HYDROGEN OFFSHORE PRODUCTION PROJECT

HOP2 Phase 3

Summary Report

A credible pathway to large-scale offshore green hydrogen production

Net Zero Technology Centre

Technology Driving Transition



Contents

Contents 2
Executive Summary 3
Phase 3 Scope Overview 5
A Vison for 2045 7
Art of the Possible 16
Bridge to the Future 23
Conclusions & Next Steps 29

Executive Summary

The UK stands at a crucial point in its energy transition. While the North Sea boasts vast offshore wind resources, much remains untapped due to distance from the grid. Unlocking this potential is vital to benefit our communities, workforce, and climate goals.

The main question is how to harness these remote wind assets to deliver positive outcomes, especially for people in Scotland's North-East and Moray, where oil and gas history presents both opportunities and responsibilities.

The Hydrogen Offshore Production Project (HOP2) is an initiative designed to review the practicality and viability of large-scale offshore green hydrogen production at a capacity of 500MW. HOP2 is funded by the Scottish Government's Just Transition Fund with the aim of anchoring the hydrogen production sector in Scotland and creating a positive impact on jobs, skills, education and decarbonisation across Scotland and in the North-East and Moray specifically.

The HOP2 project is being delivered across three distinct phases, each addressing a critical aspect of offshore hydrogen production:

Phase 1 found that is it technically feasible to repurpose existing substructures for 500MW Offshore Hydrogen production.

Phase 2 transformed the initial vision delivered under Phase 1, a design based on onshore layout principles into a detailed, actionable design of an optimised offshore integrated hydrogen system, addressing critical challenges in electrolyser selection, system integration, and operational efficiency. This marks a significant milestone in the journey towards large-scale offshore green hydrogen production, focusing on the concept definition and engineering integration required for a 500MW facility.

Phase 3 Overview & Outcomes

Phase 3 of the project, summarised in this report, builds upon the technical foundations established in previous phases, retaining the ambitious scale of 500MW for offshore hydrogen production. This phase is distinguished by its visionary outlook, exploring not only immediate engineering solutions but also the evolution of new-build facilities, with perspectives extending to both 2045 and 2080. The report positions Phase 3 as a bridge between pragmatic near-term advancements and transformative long-term possibilities, reflecting the sector's commitment to innovation and sustainable growth.

The key outcomes of this project are:

A Vision for 2045: The Vision for 2045 establishes a credible and achievable end-state for large-scale offshore green hydrogen production, demonstrating that a purpose-designed, 500 MW offshore facility could be realised through the evolution of known technologies combined with targeted intervention where offshore-specific challenges persist.

The work confirms that a normally unmanned, autonomous hydrogen production system is technically plausible within a 2045 horizon, provided advances in electrolysis, automation, digital systems and modular design are aligned through coordinated development and qualification.

Critically, the vision translates long-term ambition into a structured pathway, identifying where market-led technology progress is sufficient and where focused action is required to unlock commercial offshore deployment. In doing so, Vision 2045 provides a robust reference point for industry, policymakers and investors, reducing uncertainty around offshore hydrogen viability and creating a shared framework for strategic decision-making.

Art of the Possible: Art of the Possible reframes offshore hydrogen production beyond incremental improvement, setting out a fundamentally different long-term model for how offshore energy systems could be conceived, governed and operated by 2080. The outcome is not a deployment plan, but a set

of enduring principles that challenge conventional offshore design assumptions and place digital systems, autonomy and outcomes-first thinking at the centre of future developments.

This work demonstrates how offshore hydrogen facilities could evolve into digitally defined, modular and fully unmanned systems, with human oversight focused on governance rather than direct operation. By separating execution, supervision and governance, and embedding assurance and confidence management into system design, Art of the Possible establishes a coherent vision for scaling offshore hydrogen safely and predictably over multiple decades.

It provides a powerful reference against which future concepts can be tested, ensuring that long-term innovation can proceed without compromising safety, accountability or public trust.

Bridge to the Future: Bridge to the Future extends the value of HOP2 beyond offshore hydrogen production itself, identifying how the technologies, capabilities and supply chains required for future offshore hydrogen systems can support wider economic growth across Scotland and the UK. Through a structured assessment of technology opportunities, the work identified a series of priority areas spanning materials science, electrochemistry, advanced manufacturing, circularity, infrastructure and emerging hydrogen production technologies. These areas align strongly with existing regional strengths in offshore engineering, energy systems and industrial innovation, highlighting opportunities to develop new products, services, intellectual property and high-value supply chains.

The work also examined the evolving European hydrogen landscape, including hydrogen valleys, funding programmes and large-scale deployment initiatives. The findings demonstrate that maintaining strong links with European hydrogen ecosystems will be critical to ensuring that capabilities developed through projects such as HOP2 are translated into long-term economic value, export opportunities and industrial growth. Bridge to the Future therefore establishes a clear pathway through which offshore hydrogen innovation can contribute not only to future energy systems, but also to regional competitiveness, skills development and economic resilience.

Long-term value and regional impact: The outcomes of Phase 3 hold significant implications for the energy sector, local communities, and national climate objectives. By charting a course from technically feasible solutions in the near term to visionary paradigms for the future, the report outlines a roadmap that supports economic revitalisation, skills development, and environmental progress.

The sustained focus on Scotland's North-East and Moray ensures that regional benefits are prioritised, while the broader impact contributes to the UK's leadership in offshore hydrogen and climate action. Ultimately, Phase 3 exemplifies a commitment to harnessing innovation for societal and environmental gain, setting the foundation for a sustainable, prosperous energy future.

Next Steps

Targeted technology development and qualification: Progress those technologies identified as critical enablers for offshore hydrogen deployment that are unlikely to mature through business-as-usual market development alone. The Technology Roadmap and associated Technology Qualification Plan provide a structured basis for prioritising research, development, demonstration and qualification activities, ensuring that technology readiness, system integration and assurance mature in step with deployment ambitions.

Translation of vision into future programmes and policy alignment: Use the Vision 2045 and Art of the Possible outputs as reference frameworks to inform future offshore hydrogen programmes, investment decisions and policy development. By anchoring near-term projects within a clearly articulated long-term vision, stakeholders can ensure coherence between early deployment, infrastructure planning and the evolution toward autonomous, scalable offshore hydrogen systems.

Phase 3 Scope Overview

Background

Phase 1 of the HOP2 project delivered a Basis of Study and Concept Development to assess the technical, economic, regulatory, and logistical feasibility of repurposing existing UK Continental Shelf oil and gas assets for large-scale hydrogen production in the early 2030s. The scope included evaluation of platform and pipeline reuse, selection of key production and processing systems, and identification of regulatory gaps.

While reuse of existing substructures was deemed feasible, repurposing or retrofitting topsides was not viable at the target production scale of 500 MW, requiring new-build topsides. Phase 1 also identified the need for further concept engineering to optimise space, weight, cost, and system integration, particularly between electrolysers, Balance of Stack (BoS), Balance of Plant (BoP), and primary electrical systems.

Building on these findings, Phase 2 progressed to the Concept Definition stage, structured around four specialist work packages covering electrolyser selection, BoS and BoP design, primary electrical systems, and integrated topsides design to retrofit onto an existing substructure. Together, these packages developed a fully integrated offshore hydrogen production concept, consolidating process, electrical, and topsides systems into a coherent and technically robust facility design.

Updated Economics

An initial economic assessment was completed in Phase 1, which was revised at the beginning of Phase 3. The revised economics considered four hydrogen production cases with offshore cases based on repurposed asset:

- **Case 1** – onshore production (considered to be the counterfactual)
- **Case 2** - offshore production powered by dedicated fixed wind
- **Case 3** - offshore production powered dedicated by floating wind
- **Case 4** - offshore production powered by hybrid wind power (wind generator also sells to grid)

The economic study demonstrates that electricity cost and electrolyser utilisation are the dominant drivers of the levelised cost of hydrogen across all production pathways.

Onshore hydrogen production remains the lowest-cost option in the near term, benefiting from higher utilisation, lower capital and operating costs, and greater flexibility in accessing electricity markets. Offshore hydrogen production, whether powered by fixed or floating offshore wind, currently carries a cost premium due to higher capital expenditure, lower capacity factors and increased operational complexity. The study shows offshore hydrogen production costs 70 – 120% more than the onshore counterfactual, see Figure 1.

Critically, the study highlights that offshore hydrogen's long-term viability depends less on individual cost reductions and more on system-level alignment. Improved utilisation through hybrid or overbuild strategies, maturation of offshore wind technologies, alignment between wind and hydrogen market mechanisms, and the development of transport, storage and export infrastructure are all identified as necessary enablers. The work also demonstrates that reliance on curtailed wind alone is unlikely to provide a robust long-term business model, as grid reinforcement and market evolution are expected to reduce curtailment over time.

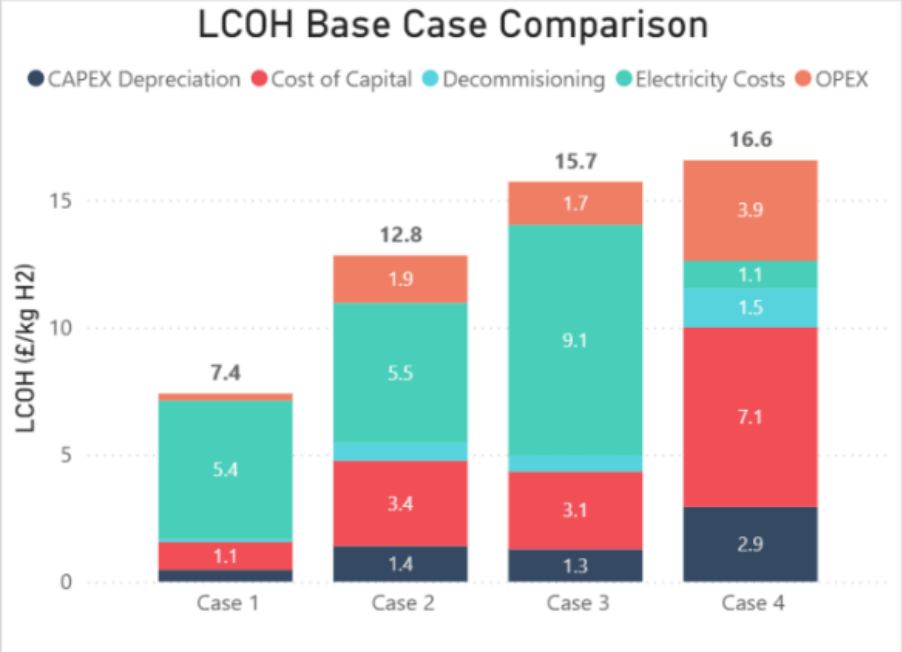


Figure 1: Levelised Cost of Hydrogen (LCOH) base case comparison

Beyond economics, the study confirms that offshore hydrogen offers meaningful strategic and societal value. Offshore deployment can support a just transition for the existing offshore workforce, reduce onshore planning and land-use constraints, and strengthen the UK's position in emerging European hydrogen markets. While offshore hydrogen introduces additional challenges, including higher safety risk and increased interaction with other marine users, these impacts are manageable through appropriate siting, governance and system design.

Phase 3 Scope Overview

Phase 3 of project retains the ambitious scale of 500MW for offshore hydrogen production but this phase is distinguished by its visionary outlook, exploring not only immediate engineering solutions but also the evolution of new-build facilities, with perspectives extending to both 2045 and 2080.

Phase 3 has been delivered through three core activity sets:

- **A Vision for 2045:** Creating a credible offshore hydrogen production asset for 2045, based on technologies that are on or just over the horizon and a shift in operating principles.
- **Art of the Possible:** Reimagining offshore hydrogen production without the constraints of existing or known technologies, and with a paradigm shift in system design and operation.
- **Bridge to the Future:** Applying the insights from HOP2 to the onshore sector to highlight regional and national economic opportunities.

The activities and key finding are summarised in this report.

A Vison for 2045

Overview

The 2045 vision moves beyond adaptation of today's offshore assets and instead considers a purpose-designed, autonomous hydrogen production facility, optimised from the outset for offshore deployment. The concept reflects anticipated advances in electrolysis, robotics, digital systems and artificial intelligence, alongside the increasing scale of offshore wind and the emergence of dedicated hydrogen export infrastructure. The result is a system designed to operate safely, efficiently and with minimal human intervention in the harsh North Sea environment, while remaining scalable, replicable and economically viable.

Methodology and Development Approach

The Phase 3 Vision 2045 work followed a structured and evidence-based methodology. A comprehensive assessment of potential offshore hydrogen production configurations was undertaken from a new-build perspective, unconstrained by legacy infrastructure. This ensured that the resulting vision reflects what could be optimal for offshore hydrogen production, rather than what can be retrofitted from existing offshore oil and gas assets.

From this assessment, two representative production concepts were brought forward:

- a Reference Case, based on hydrogen production on topsides, supported by subsea export infrastructure
- an Opportunity Case, which explores the longer-term potential for predominantly subsea hydrogen production systems

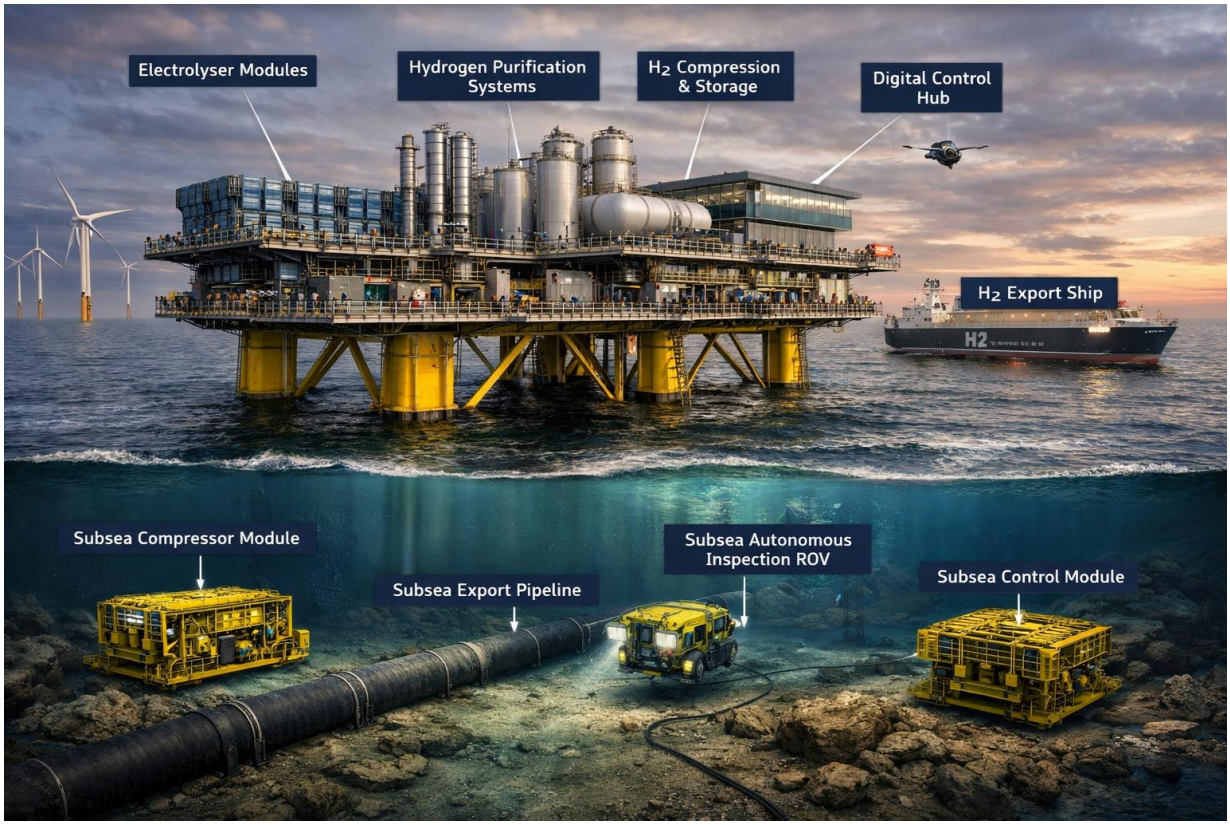


Figure 2 – Vision 2045 for an Offshore Hydrogen Production System – Reference Case

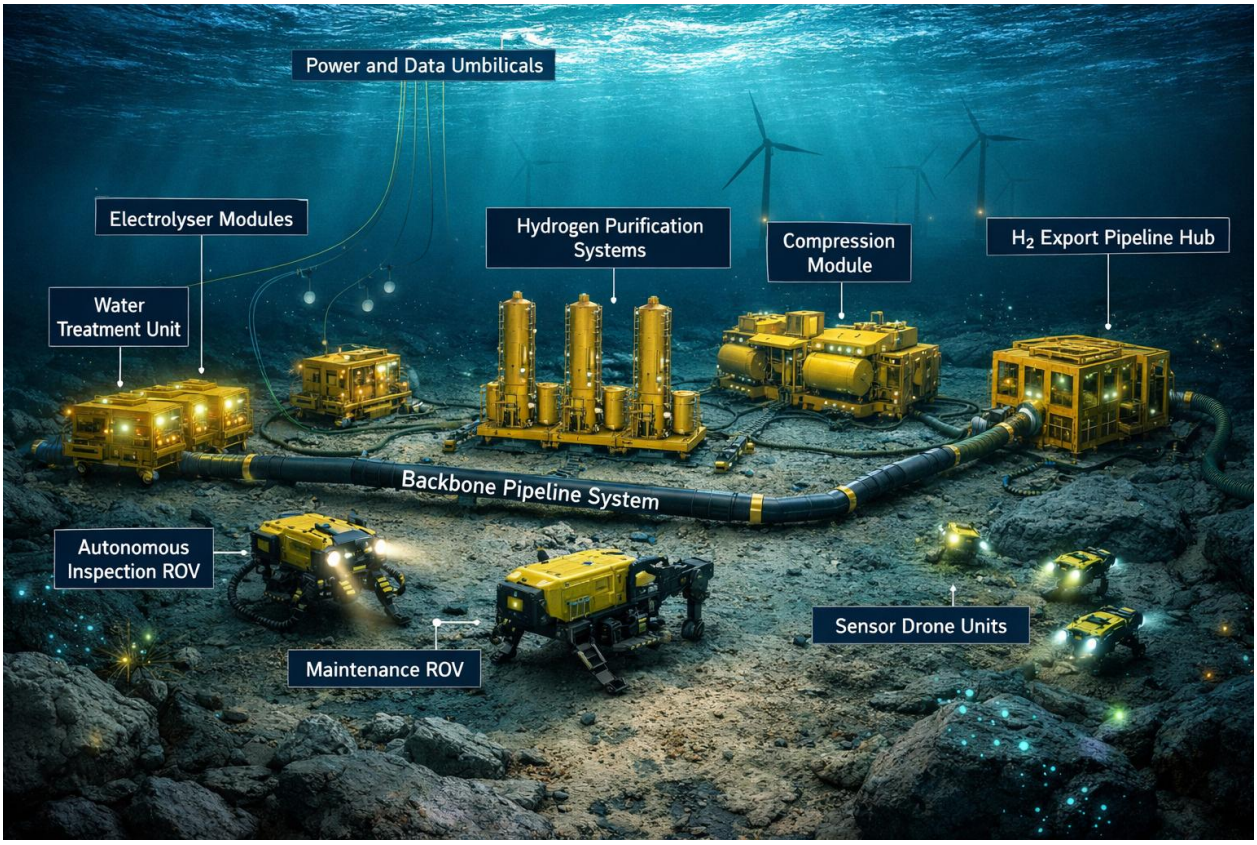


Figure 3 – Vision 2045 for an Offshore Hydrogen Production System – Opportunity Case

A detailed Basis of Design (BoD) and Concept of Operations (CoO) were developed for the Reference Case, establishing a coherent and internally consistent description of system architecture, operating philosophy and design assumptions. Within these documents, specific sections highlight how requirements, interfaces and operating concepts would differ for the subsea Opportunity Case, allowing both concepts to be assessed within a common framework.

Building on the Reference Case BoD and CoO, a system identification and technology assessment was undertaken, covering electrolysis, compression, water management, robotics, autonomy, digital systems and offshore integration. Each system was assessed in terms of offshore suitability, maturity and development needs.

The final step was a back-casting exercise, using the 2045 vision as the target end-state to identify where technology progress cannot be assumed to follow business-as-usual trajectories. This analysis directly informed the Technology Roadmap, highlighting where coordinated intervention will be required to align technology readiness with a credible pathway to offshore hydrogen production by 2045.

Basis of Design

The 2045 vision is underpinned by a reference basis of design representing a large-scale offshore hydrogen production facility with a nominal electrical input of 500 MW, powered by adjacent offshore wind generation. The facility is assumed to be a new-build asset, unconstrained by legacy infrastructure, and designed for deployment across a wide range of North Sea locations.

Key design assumptions include:

- Operation as a normally unmanned, no-people environment, with no permanent offshore accommodation.
- Modular system architecture to enable phased expansion, technology upgrades and replication at scale.

- Export of hydrogen in gaseous form via dedicated offshore pipeline infrastructure.
- Integration of advanced automation, robotics and digital systems as core design features rather than add-ons.

The basis of design reflects an evolution of known offshore and hydrogen technologies, rather than reliance on speculative or disruptive breakthroughs, while acknowledging that significant technology maturation is required to reach full commercial readiness by 2045.

Concept of Operations

The concept of operations for 2045 is centred on fully autonomous production and maintenance, supported by shore-based human oversight. Under normal conditions, hydrogen production, compression, utilities and export systems operate without offshore human presence, managed by hierarchical control systems and AI-enabled decision support.

Operational states include normal operation, degraded operation and recovery, all of which are managed autonomously within defined safety envelopes. Human intervention is limited to exception handling, strategic decision-making and regulatory oversight, conducted from an onshore control centre.

Maintenance is fundamentally transformed from today's offshore practices. Rather than frequent inspection and repair, the system is designed around predictive maintenance and planned replacement, with intervention activities scheduled based on asset condition, production impact and logistics constraints. Offshore visits are infrequent and typically associated with major upgrade or life-extension campaigns rather than routine operation.

Hydrogen System Technology Selection

Overview of the Hydrogen System

The hydrogen system technology selection for the 2045 vision focuses on identifying production, conditioning and export technologies that are both credible for offshore deployment and compatible with long-term autonomous operation. The system is considered holistically, encompassing electrolysis, water management, hydrogen purification, compression and interfaces to export infrastructure.

The reference design assumes a nominal electrical input of 500 MW supplied directly from offshore wind generation, with the hydrogen system configured to operate efficiently across a wide power turndown range. Technology selection is therefore driven not solely by efficiency, but by offshore robustness, maintainability, system integration and lifecycle performance.

Electrolysis Technology

For the 2045 timeframe, the preferred hydrogen production technology is electrolysis that is inherently compatible with offshore environments. The reference case assumes that seawater-compatible electrolysis technologies, such as direct seawater electrolysis or equivalent architectures, will have matured to commercial readiness. This removes the need for large-scale desalination and demineralisation systems, reducing topsides footprint, energy consumption and operational complexity.

In the opportunity case, electrolysis technology must also be suitable for subsea deployment. This places additional emphasis on pressure tolerance, long-term material durability, minimal auxiliary systems and the ability to operate reliably without routine physical access. As a result, the subsea case is more sensitive to technology maturity and qualification timelines.

Hydrogen Conditioning and Compression

Both cases assume that hydrogen must be delivered to export infrastructure at elevated pressure and high purity. Conditioning systems—including drying, purification and compression—are therefore integral to technology selection.

The reference case allows greater flexibility in technology choice, as topsides installation enables more conventional approaches to compression and conditioning. In contrast, the opportunity case prioritises electrochemical or inherently modular compression technologies, which avoid large rotating machinery and are better suited to subsea environments.

Across both cases, hydrogen processing systems are designed as modular units, supporting replacement rather than repair and enabling degraded-mode operation without full system shutdown.

Technology Selection Summary

Aspect	**Reference Case Topsides Production**	**Opportunity Case Subsea Production**
Electrolysis location	Topsides	Subsea
Electrolysis type	Seawater-compatible electrolysis or membrane free	Seawater-compatible electrolysis essential
Compression approach	Mechanical or electrochemical options viable	Preference for electrochemical or low-complexity compression
Maintainability	Robotic and modular, with topsides access	Fully remote, replacement-only philosophy
Technology maturity required	High, but aligned with near-term offshore practice	Very high, requiring extended qualification
Deployment timeline	Earlier commercial viability	Longer-term potential beyond initial deployments

Table 1 – Summary of Technologies for the 2045 Reference and Opportunity Case

The comparison highlights that while the reference case is achievable through an evolution of existing offshore and hydrogen technologies, the opportunity case depends on breakthroughs in subsea-ready electrolysis, compression and autonomous operation. These findings directly informed the Technology Roadmap, identifying where targeted intervention is required to enable subsea hydrogen production within a 2045 horizon.

Operations and Maintenance Philosophy

The operations and maintenance philosophy represents a step change from conventional offshore assets. The facility is designed to operate with minimal offshore intervention, relying on high reliability, redundancy and the ability to continue operating in a controlled degraded state.

Key features include:

- Extensive use of line replaceable units (LRUs) for electrolysers, compression and balance-of-plant systems.
- Replace rather than repair as the primary maintenance strategy.
- Autonomous handling systems and robotics for inspection, isolation and LRU change-out.
- Shore-based logistics planning, supported by predictive maintenance analytics.

This philosophy reduces exposure to offshore safety risk, improves availability and enables a more predictable cost base over the asset lifecycle.

Replacement-Based Maintenance and Modularity

Across both cases, maintenance is based on a replacement-rather-than-repair approach. Key hydrogen production, conditioning and utility systems are configured as modular units that can be isolated, removed and replaced without shutting down the entire facility. This enables continued operation in a controlled degraded mode and avoids reliance on offshore fault diagnosis and repair.

Predictive maintenance, supported by continuous condition monitoring and digital diagnostics, is used to anticipate degradation and schedule interventions proactively. Offshore visits are therefore planned, infrequent and risk-based, rather than reactive.

Reference Case – Topsides O&M Concept

In the reference case, hydrogen production is located on topsides, enabling greater flexibility in access, lifting and intervention strategies. Autonomous and robotic systems are assumed to undertake routine inspection, monitoring and basic handling tasks, with periodic offshore campaigns for module replacement, upgrades or major maintenance.

Human presence offshore is limited and episodic, typically associated with planned campaigns rather than day-to-day operation. This model builds on existing offshore experience while significantly reducing exposure and intervention frequency.

Opportunity Case – Subsea O&M Concept

The opportunity case requires a more radical O&M approach. With hydrogen production located subsea, all routine maintenance must be performed remotely, with no expectation of in-situ repair. Equipment is designed for long life, fault tolerance and complete retrieval or replacement using remotely operated or autonomous systems.

This places much stronger requirements on component durability, monitoring fidelity and logistics planning. As a result, the subsea case carries higher technology development and qualification demands, but offers the potential for step-change reductions in offshore intervention and lifecycle cost in the longer term.

Operations and Maintenance Summary

Aspect	Reference Case – Topsides	Opportunity Case – Subsea
Human presence	Episodic, campaign-based	None under normal operation
Maintenance strategy	Modular replacement with limited access	Full retrieval and replacement
Use of robotics	Inspection, handling, assistance	Essential for all intervention
Degraded operation	Yes	Yes, but more tightly constrained
Technology maturity	Evolves from current offshore practice	Requires significant advancement

Table 2 – Summary of the Operations and Maintenance approach for the 2045 Reference and Opportunity Case

Digital and AI Enablement

Digitalisation and artificial intelligence (AI) are foundational enablers of the 2045 offshore hydrogen vision. Rather than supporting operations retrospectively, digital systems are assumed to be embedded at the core of design, operation and assurance, enabling autonomous operation at scale while maintaining safety, transparency and regulatory confidence.

The digital architecture spans sensing, control, optimisation, maintenance and safety assurance, with human operators retained in a supervisory and decision-making role.

Key features that AI-enabled systems support include:

- Real-time optimisation of hydrogen production in response to variable power input.
- Predictive maintenance through continuous condition monitoring and degradation modelling.
- Autonomous fault detection, diagnosis and response within defined safety limits.
- Dynamic safety case management, providing continuous assurance for regulators and operators.

Human-machine interfaces are designed to present complex system behaviour in an intuitive, transparent way, ensuring that human supervisors remain accountable decision-makers even in highly autonomous operating modes.

Digital Twin and System Intelligence

A high-fidelity digital twin of the offshore hydrogen facility is assumed to exist throughout the asset lifecycle. This digital twin integrates design data, real-time operational data and predictive models, enabling continuous performance optimisation, fault detection and scenario evaluation.

AI-based systems use this digital representation to balance hydrogen production against variable offshore wind input, manage operating envelopes and anticipate degradation before failures occur. Importantly, AI systems operate within defined safety constraints and do not override safety-critical controls.

Predictive Maintenance and Autonomous Decision Support

Predictive maintenance is a primary application of AI in both cases. Continuous condition monitoring feeds machine-learning models that identify emerging faults, estimate remaining useful life and recommend optimal intervention windows.

Decision support tools present this information to shore-based operators in a transparent and explainable manner, enabling informed approval of actions rather than opaque automation. This approach supports regulatory acceptance and operational trust.

Technology Roadmap & Qualification Plan

The 2045 vision described in this report relies on the maturation of a range of technologies that extend beyond those required for near-term offshore hydrogen deployment. While some of these technologies are expected to progress through business-as-usual development driven by the wider hydrogen and offshore wind markets, others represent step-changes that will only materialise through targeted intervention.

To address this, Phase 3 developed a Technology Roadmap and a linked Technology Qualification Plan. Together, these provide a structured view of how offshore hydrogen production could evolve from today's state of practice to a credible, deployable system by 2045. The intent is not to predict a single future outcome, but to identify where focused research, development and qualification effort would be required to unlock new offshore production concepts.

Reference Case and Opportunity Case

The Technology Roadmap and Qualification Plan are structured primarily around the Reference Case developed in Phase 3, providing a credible and staged pathway toward offshore deployment. This includes a focus on architectural simplification, electrochemical integration, and the validation of reduced offshore processing where hydrogen quality and safety envelopes allow.

The Opportunity Case extends this thinking further, capturing longer-term options such as deeper electrochemical integration, alternative electrical architectures and more ambitious subsea-led concepts. These technologies are documented to inform future programmes and investment decisions but are not all carried forward into the current qualification pathway.

Role of the Technology Roadmap

The Technology Roadmap outlines all possible technologies that may shape the future design of offshore hydrogen production systems. This includes hydrogen production and processing technologies, supporting electrical and power conversion systems, and the digital, autonomous and robotic technologies required to operate safely in a low-intervention offshore environment.

The Roadmap distinguishes between technologies that are likely to mature incrementally through market adoption and those that could fundamentally reshape offshore system design, such as highly integrated electrochemical production pathways, advanced solid-state electrical systems, or autonomous modular maintenance concepts. In doing so, it provides the foundation for prioritising development effort and for understanding how different technology choices interact at system level.

From Roadmap to Qualification

The Technology Qualification Plan (TQP) represents a focused subset of the Roadmap. It identifies those technologies that are critical to the HOP2 2045 concepts and that carry sufficient uncertainty, novelty or system impact to warrant structured qualification.

The TQP defines how selected technologies should be progressed from their current maturity to a level suitable for offshore deployment, using a staged approach based on recognised readiness measures and qualification phasing.

Readiness Levels & Qualification Phasing

Individual technologies are assessed using Technology Readiness Levels (TRL), while the maturity of interfaces and integration is assessed using Integration Readiness Levels (IRL) and System Readiness Levels (SRL). This ensures that both component performance and system-level behaviour are addressed.

Technology qualification is then structured across three progressive phases:

- **Phase I – Laboratory & Material Benchmarking:** establishing feasibility boundaries, operating envelopes and degradation mechanisms, and enabling early down-selection where multiple technology variants are considered.
- **Phase II – Pilot and Field Integration:** demonstrating integrated performance at pilot scale under representative boundary conditions, with particular focus on interfaces, controllability and reliability growth.
- **Phase III – Industrial Scaling:** progressing validated solutions to industrial module scale, including endurance testing and prototype demonstration aligned with offshore deployment.

Qualification effort is scaled in proportion to novelty and risk, with higher novelty technologies requiring more extensive evidence generation. Commercial readiness and regulatory alignment are treated as parallel enabling activities, ensuring that technically qualified solutions can ultimately be deployed at scale. This yields the following technology qualification plan for the 2045 vision for HOP2:

HOP2 Phase 3 Technology Development Roadmap

Enabling technology families by technology group — qualification phases and decision gates, 2026–2045

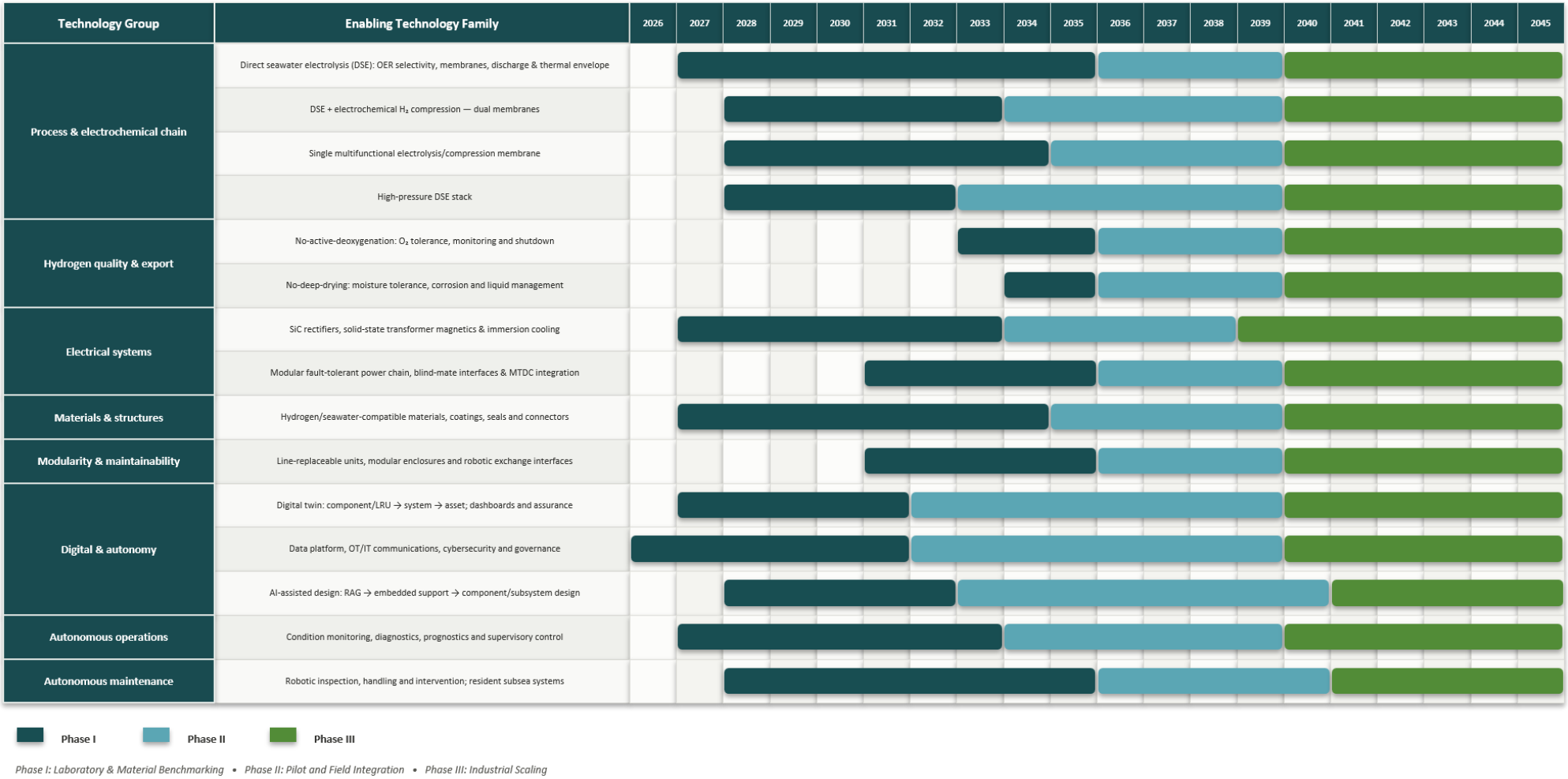


Figure 4 – Technology Development Roadmap

Technology Marinisation

Technologies used in large-scale hydrogen production are typically developed and proven in controlled onshore industrial environments. Offshore deployment introduces a set of additional constraints that must be addressed through a structured process of technology marinisation.

Marinisation in this context involves adapting technologies and supporting systems so that they can operate reliably and safely within the physical, operational and regulatory conditions associated with offshore facilities.Key factors influencing marinisation include:

- Exposure to marine environments characterised by salt spray, humidity, temperature variation and corrosion risk.
- Structural loading associated with offshore installation, including vibration, wave-induced motion and wind loading.
- Space and weight constraints that influence equipment configuration and layout.
- Restricted access for intervention and maintenance compared with onshore facilities.
- Integration with offshore safety systems, hazardous area requirements and marine regulatory frameworks.

Within the HOP2 concept, marinisation considerations influence the design and configuration of electrolysis modules, process equipment, electrical infrastructure and supporting utilities. Equipment selection and layout must accommodate marine exposure while maintaining accessibility for inspection, intervention and safe operation over extended service lifetimes.

Modular configuration plays an important role in enabling effective marinisation. By grouping production systems and supporting equipment into defined modules with clear physical and functional boundaries, technologies can be integrated within the offshore facility while preserving maintainability and replacement capability.

Marinisation therefore represents an essential step in translating hydrogen production technologies from laboratory or onshore deployment into robust offshore industrial systems. Addressing these factors early in concept development helps ensure that system architecture, operational philosophy and maintenance strategy remain aligned with the realities of offshore deployment.

Technology Development Intervention – Latent Drive

Through combined support from the Energy Hubs (EHUBS) programme and HOP2, NZTC supported Latent Drive in advancing its SeaStack direct seawater electrolysis technology toward offshore relevance. The activity focused on addressing key barriers to offshore hydrogen production, including the need to avoid energy-intensive desalination, manage chlorine evolution, and improve durability under marine conditions.

EHUBS support enabled laboratory validation of a two-stage seawater electrolysis concept using integrated membrane architectures, progressing SeaStack from TRL 2 to TRL 4. HOP2 funding provided flexibility to pivot development and focus on offshore-critical components, including bipolar membranes and scalable bipolar plate designs. This resulted in improved materials performance, reduced manufacturing costs, and the validation of a split-stack architecture that enhances safety and system flexibility.

The progress achieved under NZTC support directly underpinned Latent Drive’s transition toward pilot-scale deployment and subsequent Innovate UK funding for real-world demonstration.

Art of the Possible

Overview

The preceding sections of this report describe a credible pathway for offshore hydrogen production to the mid-century, grounded in technologies that are either commercially available or expected to mature through near-term development. Art of the Possible serves a different purpose. It summarises a body of work undertaken during Phase 3 to explore how offshore hydrogen production could be fundamentally re-imagined by 2080, once current constraints around human presence, operational access and system control are no longer dominant design drivers.

This work does not represent a forecast, a deployment plan, or a recommended development pathway. Instead, it provides a conceptual reframe of offshore hydrogen production, intended to test the limits of current thinking and to challenge assumptions that may otherwise be unconsciously carried forward into future designs. The emphasis is on operability, governance and lifecycle behaviour, rather than on individual technologies.

A defining characteristic of this reframe is its digital-first perspective. Across all aspects of the 2080 work, digital systems are treated not as supporting tools, but as the primary means through which performance, safety, assurance and change are managed. Physical infrastructure is considered the execution layer of a system whose intent, behaviour and evolution are increasingly defined digitally.

A Paradigm Shift: From Plant-First to Capability-First Operation

The 2080 work adopts a fundamentally different design starting point from that used in earlier phases of HOP2. Traditional offshore facilities are typically designed by defining physical systems first, followed by operating and maintenance models to manage those systems. In contrast, the 2080 concepts begin with desired capability or operational outcomes and work backwards to define the physical infrastructure required to support them.

At the scales envisaged for offshore hydrogen production, operational resilience and maintainability become primary design drivers, shaping both the physical architecture of production systems and the supervisory control strategies required to operate them safely.

Examples of these outcomes include:

- Continuous operation without routine offshore human presence
- Predictable intervention patterns rather than reactive maintenance
- Controlled degradation rather than binary failure
- Clear allocation of authority between automated systems and human oversight

By addressing these questions upfront, the work moves away from bespoke, tightly coupled facilities toward modular and replaceable system architectures, where flexibility and resilience are designed in rather than added later.

This capability-first approach also reframes autonomy. Rather than being treated as a technological feature, autonomy emerges as a consequence of disciplined system architecture, clear authority boundaries and robust assurance mechanisms.

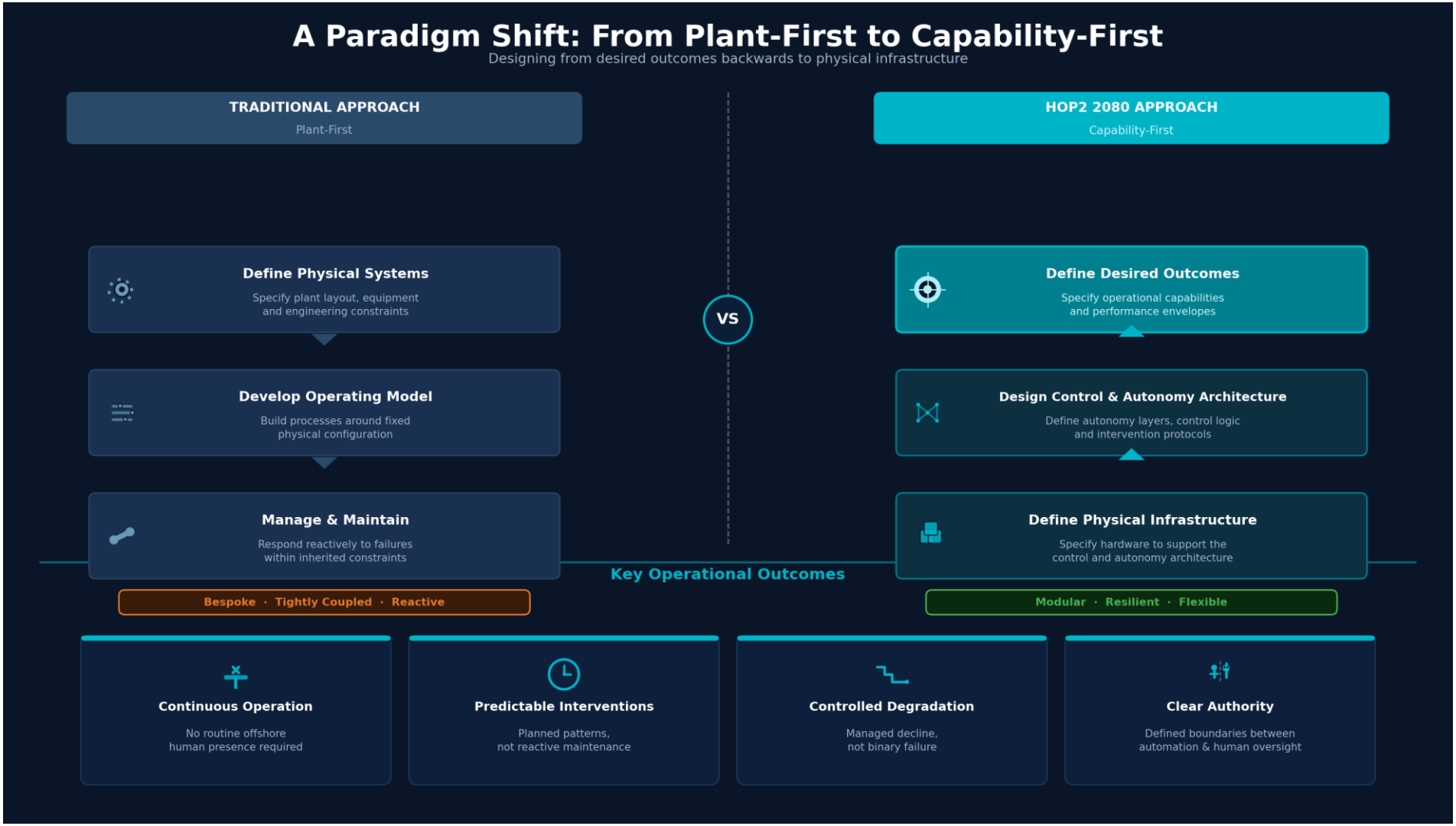


Figure 5 – Art of the Possible mindset shift from traditional plant first engineering design to capability first

Reference Platform in 2080

To provide a common reference point for the 2080 studies, a conceptual reference platform was defined. This platform is not intended to represent a deployable design, but rather a consistent context against which different ideas could be tested and compared.

In this context, the platform is conceived as permanently unmanned under normal operation. The design therefore excludes accommodation, routine access routes and human-centric facilities that dominate conventional offshore layouts. Instead, space, layout and structural design are driven by production modules, power handling systems, robotic access requirements and interface standardisation.

The platform is treated as a long-lived host structure, providing stable mechanical, electrical and data interfaces. Hydrogen production systems, compression units and auxiliary equipment are assumed to have shorter lifetimes and to be replaced or upgraded multiple times over the platform's life. This decoupling allows the platform to persist while technology evolves.

A further defining feature is the platform's digital identity. A high-fidelity digital representation defines the platform's configuration, operating envelopes and authority boundaries. Physical assets are continuously reconciled against this digital baseline, enabling changes to be planned, assessed and assured before execution.

Horizon Technologies Towards 2080

The 2080 work does not rely on a single breakthrough technology. Instead, it assumes incremental but sustained progress across a range of domains, including electrochemistry, materials, power electronics, sensing and robotics.

Electrochemical systems are assumed to become more integrated and tolerant of variable operating conditions, reducing reliance on extensive balance-of-plant. Materials advances improve durability in aggressive marine environments and reduce dependence on constrained supply chains. Electrical architectures move toward higher efficiency and lower footprint through solid-state and direct-current systems.

Importantly, the work assumes that these technologies are designed with autonomy and remote operation in mind, rather than adapted from human-operated systems. This shifts priorities toward predictability, simplicity and standardisation, which are critical enablers of unmanned operation.

Digital Futures

Digital Futures is the principal enabler of the 2080 reframe and represents the most significant departure from conventional offshore design thinking.

In the 2080 concepts, digital systems are not treated as optimisation layers applied to a physical plant. Instead, they provide the primary framework through which the facility is defined, operated and governed. This digital definition is maintained throughout the lifecycle of the facility.

The physical installation therefore becomes an expression of a digital model, rather than the other way around. This allows change to be assessed, simulated and assured digitally before it is implemented offshore, reducing uncertainty and supporting unmanned operation.

Separation of Execution, Supervision and Governance

A central theme of the Digital Futures work is the explicit separation between different types of decision-making within the system. Three distinct layers are considered:

- Governance, covering the definition of operating envelopes, approval of change and management of escalation
- Management, covering digital systems that coordinate, optimise and anticipate behaviour within defined limits

- Execution, covering deterministic control and safety functions that operate continuously and are not subject to adaptive modification

This separation is critical in enabling greater use of autonomy without undermining safety or accountability. Management and supervisory digital systems may adjust operating modes, rebalance load across modules or plan interventions, but they do so only within limits defined by governance and without the ability to override safety functions.

By making these boundaries explicit, the work avoids the ambiguity that often arises when automation, control and governance responsibilities become blurred.

Digital Twins Across the Lifecycle

Digital twins are a core enabler of the 2080 vision, but their role extends beyond traditional simulation or visualisation. During Phase 3, the work explored how digital twins could be used consistently across design, qualification, operation, maintenance and requalification, rather than being applied selectively at different stages.

In early phases, digital twins are used to test assumptions, explore failure modes and assess integration challenges. As the system matures, the same digital constructs evolve to support commissioning, operational monitoring and degradation forecasting.

Crucially, digital twins are not treated as static representations. They evolve alongside the physical system, incorporating operational data and updated understanding of system behaviour. This allows confidence in digital predictions to be assessed continuously and provides a basis for deciding when supervisory authority can be expanded or must be constrained.

Evidence-Led Expansion of Autonomy

A defining principle of the Digital Futures work is that autonomy is not assumed. Instead, it is introduced progressively and only where supported by evidence.

In early stages, digital systems provide decision support and insight to human operators. As confidence grows in their predictions and recommendations, limited supervisory actions may be permitted within tightly defined envelopes. Further expansion of autonomy is contingent on demonstrated stability, predictability and alignment with safety constraints.

This evidence-led approach ensures that digital capability grows in step with assurance, rather than outpacing it. It also provides a clear mechanism for limiting or rolling back autonomy where confidence degrades, maintaining trust in the system.

Confidence Monitoring and Escalation

The Digital Futures concepts explicitly recognise that digital models and analytical systems are only valid within the conditions for which they have been developed and validated. Changes in operating regime, environment or system configuration can erode that validity over time.

As a result, the work explored mechanisms for monitoring confidence in digital outputs, rather than simply monitoring process variables. Indicators such as divergence between predicted and observed behaviour, narrowing operating margins or increased frequency of corrective action are used to trigger escalation.

When confidence degrades, supervisory authority is reduced and responsibility is transferred to human operators. This ensures that uncertainty is managed deliberately rather than masked by continued automation.

Re-Engineering the Human Role

While the 2080 concepts assume permanently unmanned offshore operation, they do not remove humans from the system. Instead, the Digital Futures work redefines the human role from direct operator to steward of intent and governance.

During normal operation, human operators provide distributed oversight across multiple systems or assets, supported by digital situational awareness. Their role is to confirm that the system is operating within its intended envelope, review digital recommendations and approve planned changes.

During abnormal conditions, attention is deliberately concentrated. Control areas are reassigned, and human operators take direct responsibility for managing escalation, approving interventions or redefining operating constraints. This structured approach avoids cognitive overload and ensures that responsibility is clear.

Enabling Scale and Replication

A key motivation for the Digital Futures work is scalability. By defining facilities digitally and governing change explicitly, the approach supports replication across multiple offshore assets without bespoke redesign.

Standardised digital architectures, common authority frameworks and repeatable qualification processes allow lessons learned on one installation to be transferred to others. This is particularly important in the context of large-scale offshore hydrogen deployment, where fleets of similar assets are expected rather than isolated developments.



Figure 6 – Art of the Possible – a vision for offshore hydrogen production in 2080

Hydrogen Production System in 2080

The hydrogen production system envisaged for 2080 is markedly different from near-term offshore concepts. Rather than a chain of discrete process units, it is treated as a highly integrated electrochemical system, packaged into modular production units.

Water intake, electrolysis, separation and pressure management are increasingly combined, reducing interfaces and failure points. Electrolysis chemistry is assumed to evolve to support wider operating envelopes, greater tolerance to variable feed conditions and improved durability under cyclic operation.

System design prioritises controlled behaviour over peak efficiency. Individual modules are expected to degrade over time, with performance managed through derating and replacement rather than corrective

repair. This aligns directly with unmanned operation and supports continuous production with predictable intervention.

The hydrogen system is therefore designed as part of a wider operational concept, not as an isolated process plant.

Safety and Assurance

Safety in the 2080 concepts is achieved through a combination of design elimination, deterministic protection and continuous assurance.

With no routine offshore human presence, many traditional hazards are removed by default. Remaining risks are managed through fixed safety functions that are not subject to modification by digital supervisory systems. These functions provide a stable baseline upon which innovation can occur.

Assurance is treated as a continuous activity. Digital models, operational data and predictive analytics are used to maintain an up-to-date understanding of system behaviour. Safety cases evolve from static documents to living artefacts, supporting transparency and regulatory confidence over long asset lifetimes.

The Integrated Vision

Taken together, the Art of the Possible work presents a fundamentally different way of thinking about offshore hydrogen production. The 2080 concepts describe systems that are:

- Digitally defined rather than physically constrained
- Modular and replaceable rather than bespoke and static
- Unmanned by default but human-governed
- Designed for evolution rather than fixed end states

The Art of the Possible work undertaken in Phase 3 reframes offshore hydrogen production as a governed digital system, rather than a digitally supported physical asset. It demonstrates how autonomy, robotics and advanced analytics could be introduced in a controlled, evidence-led manner while preserving safety, accountability and human oversight.

This work does not prescribe a solution for deployment. Instead, it establishes a set of principles and patterns that allow long-term innovation to occur without undermining assurance. In doing so, it provides a critical foundation for the Art of the Possible vision and a reference point against which future offshore hydrogen concepts can be assessed.

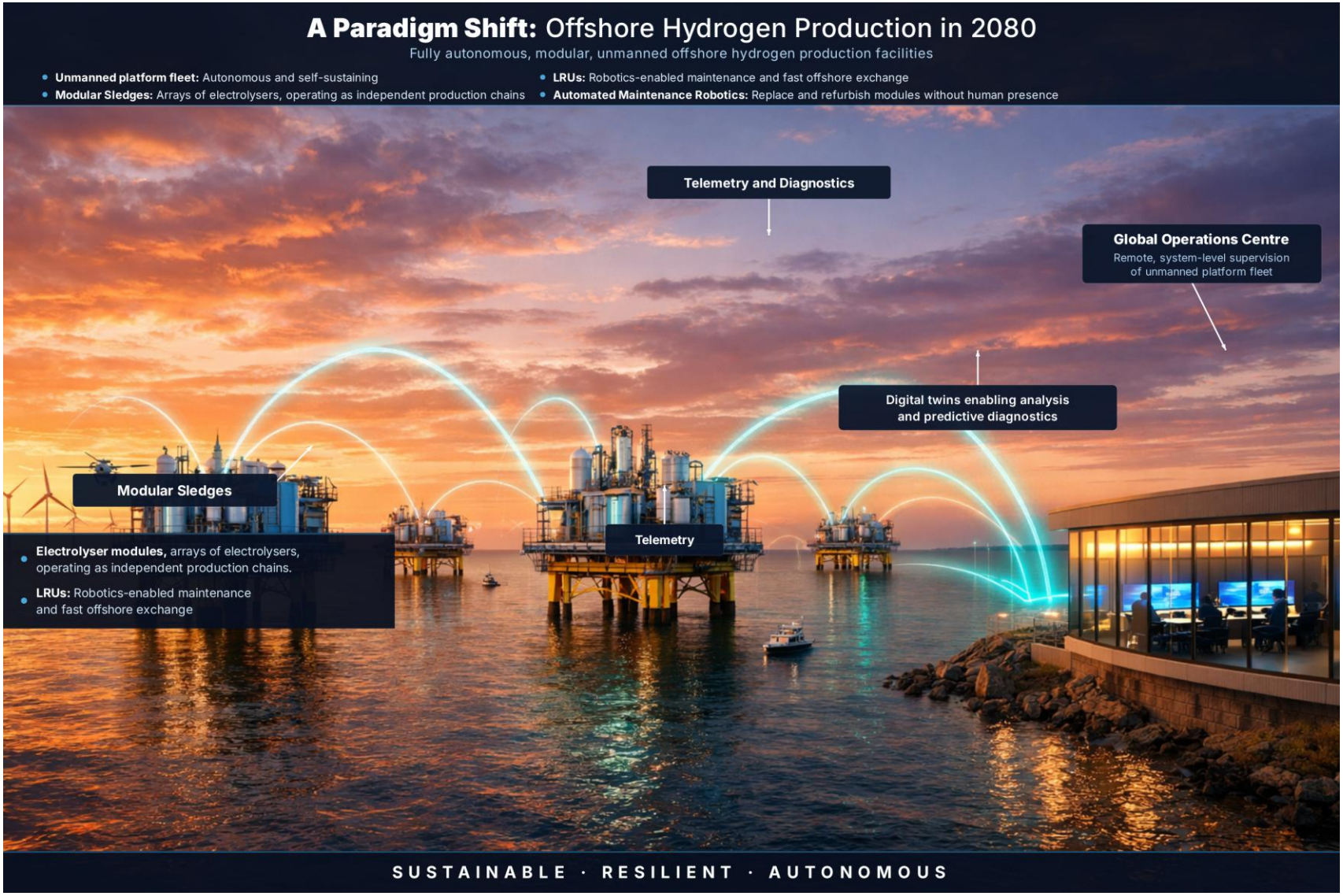


Figure 7 – Art of the Possible – a vision for offshore hydrogen production in 2080

Bridge to the Future

Overview

Bridge to the Future examines how the technologies, capabilities and operating philosophies required for offshore hydrogen production can create wider economic opportunities for Scotland and the UK. While HOP2 has focused on the challenges of producing hydrogen offshore, many of the enabling technologies are equally relevant to onshore deployment and represent areas where regional capability can be developed, strengthened and exported.

Analysis undertaken through the Bridge to the Future work identified a series of technology groups that are likely to play a critical role in the future hydrogen economy. Each technology group contains several subcomponents relevant to that area. These groups were assessed against regional, Scottish and UK strengths to identify where existing capability can be exploited, where further development is required, and where strategic investment could create long-term competitive advantage. The work also considered the evolving European hydrogen landscape, recognising that future growth is likely to be shaped not only by technology development but also by participation in large-scale European deployment programmes, hydrogen valleys and future funding mechanisms.

Technology Group 1 – Materials Science

Description

Materials science underpins every aspect of the hydrogen value chain and is fundamental to reducing cost, improving reliability and enabling large-scale deployment. Priority areas include advanced catalysts, next-generation membranes, hydrogen-compatible pipeline materials, intelligent coatings, novel hydrogen storage materials and improved understanding of hydrogen damage mechanisms. Offshore deployment places particularly demanding requirements on materials performance, durability and maintainability, making this an area where offshore-led innovation can directly benefit the wider hydrogen sector.

Regional & UK Opportunities and Strengths

Scotland and the UK possess strong research capability in materials science, supported by universities, industrial research centres and established offshore engineering experience. Existing strengths in metallurgy, coatings, polymers, corrosion management and oil and gas infrastructure provide a strong foundation from which to develop hydrogen-specific materials technologies.

The analysis highlights significant opportunities around non-precious metal catalysts, fluorine-free membranes, recyclable components, self-healing materials, advanced pipeline materials and novel storage media such as metal-organic frameworks and hydrides. These represent areas where targeted investment could create intellectual property, strengthen domestic supply chains and support future manufacturing activity.

European Alignment

European programmes are increasingly focused on scaling hydrogen deployment and strengthening strategic supply chains. Advanced materials, circularity, recycling and reduced dependence on critical raw materials are all becoming progressively more important within European hydrogen initiatives. As deployment increases across Europe, demand for improved materials, coatings, membranes and hydrogen-compatible infrastructure components is expected to grow substantially.

Technology Group 2 – Electrochemistry and Hydrogen Processing

Description

Electrochemistry forms the foundation of green hydrogen production and extends beyond electrolysis to include compression, purification, drying, desalination and sensing technologies. The work identified particular opportunities around integrated electrochemical systems capable of combining multiple process functions within simplified architectures.

Looking forward, offshore hydrogen production could benefit from seawater-compatible electrolysis, electrochemical compression, integrated purification systems and hybrid electrochemical stacks that reduce complexity while increasing automation and reliability.

Regional & UK Opportunities and Strengths

The UK has an internationally recognised electrochemistry research base, with Scotland contributing a significant proportion of national capability. Strong academic expertise, emerging technology companies and existing hydrogen programmes provide a platform for innovation.

Key opportunities exist in advanced sensing, integrated electrochemical processing, electrochemical compression, hybrid stack development, electrochemical desalination and novel electrolysis technologies. These areas align particularly well with the requirements of autonomous offshore systems where minimising moving parts, maintenance requirements and operational complexity will be critical.

European Alignment

Hydrogen technology scale-up remains a major focus of European research and innovation funding. While Europe is increasingly shifting from basic research towards commercial deployment, continued demand exists for technologies that improve efficiency, reduce cost and simplify hydrogen production systems. The development of integrated electrochemical systems aligns strongly with European ambitions to improve competitiveness and accelerate deployment.

Technology Group 3 – Components, Systems and Industrial Supply Chains

Description

Large-scale hydrogen production requires a wide range of supporting components and systems including valves, compressors, drying systems, purification equipment, sensors, power electronics, control systems and modular balance-of-plant equipment.

Although less visible than electrolysers, these components represent a substantial proportion of total project value and provide important opportunities for domestic supply chain participation.

Regional & UK Opportunities and Strengths

North East Scotland possesses a mature engineering and manufacturing base developed through decades of offshore energy activity. Existing expertise in pressure systems, process equipment, rotating machinery, instrumentation, electrical systems and offshore operations provides a strong foundation for participation in the future hydrogen economy.

The opportunity is not simply to supply traditional equipment but to develop hydrogen-ready products, standardised modular systems and next-generation equipment designed specifically for autonomous operation. This creates a pathway for existing companies to transition into future energy markets while retaining skills, employment and industrial capability.

European Alignment

As Europe moves towards large-scale deployment, significant demand will emerge for industrial supply chains capable of delivering reliable hydrogen equipment at scale. Participation in European projects, hydrogen valleys and demonstration programmes offers an opportunity for Scottish and UK companies to access these growing markets.

Technology Group 4 – Future Hydrogen Production Technologies

Description

Alongside conventional electrolysis, a range of emerging hydrogen production concepts could improve efficiency, reduce infrastructure requirements or open up entirely new deployment models.

Examples identified through the analysis include direct seawater electrolysis, membrane-free electrolysis, high-pressure electrolysis, biological hydrogen production, waste-to-hydrogen processes, natural hydrogen and other novel production routes.

Regional & UK Opportunities and Strengths

Many of these technologies remain at low technology readiness levels but offer the potential for transformational rather than incremental improvement. Offshore hydrogen production provides a valuable challenge environment for testing and demonstrating such technologies.

Particularly relevant opportunities include direct seawater electrolysis, which could significantly simplify offshore system architecture, and natural hydrogen, which has the potential to create an entirely new resource opportunity drawing upon capabilities developed through the UK's oil and gas sector.

European Alignment

European funding programmes continue to support breakthrough technologies where they can contribute to strategic energy security, industrial competitiveness and decarbonisation. Demonstration and validation of emerging production technologies are expected to remain important themes throughout the coming decade.

Technology Group 5 – Circularity and Resource Efficiency

Description

The future hydrogen economy must be developed with circular economy principles embedded from the outset. Circularity extends beyond recycling to include material selection, design for disassembly, resource recovery and the productive use of process by-products.

Opportunities identified include recovery and recycling of catalysts and membranes, capture and utilisation of oxygen and brine streams, improved material recovery processes and circular design approaches for hydrogen infrastructure.

Regional & UK Opportunities and Strengths

Scotland has developed strong policy leadership around circular economy principles. Combined with engineering expertise and industrial capability, this creates an opportunity to position the region as a leader in circular hydrogen technologies.

Embedding circularity early provides a route to reduced lifecycle costs, improved resource security and new commercial opportunities associated with refurbishment, remanufacturing and material recovery.

European Alignment

Circularity is becoming increasingly important within European industrial policy. The growing focus on critical raw materials, supply chain resilience and sustainability reporting creates a strong alignment between European priorities and the opportunities identified through Bridge to the Future.

Technology Group 6 – Infrastructure, Markets and Hydrogen Ecosystems

Description

Hydrogen production facilities do not operate in isolation. Long-term success depends on the development of transport, storage, export and utilisation infrastructure capable of supporting large-scale deployment.

The work identified strategic opportunities around hydrogen transport networks, storage infrastructure, port developments, offshore refuelling concepts, hydrogen hubs and integration with wider energy systems.

Regional & UK Opportunities and Strengths

North East Scotland is uniquely positioned to benefit from investment in hydrogen infrastructure. Existing offshore assets, ports, pipelines, supply chains and engineering expertise provide a strong starting point for future development.

The region's experience in managing large-scale energy infrastructure can be utilised to support hydrogen transport, storage and export systems while enabling integration with offshore wind, carbon capture and wider energy transition initiatives.

European Alignment

Infrastructure development is becoming a defining characteristic of European hydrogen strategy. Hydrogen valleys, transport corridors, storage projects and cross-border networks are all progressing. The Hamburg Declaration and wider North Sea cooperation initiatives reinforce the strategic importance of hydrogen production, transport and storage infrastructure across the region.

Participation in these initiatives provides an opportunity for Scotland and the UK to influence future hydrogen system development while ensuring regional capabilities remain visible within emerging European supply chains.

Hydrogen Capability Landscape Summary

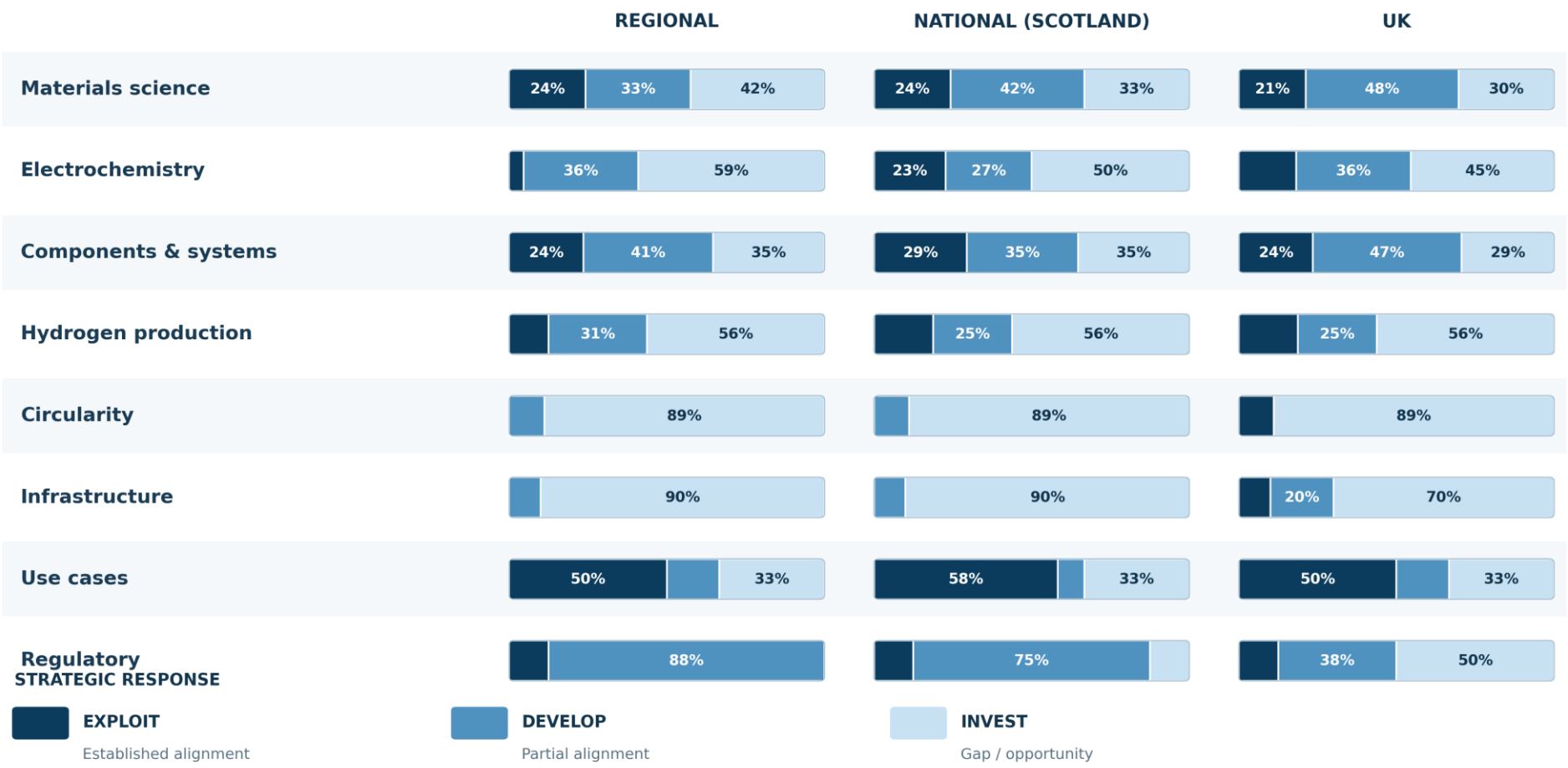
The assessment highlights distinct differences in capability maturity across the hydrogen value chain. The Hydrogen Capability Chart shown in Figure 8. Use cases represent the strongest area of existing capability, with a significant proportion of opportunities already aligned with regional, national and UK strengths. Materials science and components and systems demonstrate broad capability bases, although further development is required to maximise future opportunities.

By contrast, infrastructure, circularity and aspects of hydrogen production are characterised by a high proportion of gaps and investment needs, indicating areas where additional capability, partnerships and targeted intervention could be required to support future growth. Electrochemistry and regulatory capabilities occupy a more transitional position, with a mixture of existing strengths and development needs across geographic scales.

Taken together, the findings suggest that future hydrogen growth can build on established strengths in application-focused technologies while prioritising investment in enabling infrastructure, circular systems and production technologies to address identified capability gaps.

Hydrogen capability landscape

The balance of capabilities to exploit, develop and invest in — from regional to UK scale



Each bar shows the share of opportunities in the workbook assessment. Labels are shown for segments of 20% or more.

Source: NZTC B2F gap analysis

Figure 8 – Hydrogen Capability Landscape – The % figures within the chart represent the number of subcomponents with each technology group that can be classed as having: established skills and expertise (Exploit), partial capability (Develop) or represents a gap in the existing skill base (Invest).

European Hydrogen Funding and Deployment Landscape

The Bridge to the Future work also examined the evolving European hydrogen funding landscape and its implications for future technology deployment, innovation collaboration and market development. The analysis confirms that hydrogen remains central to European decarbonisation and energy security strategies, supported by a broad range of funding mechanisms spanning research, technology development, demonstration and large-scale commercial deployment. These include Horizon Europe, the Clean Hydrogen Partnership, the EU Innovation Fund, the European Hydrogen Bank and a range of national and transnational investment programmes.

A clear trend emerging across European programmes is the transition from research-led funding towards industrial deployment at scale. While continued support remains available for technology development, increasing emphasis is being placed on accelerating commercial projects, hydrogen valleys, infrastructure development and integrated hydrogen ecosystems capable of supporting industrial decarbonisation and energy system transformation.

The findings highlight that maintaining visibility and active participation within European hydrogen networks will be increasingly important for Scotland and the UK. Although direct access to some funding mechanisms remains limited, opportunities continue to exist through collaborative programmes, hydrogen valleys, international partnerships and participation within wider European hydrogen value chains.

Taken together, the analysis demonstrates that Europe is likely to remain a major driver of hydrogen investment and deployment well beyond 2030. Continued engagement with European programmes, projects and industrial partnerships will therefore be essential to ensuring that technologies, capabilities and supply chains developed through initiatives such as HOP2 can access future markets, attract investment and contribute to long-term regional economic growth.

Bridge to the Future Conclusions

Bridge to the Future demonstrates that the technologies required for offshore hydrogen production have applicability far beyond a single offshore facility. The analysis highlights a portfolio of opportunities spanning materials science, electrochemistry, advanced manufacturing, circular economy solutions, infrastructure development and future hydrogen production technologies.

Many of these opportunities align strongly with established strengths in North East Scotland and the wider UK, particularly where offshore engineering capability, industrial supply chains and energy sector experience can be transferred into emerging hydrogen markets. In several areas the opportunity extends beyond simple adoption of new technologies towards the creation of new intellectual property, industrial capability and exportable expertise.

The work also highlights the increasing importance of Europe as a future market and development partner. Hydrogen valleys, infrastructure programmes, funding mechanisms and North Sea cooperation initiatives are collectively shaping the next phase of hydrogen deployment. Maintaining a strong presence within these networks will be essential if regional capabilities developed through HOP2 are to translate into long-term economic value.

Taken together, the findings demonstrate that offshore hydrogen production should not be viewed solely as a future energy project. It represents a catalyst for wider industrial innovation, supply chain development and economic growth, providing a pathway through which Scotland and the UK can establish leadership positions in the emerging hydrogen economy.

Conclusions & Next Steps

Phase 3 Conclusions

The following conclusions can be drawn from the Phase 3 activity:

Economic challenges remain for offshore hydrogen production

Offshore hydrogen production, whether powered by fixed or floating offshore wind, currently carries a cost premium due to higher capital expenditure, lower capacity factors and increased operational complexity. Critically, the study highlights that offshore hydrogen's long-term viability depends less on individual cost reductions and more on system-level alignment. The work also demonstrates that reliance on curtailed wind alone is unlikely to provide a robust long-term business model, as grid reinforcement and market evolution are expected to reduce curtailment over time.

Realising offshore hydrogen production provides long-term economic value and North East Scotland regional impact

The outcomes of Phase 3 hold significant implications for the energy sector, local communities, and national climate objectives. By charting a course from technically feasible solutions in the near term to visionary paradigms for the future, the report outlines a roadmap that supports economic revitalisation, skills development, and environmental progress.

The sustained focus on Scotland's North-East and Moray ensures that regional benefits are prioritised, while the broader impact contributes to the UK's leadership in offshore hydrogen and climate action. Ultimately, Phase 3 exemplifies a commitment to harnessing innovation for societal and environmental gain, setting the foundation for a sustainable, prosperous energy future.

There is a credible pathway to large-scale offshore hydrogen by 2045

Phase 3 demonstrates that large-scale offshore green hydrogen production is achievable within a 2045 horizon through the evolution of known technologies, supported by targeted intervention where offshore-specific challenges remain. The Vision 2045 provides a coherent and technically credible end-state for a 500 MW offshore hydrogen facility, reducing uncertainty around system architecture, operability and autonomy. By distinguishing between technologies expected to mature through market forces and those requiring focused development and qualification, the project establishes a practical framework for aligning industry, policy and investment decisions.

An opportunity exists to entirely reframe offshore hydrogen for long-term scalability and assurance

The Art of the Possible work delivers a fundamental reframing of offshore hydrogen production, shifting the focus from incremental adaptation of existing offshore models to outcomes-led, digitally governed systems designed for long-term evolution. By exploring how autonomy, modularity and digital assurance could be embedded at system level, Phase 3 defines principles that enable scale, replication and predictable lifecycle behaviour without compromising safety or accountability. This reframing provides a durable reference for future innovation, ensuring that long-term ambition can be pursued in a controlled, evidence-led manner.

Building Long-Term Economic Value

The opportunities identified through Bridge to the Future demonstrate that offshore hydrogen has the potential to deliver value far beyond energy production alone. Many of the technologies and capabilities required align closely with existing strengths in offshore engineering, energy systems, advanced manufacturing and industrial innovation. Future programmes should therefore seek to connect technology development and qualification with wider industrial and skills strategies, enabling emerging capabilities to translate into new products, services and high-value supply chains. By maintaining strong links with UK and European hydrogen ecosystems, Scotland can strengthen regional competitiveness, attract investment and support sustainable long-term economic growth.

Next Steps

Targeted technology development and qualification: Progress those technologies identified as critical enablers for offshore hydrogen deployment that are unlikely to mature through business-as-usual market development alone. The Technology Roadmap and associated Technology Qualification Plan provide a structured basis for prioritising research, development, demonstration and qualification activities, ensuring that technology readiness, system integration and assurance mature in step with deployment ambitions.

Translation of vision into future programmes and policy alignment: Use the Vision 2045 and Art of the Possible outputs as reference frameworks to inform future offshore hydrogen programmes, investment decisions and policy development. By anchoring near-term projects within a clearly articulated long-term vision, stakeholders can ensure coherence between early deployment, infrastructure planning and the evolution toward autonomous, scalable offshore hydrogen systems.