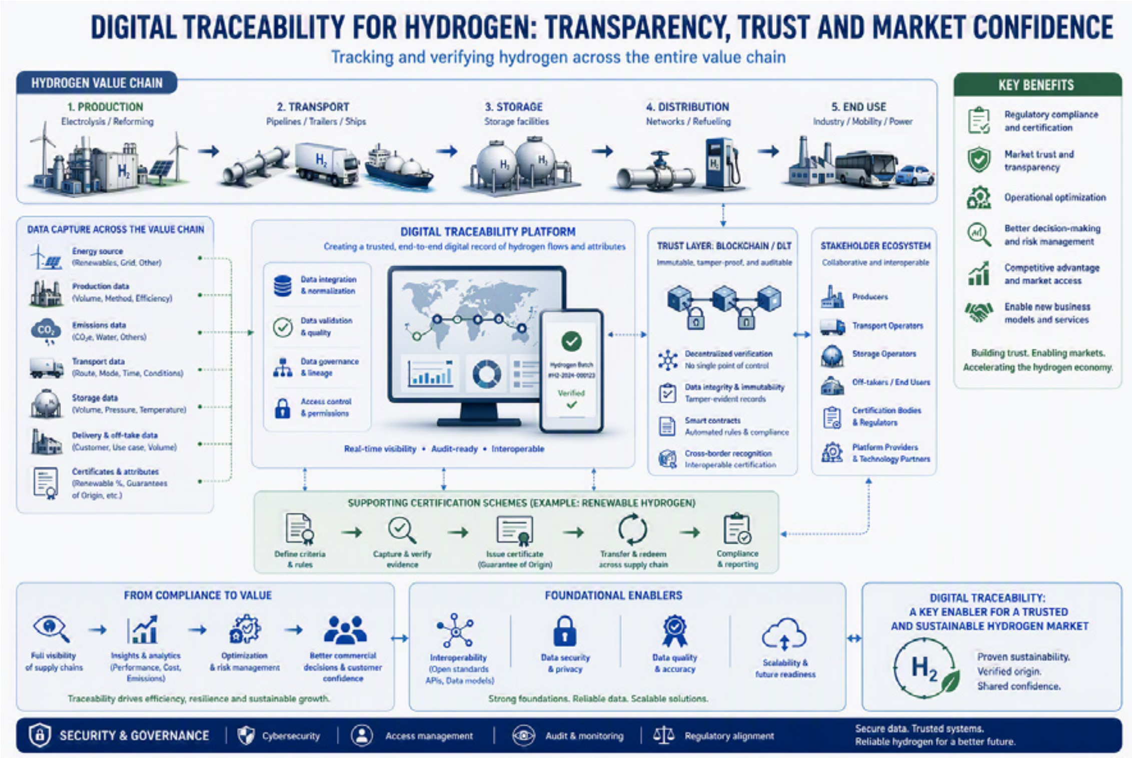


Figure 7. Digital Traceability for H2 Infrastructures.

2.8 GIS (Geographic Information Systems)

Geographic Information Systems provide a spatial dimension to the digitalization of the hydrogen value chain, enabling the integration and analysis of geographically referenced data. These systems support planning, risk management and operational decision-making by connecting assets, infrastructure and environmental context.

Hydrogen deployment has a strong territorial component, involving renewable resources, infrastructure networks and industrial demand. GIS platforms enable these elements to be analysed within a unified spatial framework, supporting the identification of optimal locations, routes and investment priorities.

In planning phases, GIS supports multi-criteria analysis by combining technical, environmental and economic data. This enables more informed decisions regarding site selection, infrastructure routing and project prioritization. The integration of Earth observation data further enhances the accuracy and relevance of these analyses.

During project development and operation, GIS provides continuous visibility of asset status and contextual conditions. It supports monitoring, maintenance and emergency response by linking physical assets with digital systems and real-time data.

The integration of GIS with other technologies such as BIM, IoT and digital twins creates a comprehensive digital ecosystem, where spatial context enhances the understanding of system behaviour. Advanced capabilities such as GeoAI further extend these functionalities by enabling automated analysis and pattern detection.

GIS is therefore not only a visualization tool but a strategic platform for managing the hydrogen value chain. Its ability to connect data, territory and decision-making processes makes it a critical enabler of efficient and sustainable hydrogen deployment.

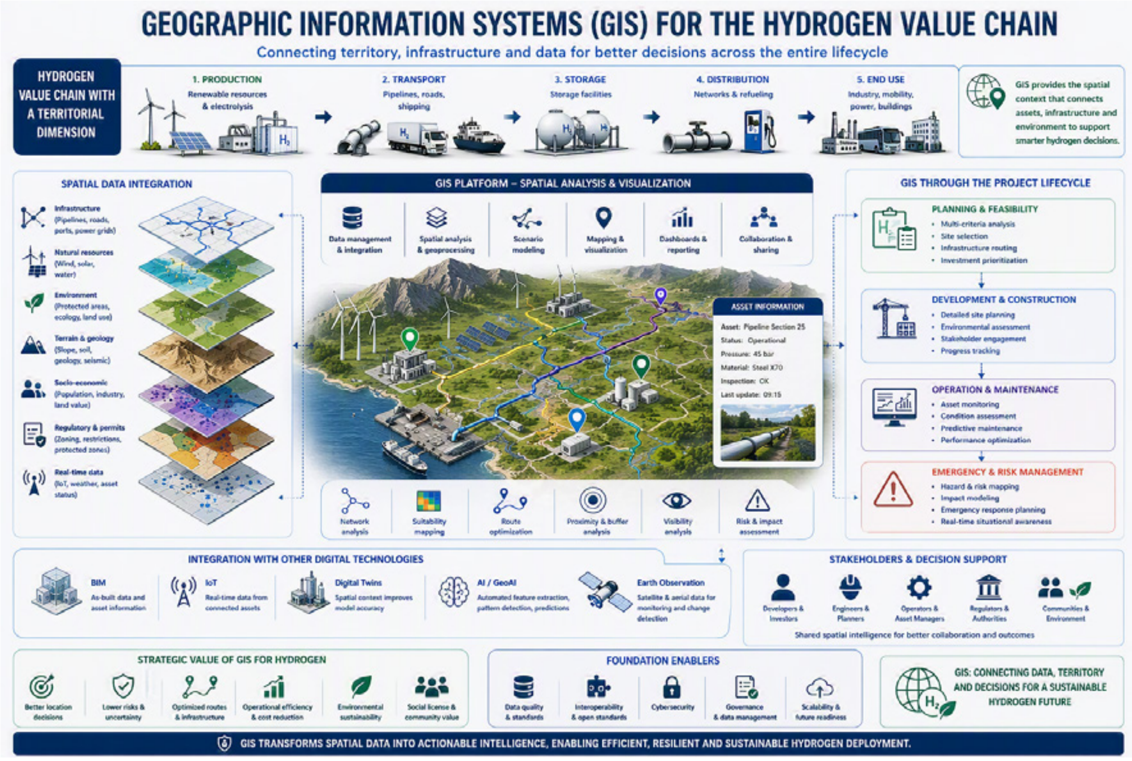


Figure 8. GIS for H2 Infrastructures.

3 DIGITAL CHALLENGES AND BARRIERS IN THE HYDROGEN VALUE CHAIN

Hydrogen is expected to play a key role in decarbonizing. Global hydrogen demand reached approximately 100 Mt in 2024, yet less than 1% was produced through low-emissions pathways, resulting in around 1.8 $GtCO_2$ of annual emissions.

Achieving these objectives will require not only new production, transport and storage infrastructure, but also advanced digital capabilities. Digitalization is becoming a fundamental enabler of the hydrogen economy rather than a supporting function.

This chapter identifies the main digital challenges currently faced by hydrogen projects, highlighting similarities and differences across upstream, midstream, storage and downstream segments.

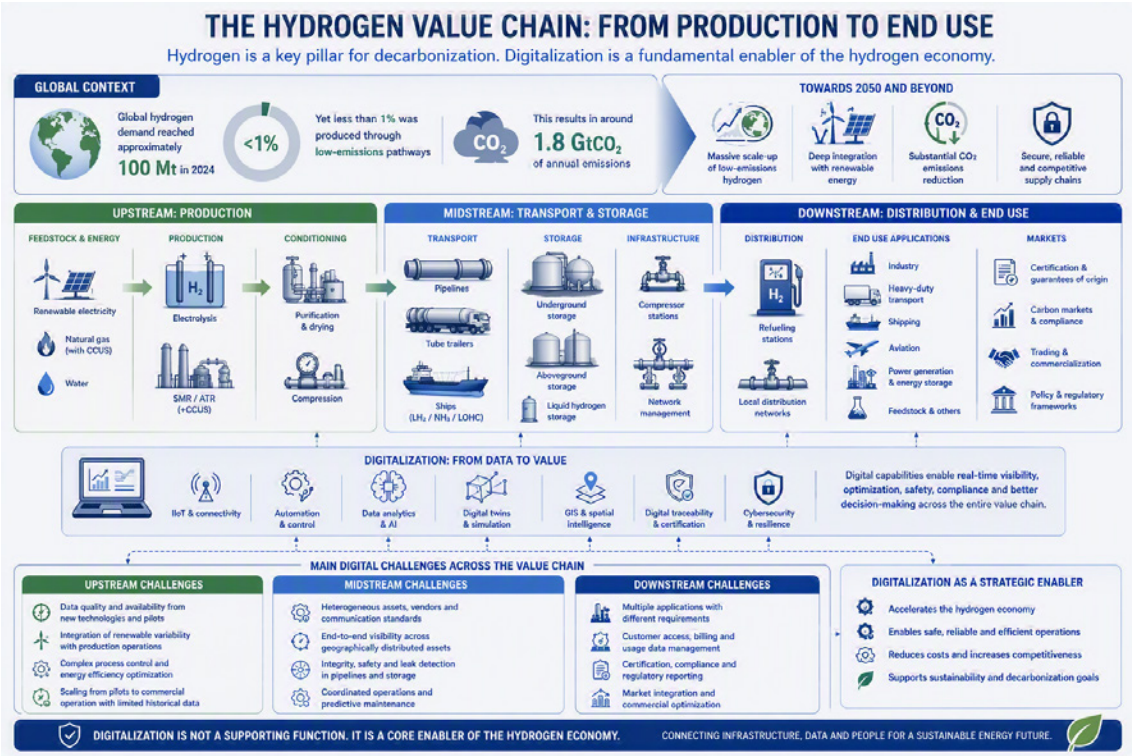


Figure 9. Hydrogen Value Chain.

3.1 Cross-Cutting Challenges (Those impacting to all value chain)

The challenges described below directly affect the ability to extract, transform, contextualize and operationalize data across the hydrogen value chain. As highlighted in previous sections, the value of advanced analytics, artificial intelligence, digital twins and traceability systems depends on the existence of a robust, scalable and trusted digital foundation.

Cost Competitiveness and Operational Optimization

The main barrier to renewable hydrogen deployment remains its cost relative to fossil-based hydrogen. Unlike conventional hydrogen production, renewable hydrogen relies on variable renewable electricity and must increasingly comply with stringent temporal correlation requirements between electricity consumption and hydrogen production to qualify as a Renewable Fuel of Non-Biological Origin (RFNBO). These constraints, combined with the operational dynamics and efficiency limitations of electrolyzers, reduce utilization factors, limit hydrogen output and increase the Levelized Cost of Hydrogen (LCOH).

Renewable hydrogen intermittency also affects downstream consumers. Many industrial processes that use hydrogen as a feedstock operate continuously and have limited flexibility to adapt to variable hydrogen supply. This creates an additional layer of complexity that can only be mitigated through hydrogen storage, oversized production assets, flexible demand strategies or grid electricity imports, each of which introduces additional costs or may compromise sustainability credentials.

As projects scale from pilot installations to hundreds-of-megawatts facilities, operational optimization becomes a critical business challenge. Production planning, renewable generation forecasting, energy management, storage utilization and downstream supply commitments must be continuously balanced under changing operating conditions. Achieving competitive hydrogen costs therefore requires advanced forecasting, optimization and digital decision-support capabilities capable of integrating technical, commercial and regulatory constraints across the value chain.

Perception of High Cost and Low ROI Visibility for Digital Investments

Currently, the market uncertainties drive CAPEX decisions focusing on minimum viable scopes, where digital solutions are often seen as non-essential investments upfront. Typical consequences of this approach are:

- OT/IT infrastructure and architecture are not set with a scalability vision; hence the organizations might find themselves in the challenges already highlighted for other energy industries: siloed architecture, applications costly to maintain, applications difficult to scale, etc…
- Digitalization is managed as an OPEX cost; hence justification and implementation of digital plans are always at risk, delaying digital adoption.

Fragmented Ecosystem

The hydrogen value chain typically involves multiple stakeholders, each managing their own data under distinct contractual frameworks, resulting in a fragmented data ecosystem that limits value creation. Critical operational and asset data is often siloed across organizations. This fragmentation creates barriers for analytics, digital twins, asset management and optimization applications. High-value use cases require not only access to data but also consistent interpretation across assets, processes and organizations. Many hydrogen projects still struggle to connect heterogeneous data sources and ensure that data are complete, validated, standardized and usable.

Recent reviews of green hydrogen deployment emphasise that coordinated regulation, infrastructure development, digital integration and harmonised standards are necessary for scalability.

Limited availability of historical and representative operational data

Many hydrogen assets, particularly large-scale electrolysis plants, hydrogen hubs and hydrogen-to-derivatives facilities, remain at an early stage of industrial deployment. Existing references are typically pilot-scale installations or projects operating in the tens-of-megawatts range.

Moving toward hundreds-of-megawatts facilities requires achieving scale efficiencies while operating technologies whose long-term performance, degradation mechanisms, maintenance requirements and optimal operating strategies are not yet fully understood. The lack of representative datasets limits benchmarking across projects, reduces the applicability of purely data-driven approaches and complicates the development of reliable predictive models.

This challenge is particularly relevant for predictive maintenance, operational optimization and digital twin applications, where model performance depends on both data quality and operating history. Limited data availability increases uncertainty and slows the industrialization of advanced digital solutions.

Lack of Scalable Digital Twin Implementations

Digital twin deployment is a strategic priority but constrained by model complexity and lack of standardization. Indeed, some OEM equipment suppliers propose their own digital twin applications, but they are often based on internal developments (scaled from pilot plants) and not commercial tools. This leads to two main challenges:

Maintainability of the application: Digital twins are often project-specific, not reusable, or require high engineering efforts to upgrade, limiting their scalability.

Digital twins, optimization engines and AI models must evolve as assets progress from design and engineering phases to commissioning and operation. As new operational data become available, models require continuous calibration, validation and adaptation.

The challenge is not simply developing models but selecting the appropriate modelling approach for each use case while maintaining consistency, transparency and traceability throughout the asset lifecycle.

Digital Traceability and Certification

Hydrogen traceability is becoming a core requirement for the development of hydrogen market. The commercial value of the molecule increasingly depends on its certified attributes: production pathway, electricity source, carbon intensity, sustainability compliance, chain of custody and allocation to final uses. tThis is particularly relevant in Europe, where renewable hydrogen must comply with the rules applicable to Renewable Fuels of Non-Biological Origin (RFNBOs). Traceability impacts market access, eligibility for incentives, compliance with RED III, which determine the green premium paid by off takers. Several traceability schemes are currently being used or developed to address this challenge.

- Guarantees of Origin disclose the origin of energy supplied to consumers such as production technology, energy source, location, production period and potentially additional voluntary data fields, including greenhouse gas emissions. However, Guarantees of Origin do not necessarily prove full regulatory compliance with RFNBO sustainability requirements.
- RFNBO certification is designed to demonstrate that renewable hydrogen and hydrogen-derived fuels comply with the sustainability and greenhouse gas reduction requirements established under EU regulation. This includes evidence on renewable electricity sourcing, additionality, temporal correlation, geographical correlation and emissions accounting. RFNBO certification requires a more granular and auditable data foundation than a simple Guarantee of Origin.
- Chain of Custody Models: In addition to the type of certificate, traceability also depends on the chain of custody model used to connect certified production with final consumption. Three different models can be applied depending on the specific context:

    - Segregation. Certified hydrogen is physically separated from non-certified hydrogen throughout the value chain.
    - Mass balance. Certified and non-certified products may be physically mixed, but the certified attributes are tracked through an accounting system.

- o Book-and-claim. Environmental attributes are separated from the physical product and traded through certificates.

Hydrogen traceability cannot be achieved through manual reporting alone. RFNBO certification requires the continuous integration of multiple data sources. Digital platforms automate data acquisition through APIs and industrial communication protocols, contextualize information around assets and production batches, and generate an auditable digital thread linking renewable electricity consumption to the final hydrogen-derived product. Consequently, the role of IT systems is not simply to store certificates, but to provide the digital backbone that connects physical hydrogen flows, sustainability credentials and commercial transactions into a single trusted ecosystem.

Cybersecurity exposure in increasingly connected hydrogen infrastructure

Digitalisation implies more sensors, remote access, cloud connectivity, automated control, digital twins and data exchange with external stakeholders. This increases the cyber-physical attack surface of hydrogen infrastructure, especially where operational technology and information technology become more integrated. The challenge exists because cyber incidents in hydrogen systems could affect not only data availability or confidentiality, but also physical operations, safety systems, refuelling availability, metering integrity and stakeholder confidence. Hydrogen infrastructure therefore inherits the cybersecurity complexity of critical energy systems while adding specific safety and public-acceptance sensitivities associated with a developing market.

Organizational Adoption and Digital Governance

Finally, digitalization only creates value when insights are embedded into operational and business decision-making processes. The successful deployment of digital solutions depends not only on technology, but also on organizational readiness, governance structures and user adoption.

Digital initiatives must therefore be co-designed with engineering, operations and maintenance teams to ensure alignment with operational responsibilities and business objectives. Early stakeholder involvement, clear governance mechanisms and measurable business outcomes are essential to minimize adoption risks and ensure long-term sustainability.

3.2 Upstream Challenges

Electrolyser manufacturing scale-up

As electrolyzers deployment moves towards gigawatt-scale production, manufacturing becomes a critical success factor for electrolyzers deployment. Digital technologies play a central role in enabling industrial production with consistent quality and performance.

A key challenge is maintaining consistent performance across large production volumes while rapidly increasing manufacturing capacity. Digital monitoring and analysis of production parameters ensure consistent stack and component quality, standardizing manufacturing processes across multiple production lines and locations and ensuring full traceability of components throughout their lifecycle. Another important aspect is the creation of digital feedback loops between manufacturing and system design.

For electrolyzers OEMs, competitive advantage will increasingly depend not only on engineering excellence, but also on the ability to integrate design with digitally enabled industrial production capabilities.

Construction and manufacturing of electrolysis plants

During construction and commissioning, the focus shifts from system design to system integration, testing and operational readiness. At this stage, the success of a hydrogen project depends not only on the performance of individual equipment, but also on the ability to integrate multiple subsystems supplied by different vendors into a fully functional and reliable plant.

Digitalization plays a key role in managing this complexity. It supports configuration management, quality assurance and system integration. At the same time, digital tools facilitate the validation of system performance under real operating conditions, reducing technical risks, accelerating project handover and improving operational readiness.

Electrical grid interface

Electrolysers are large electrical systems and create an interface between the electrical grid and industrial hydrogen assets. When scaled to the tens or hundreds of MWs, electrolyser are no simple electrical loads operating behind the meter, their operation impacts the whole grid. This creates new upstream challenges related to grid stability, renewable integration, operational flexibility, market participation and system resilience.

When adequately managed their power conversion system turn into a grid asset that contributes to grid reliability, resiliency and supports renewable energy integration. Some key grid support features of electrolysers are:

- **Grid-Forming Operation:** Grid-forming capabilities to allow the electrolyzer to contribute to frequency stabilization under low-inertia conditions. It should evolve aligned with European requirements.
- **Balancing & Frequency Services:** Active power control systems and real-time tools, enabling the electrolyzer to participate in FCR, aFRR, and mFRR markets. It contributes to grid stability and facilitates additional revenue streams. Participation in these markets requires real-time control, accurate forecasting, operational optimization and clear management of the trade-off between grid services revenues and hydrogen production commitments.
- **Voltage Support:** Coordinated control of electrolyzer power systems and grid-support equipment, including STATCOM technologies where required, enables voltage regulation at the high-voltage connection point, facilitating renewable integration and strengthening transmission system stability.
- **Black Start & System Restoration:** Enable the electrolyzer to operate as a flexible load during black starts, improving system resilience and accelerating recovery after outages.
- **DC Architecture:** Development of a medium voltage DC bus interconnecting electrolyzer units, renewable generation and storage systems to reduce losses and increase efficiency.
- **AI-Driven EMS:** AI based digital tools to maximize hydrogen production, market participation, and grid support services simultaneously.
- **EMT Digital Twin & Adaptive Protection:** EMT digital twin to validate control strategies, protection schemes, and operational scenarios, lowering technical risks and supporting smoother commissioning.

3.3 Midstream Challenges

The development of renewable hydrogen as a key energy vector for decarbonisation introduces a structural challenge in the midstream segment: the need to design and deploy dedicated or adapted transport infrastructures for a gas with physical and chemical properties that differ significantly from natural gas.

Unlike other energy transitions, hydrogen deployment requires the progressive construction of a network, that mostly lacks large-scale operational precedents, increasing technological and planning uncertainty.

While there are hydrogen networks in operation today, these are quite different compared the hydrogen backbone. While existing hydrogen pipelines have been in operation for decades in US Gulf Coast or in the Benelux region, they linked multiple Steam Methane Reformers (SMR) with stable and predictable supply to nearby demand sites such as refineries, ammonia and methanol plants or another chemical industry.

Future hydrogen backbone networks, such as the European Hydrogen Backbone (EHB), will instead connect geographically dispersed renewable production in favourable locations with industrial demand under highly variable operating conditions.

As a result, the transport system becomes an active energy flexibility asset absorbing production surplus, buffering temporary deficits and redistributing hydrogen flows from cost competitive production sites to large consumption hubs.

Although being essential for a competitive hydrogen uptake, building and operating such infrastructures has multiple challenges.

Design and dimensioning under high uncertainty

Network dimensioning represents one of the main technological challenges. Unlike mature natural gas infrastructure, future hydrogen backbones must be designed before production, demand and utilization levels are fully established.

Advanced hydraulic simulation models, scenario definition and network operational optimization become essential to evaluate pipeline sizing, compression requirements, operating pressures and future expansion strategies under uncertain production and demand scenarios.

This challenge is further increased by the progressive coexistence of repurposed natural gas pipelines and newly built hydrogen infrastructure, requiring careful assessment of material compatibility, equipment suitability and operational integration.

Technical constraints of hydrogen transport

Hydrogen transport introduces additional engineering challenges compared with conventional natural gas infrastructure due to the specific physical properties of the molecule. Hydrogen gas has one third of natural gas volumetric energy density. This requires higher flow rates, impacts pipeline sizing, increases compression energy requirements and narrows operational bands to ensure stable and reliable network operation.

These operating conditions also have implications for infrastructure integrity. Hydrogen transport systems are more sensitive to pressure transients and cyclic loading increasing the importance of monitoring pipeline integrity, material compatibility and operating conditions throughout the asset lifecycle. Digital technologies are essential for advanced simulation, condition monitoring and asset management to ensure safe and reliable operation.

Infrastructure strategy: repurposing vs. new build

Considering the large investments needed to deploy an European-wide infrastructure such as the EHB, determining the optimal balance between repurposing existing natural gas infrastructure and developing dedicated hydrogen pipelines is essential to minimize future system costs. Repurposing existing assets offers a significant opportunity to reduce capital investment and accelerate network deployment.

However, repurposing also introduces important technical and operational challenges. in terms of material compatibility and equipment adaptation or replacement and operating constraints. Additional complexity arises where hydrogen blending is used as a transitional strategy.

Conversely, new hydrogen infrastructure optimizes pipeline routing, materials, compression systems and operating conditions, providing greater operational flexibility and long-term performance control at the expense of higher capital investments.

Infrastructure planning turns into a dynamic optimization problem that can only be handled with the use of digital technologies.

Flexibility and storage requirements

Intermittent renewable hydrogen production creates a mismatch with stable industrial demand. The hydrogen backbone provided the exibility between production and consumption.

Network design must consider minimum autonomy requirements. The intrinsic linepack capacity of the pipeline combined with large-scale underground storage and the deployment of intermediate storage enables intraday balancing and operational exibility.

The network thus evolves from a pure transport system into a hybrid transport–storage system where digital forecasting, storage optimization and coordinated network operation contribute to the security of supply.

Underground Hydrogen Storage Digitalization

Underground hydrogen storage, whether in salt caverns or depleted gas elds, presents a structural digitalization gap. These assets are extremely difficult to instrument due to their depth, limited physical accessibility and heterogeneous geological conditions, which result in scarce, low-frequency and hard-to-validate operational data. This lack of reliable subsurface information constrains the deployment of advanced digital technologies: continuous sensing, real-time monitoring, predictive models, digital twins and AI-based optimization cannot be applied with the same maturity as in surface assets, and often rely on synthetic or incomplete datasets.

Recent technical literature consistently highlights several digital bottlenecks: insufficient deep-monitoring capabilities, limited geomechanical and geochemical data acquisition, lack of interoperable digital frameworks connecting subsurface behaviour with operational decision-making, and the absence of dynamic digital twins capable of updating their state with real operational data. Furthermore, current MRV systems remain largely manual or discontinuous, and risk-assessment tools are not yet integrated into uni ed digital platforms.

Without advances in these areas, and without explicit organizational commitment to incorporate subsurface assets into digitalization strategies, this fundamental and primary part of the hydrogen infrastructure will continue to fall outside corporate digital roadmaps. As long as underground storage remains digitally underdeveloped, uncertainty in cavern integrity, pressure evolution, hydrogen behaviour in porous media and potential leakage pathways will persist as a barrier to large-scale deployment.

Conclusion

The development of hydrogen transport networks represents a cross-cutting engineering challenge, combining uncertainty in the evolution of hydrogen production and demand, the specific physical properties of hydrogen, new design and operational methodologies, and long-term infrastructure investment decisions.

In this context, the midstream segment emerges as a critical enabler of the hydrogen economy. Digital capabilities—including advanced simulation, digital twins, GIS, forecasting and network optimization—become essential to support planning, operation and future expansion, enabling infrastructure to evolve alongside the hydrogen market while minimizing technical risks and stranded investments over time.

3.4 Downstream Challenges

As hydrogen projects move from demonstration scale to larger commercial deployment, digitalisation becomes increasingly relevant because downstream assets must operate across dispersed locations, multiple ownership boundaries, high-pressure equipment, strict quality requirements and emerging certification schemes. However, the same features that make digitalisation valuable also create barriers: limited operating history, fragmented data ownership, immature standards, scarce failure datasets and the need to connect physical safety management with trustworthy digital information flows. Recent reviews of hydrogen infrastructure highlight that storage, transport and distribution are not secondary issues but essential conditions for large-scale hydrogen adoption, and that infrastructure constraints remain one of the main barriers to commercial deployment.

Data Availability, Quality, and Management Constraints

Hydrogen infrastructure is still at an early stage compared with natural gas, oil products or conventional industrial gases, so operators have fewer long-term datasets covering degradation, abnormal events, transient operation, maintenance history and asset ageing. This matters because many digital applications depend on representative historical data to identify patterns, classify anomalies and support risk-based decision-making. The difficulty is amplified by hydrogen's specific physical behaviour, including high diffusivity, low molecular size, material compatibility issues and the possibility of leakage through small defects or seals. These characteristics increase the importance of monitoring, but they also make it harder to build reliable datasets because relevant events may be rare, fast, localised or difficult to detect consistently.

Digitalisation of safety-critical operations

Downstream hydrogen systems operate with high-pressure storage, compression, cooling, dispensing and transfer operations, where process deviations may have safety implications. Reviews of hydrogen refuelling infrastructure identify leak detection, pressure management, temperature monitoring, emergency shutdown logic, accurate flow measurement and storage/cooling control as central safety-related areas. The challenge exists because digital systems must not only collect data but also represent safety-relevant conditions with sufficient reliability, traceability and response time. This is particularly demanding in hydrogen because leaks, over-pressurization, material degradation and ignition hazards can form cascading risk pathways rather than isolated failures.

Limited robustness of predictive models for downstream risk assessment

The use of advanced analytics, AI-enabled safety systems and digital twins is increasingly discussed in hydrogen infrastructure, but recent literature still identifies gaps in predictive modelling, material durability assessment, human-error analysis and the maturity of AI-enabled safety frameworks. This barrier exists because predictive digital tools require validated relationships between measured variables, equipment condition, operating context and risk consequences. In hydrogen systems, these relationships are affected by pressure cycles, temperature transients, embrittlement mechanisms, leak dispersion, ventilation conditions and operational procedures. As a result, downstream digital models may face uncertainty when extrapolating beyond the limited operating data available from early deployments.

Hydrogen quality monitoring and data traceability

Hydrogen delivered to end users, particularly fuel-cell-related applications, must comply with strict fuel-quality specifications because trace contaminants can affect performance, durability and safety. ISO 14687 defines minimum hydrogen fuel quality characteristics for several applications, while scientific reviews show that impurity analysis remains complex, expensive and technically demanding. The barrier is digital as much as analytical: quality data must be sampled, validated, linked to batches or delivery events, exchanged between actors and trusted by customers and regulators. Continuous or near-real-time quality monitoring is still constrained by the fact that sensors are not commercially available for all contaminants listed in fuel-quality standards and that standardised testing protocols remain a development need.

In summary, the key downstream digital barriers are not merely the absence of sensors or software. They arise from the interaction between hydrogen's physical properties, safety-critical operations, immature infrastructure, strict quality requirements, evolving certification schemes, fragmented stakeholders and the need for trusted data across commercial boundaries. Digitalisation is therefore highly relevant to downstream hydrogen projects, but its deployment is constrained by data scarcity, interoperability gaps, model uncertainty and metrology limitations.

Figure 10 summarizes the main challenge areas identified in Chapter 3 and translates them into the digital needs that must be addressed across the hydrogen value chain, including economics and optimisation, data foundations, modelling and intelligence, operations and safety, trust and compliance, and infrastructure planning. Chapter 3 defines these cross-cutting and segment-specific challenges as the problem baseline for the later mapping of digital capabilities and use cases.

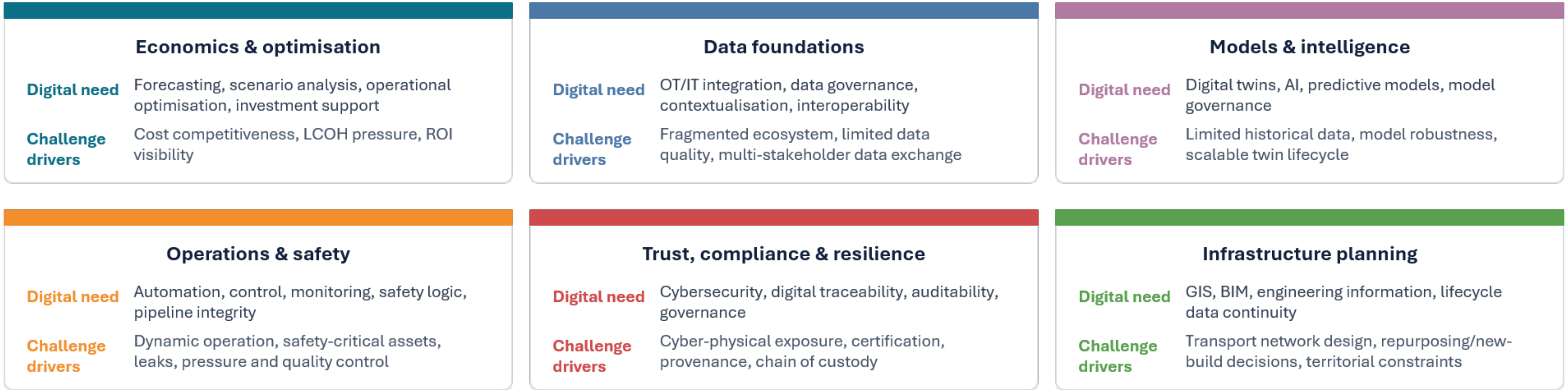


Figure 10 - Digital challenge map for the hydrogen value chain.

4 LESSONS LEARNED FROM DIGITALLY MATURE INDUSTRIAL SECTORS

Digitally mature industrial sectors such as Oil & Gas, LNG, power systems, and process industries provide proven patterns of how digital technologies create value at scale. All in all, successful digitalization depends less on individual technologies and more on how they are deployed, integrated, and governed.

The following lessons synthesize what works and what fails and are directly applicable to the hydrogen value chain; if adaptations are made for hydrogen-specific constraints (e.g., data scarcity, safety envelope, evolving standards).

4.1 Data Integration and Data Governance

Success factors:

- Establish a unified data foundation early, integrating OT and IT data into a consistent environment.
- Define standard data models and asset hierarchies.
- Implement automated data pipelines connected to source systems.
- Embed clear data governance (ownership, quality, standards).

Common mistakes to avoid:

- Treating data integration as a secondary activity.
- Allowing fragmented, siloed data environments.
- Building on non-standardized or poorly contextualized data.
- Underestimating effort for data harmonization.

Implication for hydrogen:

- Prioritise data foundation (Extract–Transform-Contextualize-Collaborate) as a prerequisite.

4.2 Data Analytics and Artificial Intelligence

Success factors:

- Design analytics around operational decision workflows (detect → diagnose → decide → act → learn).
- Integrate analytics into maintenance, operations, and planning processes.
- Combine domain knowledge with analytics models.

Common mistakes to avoid:

- Deploying dashboards without embedding into decisions.
- Treating AI as a technology-only exercise.
- Developing models disconnected from operations.

Implication for hydrogen:

- Focus on operationalization of insights.

4.3 Digital Twins and Simulation

Success factors:

- Select modelling approaches based on use case and lifecycle phase.
- Maintain consistency between models and operational data.
- Ensure traceability and transparency of models.

Common mistakes to avoid:

- Over-reliance on purely data-driven models.
- Treating digital twins as static deliverables.
- Lack of model ownership and maintainability.

Implication for hydrogen:

- Adopt hybrid modelling strategies with lifecycle governance.

4.4 Automation and Control Systems

Success factors:

- Design automation architecture with scalability in mind.
- Combine control and optimization layers coherently.
- Align control systems with analytics and workflows.

Common mistakes to avoid:

- Treating automation as isolated infrastructure.
- Ignoring future data and analytics needs.
- Late integration between control and digital layers.

Implication for hydrogen:

- Ensure early automation design supports long-term digital readiness.

4.5 Industrial Connectivity and OT/IT Integration

Success factors:

- Implement standardized connectivity layers.
- Ensure consistent data exchange across systems.
- Enable end-to-end visibility.

Common mistakes to avoid:

- Maintaining separation between OT and IT.
- Building point-to-point integrations.
- Lack of alignment with enterprise systems.

Implication for hydrogen:

- Develop end-to-end integration patterns across the value chain.

4.6 Predictive Maintenance and Asset Management

Success factors:

- Develop condition-based and predictive approaches.
- Combine inspection, operational and maintenance data.
- Ensure models are transparent and maintainable.

Common mistakes to avoid:

- Relying only on time-based maintenance.
- Lack of connection to operational workflows.
- Treating asset management as standalone.

Implication for hydrogen:

- Build structured asset data models early.

4.7 Interoperability and Standardization

Success factors:

- Adopt standardized data models and architectures.
- Design modular and reusable solutions.
- Ensure interoperability across systems and vendors.

Common mistakes to avoid:

- Developing non-reusable project-specific solutions.

- Using proprietary interfaces that limit scaling.
- Ignoring interoperability at design stage.

Implication for hydrogen:

- Make interoperability a design principle from the outset.

4.8 Organizational Adoption and Digital Governance

Success factors:

- Co-design solutions with engineering and operations teams.
- Align digital initiatives with workflows.
- Establish governance and responsibilities.

Common mistakes to avoid:

- Developing solutions in isolation.
- Misalignment with operational practices.
- Lack of ownership.

Implication for hydrogen:

- Embed digitalization in organizational processes.

4.9 Scalability and Deployment Approach

Success factors:

- Start with targeted use cases but design for scalability.
- Use modular architectures.
- Incorporate iterative development.

Common mistakes to avoid:

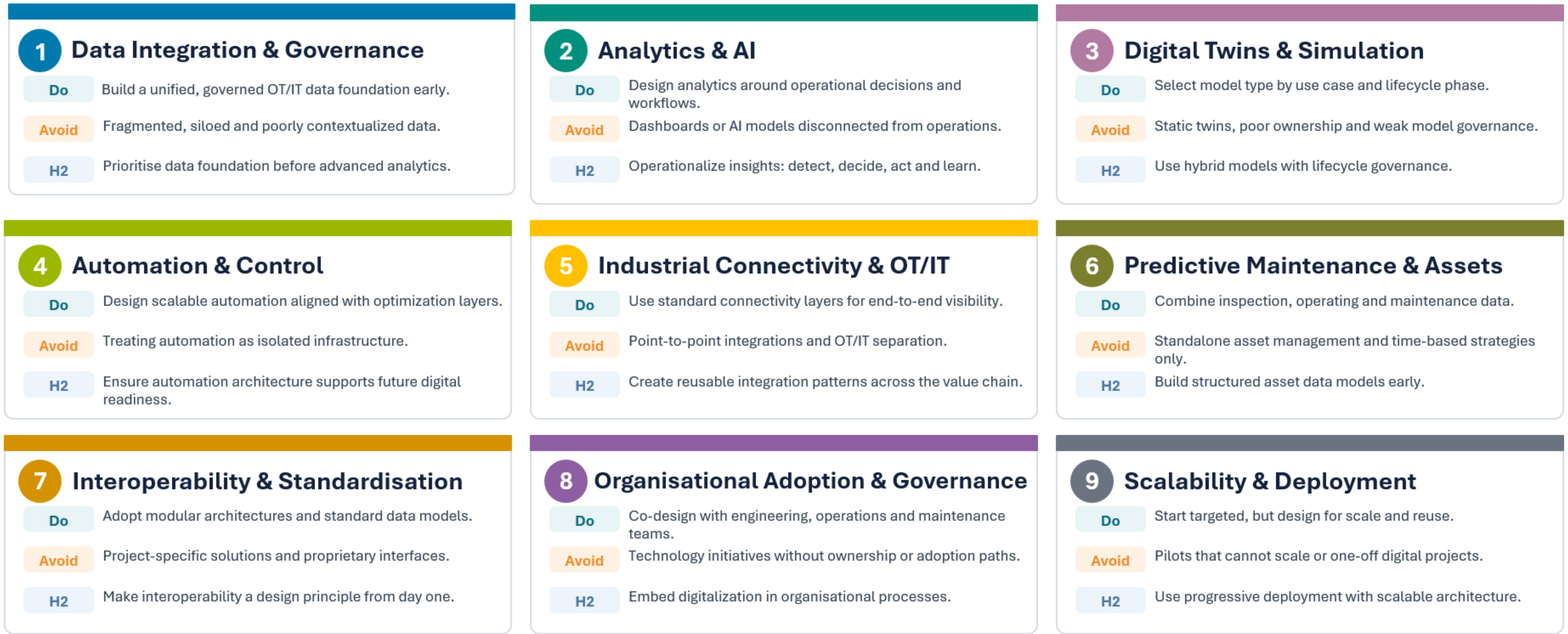
- Developing pilots that cannot scale.
- Lack of standardisation.
- Treating digitalization as a one-time project.

Implication for hydrogen:

- Combine progressive deployment with scalable architecture.

Figure 11 summarizes the main implementation lessons across data governance, analytics, digital twins, automation, connectivity, predictive maintenance, interoperability, governance, and scalability, highlighting that successful digitalization depends on integrated foundations, operational adoption, and scalable deployment rather than isolated technologies.

Figure 11. Key lessons from digitally mature sectors and their implications for hydrogen digitalization.



5 APPLICATION OF DIGITAL SOLUTIONS ALONG THE HYDROGEN VALUE CHAIN

This Chapter builds on the digital technologies described in Chapter 0 and the challenges identified in Chapter 0, by translating them into practical, application-oriented solutions across the hydrogen value chain.

By connecting challenges, technologies, and proven applications, this chapter provides a practical bridge between conceptual digital capabilities and their implementation in hydrogen projects across the lifecycle and value chain segments, enabling a clear understanding of how digital technologies contribute to solving identified challenges and where solutions are already directly transferable. See Chapter 3.

Note: Transferability to Hydrogen column has been categorized as follows:

Strong – Hydrogen-native references**,** use cases include hydrogen-specific use cases.
Emerging – Not Hydrogen-native references, use cases explicitly described as directly transferable or analogous. None or very low adaptation is required.
Weak – Not Hydrogen-native references, use-case evidence applicability is currently limited or indirect. Needs significant adaptation efforts.
GAP- No representative use case, direct or indirect, is documented.

Table 3. - Challenges, Digital Capabilities and Maturity Mapping.

Challenge	Segment	Phase	Digital Capability	Transferibility to H_2	Use Case Reference
Cost competitiveness & LCOH pressure	Cross-cutting	Design	Data Analytics – Economic Analysis	Strong	5.2.1; 5.2.2;5.2.3;5.3.1; 5.10.1;5.11.1
Low ROI perception for digital investments	Cross-cutting	Design	Data Analytics – Economic Analysis	Strong	5.2.1; 5.2.3; 5.2.2;5.10.1; 5.11.3;
Uncertainty in system design and asset sizing	Cross-cutting	Design	Data Analytics – Economic Analysis	Strong	5.2.1;5.2.3;5.3.1;5.8.1;5.8.3;5.10.1;5.11.1
System-wide operational optimization complexity	Cross-cutting	Operation & Maintenance	Data Analytics – Operations Management	Emerging	5.3.3;5.4.2;5.4.3;5.8.1;5.8.2;5.11.2;
Intermittency vs demand mismatch	Upstream	Operation & Maintenance	Data Analytics – Operations Management	Strong	5.3.1;5.3.3
Integration with energy markets	Cross-cutting	Operation & Maintenance	Data Analytics – Operations Management	Strong	5.3.1; 5.3.2
Fragmented ecosystem / data silos	Cross-cutting	Operation & Maintenance	Data Integration / OT–IT	Strong	5.5.1; 5.5.2;5.8.2;5.8.3

Challenge	Segment	Phase	Digital Capability	Transferibility to H_2	Use Case Reference
Organizational adoption & digital governance	Cross-cutting	Operation & Maintenance	Collaboration / workflows	Weak	
Limited availability of historical data	Cross-cutting	Operation & Maintenance	AI / Predictive Models	Emerging	5.5.1;5.5.2;5.7.1;5.8.3;5.11.1;
Lack of scalable digital twin implementations	Cross-cutting	Design	Digital Twin	Emerging	5.5.1; 5.11.1; 5.11.2; 5.11.3
Digital traceability & certification	Cross-cutting	Operation & Maintenance	Digital Traceability	Emerging	5.4.2;5.5.1;5.5.2;
Hydrogen quality & traceability	Downstream	Operation & Maintenance	Digital Traceability	Emerging	5.5.1;5.5.2;
Cybersecurity exposure in H2 infrastructure	Cross-cutting	All	Cybersecurity	Strong	5.1.1;5.1.1;5.8.2;5.10.1;
Grid-forming, balancing & ancillary services	Upstream	Operation & Maintenance	Advanced control / EMS	Emerging	5.3.1;5.3.2;5.3.3;5.7.1;5.11.2
DC architecture integration	Upstream	Engineering	Automation & control	GAP	
AI-driven energy management	Upstream	Operation & Maintenance	Data Analytics – Operations Management	Emerging	5.3.3;5.5.2;5.7.1;5.11.2;
EMT digital twin & adaptive protection	Upstream	Engineering	Digital Twin	Weak	5.11.1;5.11.2; 5.11.3
Pipeline integrity & leak detection	Midstream	Operation & Maintenance	Pipeline Management	Strong	5.4.1
Operational outages & system reliability	Midstream	Operation & Maintenance	Pipeline / Digital Twin	Strong	5.4.2; 5.4.3;5.5.3;5.6.1;5.8.1;5.8.2;5.11.1; 5.11.2; 5.11.3
Hydrogen backbone engineering constraints	Midstream	Design	GIS	Strong	5.9; 5.9.1;
Engineering–operations data continuity	Midstream	Design	BIM + GIS	Strong	5.4.2;5.4.3;5.5.1;5.8.1;5.8.2;5.9.1
Lack of operational data (storage/distribution)	Downstream	Operation & Maintenance	IoT / Analytics	Emerging	5.5.1;5.5.2;5.8.3;5.11.1;5.11.2;

Challenge	Segment	Phase	Digital Capability	Transferibility to H_2	Use Case Reference
Digitalisation of safety-critical operations	Downstream	Operation & Maintenance	Automation & control	Emerging	5.3.1;5.4.1;5.4.3;5.5.3;5.6.1;5.8.1;5.8.2;
Limited robustness of predictive models	Downstream	Operation & Maintenance	Digital Twin & AI	Emerging	5.11.1; 5.11.2; 5.11.3

5.1 Cybersecurity

Capability Description: A cybersecurity solution built specifically for industrial operational technology environments can consolidate all security tools, automate threat detection, and fix problems — replacing the current complexity of multiple vendor solutions with a single, easy-to-use interface. This type of approach can reduce the risk of cybersecurity threats by up to 80 to 90 percent. A key difference favours hydrogen infrastructure: it can be designed with the integrated automation and security approach from the beginning, rather than retrofitting it to existing systems. Hydrogen infrastructure can be built to operate as a unified network from commissioning day one. See 2.1 for additional details.
Value Chain Segment: Cross-Cutting.
Lifecycle phase: Design, Operation&Maintenance.
Addressed Challenges:

- Automatic security updates and patches across all connected devices.
- Anti-malware systems monitoring and protection failure alerts.
- Automatic management of backups, ensuring data restoration at any time.
- Critical system isolation to contain threats.
- Remote access control and sessions management (activation and termination).
- Real-time inventory of network connected assets.

5.1.1 Cybersecurity for Backbone Network Operations

Context: A large European refined product pipeline operator manages over 4,000 kilometres of pipelines connecting 40 storage terminals, 26 airport installations, 8 refineries, and 14 port facilities across the Iberian Peninsula and beyond.

The provided system monitors all network communications, detects anomalies in equipment behaviour, manages access controls across operator workstations, automatically patches vulnerable systems, and isolates compromised equipment before threats can propagate. Network access is controlled and authenticated. All operational decisions are logged. All security events are recorded. When regulators or auditors request evidence that the system is secure and operating safely, the data is automatically available.

Value Chain Segment: Midstream.
Lifecycle phase: Design, Operation&Maintenance.
Observed Benefits:

- Safety and compliance improved.
- Incidents are detected faster. Anomalies are caught before escalation.
- Complete audit trails provide evidence of proper operation and security.
- Operations became more coordinated (Reduced storage time and maximized throughput).

Transferability: Directly transferable to hydrogen projects, because the underlying challenges are analogous. Both have similar Network Topology, Operational Challenges, Cybersecurity risks and Regulatory Framework (NIS2) Alignment.
Reference: ABB Case study, Anonymous.

5.1.2 GUARDIANE-Q

Context: GUARDIANE-Q is an industrial research project focused on the design and conceptual validation of an advanced comprehensive security architecture for critical underground renewable hydrogen storage infrastructures.
Value Chain Segment: Midstream.
Lifecycle phase: Design, Operation&Maintenance.
Observed Benefits: The project integrates capabilities ranging from geological modelling of the subsurface to post-quantum cybersecurity, including multi-sensor monitoring, artificial intelligence, and resilient satellite communications.
The combination of these technological domains allows for the exploration of a new paradigm of comprehensive protection for strategic energy infrastructures in the post-fossil energy system era.
Transferability: Direct applicability across the hydrogen value chain.
Reference: guardianeq.eu (https://www.guardianeq.eu/).

5.2 Data Analytics and Artificial Intelligence. Economic Analysis

Capability Description: Probability distributions to uncertain inputs (e.g., renewables availability, electrolyser performance, storage capacity, dynamic weather and demand) and predicts future system performance metrics like production, revenue, costs, availability and emissions. See 2.2 for additional details.
Value Chain Segment: Cross-Cutting.
Lifecycle phase: Design.
Addressed Challenges:

- Low ROI perception for digital. Evaluation of various hydrogen production routes, renewable capacity sizing, storage options and product derivatives such as green ammonia. Comprehensive optioneering during concept evaluation and design allow designers to right-size assets and storage to minimise CAPEX while ensuring target throughput.
- Cost competitiveness & levelized cost of hydrogen (LCOH) pressure. Green hydrogen projects face high-cost volatility due to intermittent renewable power and uncertain utilisation (e.g., electrolyser technologies, storage options, renewable mixes) and identifies designs that minimise total cost and meet target hydrogen prices while maintaining reliability.
- Uncertainty in system design and asset sizing. Probabilistic results (e.g., 90% certainty of meeting production targets) and clear cost/benefit trade-offs overcome scepticism about digital investments, helping secure funding and aligning internal and external stakeholders.
- Enhanced investment confidence and stakeholder alignment. Stabilises electrolyser operation under variable renewable supply and optimises energy consumption.

5.2.1 Green ammonia and hydrogen complex optimisation

Context: A major energy & chemicals company developing an integrated green ammonia project used a probabilistic economic-analysis tool to unify financial and technical data. The model assessed alternative configurations (power sources, electrolyser technology, battery and ammonia storage) and

their impacts on production and revenue under variable weather and electricity prices. Workshops with process, power and commercial teams identified improvement opportunities and a right-sized design.
Value Chain Segment: Upstream.
Lifecycle phase: Design.
Observed Benefits:

- Identified ~US$500 million CAPEX savings while maintaining target production.
- Enabled recognition of configuration trade-offs, reducing project risk and accelerating FID.

Transferability: Direct.
Reference: Emerson–AspenTech case study, "Envision. 1323746 End-to-End Green Ammonia".

5.2.2 Network optimisation of blue hydrogen plants

Context: An operator managing more than fifteen blue hydrogen facilities employed a scenario-based economic model to optimise maintenance and production scheduling across the network. The solution synthesised demand forecasts, availability of steam methane reformers and CCS units, and carbon pricing scenarios to minimise the levelized cost of hydrogen.
Value Chain Segment: Operation&Maintenance.
Lifecycle phase: Design.
Observed Benefits:

- Achieved >1% reduction in operating costs via better asset utilisation and maintenance planning.
- Improved ability to meet contractual hydrogen deliveries and reduce carbon emissions.

Transferability: Direct applicability across the hydrogen value chain.
Reference: Emerson–AspenTech case study. "Air Products. hydrogen network optimisation case".

5.2.3 Web tool AIHRE

Context: The European project AIHRE has developed a sizing platform designed to support the design and preliminary evaluation of renewable hydrogen-based projects. The tool allows for the analysis of the technical, economic, and environmental feasibility of different configurations before undertaking detailed engineering studies, thus helping to reduce the uncertainty associated with the initial planning stages.
Value Chain Segment: Cross-Cutting.
Lifecycle phase: Design.
Observed Benefits: The platform has been designed as a decision-support tool for companies, public administrations, technology centres, and other stakeholders interested in developing renewable hydrogen-based solutions. Its main objective is to facilitate the comparison of technological alternatives and business models through a flexible and easily configurable methodology.
Transferability: Direct applicability across the hydrogen value chain.
Reference: aihre.eu (https://aihre.eu/aihre-lanza-una-plataforma-para-evaluar-la-viabilidad-de-proyectos-de-hidrogeno-renovable/)

5.3 Data Analytics and Artificial Intelligence. Operations Management & Optimization

Capability Description: Real-time operational planning, renewable energy integration, market participation and enterprise-wide optimization across the hydrogen value chain. See 2.2 for additional details.
Value Chain Segment: Cross-Cutting.

Lifecycle phase: Operation&Maintenance.

Addressed Challenges:

- System-wide operational optimization complexity. DERMS and enterprise optimization tools provide the analytical and control framework to manage this multi-variable optimization problem in real-time.
- Intermittency vs. demand mismatch. DERMS, microgrid control, and dynamic process control directly address this by enabling intelligent demand response, energy storage dispatch, and dynamic plant operations that follow renewable generation profiles.
- Midstream system balancing complexity. DERMS and pipeline management systems provide the real-time visibility and optimization needed to balance midstream hydrogen systems.
- Integration with energy markets. Hydrogen producers need to respond to real-time market price signals, participate in ancillary services markets, and optimize dispatch to maximize revenue. DERMS and energy management systems provide the market integration and optimization capabilities needed.
- Organizational adoption gaps. Lack of alignment between digital and operations teams is a barrier to effective implementation. Proven DERMS deployments demonstrate that rapid user adoption is achievable when solutions integrate seamlessly with familiar interfaces.
- Operations Management for H2 injection into NG pipelines. Managing the injection of hydrogen into natural gas pipeline networks requires specialized operations planning tools that can handle blending constraints, pressure management, flow tracking, and regulatory compliance.
- Fiscal Metering / Custody Transfer. Accurate custody transfer measurement is critical for commercial hydrogen transactions. High-accuracy fiscal metering enables customer invoicing, tax calculations, and regulatory compliance.

5.3.1 End-to-End Dynamic Green Ammonia Solution

Context: A green hydrogen-to-ammonia project in China (Chifeng, targeting 1,520 KTon ammonia/year, 20 KTon liquid green hydrogen/year, 200 KTon methanol/year) implemented an end-to-end dynamic solution to follow renewable wind variability without requiring large grid stabilization or battery storage. The approach minimizes storage and batteries from design through operation, keeping the product genuinely green by limiting grid power usage.

Value Chain Segment: Downstream.

Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- Dynamic load flexibility (10%–100% in 10 minutes for electrolyzer, 30 minutes for ammonia synthesis).
- Validated end-to-end renewable-to-product dynamic control strategy.
- Optimised Energy and Production to attain green ammonia /H2 market price (LCOH pressure).
- Safe dynamic operation validated at pilot scale.
- Minimized CAPEX from reduced storage and battery requirements.

Transferability: Direct.

Reference: Emerson–AspenTech case study, "Envision. 1323746 End-to-End Green Ammonia".

5.3.2 DERMS for Flexibility on a Renewables-Heavy Grid

Context: Iberdrola Group, managing approximately 20 GW of renewables in Spain toward a 100% renewable electricity target by 2050, deployed DERM. The system integrates SCADA-controlled devices,

EVs, BESS, solar, and building control systems into a single platform for enterprise-wide optimization. DERMS manages EV charging schedules, battery dispatch, HVAC loads via building management integration, load and renewable generation forecasting, and maximum power consumption controls.
Value Chain Segment: Downstream.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- Seamless integration of diverse DER types into a single optimization platform.
- Ability to orchestrate energy resources across different locations; dynamic demand balancing to grid needs.
- Validated VPP (Virtual Power Plant) creation for market participation.

Transferability: Directly transferable to hydrogen projects. The key adaptation required is extending asset models to cover electrolyzers as controllable flexible loads, hydrogen storage as a "battery" analog, and hydrogen off-take commitments as market obligations.

Reference: Emerson–AspenTech case study, "AT-1563_CS_Iberdrola_DERMS_v2".

5.3.3 Transmission DERMS for Renewable Portfolio Decarbonization

Context: Public Service Company of New Mexico (PNM) — the state's largest electricity provider serving 530K+ customers — deployed DERMS to manage two large solar-plus-energy storage units (150 MW and 20 MW) connected to the high-voltage transmission grid. The solution manages real-time battery state-of-charge based on solar forecasts, executes day-ahead bids in the California ISO Energy Imbalance Market (EIM), responds to frequency violations (ACE events), and provides emergency reserve power.
Value Chain Segment: Downstream.
Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- 32% reduction in CO_2 emissions between 2005 and 2022.
- Real-time energy storage management based on solar forecasts.
- Optimized dispatch into California ISO EIM; monitoring and adjustment of charging based on balancing area ACE.

Transferability: The value demonstrated is directly transferable. Minor adaptations include modelling electrolyzer dynamics and hydrogen storage constraints.
Reference: Emerson–AspenTech case study, "PNM Uses Real-Time DERMS to Decarbonize Generation Portfolio".

5.4 Data Analytics and Artificial Intelligence. Pipeline Management, Integrity & Leak Detection

Capability Description: Provides continuous, real-time visibility of what is happening inside a pipeline network — monitoring pressure, flow, temperature and composition — and translate that data into actionable insights for operators: detecting anomalies, alerting to potential loss of containment, verifying that operations remain within safe and compliant limits, and supporting day-to-day scheduling and throughput decisions. See 2.2 for additional details.
Value Chain Segment: Midstream.
Lifecycle phase: Operation&Maintenance.
Addressed Challenges:

- Safety-critical leak and rupture detection for hydrogen infrastructure. A layered detection approach — combining physics-based models, machine-learning analytics, and statistical pattern recognition — addresses the full spectrum from slow microleaks to instantaneous ruptures, under all pipeline operating conditions.
- Pipeline integrity under hydrogen service. Integrity management frameworks that quantify and track degradation mechanism, alongside risk analysis and compliance reporting, to maintain safe operation over the asset lifecycle.
- Energy transition readiness. Handle hydrogen, CO_2, natural gas blends, renewable oils, and conventional hydrocarbons within the same operational framework. Operators introducing hydrogen into existing infrastructure reconfigure and recalibrate the existing digital layer to reflect the new product's properties, protecting capital investment in both infrastructure and software.
- Regulatory compliance in a tightening enforcement environment. Remove the need for manual data aggregation during audits and provides a documented record of leak detection system performance.
- Sensor and measurement gaps for hydrogen pipelines. Computational pipeline monitoring compensates for instrumentation limitations by using physics-based hydraulic models to infer pipeline state across segments where direct sensing is limited.
- Operational efficiency and throughput optimisation. Reduce transmix in liquid pipelines, improve asset utilisation, and support confident decision-making.

5.4.1 Leak Detection for Less-Instrumented Gathering Systems

Context: A major North American refining and midstream company deployed machine-learning-based analytical leak detection for a portfolio of shorter, less-instrumented pipelines where full-scale physics-based modelling was not cost-optimal. The system was trained on historical operational data and progressively improved its performance through reinforcement learning, without requiring additional field instrumentation.
Value Chain Segment: Midstream
Lifecycle phase: Operation&Maintenance
Observed Benefits:

- Detection of simulated leaks at 5%, 8%, and 10% of pipeline flow substantially faster than legacy monitoring processes.
- Detection of a subset of leak events that legacy methods failed to identify.

Transferability: Directly transferable, because the core computational approach is product-agnostic. The principal adaptations required when applying these capabilities to dedicated hydrogen service relate to model calibration, sensor selection, and regulatory mapping.
Reference: Emerson case study, "Alyeska Pipeline Service Company".

5.4.2 Minimise Operational Outages

Context: A European gas transmission company deployed a digital-twin-based pipeline management solution to improve operational decision support and reduce unplanned production outages. The solution provided real-time hydraulic profiling, early anomaly detection, and automated reporting, replacing a manually intensive monitoring process.
Value Chain Segment: Midstream.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- Reduced frequency and duration of production outages.
- Improved confidence in operational decisions.
- Streamlined compliance reporting.

Transferability: Directly transferable. The principal adaptations required when applying these capabilities to dedicated hydrogen service relate to model calibration, sensor selection, and regulatory mapping.
Reference: Emerson case Study, "TGI Minimizes Production Outages by Improving Decision Support with Digital Twin".

5.4.3 Stable and Safe Energy Supply Throughout the Country

Context: Spain's national gas transmission system operator — managing more than 11,000 kilometres of gas pipeline and actively transitioning its network to carry biomethane and hydrogen alongside conventional natural gas — selected a digital grid management solution to supervise, operate, and optimise the national transmission network. The solution integrates real-time SCADA-based data with advanced pipeline management software to deliver real-time energy calculations, continuous gas tracking across the network, and proactive mitigation of hazardous conditions including overpressure detection and rupture detection. The deployment directly supports the operator's decarbonisation strategy by enabling reliable monitoring of a multi-gas network as hydrogen and biomethane volumes increase.
Value Chain Segment: Midstream.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- Full real-time visibility and digital supervision across 11,000+ km of national pipeline infrastructure.
- Proactive rupture and overpressure detection.
- Multi-gas tracking capability supporting biomethane and hydrogen blends alongside conventional gas.
- Digital platform aligned to national energy decarbonisation objectives.

Transferability: Directly transferable. The operator is actively managing a network that carries biomethane and hydrogen alongside conventional gas; it is a direct hydrogen-relevant reference.
Reference: Emerson Press Release, "Emerson Selected by Spain's National Gas Grid Operator to Support Stable and Safe Energy Supply Throughout the Country".

5.5 Data Analytics and Artificial Intelligence. Industrial Data Integration

Capability Description: Industrial data integration & contextualization creates a data fabric that aggregates, normalizes and contextualizes information from operational technology (OT) sources (sensors, control systems, historians) and information technology (IT) systems (enterprise resource planning, scheduling, certification) into a single, secure layer. It creates a consistent and structured data environment, supporting real-time visibility, interoperability, and advanced analytics across the hydrogen value chain. The data fabric therefore forms the backbone for advanced analytics, digital twins and AI-enabled workflows, providing a trusted, contextualized information resource across the hydrogen value chain. See 2.2 for additional details.
Value Chain Segment: Cross-Cutting.
Lifecycle phase: Operation&Maintenance.
Addressed Challenges:

- Non-scalable OT/IT architecture and data silos. Hydrogen facilities comprise multiple electrolysers, compressors and storage units designed using diverse standards and tools. During project handovers, large volumes of documents and technical data are exchanged and are often stored in fragmented systems, making it difficult to organize, validate and verify information.
- Foundation for advanced analytics, digital twins and autonomy. High-quality, contextualized data are the prerequisite for digital twins, predictive maintenance and AI-enabled optimisation. The data fabric feeds advanced analytics platforms and AI models, unlocking insights that improve reliability, optimize energy use and support autonomous operations.
- Reduced integration complexity and vendor lock-in. A scalable, vendor-agnostic architecture simplifies integration of new assets and partners, reducing project risk and enabling rapid scaling across new hydrogen projects standardised connectors and semantic models ease the addition of new sensors, instruments and application modules, accelerating deployment.
- Coordination across value-chain actors. Producers, transport operators and off-takers often use different protocols and platforms. Integrated data infrastructure enables consistent information exchange, aligning operational metrics with commercial and regulatory requirements.
- Traceability and certification complexity. As hydrogen markets mature, buyers, regulators and investors require trustworthy information on the carbon footprint, origin and movement of each batch of hydrogen. A unified data fabric with contextualized data supports the development of digital product passports and intelligent traceability platforms.

5.5.1 Standardize and connect operations

Context: A Life Science company has globally adopted a Data Fabric integrating real-time shop floor manufacturing data with enterprise, cloud, and quality management systems to drive operational excellence and fuel digital manufacturing initiatives.
Value Chain Segment: N/A.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- IT/OT Integration: Bridges the gap between the operational technology (OT) of the manufacturing plant floor and the enterprise IT systems, with 10-15% saving in IT spend.
- Data Standardization & Contextualization: Provides a single, unified view of operations data across hundreds of plant historians, allowing the company to track drug manufacturing, with 2-5% Reduced IT costs.
- Enterprise-Wide Analytics: Enables robust Industrial AI and real-time machine learning applications to monitor and enhance production performance, with 10-15 % increase in throughput.
- Regulatory Compliance: Consolidates data beneath the enterprise firewall with native security and compliance to meet strict pharmaceutical manufacturing regulations, with 5-7 % cost reductions.

Transferability: Directly transferable. Hydrogen facilities face similar complexity, safety requirements and data volumes.
Reference: Emerson–AspenTech case study, "AT-4654 BRO Inmation Pharma V3".

5.5.2 Aggregate and centralize millions of real-time data points

Context: By unlocking unified access to operational data, a multinational integrated energy and petroleum company, is accelerating the integration of AI into industrial processes.

Value Chain Segment: Midstream.

Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- Enterprise Data Integration: Continuously collects and contextualizes real-time sensor and machine data across upstream, refining, and chemical facilities to break down operational silos.
- Emissions & Energy Optimization: Integrates real-time process control data to optimize energy consumption, reduce environmental footprint, and meet company sustainability objectives.
- Artificial Intelligence (AI) Enablement: Prepares and feeds cleaned operational data into advanced AI and machine learning applications to support smarter, data-driven decision-making.

Transferability: Directly transferable. Specific adaptation might be required for as the data fabric should support secure provenance records and interface with certification schemes like CertifHy.

Reference: Data & Digital: TotalEnergies Boost the Value of Industrial Data Press Release (https://totalenergies.com/newsroom/data-digital-totalenergies-and-emerson-sign-strategic-collaboration-boost-value/)

5.5.3 Asset Health Index for Condition-Based Asset Management

Context: A large scale gas and LNG infrastructure with long-life assets and multiple heterogeneous data sources (inspection data, maintenance records, operational data) uses asset health indicators, Asset Health Index, combining this information into a consolidated view of asset condition. Moving from fragmented condition assessments to a standardized, algorithm-based Asset Health Index enables consistent, scalable, and forward-looking asset management decisions.

Value Chain Segment: Midstream.

Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- Objective and comparable asset condition assessment across the fleet.
- Ability to anticipate degradation trends.
- Improved prioritization of maintenance and investments.
- Support to long-term asset strategy.

Transferability: The value demonstrated is directly transferable. Specific adaptation might be required to define hydrogen-specific degradation mechanisms from early deployments. Incorporate uncertainty due to limited operational history.

Reference: Implemented Asset Health Index for high-capitalization assets, Enagás (Spain).

5.6 Data Analytics and Artificial Intelligence. Prescriptive and Predictive Maintenance

Capability Description: AI and machine learning models — specifically failure-signature-based agents — analyse real-time and historical sensor data to detect early equipment degradation patterns and predict failure. es weeks or months before occurrence. These agents prescribe corrective actions and integrate with maintenance workflows, moving operations from reactive and preventive maintenance toward predictive and prescriptive strategies.

Value Chain Segment: Cross-Cutting.

Lifecycle phase: Operation&Maintenance.

Addressed Challenges:

- Operational Continuity. By detecting failure patterns weeks to months in advance, unplanned shutdowns are significantly reduced. For hydrogen assets — where unexpected downtime directly impacts production commitments, renewable energy curtailment costs, and safety — this reliability improvement is foundational to economic viability. Early warning also improves worker safety and reduces the risk of hydrogen release events.
- Scalability and Fleet-Level Knowledge Transfer. Failure signatures developed on one asset or facility can be transferred to identical or similar assets, dramatically accelerating enterprise-wide deployment. This transfer-learning capability is strategically important for the hydrogen sector, where replication of similar plant architectures is expected as the industry scales.
- Lifecycle Cost Reduction. Moving from time-based to condition-based maintenance reduces unnecessary preventive interventions while preventing costly corrective events.

5.6.1 Hydrogen Compressor Prescriptive Maintenance

Context: A large, diversified energy company operating more than a dozen refineries undertook a digital transformation initiative based on big data, machine learning, and AI. Three previous failures of a hydrogen compressor had resulted in production losses and maintenance costs totalling over $250M across three events.

Value Chain Segment: Midstream.

Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- Reduced shutdown by up to 8 days by scheduling maintenance at an optimal time within the warning window.
- 30% maintenance cost reduction compared to emergency maintenance.
- ~$30M USD potential savings per event by planning the shutdown to minimize production losses.
- Combined potential savings across three historical events: >$75M.
- Improved health, safety and environmental performance by avoiding emergency shutdowns.
- Solution subsequently scaled to monitor 300+ assets across 12 refineries and 6 pipelines.

Transferability: Direct. The asset involved is a hydrogen compressor — a core component of the hydrogen value chain across upstream (compression post-electrolysis), midstream (pipeline compression), and downstream (refueling station compression) applications. Failure modes on hydrogen compressors are directly analogous across production types.

Reference: Emerson–AspenTech case study," Digital Transformation with Predictive Maintenance Drives Cost Savings — Hydrogen Compressor Case Study. AT-05064".

5.7 Data Analytics and Artificial Intelligence. Process Analytics and Multivariate Quality Optimization

Capability Description: Multivariate statistical process control and online analytical models identify the minimum critical set of variables driving process quality, yield, and productivity across continuous and batch operations. These models detect subtle shifts from optimal operating conditions, pinpoint root causes of quality deviations, and recommend corrective setpoints, enabling consistent product quality and throughput optimization.

Value Chain Segment: Cross-Cutting.

Lifecycle phase: Design, Engineering, Operation&Maintenance.

Addressed Challenges:

- Process Optimization and Quality Assurance. Multivariate process analytics enable systematic identification of the key variables driving hydrogen purity, electrolyzer efficiency, energy consumption, and yield. Rather than relying on threshold-based monitoring, these tools correlate complex multi-variable patterns to outcomes, surfacing root causes that cannot be identified through traditional single-variable trend analysis. This capability is particularly relevant for ensuring product quality specifications (e.g., ISO 14687 hydrogen fuel quality), optimizing electrolysis efficiency under variable power inputs, and reducing off-specification production.
- Scalability and Fleet-Level Knowledge Transfer. Process optimization models developed on one asset or facility can be transferred to identical or similar assets, dramatically accelerating enterprise-wide deployment. This transfer-learning capability is strategically important for the hydrogen sector, where replication of similar plant architectures is expected as the industry scales.
- Data Foundation for Digital Twins and Autonomous Operations. Advanced analytics serves as the data intelligence layer underpinning higher-order digital capabilities. Validated AI models feed digital twins, inform autonomous control systems, and support the progression toward self-optimizing assets — the long-term vision for hydrogen production under variable renewable integration.

5.7.1 On-Demand Data Reconciliation for a Fleet of Hydrogen Plants

Context: World's largest hydrogen supplier operates a global leadership position in hydrogen supply with over 80 hydrogen production facilities and 1,800 miles of industrial gas pipeline. Managing a distributed fleet of Steam Methane Reformer (SMR) plants of varying configurations — each generating vast operational datasets — required a scalable analytics approach to enable process optimization and troubleshooting.
Value Chain Segment: Cross-Cutting.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- Reconciled data enabled process engineers to detect a feed condition shift following a power trip that would otherwise have been dismissed as an analyser error — preventing >$1M in potential catalyst damage and unplanned shutdown costs.
- Proactive optimization of reactor approach-to-equilibrium: process engineers can now detect and correct performance deterioration before it impacts production, with estimated value of $250–500K/year per plant.
- Total demonstrated benefits and avoided costs >$1M per deployment.
- Democratized access: non-specialist engineers can run advanced process analytics without simulation tool expertise.

Transferability: Direct. Extension to green hydrogen requires adapting the reconciliation superstructure from SMR thermodynamics to electrolyzer energy-balance and electrochemical models.
Reference: Emerson–AspenTech case study,"Air Products & Chemicals, Presentation at AspenTech Chemicals OPT21".

5.8 Automation and control systems

Capability Description: Automation and control systems constitute the operational foundation of any hydrogen asset. They convert engineering intent into real-time action on field equipment and ensure that processes remain within their safe, efficient, and compliant operating envelope across every phase of the asset lifecycle. See 2.3 for additional details.

Value Chain Segment: Cross-Cutting.

Lifecycle phase: Operation&Maintenance.

Addressed Challenges:

- Dynamic response to variable renewable power supply. Control systems must manage changing loads while protecting equipment and maintaining process stability
- Grid-forming, balancing, and ancillary services. Active power control and real-time coordination enabling electrolyser participation in frequency response and grid-balancing markets.
- DC architecture integration. Medium-voltage DC bus interconnecting electrolyser units, renewable generation, and storage, requiring coordinated automation logic.
- Stringent safety requirements. Hydrogen processing, storage, compression, and handling require robust monitoring, interlocks, emergency shutdown logic, and fire and gas detection conformant with IEC 61511.
- Digitalisation of safety-critical operations. Downstream hydrogen systems (high-pressure storage, compression, cooling, dispensing) require digital systems that represent safety-relevant conditions with sufficient reliability, traceability, and response time.
- Integration of multiple subsystems. Electrolysis units, power electronics, water treatment, storage, compression, transport interfaces, and off takers must operate in a coordinated manner across a common automation platform.
- Quality and consistency requirements. Product specifications and process conditions (e.g., hydrogen purity per ISO 14687) must be maintained despite variability in renewable feedstock or operating modes.
- Limited availability of historical data for predictive model training. Early-stage deployments lack operational baselines; automation platforms must provide structured data collection and contextualisation from commissioning onwards.
- Scalability and Fleet-Level Operations. Modular automation platforms support replication across multiple units within a plant, across a fleet of plants, and from pilot to full commercial scale — enabling remote operations centres and fleet-level performance management.

5.8.1 World's Largest Green Hydrogen and Long-Duration Energy Storage Hub

Context: The Advanced Clean Energy Storage (ACES) hub uses a 220 MW electrolyser bank to produce up to 100 tonnes of green hydrogen per day. Hydrogen is stored underground in salt caverns (300 GWh storage capacity) The stored hydrogen is expected to be used as fuel for a hybrid 840 MW combined cycle gas turbine (CCGT) power plant that to replace a retiring 1,800 MW coal-fired power plant. An integrated control and safety platform (ICSS) was selected to automate the green hydrogen production and storage facility. The system provides reliable control and monitoring of the renewable hydrogen production process and emergency shutdown, fire and gas protection, and gathers and contextualises data from the plant's wide variety of third-party systems.

Value Chain Segment: Upstream, Downstream.

Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- Reduced commissioning complexity through modular, scalable I/O connectivity.
- Simplified lifecycle maintenance across 240 electrolysers and a 600 MW power plant from a single automation platform.

- Already in operation (2025) and incrementally expanding, it is estimated to help prevent 126,517 metric tons of carbon dioxide emissions annually.

Transferability: Direct.
Reference: ADVANCED CLEAN ENERGY STORAGE WebSite

5.8.2 Offshore Green Hydrogen Pilot

Context: Europe's first offshore green hydrogen production pilot in the Dutch North Sea. Offshore wind electricity is used to power a hydrogen electrolyser on the platform; the produced hydrogen is mixed with gas and transported to shore via the existing pipeline. An integrated control and safety system (ICSS) was deployed to supervise the offshore electrolyser, manage interfaces with the wind power supply, and control hydrogen/gas blending and pipeline injection.
Value Chain Segment: Upstream.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- First validation of integrated offshore wind, offshore gas, and offshore hydrogen energy systems.
- Demonstrated safe hydrogen–gas blending and pipeline injection from a safety-critical offshore environment.
- Provided operational data for scale-up to larger offshore hydrogen facilities.

Transferability: Direct.
Reference: Emerson case study, "Emerson PosHYdon project".

5.8.3 Large-Scale Green Hydrogen Production Plant

Context: A 25 MW green hydrogen production plant — the largest under construction in Spain at time of project award — integrates five 5 MW PEM electrolysers to supply a co-located refinery, with a second phase under development for industrial and transport offtake. An Integrated Control and Safety System (ICSS) combining a power and water-optimized distributed control system platform and a fully integrated SIL3 safety instrumented system was deployed for balance-of-plant control and supervision of the electrolyzers PLCs. The system embedded cybersecurity features, and redundant ultra-reliable controllers.
Value Chain Segment: Upstream.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- SIL3-rated integrated BPCS and SIS from a single automation platform, reducing engineering complexity and lifecycle cost.
- Multi-protocol integration enabling seamless supervision of heterogeneous electrolyser and balance-of-plant packages from different OEMs.
- Embedded cybersecurity aligned with industrial operator and project partner requirements.
- Scalable architecture supporting a second-phase capacity expansion.

Transferability: Direct.
Reference: Emerson case study, "Anonymous. Green Hydrogen Plant, Spain".

5.8.4 Multi-OEM Process Orchestration

Context: Facility was transformed into a demonstration-scale hydrogen production, storage, and refuelling plant combining onsite solar PV, battery storage, an electrolyser, a fuel cell, and a hydrogen refueller. A distributed control system and natively integrated safety instrumented system were deployed to manage operations across a wide array of OEM systems with diverse communication protocols. A process orchestration layer converted multiple protocols (power meters, electrolyser, fuel cell, refueller, solar and battery inverter) to a common Ethernet-based protocol, directly terminated on a single controller, eliminating complex marshalling infrastructure.

Value Chain Segment: Upstream.

Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- Multi-OEM integration via process orchestration reduced communication complexity and lowered project cost.
- Protocol standardisation shortened the project schedule versus traditional point-to-point integration approaches.
- Technical and economic feasibility of producing, storing, and delivering hydrogen using renewable energy.
- Automated data reporting system enables compliance monitoring and renewable energy performance tracking as required by the Australian Renewable Energy Agency (ARENA).

Transferability: Direct.
Reference: Emerson case study, "Toyota Australia, Altona Emissions Testing Facility (hydrogen demonstration plant)".

5.9 BIM and Engineering Information Management

Capability Description: A BIM-GIS integration framework enables the connection of detailed engineering models with corporate geospatial platforms. See 2.4 for additional details.
Value Chain Segment: Cross-Cutting.
Lifecycle phase: Design, Engineering.
Addressed Challenges:

- BIM models contain technical and asset information.
- GIS platforms providing territorial and network context.
- Common Data Environment (CDE) for information governance.
- Standardized data models and interoperability mechanisms.

Transferability to hydrogen: Particularly relevant for hydrogen backbone projects where pipelines, compressor stations and associated facilities must be managed as part of a connected infrastructure network.

5.9.1 Integrated BIM-GIS Environment for Hydrogen Transport Infrastructure

Context: Large-scale hydrogen transport networks combine geographically distributed assets, linear infrastructure and complex engineering information. Managing these assets efficiently requires connecting engineering data generated during design with geospatial information used for planning, operation and asset management.
Value Chain Segment: Midstream.
Lifecycle phase: Design, Engineering.
Observed Benefits:

- Unified view of the hydrogen network across its lifecycle.
- Improved traceability of engineering and asset information.
- Better management of route constraints and territorial impacts.

- More efficient integration between design and operational environments.
- Enhanced support for future operation and maintenance activities.

Transferability: Directly transferable. Particularly relevant for hydrogen backbone projects where pipelines, compressor stations and associated facilities must be managed as part of a connected infrastructure network.

Reference: Enagás (Spain), "First sections of Spain's hydrogen backbone network in the design and engineering phases".

5.10 Internet of Things and Industrial Connectivity

Capability Description: Digital technologies that provide monitoring, edge connectivity and supervisory control are essential for operating complex hydrogen value chains. These capabilities allow operators to maintain a secure overview of distributed assets, make faster decisions and embed automation while avoiding high-risk manual work. See 2.5 for additional details.

Value Chain Segment: Downstream, Midstream.

Lifecycle phase: Operation&Maintenance.

Addressed Challenges:

- Metrology limitations. Flow computers with integrated pressure, differential-pressure and temperature sensors improve metrological performance, reducing reconciliation time and ensuring contract compliance.
- Quality monitoring & traceability. SCADA and IIoT platforms integrate online analysers (chromatographs, spectrometers), edge analytics and historian to continuously monitor impurities and store audit trails. Secure data storage and role-based access preserve data integrity.
- Monitoring & integrity complexity. Edge-enabled sensors, remote terminal units and cloud-hosted SCADA supply real-time visibility of pipelines.
- Enhanced safety and asset integrity. Distributed sensors and edge computing detect over-pressure events, leaks or impurities and trigger automated shutdowns.
- Reduced operational costs and labour requirements. Cloud-hosted SCADA eliminates on-premises hardware. Remote configuration tools allow fewer site visits and keep workers out of hazardous areas.
- Cybersecurity and compliance. Managed hosting provides continuous security updates and NERC-CIP compliance. Role-based security and secure data storage enhance auditability and meet regulatory requirements for hydrogen purity certificates.

Transferability: Directly transferable. Overall, the core capabilities of monitoring, edge connectivity and SCADA can be transferred to hydrogen transport and distribution with modifications to sensors, analyser calibration and safety logic.

5.10.1 Cloud technologies delivering capital cost reduction and operators to focus on critical tasks

Context: A North American utility sought to modernize its supervisory control system for electric, gas and water operations. Its legacy on-premises SCADA required significant staff time for patching and complex upgrades. The utility adopted a cloud-hosted SCADA platform technology.

Value Chain Segment: Midstream.

Lifecycle phase: Operation&Maintenance.

Observed Benefits:

- The transition saved over US$100 k in upfront capital by avoiding server replacement and improved maintenance efficiency by outsourcing software updates.
- Cybersecurity compliance improved, enabling operators to focus on grid operations rather than IT maintenance.
- Ability to manage multiple energy streams (gas, water and electricity) from a single cloud SCADA platform (hydrogen distribution networks can be monitored and controlled alongside other media).

Transferability: Directly transferable, as the ability to manage multiple energy streams (gas, water and electricity) from a single cloud SCADA platform demonstrates how hydrogen distribution networks can be monitored and controlled alongside other media. Modification will be required to sensors, analyser calibration and safety logic.

Reference: Emerson–AspenTech case study, "AT-2577_CS_DGM_Austin_SCADA".

5.11 Digital Twin and Simulation Technologies

Capability Description: Digital twin and simulation technologies provide a virtual representation of an asset, process or network. See 2.6 for additional information.

Value Chain Segment: Cross-Cutting.

Lifecycle phase: For hydrogen projects this capability spans the full lifecycle:

- **Design** to size electrolyser systems, optimise the balance-of-plant (compressors, storage and purification) and evaluate alternative process routes.
- **Engineering & Operations** for 3-D plant design, operator training simulators and real-time optimisation.

Addressed Challenges:

- Better investment decisions. Evaluation of various hydrogen production routes, renewable capacity sizing, storage options and product derivatives such as green ammonia.
- Accelerated design and reduced re-work. Early alignment between process engineering, control logic and operations. This digital-thread approach reduces re-work and supports faster design cycles.
- Improved operations. Identify sensor errors and improves data quality.
- Energy efficiency. Stabilises electrolyser operation under variable renewable supply and optimises energy consumption.
- Reliability and uptime. Predictive maintenance and root-cause analysis.
- System-wide operational optimisation complexity. Coordinated optimisation of renewable generation, electrolyser operation, storage and downstream demand, enabling improved production planning and energy management.
- Virtual commissioning and safer start-up. Allow the control system to be tested against realistic dynamic scenarios before construction is complete. Operator-training simulators derived from digital twins familiarise operators with transient events, leading to safer and faster start-ups.

Transferability: Direct.

5.11.1 Integrated green-hydrogen/ammonia plant

Context: A high-fidelity hybrid digital twin combining steady-state process models and dynamic simulation was developed for a green hydrogen and ammonia production concept. The twin modelled renewable variability, electrolyser dynamics, synthesis reactions and energy storage. It was linked to the control system simulator for virtual commissioning and operator training and reused throughout design and construction.

Value Chain Segment: Upstream, Midstream.
Lifecycle phase: Design, Operation&Maintenance.
Observed Benefits:

- Up to 30 % reduction in construction costs through early integration and optimisation of design and control strategies.
- Enhanced operational readiness through training simulators.

Transferability: Direct.
Reference: Emerson–AspenTech case study, "Doosan Fuel Cells".

5.11.2 Fleet-wide hydrogen-plant data reconciliation

Context: A global industrial gas company implemented a data-reconciliation and simulation solution for a fleet of steam methane reformer (SMR) hydrogen plants. Process models were embedded in an Excel-based tool to reconcile plant data and validate analyser readings across multiple units. This digital twin identified incorrect sensor readings, reconciled material balances and provided recommendations for adjusting reactor set points.
Value Chain Segment: Midstream.
Lifecycle phase: Operation.
Observed Benefits:

- Avoided more than US$1 million in unnecessary shutdown and catalyst replacement by correctly interpreting analyser data.
- Optimisation of reactor operation delivered US$250 000 – 500 000 per year in benefits.

Transferability: Direct.
Reference: Emerson–AspenTech case study, "Air Products Hydrogen Plant Optimisation"-

5.11.3 Digital thread in marine industry

Context: In the maritime sector, ship-to-fleet digital-twin solutions integrate design, engineering and operational models across the vessel lifecycle. Multi-purpose dynamic simulators are reused from early design through operator training and real-time optimisation, while hybrid models and advanced control improve operational efficiency and safety. Although not hydrogen-specific, this demonstrates how a digital thread accelerates scale-up, enhances reliability and enables remote operation.
Value Chain Segment: Midstream.
Lifecycle phase: Operation&Maintenance.
Observed Benefits:

- Faster commissioning and reduced re-work through reuse of dynamic models.
- Improved operational efficiency and reliability through hybrid models and advanced control.

Transferability: Directly transferable. Hydrogen assets can adopt the same digital-thread approach, but models must incorporate hydrogen-specific properties (solubility, embrittlement, flame limits) and electrochemical behaviour. Safety layers and hazard analyses must address hydrogen's wide flammability range and low ignition energy.

Reference: Emerson–AspenTech case study, "Marine Industry Synergy".

Figure 12 summarizes the representative use cases identified throughout Chapter 0 and their assessed transferability to hydrogen applications. The analysis demonstrates that several digital capabilities are already supported by hydrogen-native references or directly transferable industrial experience, while a smaller number of capability areas still require additional evidence or sector-specific development. Together, these use cases provide the practical evidence base linking hydrogen challenges to proven digital solutions and supporting the maturity and adoption assessment presented in Chapter 0.

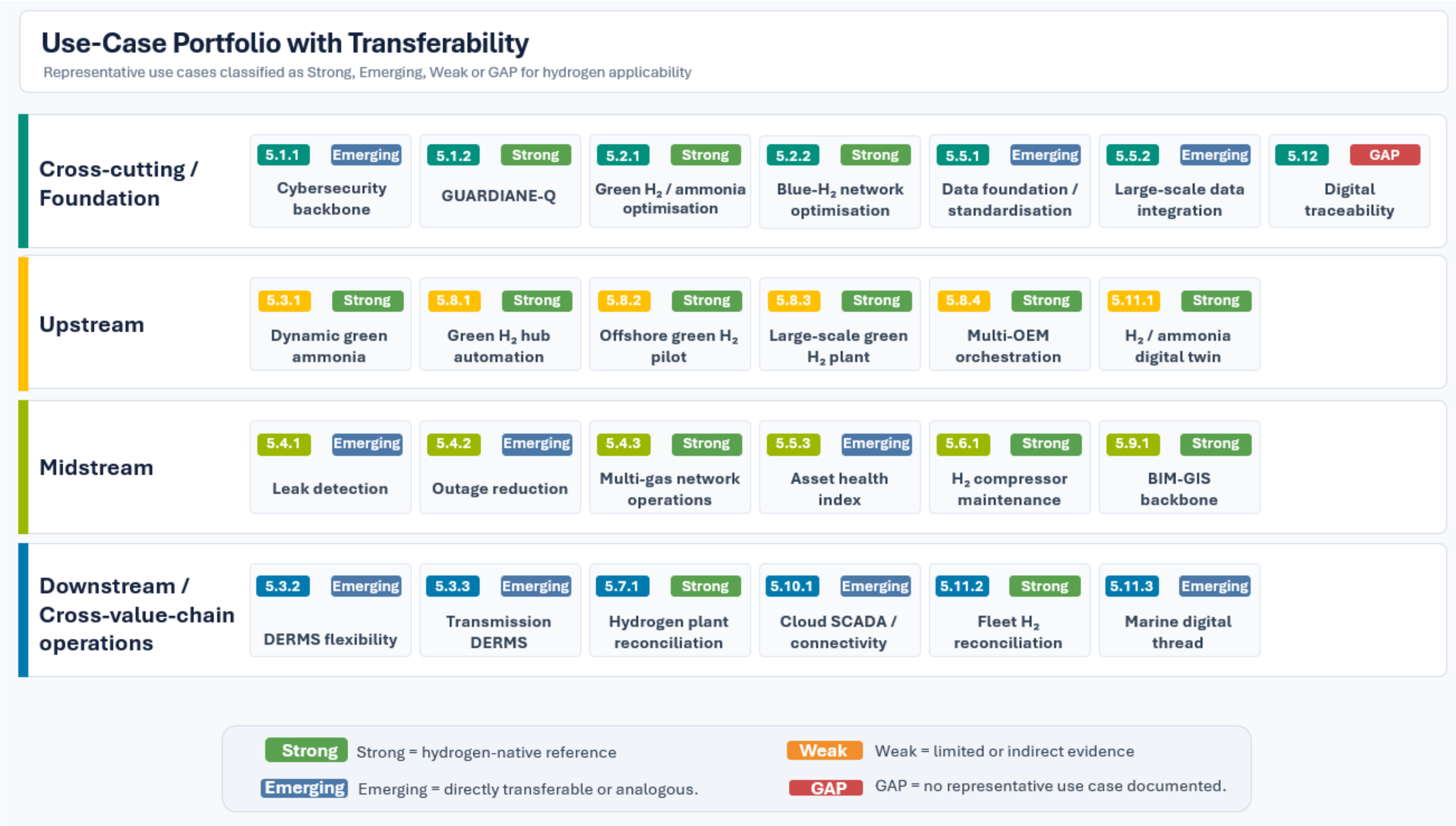


Figure 12 - Digital solution portfolio and transferability assessment across the hydrogen value chain.

6 CONCLUSIONS

The hydrogen sector is entering a critical phase of industrialisation, where success will depend not only on the deployment of production, transport, storage, and end-use infrastructure, but also on the ability to establish robust digital foundations capable of supporting safe, efficient, scalable, and economically viable operations. Throughout this study, digitalisation has been shown to be a cross-cutting enabler that influences engineering decisions, operational performance, asset integrity, regulatory compliance, and business competitiveness across the entire hydrogen value chain. The review of technologies, challenges, lessons learned, and representative use cases demonstrates that many of the digital capabilities required by the hydrogen sector already exist and have been successfully deployed in mature industrial sectors.

6.1 Maturity Assessment of Digital Capabilities

Based on the technologies, use cases, and transferability analysis presented in Chapter 0, digital capabilities can be broadly grouped into three maturity categories.

High Maturity and Directly Transferable

Several technologies already demonstrate strong industrial maturity and can be adopted with limited hydrogen-specific adaptation:

- Cybersecurity for critical infrastructure.
- Economic analysis and techno-economic optimisation.
- Operations management and DERMS-based optimisation.
- Pipeline monitoring, integrity management, and leak detection.
- Industrial data integration and contextualisation.
- BIM-GIS integration for infrastructure planning.
- Predictive maintenance for rotating equipment.
- Automation and integrated control systems.

These capabilities are supported by multiple industrial references and demonstrated deployments, including hydrogen-specific examples and adjacent industries with highly analogous operational requirements. Chapter 0 shows that the underlying technical principles, architectures, and workflows are already mature and can accelerate hydrogen deployment without requiring significant technological breakthroughs.

Medium Maturity Requiring Adaptation

A second group consists of technologies that are technically mature but require adaptation to hydrogen-specific operating conditions:

- Digital twins and simulation ecosystems.
- AI-driven optimisation and advanced analytics.
- Grid-interactive energy management systems.
- Fleet-wide operational optimisation.
- Advanced process analytics.

The primary limitation is not the technology itself but the availability of representative operational datasets, validated models, and long-term operating histories. These capabilities are expected to become increasingly important as hydrogen projects scale and operational complexity increases.

Emerging Capability Areas and Remaining Gaps

Several challenges were identified where industry-wide reference implementations remain limited:

- Digital traceability architectures for RFNBO certification and digital product passports.
- Large-scale interoperable certification ecosystems.
- Organisational digital governance models specific to hydrogen.
- Scalable lifecycle management of digital twins across heterogeneous vendor ecosystems.
- Hydrogen-specific predictive models for degradation, safety, and reliability.
- Integration of certification, operational, and commercial data across multiple stakeholders.

While the underlying technologies exist, practical large-scale implementations remain relatively immature compared with other capability domains. This reflects the early stage of hydrogen market development and the continuing evolution of certification and regulatory frameworks.

6.2 Recommended Practical Adoption Approach

The experience of mature industrial sectors suggests that hydrogen organisations should avoid attempting to deploy all digital capabilities simultaneously. Instead, digitalisation should follow a progressive and scalable roadmap. A potential phased approach could be as follows.

Phase 1 – Establish the Digital Foundation:

<u>Focus on:</u>

- OT/IT integration
- Data governance
- Industrial connectivity
- Cybersecurity-by-design
- BIM-GIS
- Digital twins
- Virtual commissioning
- Standard information models
- Common data environments

The objective is to ensure that future digital capabilities are built on trusted and interoperable data foundations, also considering all assets dimensioning and economic feasibility analysis.

Phase 2 – Operational Visibility and Decision Support

Introduce:

- Operational dashboards
- Data contextualisation
- Process analytics
- Asset health monitoring
- Performance management

At this stage, digitalisation supports operational efficiency and situational awareness while generating the datasets needed for future advanced applications.

Phase 3 – Predictive and Optimisation Capabilities

Deploy:

- Predictive maintenance
- Economic optimisation
- DERMS and energy optimisation
- Process analytics
- Fleet-level operational management

These capabilities enable proactive decision-making and support economic competitiveness.

Phase 4 – Integrated Lifecycle Digitalisation

Expand toward:

- Lifecycle information continuity
- Digital traceability platforms
- BIM-GIS integration
- Digital twins' integration

The goal is to create a continuous digital thread spanning design, construction, operation, certification, and future asset evolution.

Figure 13 illustrates how digital capabilities can be progressively introduced from Pre-FEED through optimisation and expansion, starting with foundational digital architecture and engineering information management, then expanding toward operational visibility, predictive and optimisation capabilities, and finally an integrated digital thread across the full asset lifecycle.

Adoption Layer	Pre-FEED	FEED	Design	Construction	Operation	Maintenance	Optimisation / Expansion
Phase 1 Digital Foundation Data governance • OT/IT integration • Cybersecurity-by-design • Industrial connectivity • Standard information models • Common data environments	**Digital requirements**	**Architecture & standards**	**Embed in design**	**Handover structures**	Operational backbone	Trusted data foundation	Extend to new assets / sites
Phase 1+ Engineering & Simulation Foundation BIM-GIS • Digital twins • Virtual commissioning • Engineering information management	Concept modelling	**Simulation validation**	**Detailed digital models**	**Virtual commissioning**	Model-based operations	Maintain model validity	Debottleneck / retrofit reuse
Phase 2 Operational Visibility & Decision Support Operational dashboards • Data contextualisation • Process analytics • Asset health monitoring • Performance management			Use cases & KPIs	**Monitoring commissioning**	**Operational visibility**	**Asset condition visibility**	Performance improvement
Phase 3 Predictive & Optimisation Capabilities Predictive maintenance • Economic optimisation • Energy / DERMS optimisation • Process analytics • Fleet-level management	Economic scenarios	Operational strategy	Model integration	Data collection for models	**Optimisation & decision support**	**Predictive maintenance**	**Fleet & lifecycle optimisation**
Phase 4 Integrated Lifecycle Digitalisation Lifecycle information continuity • Digital traceability • BIM-GIS integration • Digital twin integration • Continuous digital thread	Digital thread scope	Traceability & handover reqs.	**Connect engineering & asset data**	**Digital handover**	**Digital thread in operation**	**Lifecycle information continuity**	**Certification / expansion / repurposing**

Legend Primary focus in this lifecycle phase (bold) · Early definition, preparation, reuse or progressive extension · Not a primary focus

Figure 13 - Recommended practical adoption roadmap for digital capabilities across the hydrogen project lifecycle.

6.3 Final Remark

The central conclusion of this report is that the **hydrogen sector does not need to invent an entirely new digital paradigm**. Most of the required capabilities already exist and have been proven in other industrial sectors. The **challenge for hydrogen projects is** therefore **not technology availability, but selecting the appropriate capabilities,** integrating them effectively, **and** adopting **deployment strategies that align with project objectives and available budgets**.

The report also shows that **technology-adoption risk is generally lower than often perceived**. Many of the capabilities evaluated are already supported by proven industrial implementations and documented operational experience. **Their maturity reduces implementation uncertainty** while enabling organizations to benefit from established architectures, methodologies and lessons learned.

Organizations that develop scalable digital foundations early, adopt proven industrial practices, and progressively expand their capabilities **will be best positioned to achieve safe, efficient, and competitive hydrogen operations at industrial scale.**