Observatorio Tecnológico del Hidrógeno

EXECUTIVE SUMMARY

Digitalisation of the hydrogen value chain

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Digitalisation is becoming a fundamental enabler of large-scale hydrogen deployment. As projects grow in complexity, digital capabilities will play an increasingly important role in supporting operational performance, regulatory compliance, certification requirements and long-term asset competitiveness.

The hydrogen sector benefits from a significant advantage: many of the digital solutions required to support future hydrogen ecosystems are already available and have been successfully implemented in mature industries. This reduces technology-adoption risk and provides access to proven approaches that can accelerate deployment.

The greatest opportunity lies not in adopting individual technologies, but in establishing robust digital foundations from the outset. Early decisions on data management, interoperability, cybersecurity and lifecycle information continuity can determine a project's ability to scale efficiently over time.

A progressive deployment approach allows organisations to prioritise investments while building the capabilities needed to support increasingly advanced operational, optimisation and certification requirements.

Ultimately, the projects best positioned for long-term success will be those that view digitalisation not as an additional cost, but as a strategic enabler of safe, efficient and competitive hydrogen operations.

This executive summary sets out the main conclusions of the report 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**.

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DIGITALISATION AS AN ENABLER OF HYDROGEN SCALE-UP

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. This report examines **how digital technologies can support the development and operation of the full hydrogen value chain: upstream, midstream, storage and downstream**.

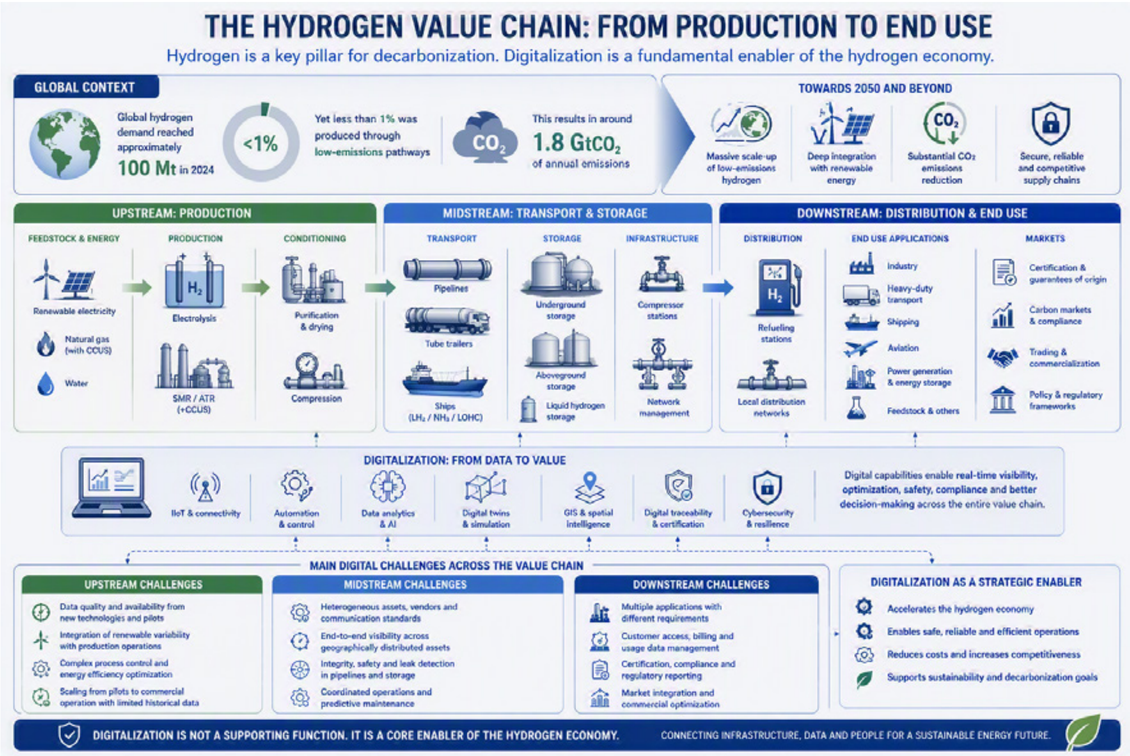

Figure 1. Infographic figure of the Hydrogen Value Chain (own work)

As hydrogen projects move towards larger-scale industrial deployment, **digitalisation** is becoming a core capability for improving efficiency and **supporting the technical, operational and economic development of the sector**. 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.

In this context, digitalisation provides a **practical framework for addressing real challenges** across the hydrogen value chain. The report identifies a broad portfolio of digital **capabilities that can contribute to the development of hydrogen ecosystems, including cybersecurity, advanced data analytics and artificial intelligence, automation and control systems, engineering information management, industrial connectivity, digital twins, digital traceability and geographic information systems**.

UPSTREAM | ▼ MIDSTREAM | ▼ STORAGE | ▼ DOWNSTREAM

The value of these capabilities increases when they are deployed as an integrated ecosystem rather than as isolated technologies. Together, they provide the digital infrastructure required to manage complex hydrogen value chain processes, including electrochemical conversion, compression, storage and transport, as well as product quality assurance, interaction with electrical networks and coordination with industrial demand centres.

Proven capabilities, not a new digital paradigm

Importantly, many of these digital capabilities are not future concepts awaiting technological validation. Hydrogen-specific reference projects are already deploying these technologies in areas such as large-scale green hydrogen production, integrated green hydrogen and ammonia systems, hydrogen transport infrastructure and hydrogen network optimisation. These examples demonstrate that many of the digital solutions required to support the future hydrogen economy are already proven industrial capabilities.

This experience is complemented by solutions and implementation approaches developed in digitally mature sectors such as Oil & Gas, LNG, power systems, industrial gases and process industries. Many of the challenges addressed in these sectors are highly analogous to those expected within hydrogen ecosystems. The combination of hydrogen-specific applications and directly transferable industrial experience significantly reduces technology-adoption risk and gives project developers access to established architectures, methodologies and lessons learned.

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: 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.

This consideration is particularly relevant under current market conditions, where many hydrogen projects face significant CAPEX constraints. The pressure to concentrate investment on assets considered essential for initial operation can lead digital capabilities to be reduced, deferred or excluded during project development. Although this can reduce initial expenditure, **experience from mature industries shows that retrofitting digital capabilities after commissioning can be substantially more expensive than integrating them during the design phase**.

> **“Hydrogen sector does not need to invent an entirely new digital paradigm. Most of the required capabilities already exist”.**

Hydrogen, however, **has a unique opportunity** compared with more established industrial sectors. While mature industries often need to modernise assets and retrofit digital capabilities into infrastructure developed decades ago, many large-scale hydrogen projects are currently being designed as greenfield developments. This provides an opportunity **to establish digital foundations from the outset and to incorporate interoperable data architectures, automation platforms, cybersecurity-by-design, engineering information management and lifecycle digital continuity into the initial project scope**.

Greenfield Projects	Mature Industries
Digital by design	Retrofit digitalisation
Lower integration costs	Higher retrofit costs
Scalable architecture	Legacy infrastructure
Interoperability from the outset	Fragmented systems

Decisions made during the early design phases can have significant implications for future operational flexibility, scalability, integration costs and asset performance. Digital foundations should therefore be considered as a strategic component of project development rather than as an additional layer to be incorporated once physical infrastructure is already operational.

DESIGN PHASE		AFTER COMMISSIONING
Integrate digital capabilities	**VS**	Retrofit digitalisation
Lower lifecycle cost		Higher integration cost

A key challenge identified is that the development of digital foundations is not always keeping pace with the deployment of physical hydrogen infrastructure. As projects grow in scale, fragmented data environments, isolated Operational Technology and Information Technology 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 can enable future optimisation, integration and expansion while avoiding costly rework later in the asset lifecycle.

Digital foundations therefore need to be treated with strategic importance comparable to that of pipelines, electrolysers or storage assets. Their role extends beyond supporting current operations: they determine the ability of the wider hydrogen ecosystem to integrate new assets, expand its capabilities and evolve over time.

Lifecycle value and project bankability

Digitalisation can also directly improve the business case of hydrogen projects throughout the full lifecycle of an 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 are not restricted to a single project phase. Many digital capabilities can generate value repeatedly throughout the lifecycle of an asset. Digital twins, for example, can support techno-economic evaluation during Pre-FEED, design optimisation during FEED and detailed engineering, virtual commissioning during project execution, operational optimisation and predictive maintenance during plant operation, and future debottlenecking, expansion or retrofitting activities.

Pre-FEED

Techno-economic evaluation

FEED & DETAILED ENGINEERING

Design optimisation

PROJECT EXECUTION

Virtual commissioning

OPERATION

Operational optimisation & predictive maintenance

EXPANSION / REPURPOSING

Debottlenecking & retrofitting

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“Digitalisation can become a strategic lever for strengthening both the bankability and the long-term competitiveness of hydrogen projects”.

Similar lifecycle value can be obtained from engineering information management, industrial data platforms, cybersecurity architectures and digital traceability frameworks. Consequently, digitalisation should not be assessed solely in terms of its initial implementation cost. It should be considered as a long-term investment whose benefits accumulate throughout the asset lifecycle.

Digital capabilities can influence asset sizing, production optimisation, maintenance planning, operational flexibility, regulatory compliance and overall lifecycle performance. By generating value across different project phases, they can improve lifecycle economics while reducing uncertainty for developers, operators and investors. In this context, **digitalisation can become a strategic lever for strengthening both the bankability and the long-term competitiveness of hydrogen projects**.

Certification, traceability and market access

The growing relevance of hydrogen certification also creates an important role for digitalisation. Hydrogen is increasingly valued not only as a molecule, but also according to certified attributes such as its origin, carbon intensity and compliance with sustainability frameworks. This evolution shifts traceability from being exclusively a compliance activity towards becoming a commercial capability.

COMPLIANCE (requirement) → COMMERCIAL CAPABILITY

Digital traceability platforms, digital product passports and integrated data architectures can provide the foundation required to support certification schemes, market-access requirements and customer trust. **As hydrogen markets develop, organisations will increasingly need reliable digital information to demonstrate the provenance, sustainability and compliance attributes associated with their products**.

Governance as a critical success factor

At the same time, the successful implementation of digitalisation depends on more than technology alone. Digital initiatives may fail to generate their expected outcomes when ownership, responsibilities and adoption mechanisms are not clearly defined. Experience from digitally mature industries demonstrates that digital governance needs to be embedded alongside engineering, operations and business management.

OWNERSHIP | RESPONSIBILITIES | GOVERNANCE | ADOPTION

Organisations that establish effective governance models early are more likely to convert technological capabilities into measurable business outcomes. Digital transformation should therefore be understood as an organisational challenge supported by technology, rather than simply as a technology project. The selection and implementation of digital capabilities need to be accompanied by clear responsibilities, governance structures and mechanisms that support their effective adoption throughout the organisation.

The current stage of development of the hydrogen sector creates a particular opportunity to address these issues from inception. Because many hydrogen assets are still being designed or constructed, the sector has the possibility of establishing cybersecurity-by-design, lifecycle digital threads, interoperable architectures, engineering information management systems and digital twin environments from the earliest phases of project development. Hydrogen can therefore avoid some of the legacy constraints faced by mature industries and move towards becoming a digitally native energy industry.

Maturity and transferability of digital capabilities

The maturity assessment carried out in the report shows that **digital capabilities applicable to hydrogen can be broadly grouped into three categories**. The **first comprises technologies with high industrial maturity that can be transferred to hydrogen applications with limited sector-specific adaptation**. These include cybersecurity for critical infrastructure, economic analysis and techno-economic optimisation, operations management and DERMS-based optimisation, pipeline monitoring and integrity management, leak detection, industrial data integration and contextualisation, BIM-GIS integration for infrastructure planning, predictive maintenance for rotating equipment, and automation and integrated control systems.

These capabilities are supported by multiple industrial references and demonstrated deployments, including both hydrogen-specific examples and applications in adjacent industries with highly analogous operational requirements. Their underlying technical principles, architectures and workflows are already mature and can therefore contribute to accelerating hydrogen deployment without requiring significant technological breakthroughs.

Strong Transferability	Emerging Transferability	Weak Transferability
Proven industrial solutions	Mature technologies requiring adaptation	Emerging capabilities
Limited adaptation	Hydrogen-specific adaptation	Limited large-scale deployment

A second category consists of technologies that are technically mature but require further adaptation to hydrogen-specific operating conditions. These include digital twins and simulation ecosystems, AI-driven optimisation and advanced analytics, grid-interactive energy management systems, fleet-wide operational optimisation and advanced process analytics. In these areas, the principal limitation is not necessarily the availability or maturity of the underlying technology, but the availability of representative operational datasets, validated models and long-term operating histories. As hydrogen projects increase in scale and operational complexity, and as additional operational experience becomes available, these capabilities are expected to become increasingly important.

The third category covers emerging capability areas and remaining gaps where large-scale industrial reference implementations are still limited. These areas include digital traceability architectures for RFNBO certification and digital product passports, large-scale interoperable certification ecosystems, organisational digital governance models specifically adapted to hydrogen, scalable lifecycle management of digital twins across heterogeneous vendor ecosystems, hydrogen-specific predictive models for degradation, safety and reliability, and the integration of certification, operational and commercial information across multiple stakeholders. In many of these cases, the underlying technologies already exist, but practical implementation at large industrial scale remains relatively immature compared with other digital capability domains. This situation reflects both the early stage of hydrogen market development and the continuing evolution of certification and regulatory frameworks. The report classifies each digital capability, classifying them into the categories mentioned: 1st category (Strong transferability), 2nd category (Emerging transferability) and 3rd category (Weak transferability) and maps them into the corresponding segments of the hydrogen value chain, highlighting those that are most specific to each part of the infrastructure.

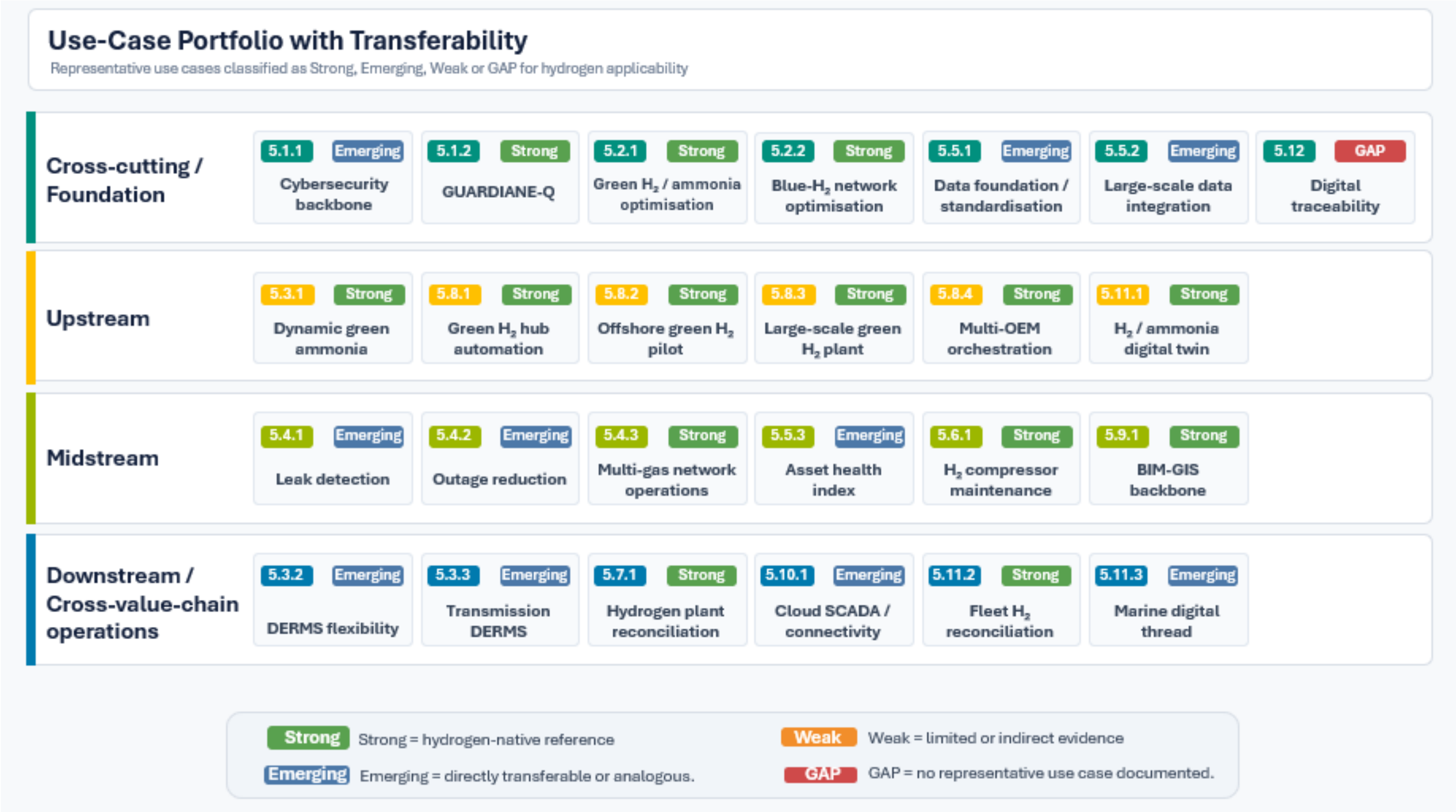

Figure 2: Digital solution portfolio and transferability assessment across the hydrogen value chain.

A progressive roadmap for digital deployment

Given these different levels of maturity and the investment constraints affecting hydrogen projects, organisations should avoid attempting to deploy every available digital capability simultaneously. Instead, **digitalisation can follow a progressive and scalable roadmap that allows capabilities to be introduced according to project needs while maintaining the foundations required for future development**.

PHASE 1

Digital Foundation

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PHASE 2

Operational Visibility

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PHASE 3

Prediction & Optimisation

▼

PHASE 4

Lifecycle Integration

The first phase focuses on establishing the digital foundation. This includes OT/IT integration, data governance, industrial connectivity, cybersecurity-by-design, BIM-GIS, digital twins, virtual commissioning, standard information models and common data environments. The objective is to ensure that future digital capabilities are built on trusted and interoperable data foundations, while also considering asset dimensioning and economic feasibility analysis.

Once these foundations are in place, the second phase introduces operational visibility and decision-support capabilities. Operational dashboards, data contextualisation, process analytics, asset health monitoring and performance management can strengthen operational efficiency and situational awareness. At the same time, operating the assets generates the datasets required to develop more advanced applications in subsequent stages.

The third phase introduces predictive and optimisation capabilities, including predictive maintenance, economic optimisation, DERMS and energy optimisation, process analytics and fleet-level operational management. These capabilities allow organisations to move from monitoring and reactive decision-making towards more proactive management of assets and operations, while directly supporting economic competitiveness.

The fourth phase expands digitalisation towards integrated lifecycle management. Lifecycle information continuity, digital traceability platforms, BIM-GIS integration and the integration of digital twins can contribute to the creation of a continuous digital thread spanning design, construction, operation, certification and future asset evolution.

Through this progressive approach, digital capabilities can be introduced from the earliest project phases and expanded as projects evolve. Foundational digital architectures and engineering information management can be established first, followed by operational visibility, predictive and optimisation capabilities and, ultimately, an integrated digital environment covering the entire asset lifecycle.

Such an approach allows organisations to balance technological ambition, project risks and available investment. It also avoids the need to implement every capability from the outset while ensuring that early architecture and design decisions do not become barriers to future integration and scalability.

PROJECT STARTS

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BUILD FOUNDATIONS

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EXPAND CAPABILITIES

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INTEGRATED ECOSYSTEM

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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 — Early definition, preparation, reuse or progressive extension — Not a primary focus

Figure 2. Recommended practical adoption roadmap for digital capabilities across the hydrogen project lifecycle.

Taken together, the report suggests 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. Organisations 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.

RENEWABLE ENERGY

+

TECHNOLOGY

+

INFRASTRUCTURE

+

SCALABLE DIGITAL FOUNDATIONS

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COMPETITIVE HYDROGEN PROJECTS

The overall assessment therefore positions digitalisation as an integral element of hydrogen industrialisation. The technology-adoption risk associated with many of the capabilities analysed is generally lower than often perceived, since numerous solutions are already supported by proven industrial implementations and documented operational experience. Their maturity allows hydrogen projects to benefit from established architectures, methodologies and lessons learned.

The differentiating factor will therefore not simply be access to digital technologies, but the ability of organisations to select the capabilities that best respond to actual project requirements, integrate them effectively and progressively expand their digital environment in line with project objectives and available budgets.

Organisations that establish 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.

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