Green Paper for the IET Sustainability & Net Zero Policy Centre

Hydrogen for a Net Zero UK: Building a Secure, Scalable and Resilient Hydrogen Economy

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Purpose: The findings in this Green Paper are intended to inform forthcoming updates to the UK Government's (DESNZ) Hydrogen Strategy.

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Executive summary

Hydrogen is not yet a universal fuel. When used selectively where direct electrification is impractical or uneconomic, it can become a powerful enabler of the UK's transition to net zero. Sectors such as high-temperature process heat, chemical feedstocks, long-haul heavy transport, and long-duration or seasonal energy storage stand to benefit the most. The UK has significant strengths, including industrial clusters with concentrated demand, internationally respected safety and standards institutions, and a maturing policy framework under the evolving UK Hydrogen Strategy. However, deployment remains slower and costlier than necessary because five enablers are not advancing in unison: infrastructure (especially storage and distribution), supply chains (manufacturing readiness and certification), workforce (skills and safety culture), finance (bankability and cost reduction), and regulation/safety (clarity and speed).

This "green paper" synthesises insights from multiple sources: a PRISMA-informed rapid review of UK and international hydrogen policy and technical literature, 15 expert interviews spanning developers, OEMs, regulators, financiers, and skills providers, and a set of in-depth MSc research projects at Cranfield University completed in 2025. The MSc studies provided focused analyses of hydrogen networks and infrastructure, supply chain readiness, and enabling ecosystems (skills, finance, and regulation). These academic findings were then triangulated with industry evidence and expert opinions to ensure robustness. The outcome is a pragmatic yet ambitious set of insights and recommended programme actions that combine academic rigour with practitioner validation, designed to inform the UK Government's evolving Hydrogen Strategy.

In response, this paper outlines a few key actions aimed at synchronising infrastructure, markets, skills, safety, and planning. These recommendations emphasise storage-first cluster development, bankable market design, manufacturing and skills readiness, streamlined consenting, and system integration. These pillars respond to clear evidence of scale and capacity. The UK already has more than 250 hydrogen facilities, either operating, under construction, or planned, representing ~28 GW of pipeline capacity, with 14 GW targeted for commissioning by 2030. The current workforce of approximately 1,600 is expected to expand to around 29,000 by 2030, with a third of roles requiring hydrogen-specific competencies. Current investment flows are significant, with billions already committed, but remain heavily reliant on government support and unevenly transparent. Mobilising larger pools of private capital will require clarity on storage, certification, skills, and consent to reduce risk and accelerate delivery. Together, these trends underline the urgency of synchronising infrastructure, supply chains, skills, and investments to translate ambition into delivery. If advanced in parallel, these actions can convert targets into operational reality at lower cost and higher safety assurance while positioning UK firms to export know-how, standards, and high-value components.

Policy signals in 2024–25 and early 2026 have further clarified government–industry priorities and strengthened the policy framework underpinning delivery. In particular, the Department for Energy Security and Net Zero (DESNZ) has confirmed the introduction of a dedicated Hydrogen-to-Power (H_2P) business model and a complementary cap-and-floor scheme for Long-Duration Electricity Storage (LDES), together forming the foundation for a clean, dispatchable power stack. These measures sit alongside the new Hydrogen Economic Regulatory Framework (July 2025), which establishes the principles for a Regulated Asset Base (RAB)-style Hydrogen Transport Business Model, a new hydrogen network code, and producer-led balancing arrangements. Collectively, they aim to reduce investor risk and lower the cost of capital for hydrogen infrastructure. Hydrogen infrastructure is now explicitly in scope of the National Energy System Operator's (NESO) new strategic planning regime. Hydrogen production, storage, and transport will be integrated from the first Strategic Spatial Energy Plan (SSEP, due 2026), followed by the Comprehensive System Needs Plan (CSNP, 2027) and the first Regional Energy Spatial Plans (RESPs, 2027). DESNZ has also stated that it will have "due regard" to NESO's outputs when allocating support under the Hydrogen Production, Transport, Storage, and Power Business Models.

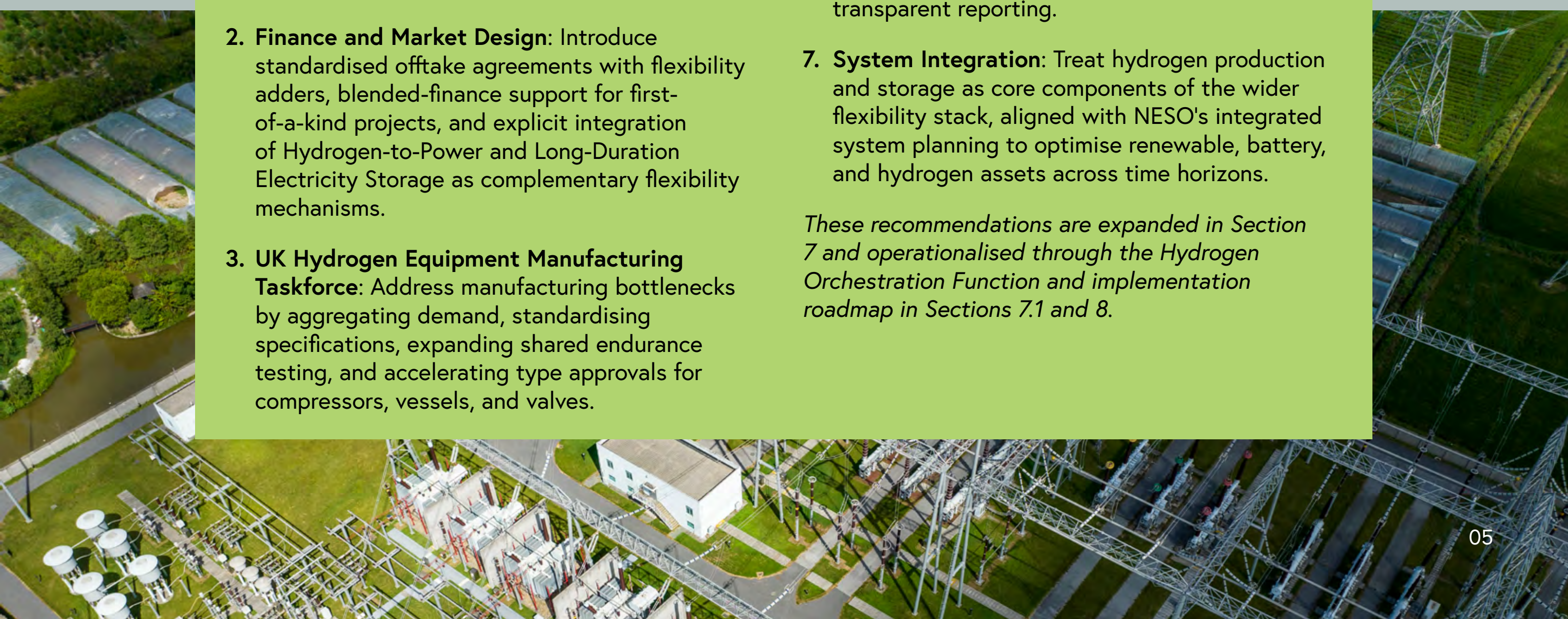
Three areas stand out. First, Hydrogen-to-Power is being established as a business model within the Clean Power Action Plan to unlock dispatchable, long-duration capacity. Second, the Hydrogen Delivery Council is advancing frameworks for early transport and storage markets, including potential licensing and legislative adjustments to enable the establishment of the first networks. Third, Hydrogen UK's Supply Chain Strategic Assessment highlights near-term 'quick wins' for domestic content—electrolyser stacks, power electronics, hydrogen network pipes, and compressed hydrogen storage tanks—alongside a voluntary 50% UK content target by 2030. Phase II identifies demand-side priorities, such as fuel cell stacks, electric motors, and hydrogen refuelling station buffer storage, with power converters and on-board storage requiring more concerted effort. Our recommendations are designed to reflect these signals while preserving the "safety-first" and "storage-first" approaches needed to convert ambition into delivery.

Key Recommendations

The UK can accelerate hydrogen deployment by sequencing the right enablers in the right order. Evidence shows that progress depends on advancing infrastructure, markets, skills, safety, and planning in parallel rather than in isolation. The following actions form a coherent delivery package:

1. **Regional Cluster Deals with Early Storage**: Build hydrogen clusters around early salt-cavern storage in the 2030s, while advancing feasibility for seasonal depleted-field storage at Rough and in the Irish Sea for the 2040s, aligned with CCC pathways and NESO planning milestones.
2. **Finance and Market Design**: Introduce standardised offtake agreements with flexibility adders, blended-finance support for first-of-a-kind projects, and explicit integration of Hydrogen-to-Power and Long-Duration Electricity Storage as complementary flexibility mechanisms.
3. **UK Hydrogen Equipment Manufacturing Taskforce**: Address manufacturing bottlenecks by aggregating demand, standardising specifications, expanding shared endurance testing, and accelerating type approvals for compressors, vessels, and valves.
4. **National Hydrogen Skills Academy**: Scale workforce capability through hydrogen-specific safety and materials-integrity training, combining simulation and rig-based learning delivered through regional clusters.
5. **Consenting Reform**: Reduce delivery risk by establishing a single-front-door consenting pathway with case managers, statutory milestones, and standardised documentation.
6. **Safety and Standards**: Codify hydrogen-specific risk-based inspection and embrittlement management, embedding these requirements in training, vendor quality assurance, and transparent reporting.
7. **System Integration**: Treat hydrogen production and storage as core components of the wider flexibility stack, aligned with NESO's integrated system planning to optimise renewable, battery, and hydrogen assets across time horizons.

These recommendations are expanded in Section 7 and operationalised through the Hydrogen Orchestration Function and implementation roadmap in Sections 7.1 and 8.



1. Introduction

The value proposition of hydrogen depends on the wider energy system. As the UK power sector decarbonises and electrification deepens, residual emissions concentrate in areas where electricity alone is ineffective. These include very high-temperature industrial heat, chemical processes that require molecular feedstocks, heavy transport with high energy density needs, and long-duration storage that exceeds practical battery capacities.

Hydrogen addresses these gaps by decoupling production from use and providing temporal and spatial balance. It can absorb surplus renewable electricity and deliver value back to the industry and transport when demand arises. International assessments caution against the idea of "hydrogen everywhere". Instead, they emphasise "hydrogen where it wins": applications where it delivers the highest emissions reduction per pound invested, while also enhancing system reliability and affordability.

The UK's trajectory combines strong fundamentals and coordination challenges. Strategic ambition and cluster initiatives are encouraging, but long-lead infrastructure, especially storage and shared distribution, must be planned with greater certainty and urgency to ensure their success. The manufacturing capacity of compressors, storage vessels, and hydrogen-ready valves strongly influences the cost, schedule, and reliability. Because hydrogen is inherently safety-critical, workforce competence and inspection regimes must be developed in parallel with new assets and not as an afterthought. This study argues for a whole-systems approach in which the right enablers are sequenced and co-funded in the right order. Taken together, this approach offers the best chance of achieving a deployment that is faster, safer, and more cost-effective.

2. Methodology

2.1 Systematic/Rapid Review

The PRISMA-informed (Preferred Reporting Items for Systematic reviews and Meta-Analyses) rapid review ,synthesised evidence from DESNZ strategy and update documents, international hydrogen assessments, HSE guidance, system operator concepts for a hydrogen backbone, and public cluster documentation. Searches combined terms for hydrogen, infrastructure, storage, clusters, electrolysers, skills, finance, and risk-based inspection, limited to the UK and comparable OECD countries.

Sources were included if they provided substantive insight around five lenses: (1) infrastructure sequencing (production–storage–offtake); (2) supply chain maturity, certification, and test capacity; (3) workforce capability and safety culture; (4) finance and market design; and (5) regulation and inspection frameworks. Grey literature (industry and consultation papers) was screened for transparency and relevance. The review prioritised breadth and triangulation over formal meta-analysis, given the assortment of sources.

2.2 Expert Interviews

Fifteen semi-structured interviews were conducted with developers, operators, OEMs and Tier-1s (electrolysers, compressors, vessels, valves and fittings), financiers, trade associations, and skills providers (Full list of roles available in Annex A). Sampling ensured diversity across the value chain and exposure to UK projects.

Interviews followed tailored guides, covered project critical paths, supply-chain bottlenecks, certification and testing, competency frameworks, consenting experience, and feasible policy instruments. Interviews were anonymised; transcripts and notes were coded inductively without personal identifiers.

2.3 Thematic Analysis and Triangulation

Coding of interview transcripts generated themes and sub-themes, including storage bottlenecks, MRL gaps, competency frameworks, RBI expectations, and flexibility valuation. Codes were iterated through constant comparison and aligned with evidence statements from the review. Seven cross-cutting themes emerged:

1. Production–offtake misalignment
2. Storage and distribution bottlenecks
3. Uneven manufacturing readiness and constrained certification capacity
4. Skills and safety culture gaps
5. Bankability and cost-down pathways
6. Regulatory complexity and consenting timelines
7. Under-specification of hydrogen's role in whole-system flexibility

Where interview perspectives diverged from literature, differences were retained and contextualised by sector, geography, or project maturity.

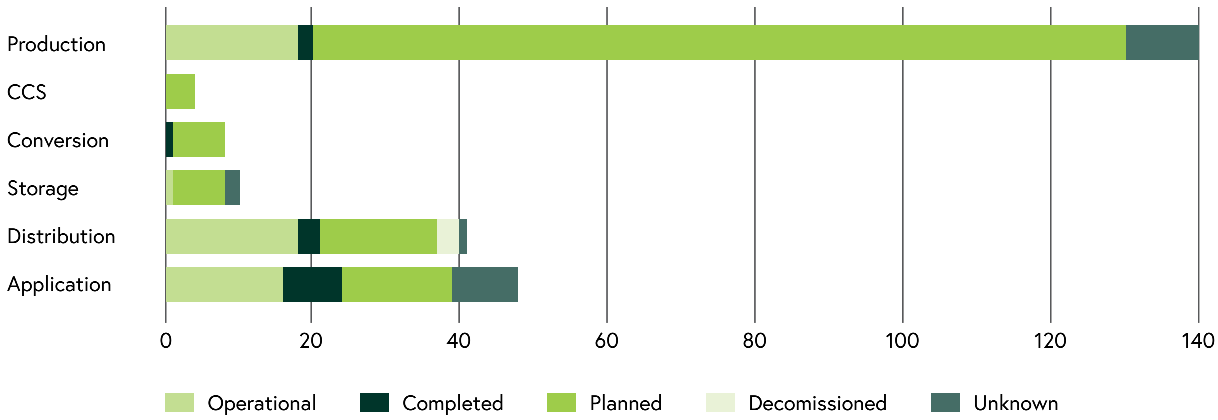
3. The UK Hydrogen Landscape

The UK's hydrogen development is centred on regional clusters such as the Northwest, Teesside, Humber, and parts of Scotland, where diversified industrial demand intersects with port access and established logistics. Policy has evolved from a technology-push phase to early market formation, marked by allocation rounds for electrolytic projects, progress on transport and storage business models, and integration with industrial decarbonisation frameworks.

Figure 1 shows the status and function of 252 hydrogen facilities identified in the UK pipeline. Production projects dominate, accounting for more than twice the number of storage, distribution, or end-use projects. However, most of these production facilities remain at the planning or proposal stage rather than in operation. This imbalance highlights the challenge of matching supply with infrastructure and demand, reinforcing the importance of coordinated cluster planning. Three realities shape the next phase:

1. Hydrogen is a systems play.
2. Long-lead infrastructure, especially storage, determines the pace of deployment.
3. Manufacturing depth and standards will set the cost, schedule, and resilience of projects.

Figure 1: Status and number of UK hydrogen projects by function (production, storage, distribution, use). Data compiled from 252 facilities.



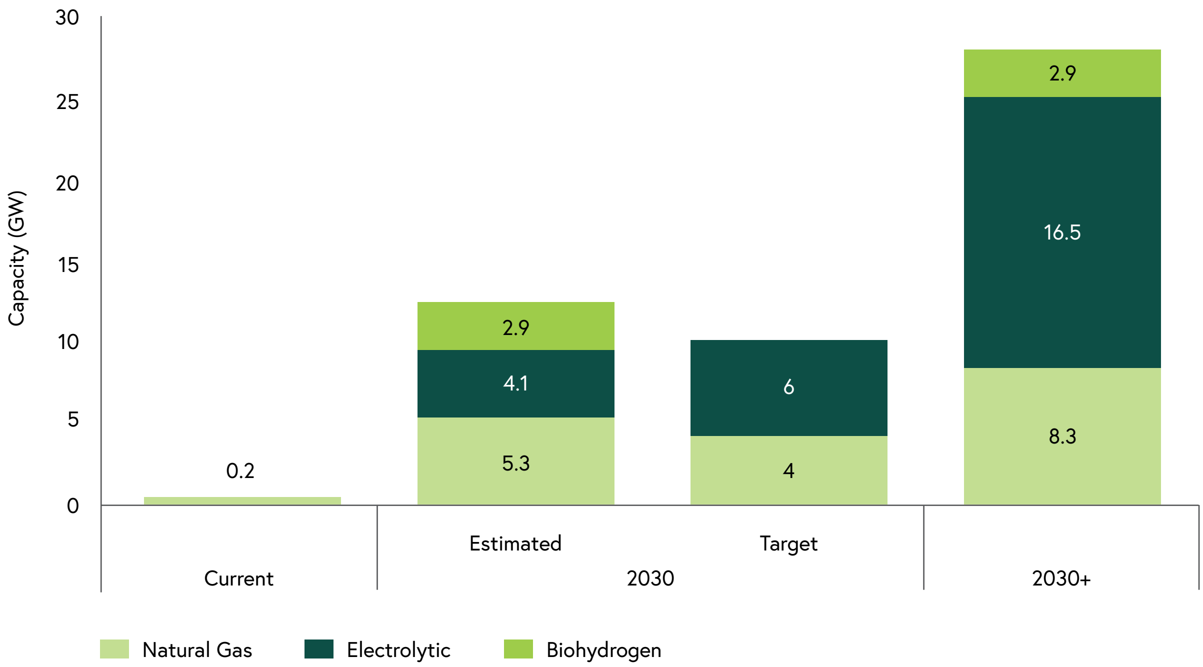
3.1 International Comparators and the Evolving UK Hydrogen Landscape

Peer economies emphasise the need for early commitment to storage and transport corridors to avoid stranded assets and to signal credible demand to manufacturers. Standardisation of specifications and fast-track type approvals has shortened lead times abroad, reducing reliance on bespoke engineering. Competency frameworks and inspection regimes are treated as primary enablers rather than secondary considerations, with early investment in training, test benches, and third-party certification capacity. These lessons map directly onto the UK's needs. The UK already has a pipeline of ~28 GW of hydrogen capacity with 14 GW targeted for 2030, suggesting that the 10 GW ambition is technically feasible (Figure 2). But delivery will depend on aligning storage and networks, deepening manufacturing capacity in compressors and vessels, and scaling workforce competence from ~1,600 jobs today to ~29,000 by 2030.

Recent government and industry updates in the Policy Pulse 2024–25 reinforce these imperatives. HAR1 contracts were awarded alongside a larger HAR2 pipeline; DESNZ confirmed timelines for the first transport and storage business-model rounds and will shortly decide on blending; consultation is underway on a Gas Shipper Obligation as a funding route for production; and the Hydrogen Delivery Council is exploring frameworks for early networks, covering commercial balancing, physical flows, and licensing adjustments. In parallel, flagship infrastructure initiatives such as Project Union (National Gas) and East Coast Hydrogen (ECH) are progressing from concept to delivery, backed by Ofgem and DESNZ funding. Together they form the foundation of the UK's future hydrogen backbone, linking major industrial clusters across Teesside, Humberside, and the East Midlands.

The Secretary of State's correspondence on H_2 Teesside (2025) confirms the Cowpen Bewley Arm as the credible interconnection point for Project Union, with implications for East Coast Hydrogen integration—demonstrating the emerging alignment between project-level consents and national hydrogen network planning. Hydrogen infrastructure has also been incorporated into the National Energy System Operator's (NESO) Strategic Spatial Energy Plan (SSEP, due 2026) and Comprehensive System Needs Plan (CSNP, 2027), ensuring that production, storage, and transport priorities will be assessed alongside electricity and gas system requirements. Together, these signals strengthen the case for storage-first sequencing and standardised offtake contracts with flexibility adders.

Figure 2: Current and future estimated production capacity.



3.2 Cluster Archetypes: Port vs Inland

While enablers are universal, their sequencing varies by geography and industry mix. Two archetypes illustrate how cluster strategies diverge.

3.2.1 Port-Centric Cluster (Storage-First)

Coastal ports such as Teesside and Humber anchor hydrogen ecosystems around refineries, chemical plants, and international terminals. Deployment typically begins with flexible electrolysers and trucking (tube-trailers), but scales rapidly into salt cavern storage and a medium-pressure pipeline spine linking port estates with chemicals parks.

- Storage advantage: Salt caverns in East Yorkshire (up to 1,465 TWh potential) and Cheshire (129 TWh) are proven and de-risked, providing the "missing middle" that balances supply and demand. Teesside has stored pure hydrogen since 1972.
- Consenting challenge: Overlapping port and planning authorities make case-managed pathways essential.
- System role: Storage enables electrolysers to dispatch against surplus renewables, supporting both industrial users and e-fuel pilots.
- Supply chain & skills: Local supplier development targets valves, fittings, and port-grade safety systems, while FE/HE partnerships train technicians for 24/7 operations.

3.2.2 Inland Industrial Cluster (Pipeline-First)

Inland basins anchored by ammonia, glass, and advanced manufacturing follow a different path. Without immediate access to geological storage, they rely initially on trucking and above-ground storage bullets, then move quickly to pipelines as anchor loads consolidate.

- Pipeline focus: Redundant compressor stations and generous storage bullets maintain supply security while awaiting geological options.
- Certification bottleneck: Early pinch points are inspection and type approval for pressure systems and composite vessels, with typical lead times of 24–36 months. Shared test benches and harmonised standards can cut this by up to a year.
- Workforces need: Hazardous-area operations and integrity engineers are scarce. A National Skills Academy would provide rig-based training for multi-skilled teams.
- Permitting reality: Planning and environmental consents often take 18–20 months (sometimes 3+ years). Consolidated evidence packs and early community engagement are required to accelerate delivery.
- Commercial model: Portfolio offtake across multiple plants stabilises revenues, with flexibility adders allowing dispatchable electrolysis without penalising users.

Ports and inland basins will anchor UK hydrogen deployment; however, their sequencing differs. Ports need early storage and streamlined port planning consents; inland clusters need pipeline development, certification capacity, and workforce investment. A national hydrogen strategy must flex to these archetypes while maintaining a storage-first and safety-first approach across the system.

4. Findings (Integrated Synthesis)

4.1 Infrastructure: Storage, Networks, and Cluster Sequencing

> *"It's a chicken and egg situation where manufacturers and hydrogen producers are ready to shift to hydrogen but face that the infrastructure in the middle is notin place."*
>
> **Professor of Energy Research**

Storage is the missing middle. Without buffer capacity, temporal mismatches between variable renewable electricity and industrial demand become unbankable. Early phases can rely on local distribution, but cluster-scale deployment requires a shared pipeline or designated corridors. Backbone concepts for repurposing transmission assets are promising, but their feasibility and sequencing now benefit from recent whole-system modelling under the Project Union programme, which suggests that repurposing approximately 25 percent of the National Transmission System (NTS) for hydrogen is technically plausible in most corridors. The Grangemouth–Teesside section is identified as a potential bottleneck requiring targeted reinforcement. Treating storage as a first-order asset and co-scheduling it with production and offtake from the outset is essential for achieving economic viability. Storage enables three complementary benefits: an increase in electrolyser utilisation, industrial reliability decoupled from power volatility, and market liquidity across multiple offtakers over time.

> *"We're going to have local hydrogen clusters, and we're already starting to see them, where producers and users congregate in a relatively small geographical area to make the transportation a lot easier."*
>
> **CEO of Green Hydrogen Technology Company**

This reflects the near-term reality: until a backbone network is operational, clusters will form as practical interim solutions. NESO's new Strategic Spatial Energy Plan (SSEP, 2026) and Comprehensive System Needs Plan (CSNP, 2027) will explicitly integrate hydrogen production, storage, and transport into national and regional energy mapping. DESNZ has confirmed that it will have "due regard" to NESO outputs when allocating support under the Hydrogen Production, Transport, Storage, and Power Business Models, aligning infrastructure roll-out with system planning milestones.

Empirical analysis supports this perspective. Compression to 700 bar consumes ~3 kWh per kg and liquefaction ~11 kWh per kg, while new salt caverns could add up to 1,465 TWh (East Yorkshire), 129 TWh (Cheshire), and 557 TWh (Wessex) of potential capacity, in addition to ~4.8 TWh from repurposed gas caverns. Teesside has already demonstrated hydrogen storage since 1972, underscoring its feasibility. Therefore, siting analysis should co-optimise storage with industrial anchors and renewable profiles to minimise curtailment and transport distances.

What we mean by "balancing storage" in Great Britain

Salt caverns deliver high withdrawal and injection rates (fast response) but smaller absolute volumes; across sites, modelled withdrawal capacity is approximately 1,800 GWh/day for around seven days in the Centrica/FTI whole-system analysis. Rough (depleted field) is modelled as seasonal storage with a very large total capacity of ~12.1 TWh H_2 and ~150 GWh/day withdrawal for ~80 days, supporting prolonged low-renewables periods.

System role: Caverns manage intra-week variability and refill in shoulder seasons, while Rough supports winter and multi-week stress events. This aligns with the Climate Change Committee's Balanced Pathway, which assumes ~3 TWh hydrogen storage in 2040 (primarily caverns) and potential to triple by 2050 as hydrogen-to-power grows.

Named strategic storage locations:

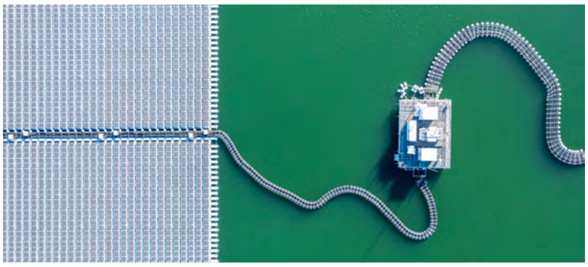
- Rough (North Sea): treated in recent modelling as the UK's key seasonal hydrogen store from ~2040, complementing fast-cycling salt caverns.
- Irish Sea: large-scale subsurface storage potential (depleted gas fields) is re-emerging through redevelopment proposals such as DcarbonX/Snam's 2025 project off Barrow-in-Furness, signalling future dual-use opportunities subject to materials, safety, and regulatory assessment.

Taken together, these data support a sequencing pathway in which fast-response cavern storage is prioritised through the 2030s, while large depleted-field options such as Rough and Irish Sea develop toward 2040 to provide long-duration balancing capacity for hydrogen-to-power integration.

4.2 Supply Chains: Manufacturing Readiness, Testing, and Certification

> *"It would be unrealistic for the UK to be the leading player in every segment. The question is where we place our bets. Those bets need to be built around current capabilities and the global competitiveness of our industrial parts sector."*
>
> **Professor of Sustainable Energy Development**

Electrolysers are approaching commercial maturity, but other critical components — compressors, storage vessels, hydrogen-grade valves/fittings, and power electronics — remain constrained by low Manufacturing Readiness Levels (MRLs) and limited certification capacity. The lead times for compressors and pressure vessels average 24 – 36 months, reflecting shortages in endurance testing, material qualification, and type-approval pathways. A consolidated TRL/MRL snapshot of the core components is provided in Annex B. These weaknesses directly slow down project deployment and increase investor risk.



> *"For short-term demand, it's good enough. For the longer-term, I think we need a really clear mapping exercise."*
>
> **Vice-President, Sustainable Technology Team at a Consulting Company**

This highlights the dual reality: the UK can manage immediate needs, but scaling requires a strategic roadmap for certification, testing, and supplier development.

To address these gaps, a UK Hydrogen Equipment Manufacturing Taskforce should be established to:

- Aggregate demand so that suppliers can justify scaling up.
- Standardise specifications to reduce bespoke engineering requirements.
- Co-fund shared test benches for compressors, vessels and electronics to accelerate qualification.
- Coordinate with standard bodies to fast-track hydrogen-ready approvals.
- Support supplier development so that SMEs can meet hydrogen quality assurance requirements.

Rather than acting as another strategy forum, the taskforce should operate as a delivery mechanism, translating supply chain needs into short, measurable programs of work. The initial priorities include commissioning shared endurance test benches, fast-tracking hydrogen-ready standards, and embedding readiness assessments into major project approvalsAnnex C consolidates Hydrogen UK's 2024–25 supply- and demand-side priorities into 12-month Taskforce sprints with clear KPIs. This shows how early actions in equipment (e.g. compressors, tanks, pipes, and power electronics) can be matched with cluster-relevant demand anchors (e.g. fuel cell stacks, motors, and refuelling systems), ensuring that manufacturing capability grows in step with deployment.

4.3 Workforce and Skills: Capacity, Competence, and Safety Culture

"So as with most engineering, there's a generic set of skills… probably 60 to 70% are standard skill sets across the industry. When you get to something specifically hydrogen, then you're looking for knowledge of the chemistry of hydrogen, its behaviour and how it reacts."

Chief Engineer in Civil Nuclear & VP, Sustainable Technology Consulting

The hydrogen workforce builds on traditional engineering capabilities but requires hydrogen-specific expertise in chemistry, safety and materials.

Approximately 60–70% of skills are transferable from oil and gas, while 30–40% represent a new knowledge base that must be developed through targeted training. The current workforce numbers ~1,600, with projected demand rising to ~29,000 by 2030, an 18-fold increase.

Acute shortages are visible in electrolyser engineering, balance-of-plant design, hazardous-area operations, and inspection/maintenance. Safety awareness, in particular, was repeatedly flagged.

"I would talk about safety awareness or skills as a critical gap more than anything else, and of course that then translates into materials knowledge and so on in that context. I mean, that's both at the design end and at the operator end."

Professor of Sustainable Energy Development

Recruitment also faces perception challenges, with the sector struggling to compete for talent.

"I think there's a lot of negativity around hydrogen, so therefore attracting new skills into the sector at the moment I think is challenging."

Chief Technologist in Nuclear Hydrogen

Training infrastructure is fragmented and lacks practical, hands-on pathways.

"There is certainly a shortage of practical focus courses on how to build a hydrogen plant."

CEO of a Green Hydrogen Technology Company

To address these gaps, a National Hydrogen Skills Academy should provide modular curricula aligned to job families, embed hydrogen safety and materials integrity, use simulation and rig-based learning, and offer stackable micro-credentials mapped to professional recognition requirements. Regional delivery through cluster employers would allow a rapid scale-up where projects are located.

Annex D provides an illustrative skill availability heatmap, colour-coded to show areas of adequate availability (green), emerging demand (yellow), and critical shortage (red) across production, storage, infrastructure, end-use applications and cross-cutting skills. It highlights where workforce gaps are most acute — particularly in hydrogen-specific technical expertise, inspection engineers, and safety management — reinforcing the case for a Skills Academy and harmonised competency frameworks.

4.4 Finance and Market Design: Bankability and Flexibility

> *"The single most important thing at the moment in the UK is the hydrogen business model. That is the thing that underpins the price of hydrogen sold from new projects and therefore underpins the financing of those new projects."*
>
> **Chief Technologist in Nuclear Hydrogen**

Bankability hinges on standardised offtake agreements with clear tenor, indexation, and balancing rules. Annex E sets out the key terms of an illustrative hydrogen offtake template covering commercial, operational, and risk-allocation provisions. A standardised approach would lower transaction costs, improve credit quality, and reduce first-mover risk.

In parallel, the Department for Energy Security and Net Zero (DESNZ) has confirmed two complementary mechanisms designed to strengthen market confidence and support bankability across the hydrogen value chain. First, a dedicated Hydrogen-to-Power (H_2P) business model will provide revenue certainty for dispatchable hydrogen generation, enabling low-carbon clean-firm capacity to complement intermittent renewables. Second, the Long-Duration Electricity Storage (LDES) scheme will operate on a cap-and-floor basis, incentivising investment in multi-day to seasonal storage assets that stabilise wholesale prices and support flexible hydrogen use. Together, these mechanisms close a critical gap between production-side and demand-side incentives, creating a full suite of bankable pathways under the Hydrogen Production, Transport, Storage and Power Business Models (HPBM, HTBM, HSBM and H_2PBM).

How the Hydrogen Business Models Fit Together

The UK's emerging hydrogen investment framework comprises four complementary business models that collectively create a whole-system pathway from production to end-use.

Model	Purpose	Contract Form	Example Levers
HPBM	Supports low-carbon hydrogen generation through revenue stabilisation.	CfD-style	Fixed strike price per MWh H_2 produced.
HTBM	Enables financing of dedicated or repurposed pipelines for hydrogen carriage.	RAB-style	Allowed revenue set by regulator; addresses WACC and utilisation risk.
HSBM	Underwrites investment in large-scale storage, including salt caverns and depleted fields.	Availability payment + cap-and-floor	Mitigates seasonal volatility and counterparty risk.
H_2PBM	Secures dispatchable capacity from hydrogen-fuelled generation for system balancing.	Cap-and-floor or CfD variant	Complements LDES and provides clean-firm capacity.

Together, these four mechanisms define the UK's hydrogen investment architecture — linking production, transport, storage, and power into a single, bankable ecosystem. Their alignment is crucial to ensure that capital flows where the system most needs flexibility.

While this architecture provides the policy foundation for investment, market traction still depends on clear offtake certainty, visible demand signals, and investor confidence in the revenue stack.

> *"There's a lot of policy support for production and companies are enthusiastic to produce hydrogen. But they're not getting the offtake. The supply chain is weak on the demand side."*
>
> **Professor in Hydrogen Systems Engineering**

Early plants must also be rewarded for grid-friendly flexibility rather than being penalised for non-flat output profiles. First-of-a-kind projects require blended finance and risk-sharing until learning effects and supply-chain maturity drive costs down. Portfolio offtake models with multiple buyers across applications can smooth demand risk and improve financing terms. These early market frameworks — especially H_2P and LDES — are expected to complement flexibility remuneration, ensuring that plants operating with variable profiles can access predictable revenue streams while providing balancing services to the grid.

Despite these emerging mechanisms, private investment remains hesitant — confidence in hydrogen markets is still limited by uncertain demand, volatile pricing, and unfamiliar risk structures.

> *"Investors at the moment are a number of years away from being willing to make investments that are fully exposed to market risk… The market is not yet mature enough such that investors would make an investment on the basis that the typical selling price for hydrogen is X and a new project could sell the hydrogen for X and be profitable at that price point."*
>
> **Chief Technologist in Nuclear Hydrogen**

The costs further limit adoption. Domestic energy prices remain high compared to peers, and hydrogen faces structural disadvantages relative to subsidised fossil fuels.

> *"Oil and gas industry are highly subsidised, but hydrogen is not. The government needs to step in to subsidise these things until the supply chain and everything are established."*
>
> **Professor and Head of Hydrogen Research**

Pricing variability adds to uncertainty.

> *"Geographical factors dictate the market pricing of hydrogen. For green hydrogen, quotes reach £30 per kilogram for bulk, and up to £190 per kilogram for small volume for research purposes."*
>
> **CEO of a Green Hydrogen Technology Company**

Funding analysis shows 236 UK hydrogen projects with £19.9 billion disclosed, although 65% do not publish funding details. Public support follows a U-shaped distribution, with strong coverage for small pilots (<£5m) and mega-projects (>£500m), but is weaker in the mid-range. The UK Government remains the largest backer, supporting over 160 projects with a £2 billion commitment. SMEs, in particular, report difficulty in navigating fragmented and complex mechanisms.

> *"The funding that is available is sort of compartmentalised… The funding that's allocated for research won't pay for the creation of a plant, and the funding for industrial growth won't pay for technical research."*
>
> **Chief Engineer in Civil Nuclear**

Lessons from electricity markets suggest that contract structures can play a decisive role in unlocking private finance. CfDs, widely used for renewable power, offer one model for long-term revenue certainty. While hydrogen business models now fulfil this role more directly, the CfD experience remains instructive — demonstrating how predictable, transparent contracting cycles can attract investors and strengthen supply-chain confidence.

> *"I would be more inclined to do the CfD, which is in the electricity industry. CfD works in a continual cycle and will be encouraging people to establish hydrogen in certain places around the country to strengthen the supply network."*
>
> **Professor in Energy Research**

Collectively, these evolving financial and regulatory instruments mark a decisive shift toward a mature hydrogen market. Sustaining investor confidence will depend on timely delivery, transparent pricing, and continued alignment between DESNZ's business models and NESO's system-planning framework.

4.5 Regulation, Safety, and Standards: Clarity and Speed

> *"Many strategies have gone wrong by focusing only on one part of the problem. This is an integrated supply chain so you have to create a means of producing hydrogen, distributing it, storing it, and then having an off-take market that can use it."*
>
> **Professor of Sustainable Energy Development**

Fragmented guidance across planning, environmental permitting, and safety regimes introduces delay and uncertainty. Permitting timelines currently average 18 to 20 months, with complex cases extending beyond 3 years, driven largely by overlaps between TCPA, DCO, COMAH, DSEAR, and environmental regimes.

Interviewees also highlighted departmental fragmentation between DESNZ and DfT that blurs accountability for hydrogen in transport.

> *"I would create a government advisory service which is able to support organisations that want to transition to hydrogen. It would be a sort of centralised best practice advisory."*
>
> **Professor in Hydrogen Systems Engineering**

Industry stakeholders consistently point to the need for clearer guidance and better-resourced certification processes. Underwriters also seek codified RBI expectations and embrittlement management to price risk more competitively. A mapping of these regimes is provided in Annex F. This illustrates the multiple approval layers hydrogen projects face and reinforces the case for a single-front-door approach. A streamlined process with case managers, time-bound milestones, and hydrogen-specific RBI (materials selection, inspection intervals, monitoring, and reporting) would reduce cycle times, increase investor confidence, and strengthen the UK's reputation for safe, world-class hydrogen delivery. These proposals align with recent policy measures that begin to formalise the regulatory and planning architecture for hydrogen infrastructure.

Latest policy developments have begun to address these structural bottlenecks. The Department for Energy Security and Net Zero's Hydrogen Economic Regulatory Framework (July 2025) establishes key positions on the future governance of hydrogen transport and storage networks. It introduces a Regulated Asset Base (RAB)-style Hydrogen Transport Business Model (HTBM) for large-scale pipelines, alongside a new hydrogen network code that sets out technical standards, operational roles, and market-balancing principles. Under the Minded to approach, early hydrogen networks will use primary balancing by producers, with transporter-led system operation and transparent cost-recovery mechanisms. These measures are designed to reduce investor risk by lowering the weighted average cost of capital (WACC) for infrastructure projects and clarifying responsibilities as networks scale from regional clusters to national interconnection during the 2030s.

In parallel, hydrogen infrastructure has now been formally integrated into the National Energy System Operator's (NESO) strategic planning remit. NESO's Strategic Spatial Energy Plan (SSEP), now due in Autumn 2027, together with the Centralised Strategic Network Plan (CSNP) and the first full Regional Energy Strategic Plans (RESPs), now planned for the end of 2028, will collectively identify spatial priorities for hydrogen production, transport and storage. In the interim, transitional Regional Energy Strategic Plans (tRESPs) are being developed to inform nearer-term network investment and regional coordination. DESNZ has confirmed that it intends to have "due regard" to these planning outputs when designing and allocating funding under the Hydrogen Production, Transport, Storage and Power Business Models, helping to align system planning with investment delivery. This coordination remains an important step toward the more coherent, single front-door approach advocated by industry stakeholders and is consistent with the streamlined consenting pathway recommended in this paper.

4.6 Digital, Data and AI Enablers

Digital and data capabilities are cross-cutting enablers that accelerate hydrogen deployment by reducing costs, enhancing safety, and building investor confidence.

At the project level, configuration control and traceability of critical components (compressors, vessels, valves, seals) ensure integrity across supply chains. Condition monitoring combined with predictive maintenance extends asset life and minimises unplanned downtime. Digital twins of storage caverns, compression systems, and pipelines allow operators to model transients, optimise inspection schedules, and test contingency scenarios before they occur.

At the cluster level, secure data-sharing frameworks can improve reliability, resilience, and coordinated response while protecting commercially sensitive information. Shared datasets strengthen the evidence base for consenting, assurance, and investment decisions.

As datasets expand, AI-enabled anomaly detection and inspection planning can materially reduce downtime and improve assurance, provided they are embedded within robust governance frameworks. AI can also support optimisation of electrolyser dispatch against power price signals, cluster-wide balancing, and early detection of integrity risks. Policy can support adoption by:

- Mandating interoperability standards for digital monitoring and inspection systems.
- Funding shared digital testbeds and secure data platforms at the cluster level.
- Embedding digital assurance requirements into business-model support and consenting guidance.
- Developing AI governance frameworks that balance innovation with safety and public trust.

Together, these measures ensure that digital, data, and AI tools act as force multipliers for safe, efficient, and cost-effective scale-up.

4.7 Costs, Learning Rates and What Policy Can Influence

Hydrogen costs are shaped mainly by electricity prices and availability, capital costs (electrolysers, compression, storage), utilisation levels, financing, and operations and maintenance (e.g. stack replacements). Early projects face "first-of-a-kind" premiums due to bespoke engineering, certification requirements, and immature supply chains.

UK analysis confirms that both blue and green hydrogen remain materially more expensive than fossil gas on an energy basis, but blue hydrogen is currently cheaper than green in most central scenarios. DESNZ's Hydrogen Production Costs 2021 report shows that for plants commissioning around 2030, CCUS-enabled methane reformation (blue hydrogen) usually costs between 60–90 £/MWh H_2, equivalent to about 2.0–3.0 £/kg. Electrolysis options generally range from approximately 90–200 £/MWh H_2, or about 3–6.5 £/kg, depending on electricity price and load assumptions. A representative UKCS case study for blue hydrogen reports a levelised cost of 2.83 £/kg, including offshore CO_2 transport and storage at 20 £/tco$_2$. The Royal Society's green hydrogen roadmap indicates current green hydrogen costs fall within a similar 2–5 £/kg range and confirms they are higher than blue hydrogen today but are expected to decrease as renewable electricity and electrolysers develop. The Climate Change Committee states that hydrogen supply costs are likely to remain above fossil gas costs before carbon pricing, through to 2050, meaning adoption will depend on policy support and targeted incentives rather than fuel-price parity alone.

These estimates carry wide uncertainty bands. Sensitivity analysis in Hydrogen Production Costs 2021 shows that levelised costs are highly sensitive to retail versus wholesale fuel prices, carbon prices, load factors, hurdle rates, and technology performance parameters. In addition, blue hydrogen costs are exposed to gas price volatility and CO_2 transport and storage fees, while green hydrogen costs are dominated by electricity prices and achievable utilisation of electrolysers. Most comparative assessments for the UK and Scotland, therefore, conclude that blue hydrogen is likely to remain lower cost than green through the 2020s and early 2030s, with green becoming competitive or cheaper later as renewables and electrolyser supply chains mature. For policy design, the implication is clear: both routes are needed to substitute gas in priority sectors, and support should focus on system value where hydrogen wins rather than on a single least-cost technology.

Costs fall as learning takes hold. Key drivers include manufacturing scale and yield, repeatable modular designs, shared test benches and faster approvals, competency-based training, remuneration for flexibility that raises utilisation, and portfolio offtake that improves credit quality.

Policy can directly accelerate these learning effects. Priority levers include:

- Standardised offtake contracts with flexibility adders
- Co-funding of storage and transport in cluster deals
- A Manufacturing Taskforce for standardisation and shared testing
- A National Skills Academy for hydrogen safety and technical training
- Single-front-door consenting with dedicated case managers

Support should avoid over-prescribing end-uses where electrification is already more efficient, and avoid bespoke one-off projects that fragment the market. Funding should be conditional on credible systems plans (including storage and distribution) and demonstrable learning capture through pre-qualification, repeatable designs, and robust inspection regimes. Electrolysers should be allowed to respond to power price signals, with better coordination between clean-power and clean-hydrogen instruments to reduce transaction costs.

In light of the latest council and industry signals, alignment with the Hydrogen Delivery Council (HDC) and Hydrogen UK (HUK) priorities for 2024–25 can be achieved through three moves that strengthen delivery while keeping the focus on "where hydrogen wins":

1. Position Hydrogen-to-Power (H2P) as a complementary route to monetise storage and flexibility, ensuring offtake adders are compatible with emerging H2P products.
2. Align the Manufacturing Taskforce's first 12-month sprints with HUK priorities (electrolyser stacks, power electronics, network pipes, compressed storage tanks), while preparing demand-side quick wins (fuel-cell stacks, motors, HRS buffer storage).
3. Anticipate early-network market-framework outcomes (including licensing and legislative adjustments), and position the single-front-door pathway and hydrogen-specific RBI as the safety and assurance counterpart to market design.

5. Risk Assessment

Hydrogen deployment carries risks that can delay projects, raise costs, or undermine public confidence. A structured risk assessment highlights where policy intervention is most critical and where industry actions are essential. Five categories dominate the landscape:

Technical and Materials Integrity: Hydrogen can cause embrittlement, permeation, seal degradation, and hydrogen-assisted cracking in metals and elastomers. Without careful material selection and validated seals, these issues increase maintenance costs and raise safety concerns. Policy support is needed for shared endurance testing and hydrogen-specific risk-based inspection (RBI) standards, while the industry must ensure conservative materials choices, supplier qualification, and robust inspection regimes.

Delivery and Cost Overruns: Projects face long lead times and escalating costs when designs are bespoke, certifications are delayed, or specifications change late. These factors have already driven overruns in pilot projects. Policy can reduce risk through standardised specifications, demand aggregation, and case-managed type approvals, while industry can tighten project controls, use framework agreements, and stage investment decisions to gate risk.

Market and Offtake Risk: Early hydrogen projects often lack stable demand. Volumes and prices are uncertain, and exposure to a single buyer can jeopardise financeability. Government can reduce this risk by publishing template offtake contracts, supporting portfolio offtake, and sharing risk through blended finance. Industry can diversify offtakers across applications to stabilise revenues.

Planning and Consenting: The current system involves multiple agencies with overlapping requirements. Typical permitting times are 18–20 months, extending to more than three years for complex cases. This undermines investor confidence and delays deployment. Policy intervention is required to create a single front-door process with statutory milestones and a shared evidence base. Industry can mitigate by engaging early with case managers and preparing complete, consistent submissions.

Safety and Social Licence: Hydrogen's public acceptance is fragile. Incidents or near misses can quickly undermine trust and delay projects. Policy must codify transparent reporting, independent assurance, and visible safety KPIs while ensuring that community benefits are delivered. Industry has to build a strong safety culture, embed hydrogen competence training, and openly share learning from near misses.

A comprehensive risk register is included in Annex G, but the implications are evident. Policy holds the most influence on delivery and consenting risks, where standardised specifications, aggregated demand, streamlined type approvals, and single-front-door processes can reduce delays and costs. Industry must lead on technical integrity and safety culture through materials qualification, supplier standards, and competence enhancement. Market risks, by contrast, require collaborative action: template offtake contracts, portfolio agreements, and public–private risk-sharing will be essential to build confidence in early projects.

An additional systemic risk relates to hydrogen storage availability. Large-scale storage—particularly in depleted fields such as Rough and the Irish Sea—is unlikely to be fully available before the 2040s. This temporal constraint underscores the need to prioritise fast-response cavern development during the 2030s while sequencing long-duration storage for later decades. Early policy visibility on this sequencing will be essential to avoid supply bottlenecks and stranded production capacity.

6. Opportunities and Industrial Strategy

The UK is well-positioned to turn hydrogen deployment into a source of competitive advantage. Existing strengths in engineering, certification, and safety can compound into exportable capabilities, particularly in areas where global demand is growing. Compressor modules engineered for hydrogen duty, hydrogen-grade valves and fittings with validated lifetimes, advanced materials, and integrity monitoring, as well as quality assurance services, are all niches where UK firms already have strong foundations.

Ports and industrial estates offer natural locations for multi-vector hydrogen hubs, where production, storage, and industrial use can be co-located to minimise costs and improve reliability. Over time, inter-cluster connections can create resilience and unlock economies of scale. Integration with renewables and storage further reduces curtailment, improves system efficiency, and positions hydrogen as a critical flexibility asset.

Realising these opportunities requires turning strategic advantages into concrete actions. The next section sets out a package of policy recommendations designed to build on the UK's industrial strengths, address current bottlenecks, and align investment, regulation, and skills development around a coherent national hydrogen strategy.

Industry Spotlight:
Kimberly-Clark's Hybrid Hydrogen Transition

Kimberly-Clark UK & Ireland is among the first major UK consumer goods firms to use green hydrogen at scale, investing £125 million in hydrogen infrastructure at Barrow and Northfleet to partly replace natural gas in steam and heat production. Installing dual-fuel boilers enables a gradual switch to hydrogen, with gas as backup. Ameresco will design five units, targeting operation by 2027. The measures should halve natural gas use and lower CO_2 emissions by 28,500 tonnes a year, making Kimberly-Clark a model for phased, risk-mitigated hydrogen adoption in high-heat industries.

7. Policy Recommendations

The UK can accelerate hydrogen deployment by sequencing the right enablers in the right order. The following recommendations form a coherent package across infrastructure, supply chains, skills, finance, regulation, safety, and orchestration (Figure 3).

Regional Cluster Deals with Early Storage: Hydrogen clusters must be built around storage. Co-funding and co-scheduling geological and above-ground storage with production and offtake will provide the "missing middle" that synchronises supply and demand. Each cluster deal should include a systems plan for siting, sizing, and interfaces, coordinated early with backbone corridors. Cluster sequencing should also distinguish between fast-response salt-cavern storage and seasonal depleted-field storage, consistent with the CCC's Balanced Pathway and NESO's planning milestones (SSEP 2026 → CSNP 2027 → RESPs 2027). Prioritising cavern deployment through the 2030s while advancing feasibility work on Rough and Irish Sea storage for the 2040s will ensure balanced system adequacy and long-term resilience.

Finance and Market Design: Investment confidence depends on a clear and fair market design. Standardised offtake agreements with optional flexibility adders, blended-finance windows for first-of-a-kind projects, and portfolio offtake models should be introduced. Support should adapt as costs fall and learning rates improve. Early momentum would also benefit from a visible flagship demonstrator acting as an anchor offtaker — a high-profile user whose adoption showcases hydrogen's practicality, builds investor confidence, and stimulates wider market participation. This pillar should explicitly integrate the Hydrogen-to-Power (H_2P) and Long-Duration Electricity Storage (LDES) mechanisms recently confirmed by DESNZ, positioning them as complementary policy levers that remunerate flexibility and anchor dispatchable capacity within the clean-power stack.

UK Hydrogen Equipment Manufacturing Taskforce: Hydrogen-ready manufacturing in compressors, vessels, and valves/fittings remains underdeveloped. A dedicated taskforce should aggregate demand, standardise specifications, co-fund shared test benches, accelerate type approvals, and support supplier development to lift manufacturing readiness levels and shorten lead times.

National Hydrogen Skills Academy: Hydrogen is safety-critical, and workforce competence must expand in step with infrastructure. A Skills Academy should provide modular, job-family curricula embedding hydrogen safety and materials integrity. Training should combine simulation and rig-based learning with stackable micro-credentials, delivered regionally through cluster employers.

Consenting Reform: Delays from fragmented permitting reduce investor confidence. A single-front-door process with case managers, statutory milestones, and standardised documentation should replace today's fragmented landscape. Early multi-agency scoping for complex sites will save months of delay.

Safety and Standards: The UK should codify hydrogen-specific risk-based inspection and embrittlement management, aligning with international standards. Embedding these in workforce training, vendor quality assurance, and open reporting will strengthen trust and exportability of UK expertise.

System Integration: Hydrogen production and storage must be recognised as part of the wider flexibility stack alongside renewables, batteries, and demand response. Planning and market frameworks should treat hydrogen as a core flexibility resource, reducing curtailment and improving security of supply. Policy alignment between H_2P, LDES, and NESO's integrated system-planning outputs will be essential to optimise renewable, battery, and hydrogen assets across multiple time horizons.

7.1 Hydrogen Orchestration Function (HOF)

Hydrogen projects require coordination to form a coherent system rather than a patchwork of isolated assets. A **Hydrogen Orchestration Function (HOF)** should act as a light, time-bounded overlay within existing DESNZ, NESO, and industry governance, with readiness-gate authority tied to business models such as the Low-Carbon Hydrogen Agreement (LCHA), Transport and Storage (T&S), and Hydrogen-to-Power (H_2P).

Its role is to ensure that storage, certification, skills, and safety are in place before projects move forward, while also providing a single escalation pathway for critical interface issues. A secondary role is knowledge capture: the systematic collection and dissemination of best practices from early hydrogen projects. Lessons on permitting, safety management, certification, and delivery should be codified and shared across clusters so that later projects can scale faster without repeating the same challenges.

Early priorities of the HOF should focus on four enablers that unlock progress across clusters:

Storage-first sequencing: synchronising salt-cavern investment decisions with Hydrogen Allocation Round (HAR) timing and ensuring alignment with NESO spatial plans and DESNZ due-regard commitments.

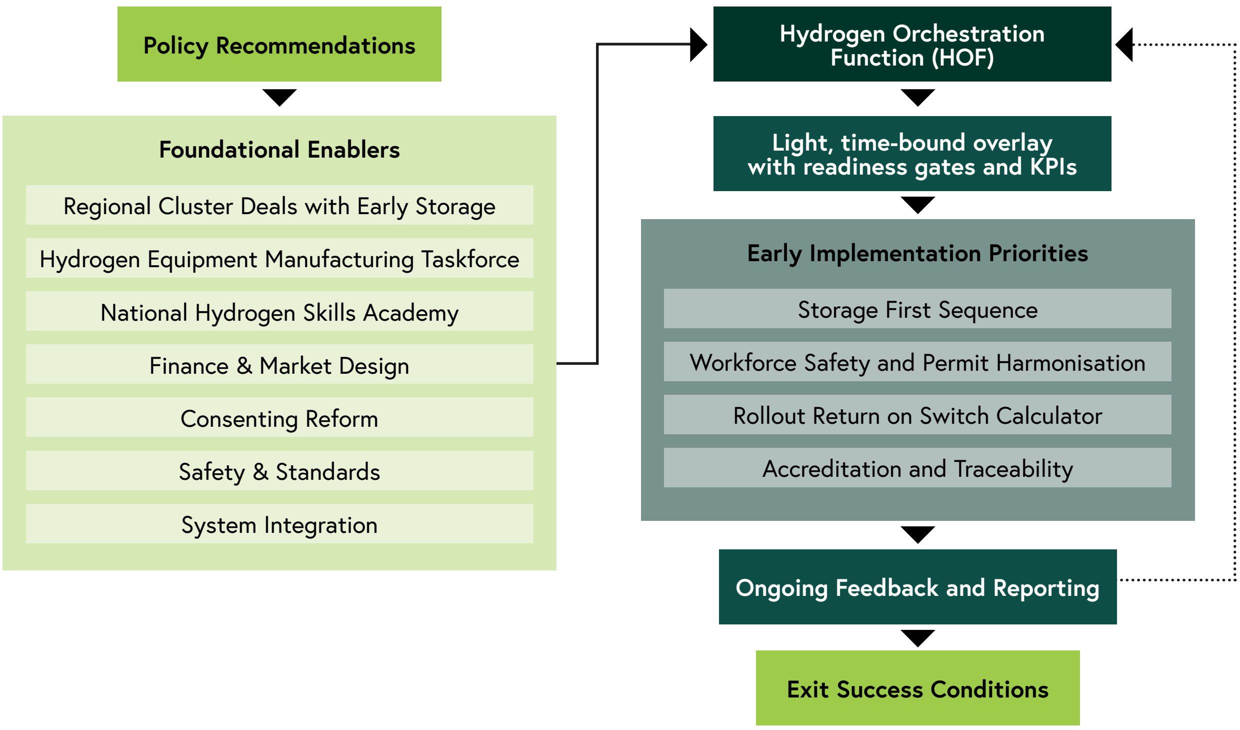
Accreditation and traceability: establishing pragmatic supplier pathways aligned to BS/PAS standards for hydrogen-ready industrial boilers and electrical/instrumentation systems.

Return-on-Switch (RoS) calculator: providing offtakers with a simple tool to integrate LCHA price signals with electricity relief for energy-intensive industries (EII). The methodology and cost-down scenarios are detailed in Annex H, which links project-level economics (RoS) to system-level progress (HOF Scoreboard).

Workforce safety: harmonising permit-to-work procedures across hydrogen sites, drawing on MSc safety-culture templates and international best practices.

The HOF should be wound down once Hydrogen-to-Power, Transport and Storage, and Allocation Rounds are consistently meeting utilisation targets, and three consecutive rounds demonstrate measurable cost-down improvements. At that point, orchestration will have achieved its purpose, and ongoing governance can revert to existing DESNZ-NESO structures.

Figure 3: Framework linking policy recommendations, foundational enablers, and the Hydrogen Orchestration Function (HOF).



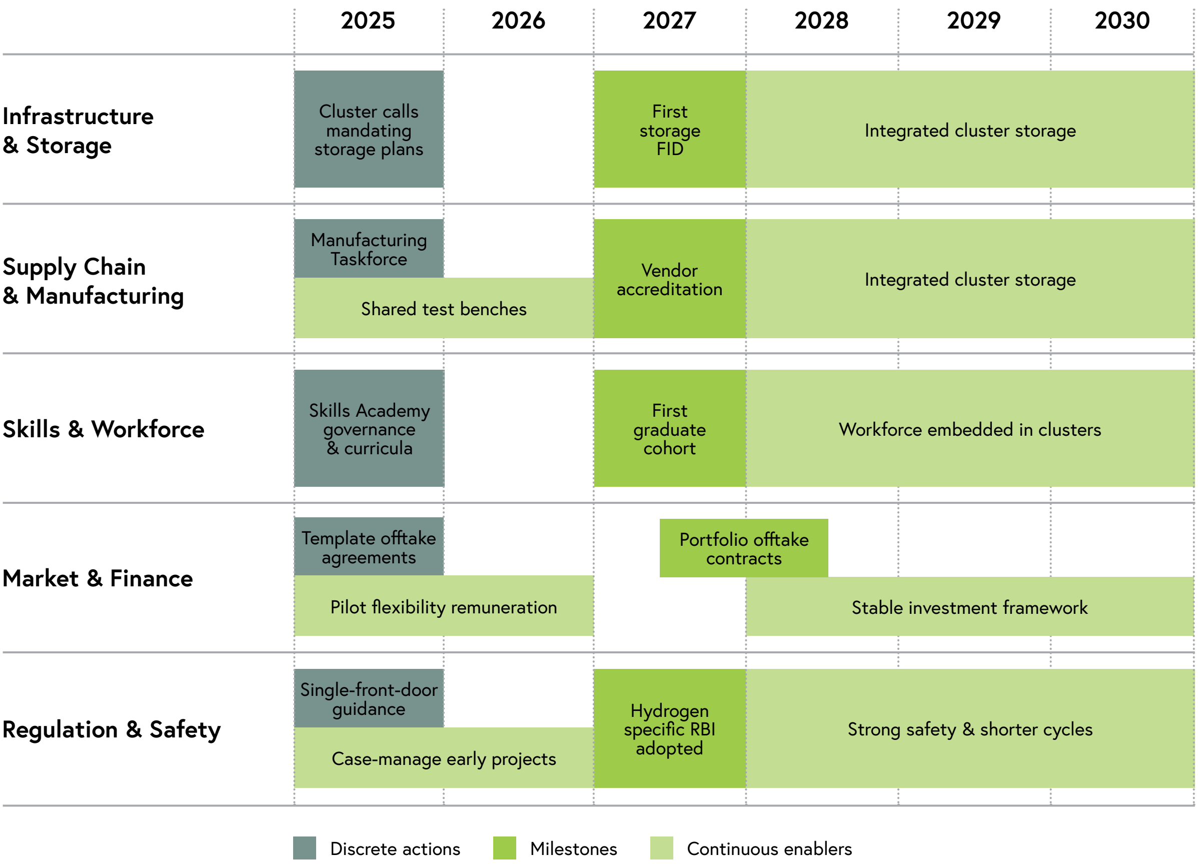
8. Implementation Roadmap and KPIs (2025–2030)

The roadmap translates the recommendations in Section 7 into a phased delivery plan with clear milestones and measurable KPIs. It ensures that policy ambition is matched by delivery discipline, enabling steady progress from foundational actions to full system integration.

The sequence moves from foundational actions (blue) in 2025–2026—such as launching cluster calls with storage plans, establishing the Manufacturing Taskforce, and setting up the Skills Academy—through scaling milestones (green) in 2027–2028, including the first storage investment decisions, vendor accreditation, and adoption of hydrogen-specific RBI. These steps establish the enabling conditions for ongoing implementation (orange) extending through to 2030, embedding skilled workforces within clusters, stabilising investment frameworks, and achieving integrated cluster storage.

By structuring progress in this way, the roadmap provides a disciplined trajectory that links early implementation priorities under the Hydrogen Orchestration Function (Section 7) with the broader goal of system integration. By 2030, the UK should demonstrate not only multiple hydrogen clusters operating at scale with strong safety performance, but also an emerging export capability in standards, quality assurance, and engineering services.

Figure 4: UK Hydrogen Implementation Roadmap 2025–2030. Actions (blue), milestones (green), and processes (orange) across five enablers show how early foundations lead to scale, system integration, and export capability.



8.1 Key Performance Indicators (KPIs)

Progress should be tracked through a consistent KPI set, including:

- Consenting cycle time (average months to approval).
- Electrolyser capacity contracted and operational (MW).
- Storage capacity permitted and commissioned (energy/deliverability).
- Vendor accreditations and lead-time reductions.
- Qualified personnel by role family.
- Share of projects using standardised offtake templates.
- Realised flexibility revenues (£/MWh).
- RBI compliance rates and safety metrics.
- Time-to-type-approval for composite pressure vessels (months).
- Number of UK pre-qualified vendors in power electronics.

9. Limitations and Further Research

This synthesis draws on rapid-review methods and semi-structured expert interviews undertaken as part of three MSc research projects. While the evidence is robust for policy scoping, it remains partial and evolving. Further research should quantify the economic and system value of storage by cluster, assess distributional and social-licence impacts of siting decisions, benchmark hydrogen pathways against credible low-carbon alternatives, and develop probabilistic risk models for embrittlement and inspection intervals calibrated to UK operating conditions.

10. Conclusion

Hydrogen, when deployed selectively where it outperforms direct electrification, complements renewable power to deliver deep decarbonisation and system flexibility. Achieving this vision requires early investment in storage and distribution infrastructure, strengthened manufacturing and certification capacity, professionalised skills and safety systems, bankable offtake structures with flexible pricing, streamlined consenting, and codified inspection regimes.

Coordinated oversight through a time-bound Hydrogen Orchestration Function (HOF) can ensure that these enablers progress in step, so projects combine into a coherent national system rather than isolated assets. With such alignment, the UK can translate strategy into operational capability, build exportable leadership in standards, quality assurance, and high-value components, and establish a hydrogen economy that is secure, scalable, and resilient.

These findings are intended to inform forthcoming updates to the UK Hydrogen Strategy (DESNZ) and to guide policy prioritisation in the years ahead.

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Annex A: Interviewee Roles (Anonymised)

Table 1: Anonymised interviewee roles contributing to the hydrogen evidence base.

Number	Job title
1	Chief engineer in civil nuclear
2	Chief technologist in nuclear role for hydrogen
3	Professor and head of hydrogen research
4	Professor in hydrogen systems engineering
5	CEO of a hydrogen Industry association
6	Lead of hydrogen operations in aviation authority
7	Professor in energy research
8	CEO of a hydrogen industry association
9	Senior engineer in gas regulator
10	Chief Scientific Officer (CSO) in green Hydrogen
11	CEO and co-founder of a green hydrogen technology company
12	Dean and professor of sustainable development in energy
13	Lecturer in hydrogen energy systems integration
14	Vice-president of the sustainable technology team of a consulting company
15	Supports low-carbon hydrogen generation through revenue stabilisation.

Annex B: TRL/MRL of Key Hydrogen Components

Purpose:
Give a concise, evidence-based view of where core components sit on technology and manufacturing maturity. Use it to target Taskforce sprints, vendor pre-qualification, and shared-test priorities.

Rubric:
TRL (technology): 1–3 concept to lab, 4–6 prototype/pilot, 7–8 demo to system qualified, 9 commercially proven.

MRL (manufacturing): 1–3 concept capability, 4–6 pilot/low-rate, 7–8 production-representative with QA, 9–10 serial production and robust supply base.

Table 2: Technology and Manufacturing Readiness Levels (TRL/MRL) of core hydrogen components and implications for UK deployment.

Component	Typical TRL (range)	Typical MRL (range)	What this means for UK delivery
Electrolysers (PEM/Alkaline)	8–9	6–8	Tech is proven, but several vendors still scaling manufacturing. Leaders show higher MRL. Prioritise stack yield, lifetime validation, and vendor accreditation.
Rectifiers	8–9	8–9	Commercial products with established lines among leading suppliers. Lower bottleneck risk relative to BoP.
Water purification systems	8–9	6–8	High technical readiness, mostly average manufacturing scale. Track QA and spares.
Refrigerated air dryers	7–8	6–7	Moderate maturity and average scale. Watch lead times and vendor QA consistency.
Gas-liquid separators (H_2/O_2)	8–9	6–7	Proven tech, average manufacturing scale. Focus on certified designs for hydrogen duty.
Compressors (H_2 duty)	8–9	6–8	Technically proven, manufacturing is the pinch point. Long lead times. Prioritise shared endurance rigs and type approvals.
Valves for hydrogen service	8–9	6–8	Proven designs, but hydrogen-specific serial production is uneven. Materials and seal qualification drive timelines.
Pipes for hydrogen networks	8–9	7–8	Mature technology and codes, with readiness dependent on spec harmonisation and NDT capacity.

- The table reports typical ranges across manufacturers in the thesis dataset. Individual vendors can be higher or lower. Electrolyser leaders (for example, Nel and Nucera) score at the top end of MRL, while several suppliers remain mid-MRL as they scale lines.
- Bottlenecks cluster around compressors, pressure vessels, valves and some BoP where certification, endurance testing, and type approvals constrain scale.
- Rectifiers consistently exhibit high TRL and MRL among leading vendors.

Annex C: Policy Alignment Pack – Supply and Demand Priorities

This annex consolidates Hydrogen UK's Supply Chain Strategic Assessment (Phase I, 2024; Phase II, 2025) into a practical framework for a proposed UK Hydrogen Equipment Manufacturing Taskforce. It maps supply-side gaps and demand-side anchors into 12-month sprints with clear KPIs. The aim is to lift Manufacturing Readiness Levels (MRLs), accelerate certification, and align supply growth with demand pull across clusters. These priorities align with the proposed Hydrogen Equipment Manufacturing Taskforce in Section 7, ensuring rapid lift in manufacturing readiness and certification throughput.

Table 3: Consolidated supply- and demand-side priorities for the UK Hydrogen Equipment Manufacturing Taskforce, with sprint focus areas and expected outcomes over 12–24 months.

Priority Area	Category	Sprint Focus	Indicative Outcomes (12–24 months)
Electrolyser stacks	Supply	Increase production yield; validate lifetime; pre-qualify vendors; introduce common quality documentation	At least 2 UK suppliers accredited; production yield improved by 10–15%; at least 2 designs type-approved
Power electronics	Supply	Secure component availability; build endurance/thermal testing rigs; develop semiconductor roadmap	Lead times reduced by 20%; first UK endurance rig in operation; at least 3 UK vendors accredited
Hydrogen network pipes	Supply	Harmonise specifications; improve weld QA and documentation; adopt standard non-destructive testing (NDT)	Common specification adopted by at least 2 clusters; weld repair rates reduced; accredited NDT procedures established
Compressed H_2 storage tanks	Supply	Expand composite tank capacity; build endurance test rigs; establish certification pathway	UK endurance rig commissioned; at least 2 designs type-approved; delivery times reduced by 25%
Fuel-cell stacks	Demand – Quick win	Establish UK pilot line; shared testing rigs for membrane–electrode assemblies (MEA); enable automotive/industrial cross-over	Pilot line commissioned; at least 2 OEM agreements signed; type-approval times shortened by 20%

Priority Area	Category	Sprint Focus	Indicative Outcomes (12–24 months)
Electric motors	Demand – Quick win	Improve high-efficiency manufacture; secure magnet supply; establish validation/ testing rigs	Vendor pre-qualified; motor efficiency improved by 10%; wider coverage of endurance testing
Hydrogen refuelling station (HRS) buffer storage	Demand – Quick win	Develop standard module designs; create safety case templates; accelerate approvals	Standard design set adopted; at least 2 approvals granted; refuelling station downtime reduced
Power converters	Demand – Medium term (concerted effort)	Define power-quality specifications; build prototypes; run grid integration tests	Prototype successfully passed grid tests; lead times reduced by 15%; at least 2 vendors qualified
On-board H_2 storage tanks	Demand – Medium term (concerted effort)	Design lightweight tanks; perform crash/penetration testing; establish certification plan	Test programme launched; 1 UK design pre-certified; certification bench operational
Hydrogen dispenser units	Demand – Longer term	Design modular dispenser; conduct metrology and safety trials	Pilot dispenser installed; certification process underway

Annex D: Skill Availability Heatmap

Table 4: Competency heatmap across the hydrogen value chain, showing areas of adequate availability (green), emerging demand or partial availability (yellow), and critical shortage (red). Sourced from literature and interview data.

Category	Competency Area	Status
Production	Electrolyser integration & inspection	Yellow
	Electrolyser operation, maintenance & servicing	Yellow
	Cryogenic hydrogen	Red
	Hydrogen behaviour analysis	Red
	Chemical engineering	Red
	Mechanical, Electrical, and Process Engineering	Green
	Electrochemistry	Green
	Hydrogen modelling and blending simulation	Red
Storage	Hydrogen gas handling & utilisation	Yellow
	Handling of hydrogen materials & systems	Yellow
	Hydrogen-specific technical expertise	Red
	Hydrogen embrittlement & material behaviour	Red
	Pressure/flame front & material resilience	Red
	Fuel storage & delivery at airports	Yellow
Distribution & Infrastructure	Trenching / pipe laying (civil works)	Green
	Land management, planning & HSE protocols	Yellow
	Contractors for downstream integration (BoP)	Yellow
	Technical integration at industrial sites	Yellow
	Valve repair & system-specific operation	Red
	Hydrogen infrastructure inspection (aerodromes)	Red
	Infrastructure compliance & permitting	Yellow

(Green) Adequate availability (Yellow) Emerging demand / partial availability (Red) Critical shortage

Category	Competency Area	Status
End-Use Applications	Servicing of end-use applications	Emerging demand / partial availability
	Refuelling procedures for hydrogen aircraft	Emerging demand / partial availability
	Purging practice	Critical shortage
	Leak testing & tightness testing	Emerging demand / partial availability
	Hydrogen system maintenance	Emerging demand / partial availability
	Fuel cell integration, servicing & inspection	Emerging demand / partial availability
	Hydrogen vehicle maintenance & retrofitting	Emerging demand / partial availability
	Human factors management at airports	Emerging demand / partial availability
Cross-Cutting (Business & Commercial)	Project planning, scheduling & control	Adequate availability
	Legal expertise	Adequate availability
	Stakeholder engagement	Adequate availability
	Commercial & business development	Adequate availability
	Value chain management	Adequate availability
	Training capacity (educational initiatives)	Emerging demand / partial availability
	Experience-based tacit knowledge	Emerging demand / partial availability
	Industrial hydrogen experience	Critical shortage
Cross-Cutting (Governance & Certification)	Risk assessment	Emerging demand / partial availability
	Legislation & regulation	Emerging demand / partial availability
	Certification & approvals	Emerging demand / partial availability
	Certification testing expertise	Critical shortage
	Compliance management	Emerging demand / partial availability
Cross-Cutting (Operational Safety)	Hydrogen-safe operations & emergency response	Emerging demand / partial availability
	Hydrogen safety management (leaks, fires, risk control)	Critical shortage
	Safety & accessibility	Critical shortage
	Process safety	Adequate availability
	Public reporting & emergency escalation (PRE)	Emerging demand / partial availability

Adequate availability · Emerging demand / partial availability · Critical shortage

Annex E: Sample Hydrogen Offtake Template – Key Terms

A standardised offtake contract is critical for reducing bankability risk, ensuring demand certainty, and enabling portfolio financing of early hydrogen projects. The following terms illustrate the features most relevant for hydrogen deployment:

Commercial Terms

- Contract Duration & Volumes: base volumes with take-or-pay commitments; flexibility for phased ramp-up and maintenance periods.
- Pricing & Indexation: linked to electricity input indices and carbon intensity, with collars to manage volatility and ensure affordability.

Operational Terms

- Quality & Delivery: specifications on hydrogen purity, pressure, and delivery profile; includes remuneration for dispatchable operation and flexibility services.
- Balancing & Curtailment: clear rules for curtailed operations, including measurement and verification protocols.

Risk Allocation

- Credit & Security: provisions for guarantees, step-in rights, assignment, and change-in-law protections.
- Health, Safety & Compliance: adherence to codes and standards; incident reporting; audit rights; continuous improvement obligations.

Annex F: Regulatory Mapping – Planning, Permitting & Safety (Overview)

Hydrogen projects in the UK are subject to multiple overlapping regimes. Planning consent may be required under the Town and Country Planning Act 1990 (TCPA) or, for nationally significant projects, the Planning Act 2008 (DCO). Environmental impacts are regulated through the Environmental Permitting Regulations 2016 (EPR), while major hazard sites fall under the Control of Major Accident Hazards Regulations 2015 (COMAH). Safety standards are also enforced through the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) and ATEX conformity requirements, alongside equipment rules such as PSSR.

This complexity creates duplication and uncertainty, contributing to average permitting timelines of 18–20 months, with complex cases extending beyond three years. The mapping in this annex shows how fragmented responsibilities across planning, environmental, and safety authorities increase risk for developers and underwriters.

By making these interactions explicit, the annex illustrates why a single-front-door consenting pathway with case managers and statutory milestones, as recommended in Section 4.5, is essential to accelerate deployment.

Table 5: Key UK regulatory regimes relevant to hydrogen projects, summarising their scope and specific implications for planning, safety, and certification.

Regime	What it Covers	Relevance for Hydrogen
TCPA / DCO	Planning approvals (local vs. nationally significant projects).	Multiple routes add uncertainty; DCOs are slow and resource-intensive.
EPR	Environmental permits for emissions, water, and waste.	Adds approvals on top of planning; coordination needed to avoid iteration.
COMAH	Major accident hazard control for hazardous substances.	Hydrogen treated as generic flammable gas; requires RBI, competence, and reporting.
DSEAR / ATEX	Explosive atmospheres regulation.	Applies to hydrogen production, compression, and storage; properties not fully accounted for.
PSSR	Inspection of pressure systems.	Pipelines, compressors, and vessels fall under scope; composite vessel approval slow.
Standards & Certification	ISO/BSI codes and conformity assessment.	Lack of harmonisation slows vendor qualification and type approvals.

This mapping supports the recommendation in Section 4.5 for harmonising consenting frameworks under NESO and DESNZ coordination.

Annex G: Risk Register

The table below distinguishes between policy-led interventions and industry-led mitigations and provides a likelihood (L) and impact (I) rating using Low (L), Medium (M), and High (H).

Table 6: Hydrogen risk register, showing key risks, examples, likelihood and impact ratings, and corresponding mitigations led by policy and by industry.

Risk	Examples	L	I	Mitigations (Policy)	Mitigations (Industry)
Technical & Materials Integrity	Embrittlement, permeation, seal degradation, hydrogen-assisted cracking	M	H	Support shared endurance testing programmes; hydrogen-specific RBI standards	Conservative materials selection; supplier qualification; non-destructive evaluation; progressive operating envelopes
Delivery & Cost Overruns	Bespoke engineering, certification bottlenecks, late specification change	H	H	Standardised specifications; demand aggregation; early type approvals through case-managed frameworks	Framework agreements; phased FID gates; improved project controls
Market / Offtake Risk	Uncertain volumes/prices; single-buyer exposure	M	H	Template offtake contracts; public-private risk-sharing; flexibility remuneration; contingent pricing	Portfolio offtake agreements; diversification of customers
Planning & Consenting	Fragmented guidance; multi-agency coordination delays	H	H	Single-front-door consenting; statutory timelines; shared evidence base	Early scoping; case management engagement
Safety & Social Licence	Incidents undermining community support	L	H	Independent assurance; visible safety KPIs; community benefits frameworks	Competency-based training; open learning from near misses; safety culture initiatives

Annex H: Return-on-Switch (RoS) method (Illustrative)

The Return-on-Switch (RoS) method provides a straightforward way to test whether switching from natural gas to hydrogen is economically attractive at a site level. It weighs the **benefits of switching** against the **extra costs**, and expresses the result as a percentage return on the additional investment required.

- Benefits include avoided carbon costs (UK ETS), avoided levies (Climate Change Levy), EII electricity reliefs, avoided CBAM exposure for exporters, and the flexibility/insurance value of hydrogen.
- Costs include the hydrogen price premium over natural gas, annualised conversion capital expenditure, and higher operations and maintenance.

Formula:

$$RoS = \frac{\text{Total benefits of switching to hydrogen} - \text{Total extra costs of hydrogen}}{\text{Total Incremental investment}}$$

Inputs are site-specific.

Worked example:

Assume gas commodity £45/MWh. Adding ETS (£7.6–8.8/MWh) and CCL (£7.75/MWh) gives an 'all-in gas' price of ~£60/MWh. Breakeven delivered hydrogen is therefore £60/MWh (£2.0/kg). Today's unsubsidised hydrogen is higher, but policy supports (LCHA, CCL removal, EII relief) narrow the gap. CBAM exposure or flexibility value can tip RoS into positive territory.

RoS can therefore be used as a **screening tool** by policymakers and industry to assess where hydrogen adoption is economically viable under different policy settings.

Annex H.1: Cost-down Scenarios & HOF Scoreboard (Illustrative)

While RoS shows viability at the site level, national deployment depends on cost-down trajectories. The Hydrogen Orchestration Function (HOF) is intended to coordinate actions that accelerate cost reductions. This annex compares outcomes with and without orchestration.

Scenarios (2026–2030, electrolytic path to 5 GW at 50% load factor):

- No-HOF / slow cost-down: ~£14.7 bn cumulative public support; ~14.8 $MtCO_2$ abated; implied abatement cost ≈ £980/tCO_2.
- With HOF / targeted cost-down: ~£6.1 bn cumulative public support; ~14.8 $MtCO_2$ abated; implied abatement cost ≈ £410/tCO_2.
- Delta: £8.6 bn support avoided over 5 years on the same abatement path. Every £10/MWh of cost-down at 5 GW is ~£219 m/year less support once fully ramped.

Table 7: Illustrative HOF Scoreboard (2026–2030), showing baseline metrics and 2030 targets for cost, reliability, and supply-chain performance.

Metric	2026 baseline	2030 target
Strike-to-Reference gap (£/MWh)	~200	≤100
Electrolyser load factor	35–45%	≥50–55% (with storage/H_2P)
Type-approval time (composite vessels)	18–24 months	≤9–12 months
Pre-qualified vendors (power electronics)	1–2	≥3–4
Shared test-bench utilisation	Ad-hoc	≥70%, pass-rates published
Curtailment avoided by electrolysis	0	£40–80m/year
Standard offtake with flexibility adders	<10%	≥75% of contracted volumes

Interpretation:

Site-level RoS provides a quick test of whether hydrogen adoption makes economic sense under different policy settings. System-level HOF scenarios show how coordinated actions—such as standardisation, shared testing, and storage-first sequencing—can drive down costs and reduce subsidy burdens. Together, they form a complementary framework: RoS for screening individual projects, and the HOF Scoreboard for tracking national progress through clear KPIs across allocation rounds.

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About Cranfield University

Cranfield University has long operated at the interface between advanced engineering, environmental systems and industrial deployment. **Hydrogen is an important component of the future energy system in the context of the UK's transition to net zero**. This is key for sectors where direct electrification is difficult or impractical. Cranfield contributes to this transition by providing applied research, and a national-level infrastructure testing capability and skills development that support the safe and scalable deployment of hydrogen technologies.

Cranfield's recent £69 Capex investment in H2 research spans the hydrogen value chain, from production and storage through to infrastructure, materials integrity and system integration. Hosting a number of dedicated hydrogen research assets, including the bulk Hydrogen Production by Sorbent Enhanced Steam Reforming (HyPER) and the Hydrogen Demonstration and Experimentation (HyDEX) facilities; this provide environments for the testing and validation of hydrogen technologies, infrastructure components and operational approaches under realistic conditions. These facilities enable researchers and industrial partners to examine issues such as materials compatibility, hydrogen embrittlement, catalyst performance, system reliability and safety assurance.

A defining feature of Cranfield's approach is its close engagement with industry and policy stakeholders. The University works with technology developers, infrastructure operators, regulators and government bodies to address the practical challenges associated with deploying hydrogen at scale. This collaboration enables Cranfield to provide independent technical insight while supporting the development of engineering standards, certification pathways and supply chain readiness.

Alongside research and technology validation, Cranfield plays an important role in developing the skills required to support the emerging hydrogen economy. Through postgraduate education, executive training and collaborative research programmes, we support the development of engineers, scientists and decision-makers capable of designing, implementing and regulating hydrogen systems responsibly.

In combining applied research capability with strong industrial engagement, Cranfield provides an independent platform for innovation, testing and knowledge exchange that supports the UK's ambition to build a secure, resilient and internationally competitive hydrogen economy.

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