A SYSTEMS ENGINEERING PERSPECTIVE ON HYDROGEN VALLEYS: DESIGN, INTEGRATION, ECONOMICS, AND OPTIMIZATION

Assignment for ESL352

By

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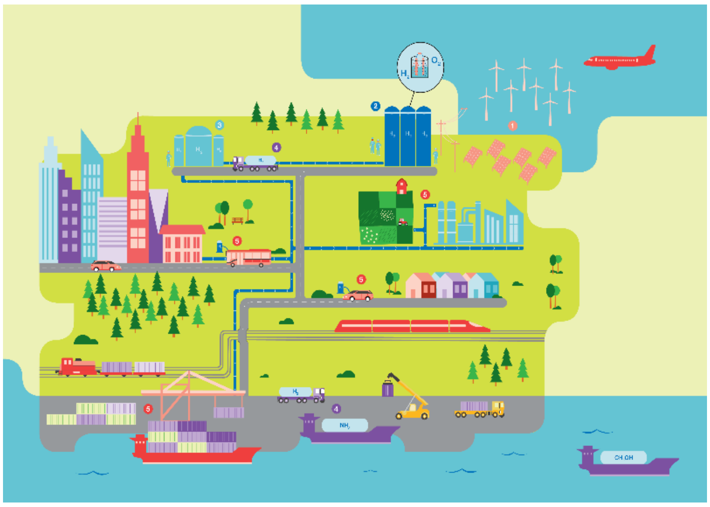
1. Abstract

The transition to a low-carbon energy system is vital to addressing the global climate crisis, with Hydrogen emerging as a key energy carrier. Hydrogen Valleys are integrated regional ecosystems where Hydrogen is produced, stored, distributed, and consumed across sectors such as industry, mobility, and power. They aim to demonstrate the full Hydrogen value chain at scale, supporting decarbonization, innovation, and economic growth. This paper examines their development and challenges, drawing on global case studies to assess technological readiness, economic viability, and policy frameworks. Through a comparative review and analysis of scale-up barriers, we identify success factors and outline strategic recommendations. Emphasis is placed on systemic integration, cross-sector collaboration, and enabling regulation. As nations pursue net-zero targets, Hydrogen Valleys offer a scalable blueprint for regional energy transitions.

Fig. 1: Typical setup of a Hydrogen Valley [1]



2. Introduction

The decarbonization of energy systems is no longer a future ambition but a present-day imperative. Hydrogen, owing to its potential as both an energy vector and industrial feedstock, is increasingly seen as central to achieving net-zero targets. However, despite growing momentum, large-scale deployment of hydrogen infrastructure faces interlinked technical, economic, and institutional challenges—ranging from high production costs to fragmented policy frameworks and underdeveloped end-use markets.

In response to these complexities, the concept of Hydrogen Valleys has emerged as a strategic solution. These valleys integrate diverse elements of the hydrogen economy—electrolysis powered by renewables, storage solutions, transportation networks, and multiple end-use applications—within a single geographic region. Unlike isolated pilot projects, they serve as living laboratories for system-wide integration and upscaling.

At the core of this concept lies the goal of achieving operational synergies between sectors such as transport, heavy industry, heating, and power generation, while leveraging regional resource advantages. This co-location model is designed not just for technical demonstration, but to catalyze cross-sectoral investment, reduce lifecycle emissions, and unlock economies of scale.

As countries begin to implement national hydrogen strategies, Hydrogen Valleys provide valuable insight into how infrastructure, market mechanisms, and governance can align to accelerate the transition. By studying existing and emerging valley models, we can identify what works, what doesn't, and what design principles are essential for making hydrogen ecosystems viable in both developed and emerging economies.

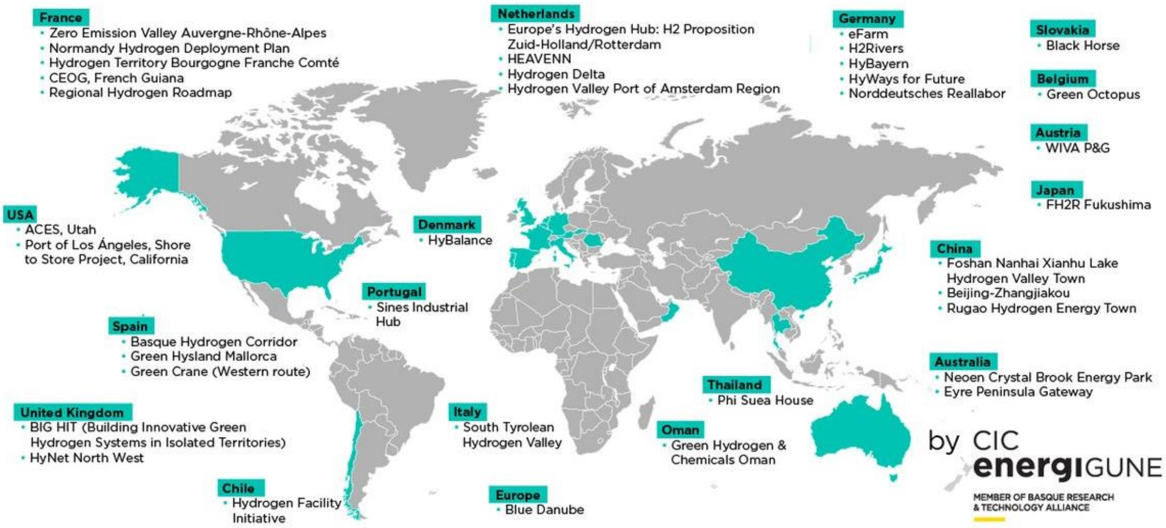
This paper adopts a systems engineering approach to assess Hydrogen Valley development across multiple dimensions. Through comparative case analysis, it seeks to extract actionable lessons for designing context-aware, scalable, and resilient hydrogen ecosystems.

3. Literature Review

3.1. Global Evolution of Hydrogen Valleys

Hydrogen Valleys originated in Europe under initiatives like the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), aimed at localizing the full Hydrogen value chain, production, storage, distribution, and use, within single geographic areas.[2,3] By 2024, over 80 valleys have been announced worldwide, with mature pilots in the Netherlands, Spain, Japan, and California.[3] The concept has rapidly expanded into Asia and the Americas, bolstered by national decarbonization plans and stimulus packages like the U.S. Inflation Reduction Act (2022).[4] *Fig. 2* illustrates this global distribution and progress across key regions.

Fig. 2: Geographical distribution of Hydrogen Valleys [5]



Valleys are increasingly seen as enablers for decarbonizing hard-to-abate sectors like steel, ammonia, long-haul freight, and high-temperature industrial heat. Their ability to co-locate renewable power, water, and offtake industries enables design and cost efficiencies. HEAVENN, a first-of-its-kind fully funded valley in the Northern Netherlands, exemplifies this model by uniting over 30 stakeholders across mobility, industry, and energy sectors into a regionally integrated hydrogen ecosystem [2]. Given its maturity and cross-sectoral depth, HEAVENN serves as a benchmark in this paper's analysis of Hydrogen Valley models worldwide. Similar clustering efforts are now being trialed in hydrogen corridors like BalticSeaH2, which connect regions through coordinated cross-border planning [22].

3.2. Strategic Frameworks and Site Selection Methodologies

Given the scale and complexity of Hydrogen Valleys, their siting requires structured, multi-criteria decision-making frameworks. The Analytical Hierarchy Process (AHP) is frequently used to evaluate site suitability based on factors such as renewable energy availability, industrial demand, land use feasibility, and water access.[23] A CSTEP (2023[6]) study applied AHP to 13 Indian states, identifying Rajasthan (solar-rich), Gujarat (industrial-port interface), and Tamil Nadu (wind-abundant) as prime candidates. In Europe, Geographic Information System (GIS)-based overlays and techno-economic models optimize site selection by balancing cost, emissions, and proximity to end-users.[7] HEAVENN utilized a similar integrated spatial planning approach to match offshore wind availability with regional Hydrogen demand, contributing to its bankability and system efficiency.[2]

Emerging approaches also include digital twin simulations and AI-based spatial optimization tools for faster scenario testing. These allow for dynamic modeling of energy flows, land-use impacts, and infrastructure synergies, significantly improving design precision. Moreover, socio-political factors such as public acceptance and regional workforce readiness are increasingly being incorporated into the early-stage siting models to anticipate long-term deployment risks.

3.3. Technical and Infrastructure Considerations

Valleys integrate renewable energy with electrolysis, storage, transport, and end-use systems. By 2023, global electrolyzer capacity hit 1 GW, expected to cross 100 GW by 2030.[8] Compressed gas storage (350–700 bar) remains standard, while pipelines, costing €0.10–0.30/kg/100 km, are gradually replacing truck delivery.[7] End-use spans transport, industry, and heating, increasingly supported by digital SCADA (Supervisory Control and Data Acquisition) and AI tools for predictive control and energy balancing.

The HEAVENN project features a 33 MW electrolyzer, 1500 kg/day storage, 13 km pipeline, and a cross-sector digital control platform, offering Europe's first fully integrated Hydrogen ecosystem.[2] Similar architectures are now being replicated in projects across Scandinavia and Australia.

3.4. Environmental and Lifecycle Analysis

Life cycle assessments (LCA) are essential in Hydrogen Valley planning, particularly in the EU, where funding eligibility requires detailed accounting of emissions, land, and water footprints. Green Hydrogen can achieve <1 kg CO_2-eq/kg H_2, compared to 9–10 kg for grey Hydrogen.[2,7] HEAVENN's LCA framework demonstrated a 70–80% reduction in lifecycle emissions by replacing diesel in public transport and district heating.[7] Co-benefits include 20–25% reuse of oxygen byproduct in nearby industries.[7]

Pilot strategies like waste heat recovery (up to 15% energy gain) and wastewater-fed electrolysis are being tested to enhance system circularity. Additionally, some valleys are experimenting with bio-hydrogen and thermochemical cycles to reduce upstream emissions and broaden feedstock diversity.

3.5. Economic Considerations

The economic viability of Hydrogen Valleys hinges on achieving a competitive Levelized Cost of Hydrogen (LCOH). In 2023, green Hydrogen costs ranged from $3–6/kg, compared to $1–2/kg for grey Hydrogen, with break-even point expected by 2030 in high-RE regions. Electrolyzer costs, down 60% since 2013, are projected to fall below $400/kW by 2030.[8]

HEAVENN reduced green Hydrogen production costs to around €4.50/kg by leveraging €90M in blended public-private funding, joint procurement of electrolyzers, and co-locating production with offtake, minimizing transport and storage costs.[2] Innovative instruments like Contracts for Difference (CfDs) and green bonds are increasingly being considered to de-risk capital.

3.6. Policy Landscape

Policy frameworks significantly shape the pace and scale of Hydrogen Valley deployment. The EU Hydrogen Strategy (2020), U.S. Inflation Reduction Act (IRA, 2022), and India's National Green Hydrogen Mission (NGHM, 2023) allocate billions in subsidies, tax credits, and R&D grants.[9,10,11] Certification schemes like the EU's Guarantee of Origin (GO) and India's pilot green Hydrogen registry enhance market confidence and help track carbon intensity.[7]

HEAVENN aligns with these frameworks, particularly the IPCEI (Important Projects of Common European Interest), allowing streamlined regulatory approval and funding.[7] It also exemplifies regional policy coordination among municipalities, research centers, and private entities to accelerate deployment. Policy synchronization remains a critical enabler for multi-stakeholder alignment.

3.7. Case Studies

A detailed comparative analysis of three valleys: HEAVENN (Netherlands), West Midlands Hydrogen Valley (UK), and India's emerging pilot (e.g., Gujarat), is presented in the Results and Discussion section. These case studies span diverse geographies, policy frameworks, and development stages, offering a holistic view of Hydrogen Valley implementation. HEAVENN, as the most mature, showcases full value chain integration and cross-sectoral synergies, while Gujarat provides insight into early-phase planning in developing contexts.

4. Problem Definition and Objectives

Despite growing momentum around Hydrogen Valleys (HVs) as decarbonization hubs, significant gaps remain in understanding how to structure, finance, and scale these complex ecosystems across geographies. While EU-led initiatives like HEAVENN have pioneered integrated models, replicability in emerging economies such as India is still in early stages. Key challenges include:

i. Identifying optimal locations that balance renewable potential, water access, land use, and industrial proximity.
ii. Quantifying lifecycle environmental and economic benefits under varying local constraints.
iii. Designing infrastructure and governance models aligning with regional capacities and policies.

India's pilot valleys, though promising, face technical hurdles in electrolysis scale-up, intermittency management, and integration with industrial off-takers. Similarly, mature regions like the UK aim to retrofit Hydrogen into existing urban infrastructure, posing unique system-level challenges. A review of recent Hydrogen Valley literature (*Fig. 3*) reveals widely varying approaches to production sources, value chain coverage, and temporal modeling, further emphasizing the fragmented understanding of how to structure and operate such ecosystems. Thus, understanding how different Hydrogen Valleys navigate technical, policy, environmental, and economic trade-offs is critical to inform future valley design.

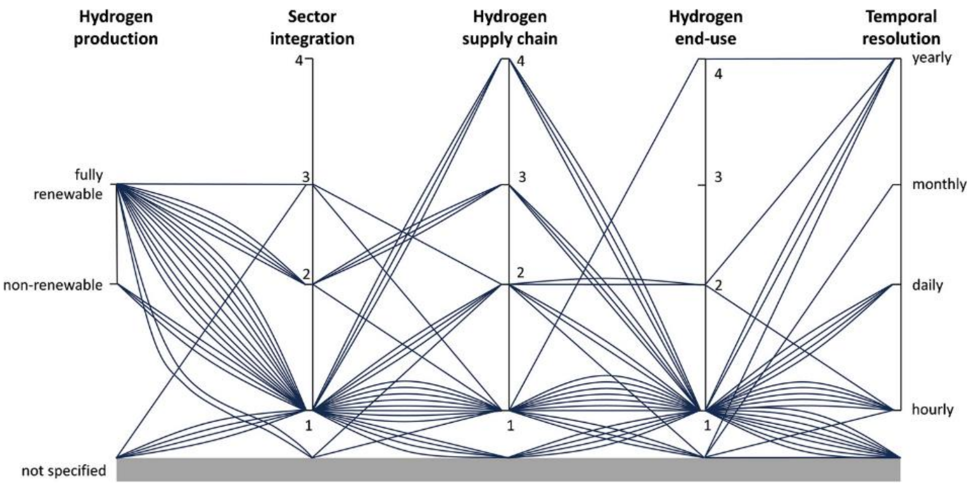


Fig. 3: Variation in modelling approaches across 26 Hydrogen Valley studies, highlighting diversity in value chain integration and reporting resolution. [8]

This paper aims to:

i. Synthesize global insights on Hydrogen Valley development across technical, environmental, economic, and policy dimensions.
ii. Analyze and compare three representative Hydrogen Valleys— HEAVENN (Netherlands), West Midlands (UK), and a pilot in Gujarat (India), to understand diverse implementation pathways.
iii. Evaluate common bottlenecks and success factors across regions with varying levels of maturity and infrastructure readiness.
iv. Propose tailored design considerations and policy recommendations for future Hydrogen Valleys, especially in the context of emerging economies.

By grounding the analysis in real-world case studies and cross-sectoral dynamics, this study offers a holistic understanding of what makes a Hydrogen Valley both viable and scalable in practice by bridging the gap between high-level strategy and implementation, offering actionable insights for developers, policymakers, and researchers alike.

5. Results and Discussions

5.1. Comparative Evaluation of Hydrogen Valley Case Studies

Fig. 4 offers a detailed comparative assessment of three prominent case studies: the HEAVENN Valley in the Netherlands, the West Midlands Hydrogen Valley in the United Kingdom, and the pilot Hydrogen Valley initiative in Gujarat, India. The comparison spans five key dimensions, technical, environmental, economic, policy, and implementation, to highlight regional strengths, bottlenecks, and unique approaches. The following insights have been derived from this comparative analysis:

i. Technological Configuration and Integration

While all three Hydrogen Valleys rely primarily on PEM electrolyzers, known for their compatibility with intermittent renewables, their system integration strategies vary significantly. The HEAVENN project stands out for its holistic multi-sector design, where Hydrogen is not a siloed application but embedded across mobility, heat, power, and industry. By combining PEM and Alkaline electrolyzers tailored to specific demand profiles, and deploying smart grid balancing, HEAVENN ensures efficient renewable energy use and maintains lifecycle emissions below 1 kg CO_2/kg H_2.[2] A unique feature is its heat integration, where waste heat from fuel cells is recycled into district heating, reducing overall energy demand and enhancing system circularity. In contrast, the West Midlands initiative, while technically competent, focuses more narrowly on fuel-cell trains and public transport, with limited energy cascading or sectoral integration. Gujarat, despite a strong solar backbone, lacks dynamic load balancing or sector coupling, making it less adaptive to curtailment and risking underutilization during off-peak demand.

ii. Environmental Performance and Infrastructure Planning

Lifecycle assessments (LCAs) vary due to both data availability and system maturity. HEAVENN's low carbon footprint results from a well-integrated ecosystem, co-located infrastructure, and consistent use of low-carbon electricity. Storage in salt caverns and pipeline-based distribution further limit indirect emissions. In the UK, the early reliance on trailers and disjointed nodes likely raises the embodied carbon. Gujarat, though solar-dominant, risks higher emissions due to fragmented off-take and reliance on diesel for Hydrogen transport. Another underexplored concern is water availability for electrolysis. Although Gujarat is coastal, its projects lack clear integration of desalination or reuse strategies. HEAVENN's circularity planning mitigates this via wastewater reuse, a design feature missing in both UK and Indian contexts.

iii. Economic and Policy Interplay

Capital costs vary, but HEAVENN demonstrates how blended financing (2–4% cost of capital [11]) enabled early scaling. Its strong public-private governance streamlined permitting and unlocked EU and Dutch funding synergies, making it an attractive destination for institutional investors. West Midlands suffers from a fragmented regulatory environment and limited Public-Private Partnership (PPP) coordination, raising capital costs (~6–7% [11]) despite policy support. Gujarat faces the highest investment risks due to unclear state-central roles and high borrowing costs (~10–12% [11]), which limit private sector participation and delay infrastructure deployment. Notably, none of the valleys yet benefit from an active Guarantees of Origin (GO) market or carbon credit trade, a missed opportunity for financial viability, especially in emerging regions. Creating robust carbon intensity scoring mechanisms and enabling cross-border GO recognition could significantly improve market access and price competitiveness. Still, India's push through Green Hydrogen Mission subsidies could reduce CapEx per MW in future phases.[12]

Fig. 4: Multi-Dimensional Comparison of HEAVENN (NL), West Midlands (UK), and Gujarat Pilot (India)

Category	Parameter	HEAVENN (Netherlands) [2,7,8]	West Midlands (UK) [7,8,12]	Gujarat Pilot Valley (India) [6,7,8,11]
Project Scope	Scale & Sectors	Multi-vector: industry, mobility, heat, power	Mobility-led with industrial applications	Pilot-scale: industrial H_2 (refineries, transport)
	Status & Timeline	Operational (2020), EU-backed	Roadmap phase (2023), under Net Zero Strategy	Feasibility stage; NGHM-supported
Hydrogen Production	Method	PEM + Alkaline from RES & biomass	Likely PEM via RES electrolysis	Alkaline (SECI tenders); pilot PEM for solar projects
	Initial / Target(2030) Electrolyzer Capacity	~20 MW → 60–80 MW	~10 MW → 50 MW	5–10 MW planned → national target: 100 MW+
Infrastructure & Use	Storage & Transport	Salt cavern, pipelines	Cylinders/trailers; limited infra	Trailer-based local storage
	Refuelling Infrastructure	5+ HRS (H_2 Refuelling Station) operational	2 HRS planned; pilot fuel-cell trains	1–2 HRS in development
	End-use Tech	FCEVs, grid blending, backup, FCs	Buses, trains (pilot)	Industrial fuel substitution
Integration	Grid & RES	Smart hybrid system	UK grid connected, early RES limited	Solar-heavy, Inter-State Transmission System (ISTS) integration planned
	Innovations	Blockchain tracking, heat-H_2 synergy	Community co-design, FC trains	AI-based dispatch, solar curtailment
Environmental Aspects	Life Cycle Assessment (LCA)	Done: <1 kg-CO_2/kg-H_2	Underway, estimated ~1.5–2.2 kg-CO_2/kg-H_2	Estimated <2.5 kg-CO_2/kg-H_2
	Land & Water Use	Circularity planning integrated	Not clearly defined	Potential land/water conflict risks
Economic Aspects	Capital Cost	€0.9–1.2 million per MW	~€1.4 million per MW (converted)	~€1–1.2 million per MW (converted)
	O&M Cost	Low – modular, established tech	Medium – early deployment phase	High – pilot stage, higher risk
	Return on Capital	2–4% (blended*)	6–7% (with guarantees)	10–12%+ (high risk premium)
Policy & Governance	Governance Model	Public-private regional board	Local authority-led; weak PPPs	PSU-led; early coordination
	Regulatory Ease	EU streamlined permitting	Fragmented local process	Central-state overlap; delays common
Stakeholders	Off-take Agreements	Industry contracts (e.g. Nobian)	Limited; mostly public sector	MoUs with PSUs, private users
System Maturity	Ecosystem Maturity	Mature industrial ecosystem with strong value chain	Emerging, partially integrated	Nascent, fragmented and developing
	Key Barriers	Scaling, permitting, pricing	Inter-agency gaps, infra deficit	High CapEx, demand assurance
	Future Outlook	High resilience, modular design	Policy-backed moderate potential	High solar-H_2 synergy, but scaling uncertain

**Blended Finance: combined cost of both debt and equity financing, resulting in an average return on capital*

iv. *Maturity, Scalability, and Spatial Design*

HEAVENN's success stems from spatial clustering, industries, mobility users, and infrastructure are co-located within a manageable radius, minimizing transport losses and synchronizing supply-demand.[2] This model is difficult to replicate in West Midlands, where legacy infrastructure and dispersed urban nodes complicate integration. Gujarat, still in early planning, has the opportunity to adopt a clustered approach, especially in port-industrial corridors like Jamnagar. However, ensuring anchor demand from industries (e.g., refineries) and building shared infrastructure will be key to avoid stranded assets. Scale also hinges on talent: while the Netherlands has vocational programs feeding into Hydrogen jobs [13], both UK and India need stronger pipelines for technicians, operators, and planners trained in Hydrogen systems.

5.2. *Economic Viability and Policy Gaps in Hydrogen Valley Deployment*

One of the most critical barriers to large-scale Hydrogen Valley development is the economic viability gap between green Hydrogen and its fossil-based counterparts. Even with falling renewable energy costs, the Levelized Cost of Hydrogen (LCOH) for green Hydrogen remains significantly higher than that of grey Hydrogen, primarily due to high capital expenditures for electrolyzers and associated infrastructure.[8] In developed economies, this gap is being narrowed through state subsidies, low-interest loans, and risk guarantees. However, in developing economies, borrowing costs can exceed 10–12% [8,12], making the financial environment far less favorable. Studies have shown that a lower cost of capital has a greater effect on LCOH than marginal improvements in electrolyzer efficiency, emphasizing the need for concessional finance and blended funding mechanisms to attract private investors.

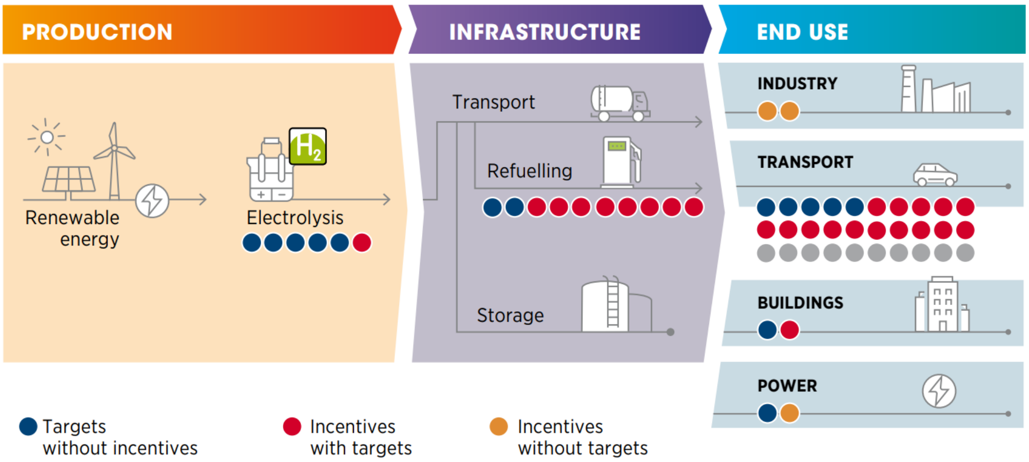


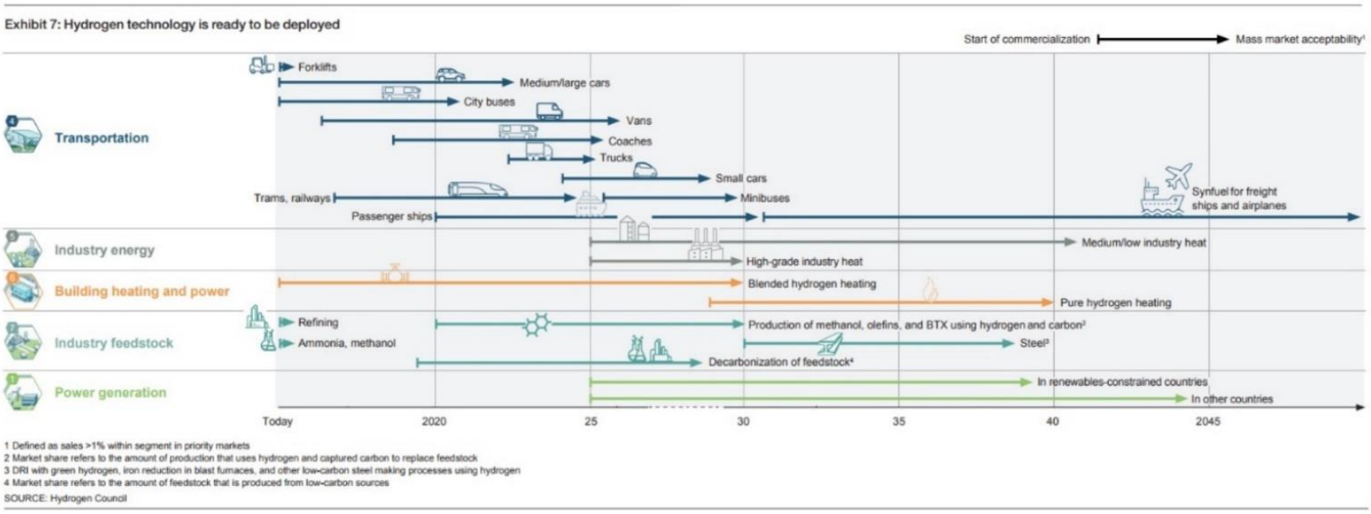
Fig. 5: Number of Hydrogen policies at a global level by value chain segments [7]

This challenge is compounded by uneven policy support across the Hydrogen value chain. As illustrated in *Fig. 5*, while some downstream segments such as transport refueling receive robust backing through targeted incentives, other critical areas, like storage, industrial off-take, and power sector integration, lag behind. This patchy distribution can result in commercially "stranded" projects: production capacity may be installed, but without coordinated infrastructure and demand creation, Hydrogen cannot be viably monetized.

For Hydrogen Valleys to scale, public policy must evolve from a production-centric model to a whole-system approach. This means equal focus on enabling infrastructure (e.g., pipelines, refueling stations), demand-side incentives, and stakeholder coordination across sectors. It also calls for adaptive regulatory frameworks that can evolve with technology maturity and market signals, rather than static policy mandates. Without this balance, even the best-funded electrolyzer projects risk becoming isolated assets rather than components of an integrated Hydrogen ecosystem.

5.3. Emerging Technologies and Future Outlook

Fig. 6: Projected technological milestones anticipated through 2050 [14]



The roadmap provided in Fig. 6 underscores three parallel trends: enhancing Hydrogen production efficiency, diversifying carrier and storage, and expanding sectoral integration. These reflect a broader shift in Valley design from centralized megaprojects to modular, digitally optimized, and locally adaptive systems. The following innovations are set to shape the technical foundations of next-generation valleys:

i. High-Temperature Electrolysis (HTE) with Combined Heat and Power (CHP) Integration

Conventional PEM and alkaline electrolyzers are limited to 60–70% efficiencies due to thermodynamic limits. High-Temperature Electrolysis, particularly using Solid Oxide Electrolyser Cells, operates at 600–850°C, allowing the partial substitution of electrical input with thermal energy.[15] This raises electrical-to-hydrogen efficiency and significantly lowers operating costs in valleys co-located with industrial waste heat, solar-thermal systems, or nuclear heat. When combined with hydrogen-fueled CHP systems, such as turbines or micro-CHP units, thermal recycling pushes efficiency >80%.[15] This dual-output setup enables power and district heating, improves grid flexibility, and resilience during peak demand periods. Challenges remain around thermal cycling durability and high material costs.

ii. Hydrogen Carriers: Liquid Organic Hydrogen Carriers (LOHCs) and Green Ammonia

As production expands beyond pipeline-reachable zones, carrier molecules are gaining traction. LOHCs like dibenzyltoluene offer chemically stable, non-pressurized transport, ideal for distributed, limited infrastructure valleys. Meanwhile, green ammonia provides a high-density, shippable hydrogen vector via established maritime logistics.[18] Advancing ammonia cracking technologies could enable high-purity hydrogen reconversion, facilitating global Hydrogen trade. These carriers reduce the need for cryogenic/high-pressure storage and increase the geographic flexibility of valleys.

iii. Underground Hydrogen Storage

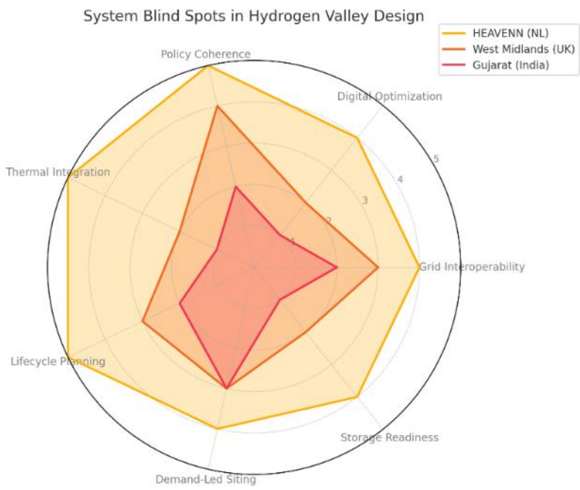
As valleys scale, temporal mismatches between hydrogen production and consumption become more pronounced. Underground hydrogen storage, particularly in salt caverns or depleted gas fields, offers a high-capacity, long-duration solution. It can buffer seasonal variations in renewable electricity, stabilize electrolyser load factors, and ensure secure reserves for industrial supply chains. While geological limitations restrict suitable formations, strategic deployment is expected to enable continent-scale integration, especially in Europe and North America. Technical challenges like hydrogen embrittlement and leakage monitoring remain under active investigation.

6. Summary and New Observations

Hydrogen Valleys represent a critical step toward the systemic decarbonization of regional economies. This paper has explored their evolution, technical configurations, and enabling policy frameworks through a comparative assessment of three representative case studies— HEAVENN in the Netherlands, West Midlands in the UK, and Gujarat in India. The analysis reveals that while all three initiatives share common technological foundations (e.g., electrolysis-based green hydrogen production), their operational maturity and integration depth vary significantly. HEAVENN's modular, co-located infrastructure with integrated heat and power loops demonstrates how spatial design and stakeholder coordination can unlock lifecycle efficiency and lower costs. In contrast, West Midlands and Gujarat face fragmentation challenges, regulatory issues, and delayed infrastructure deployment.

Hydrogen Valleys globally are converging around a new set of challenges and design imperatives. The absence of guarantees of origin, limited carbon pricing, and an overemphasis on production-side policies threaten commercial viability. Future-ready valleys will require synchronized development across the entire value chain, including storage, demand creation, and digital controls. As shown through emerging innovations such as high-temperature electrolysis, liquid hydrogen carriers, and underground storage, the sector is entering a phase where integration, flexibility, and resilience are as critical as cost reduction.

Fig. 7: Hydrogen Valley Maturity Map [2,11,12]



Merging Insights and Systemic Blind Spots

i. *Digital layer underdevelopment is a hidden bottleneck:* While hardware investments dominate valley planning, few projects prioritize integrated digital twins, predictive maintenance models, or real-time optimization algorithms. As seen in *Fig. 7*, digital optimization lags behind other maturity metrics, even in otherwise advanced valleys. This lack of digital foresight creates blind spots in operational scaling, especially under volatile grid and demand conditions.[20]

ii. *Electrolyzer deployment is not spatially optimized for load duration curves:* Many valleys prioritize co-location with renewables over proximity to stable industrial demand. This spatial mismatch leads to increased curtailment, hydrogen storage requirements, and transmission losses. Future valleys should adopt demand-led siting strategies informed by thermal maps, baseload profiles, and flexible load zoning.

iii. *Linear value chains limit long-term viability:* Most current Hydrogen Valleys pursue stepwise production-to-use architectures. However, future-ready systems may require closed-loop ecosystems that utilize byproducts like waste heat, oxygen, and desalinated brine in adjacent sectors. In water- and energy-constrained regions, circular integration may offer more resilience and economic value than pure scale-up.

iv. *Overly binary policy framing of "green hydrogen" hampers transition flexibility:* Current certification and subsidy mechanisms often define green hydrogen in absolute terms (e.g., 100% renewable-sourced), ignoring transitional or hybrid operations common in real-world systems. Without flexible grading frameworks that accommodate partial decarbonization or grid blending, innovation in adaptive valley design could be stifled.[21]

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