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European Hydrogen Valleys as catalysts for systemic decarbonization: A sustainability-oriented innovation and multi-level perspective analysis

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Hydrogen Valleys—regional ecosystems that integrate green hydrogen production, storage, distribution, and end-use—are emerging as key enablers of the European decarbonization agenda. Positioned at the intersection of energy, industry, and mobility systems, they embody sustainability-oriented innovation (SOI) by embedding environmental objectives into technological deployment, fostering multi-stakeholder collaboration, and promoting circular economy principles. Despite rapid policy and investment momentum, there is limited research that applies the multi-level perspective (MLP) framework to understand how Hydrogen Valleys evolve as systemic innovation niches capable of influencing regimen and landscape dynamics. This study introduces a novel dual-lens analytical framework that integrates SOI and MLP to assess Hydrogen Valleys not merely as technical pilots, but as sociotechnical experiments embedded in systemic transformation. By merging these frameworks, we develop a typology that distinguishes between Pilot, Transitional, and Systemic valleys across governance, circularity, digitalization, and regimen integration. The analysis reveals that Hydrogen Valleys operationalize SOI by linking diverse sectors, testing novel business models, and enabling localized hydrogen value chains. From an MLP lens, they emerge as niche innovations that increasingly interact with incumbent energy regimens under pressures from climate targets, energy security needs, and technological competition. Key success factors include stable policy roadmaps, demand-side commitments, and integrated infrastructure planning. However, major barriers remain in achieving cost reduction, regulatory harmonization, and skills development. The findings highlight that coherent policy support, social sustainability integration, and international collaboration—particularly under initiatives such as the Clean Hydrogen Mission—are critical for scaling their impact. This research contributes a theoretically grounded framework for understanding Hydrogen Valleys as catalysts in Europe's green transition, offering actionable insights for policymakers, industry leaders, and researchers.

Keywords: Hydrogen valleys; Sustainability-oriented innovation; Multi-level perspective; Renewable energy systems; Policy and governance; Energy transition management

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1. Introduction

The global energy system is undergoing a profound transformation driven by the convergence of the imperatives of climate change mitigation, energy security, and sustainable economic development. Geopolitical instability, volatile fossil fuel markets, and rapidly growing demand have heightened the urgency for implementing decarbonization strategies capable of delivering systemic change at scale.^{1,2} Hydrogen has re-emerged as a critical pillar of these strategies due to its versatility as an energy carrier, industrial feedstock, and energy storage medium capable of complementing variable renewable power generation.^{3,4}

In Europe, hydrogen occupies a central role in the European Green Deal, the Fit-for-55 package, and the REPowerEU plan, which collectively aim to achieve climate neutrality by 2050 and reduce dependence on imported fossil fuels.^{5,6} The European Commission's hydrogen strategy targets the installation of 40 GW of domestic electrolyzer capacity and the production of 10 million tons of renewable hydrogen by 2030, accompanied by large-scale hydrogen imports to meet projected demand.⁷ A flagship element of this strategy is the development of Hydrogen Valleys—geographically defined ecosystems that integrate hydrogen production, storage, distribution, and multiple end-uses across industry, mobility, and energy systems.^{8,9}

Hydrogen Valleys are designed to accelerate market creation, foster industrial competitiveness, and enable regional decarbonization. By localizing production and consumption, they reduce transportation costs, enhance energy resilience, and promote circular economy principles.¹⁰ They also serve as testbeds for business model innovation, cross-sector integration, and public-private collaboration, making them a potential catalyst for Europe's transition to a low-carbon economy.

Despite growing policy and investment momentum—over EUR 56 billion in public and private commitments in Europe alone, supporting more than 120 projects, of which 76 are operational or planned—there remains limited research that assesses Hydrogen Valleys through sustainability-oriented innovation (SOI) and multi-level perspective (MLP) frameworks.¹¹ Existing studies often address technological or infrastructural aspects but underexplore their role as systemic innovation niches capable of influencing incumbent energy regimens.^{12,13}

This study addresses this gap by applying an integrated SOI and MLP framework to assess Hydrogen Valleys as sociotechnical experiments. While SOI provides a lens for evaluating sustainability integration across governance,

circularity, and inclusion, MLP situates Hydrogen Valleys within broader regimen and landscape dynamics. The study is guided by two research questions:

- (i) How do Hydrogen Valleys function as integrated SOI ecosystems?
- (ii) What are the systemic success factors, barriers, and pathways to scaling Hydrogen Valleys within and beyond Europe?

By addressing these questions, this study provides a novel analytical approach and actionable insights to support Hydrogen Valleys as transition enablers, not only in technological terms but also as embedded agents of systemic change across Europe's evolving energy landscape.

2. Literature review

2.1. Hydrogen in the global energy transition

Hydrogen has emerged as a cornerstone in decarbonization strategies aimed at reducing greenhouse gas emissions in hard-to-abate sectors such as steel, cement, ammonia, petrochemicals, shipping, and aviation, where direct electrification is often technically or economically unfeasible.^{4,14} As both an energy carrier and an industrial feedstock, hydrogen offers flexibility across production, storage, transport, and end-use applications. It enables the large-scale integration of variable renewable energy sources—particularly wind and solar—by providing long-duration storage and helping to balance grid fluctuations.^{15,16}

The 2024 Global Hydrogen Review by the International Energy Agency (IEA) reported over 1600 announced hydrogen projects worldwide, with a projected combined electrolyzer capacity exceeding 480 GW by 2030, representing a significant scale-up from the 14 GW under construction.² Investment momentum is strong, with nearly USD 570 billion in announced hydrogen-related investments through 2030, of which approximately 10% has reached a final investment decision.¹⁷

Governments are adopting comprehensive hydrogen strategies to accelerate deployment. In the European Union, the hydrogen agenda is embedded in the European Green Deal, the Fit-for-55 package, the REPowerEU plan, and the EU Hydrogen Strategy, with targets of 10 million tons of domestic renewable hydrogen production and 10 million tons of imports by 2030.¹⁸ The United States has committed USD 7 billion to develop seven regional clean hydrogen hubs under the Bipartisan Infrastructure Law, while Japan and South Korea have updated their roadmaps to integrate hydrogen into long-term industrial and mobility sectors.¹⁹⁻²¹ Australia has positioned itself as a

major hydrogen exporter, leveraging abundant renewable resources to supply Asian markets.²²

International initiatives, such as the Clean Hydrogen Mission under the Mission Innovation initiative, and multilateral efforts like the Hydrogen Council, are fostering global coordination on technology standards, infrastructure interoperability, and certification schemes.²³ Recent literature emphasizes that without such coordination, scaling hydrogen risks fragmentation, duplicated infrastructure, and delayed cost reduction.^{24,25}

The cumulative effect of these strategies is to position hydrogen not only as a decarbonization vector but also as a driver of industrial competitiveness, energy security, and geopolitical influence in the emerging net-zero economy.^{26,27}

2.2. Hydrogen Valleys: Concept and policy frameworks

The concept of Hydrogen Valleys has emerged as a strategic tool to accelerate the hydrogen economy by creating geographically defined ecosystems where hydrogen production, storage, distribution, and multiple end-uses are co-located.^{10,12} By integrating the full value chain within a single region, Hydrogen Valleys can reduce transportation costs, improve energy efficiency, and facilitate the circular use of resources. They are designed to stimulate both supply and demand simultaneously, providing early markets for hydrogen technologies while achieving economies of scale.²⁸

The most complete definition of Hydrogen Valleys in a European Commission document or platform is provided on the Clean-Hydrogen Platform, which defines them as a geographical area—a city, a region, an island, or an industrial cluster—where several hydrogen applications are combined into an integrated hydrogen ecosystem that consumes a significant amount of hydrogen, thereby improving the economics of the project. Such projects should ideally encompass the entire hydrogen value chain: production, storage, distribution, and final use.²⁹ Consequently, the Commission refined the definition, limiting the type of hydrogen to renewable hydrogen.³⁰ In the EU, existing Hydrogen Valleys differ based on the amount of clean hydrogen produced, the number of end-uses, and the areas around which they are developed (e.g., cities, regions, islands, ports, and industrial clusters). Many also include a cross-border component. However, these projects can demonstrate business cases for various hydrogen applications and contribute to the wider acceptance of hydrogen technologies.³¹ In practice, this means co-locating electrolyzer capacity with industrial

clusters, ports, or renewable generation hubs, thereby enabling cost-efficient deployment.

Policy support for Hydrogen Valleys in the EU has intensified in recent years. The Clean Hydrogen Joint Undertaking (CHJU) targets at least 50 operational valleys by 2030, with ambitions for over 100 in the longer term.³² As of August 2025, the recent expansion to 76 mapped valleys across 22 EU and associated countries demonstrates the model's scalability and policy traction. Flagship projects such as NorthH2 (Netherlands) and Green Hysland (Spain) have become international reference points for integrated hydrogen ecosystems. However, smaller, regional-scale valleys often face scaling challenges, particularly in aligning local infrastructure with emerging transnational hydrogen corridors.³³ Cumulative public and private investment commitments in EU Hydrogen Valleys exceed EUR 56 billion, encompassing more than 120 large-scale projects.³⁴

The EU's Strategic Research and Innovation Agenda (SRIA) identifies Hydrogen Valleys as a pivotal tool for bridging innovation and market deployment, positioning them as “flagship projects” for scaling up renewable hydrogen in line with the Fit-for-55 package and REPowerEU plan objectives.³⁵ The SRIA emphasizes integration across multiple sectors, including:

- (i) Industrial decarbonization: Green steel, ammonia, and chemicals
- (ii) Transport and mobility: Heavy-duty vehicles, maritime, aviation, and rail
- (iii) Energy systems: Power-to-gas for seasonal storage and grid balancing.

Hydrogen Valleys are also expected to act as testbeds for certification schemes, safety protocols, and regulatory frameworks, providing evidence for future EU-wide policy harmonization.²⁴ From a global perspective, similar cluster-based initiatives have been launched in the United States (Regional Clean Hydrogen Hubs), Japan (Hydrogen Towns), and Australia (Renewable Energy Industrial Precincts), highlighting the growing role of geographically concentrated hydrogen ecosystems in national strategies.¹⁹⁻²²

The 2022 Roland Berger report for the European Commission and CHJU, titled *Going Global: An update on Hydrogen Valleys and their role in the new hydrogen economy*, notes that successful valleys exhibit three core features: strong local stakeholder coalitions, diversified offtake agreements across sectors, and alignment with regional economic development strategies.³⁶ This systemic integration aligns with the European Commission's broader goal of creating regional innovation ecosystems that simultaneously advance climate, industrial, and energy policy objectives.

2.3. Theoretical perspectives: SOI and MLP

2.3.1. SOI

SOI refers to innovation processes that explicitly integrate environmental and social objectives alongside economic goals, aiming for transformative change rather than incremental improvement.³⁷ SOI involves aligning technological advancements, business model innovations, and institutional changes to achieve systemic sustainability outcomes.^{38–40}

In the context of Hydrogen Valleys, SOI provides a framework for understanding how these projects go beyond technical deployment to create holistic, cross-sectoral solutions. The European Commission's policy design for Hydrogen Valleys reflects SOI principles by:

- (i) Encouraging multi-stakeholder collaboration between governments, industries, research organizations, and local communities
- (ii) Embedding circular economy strategies, such as the valorization of by-products from hydrogen production
- (iii) Linking innovation funding to broader environmental impact metrics, including life-cycle emissions reduction and local socioeconomic benefits.^{41,42}

Hydrogen Valleys, conceived as SOI ecosystems, not only deploy clean energy technologies but also act as innovation incubators, testing new regulatory models, digitalization approaches (e.g., hydrogen demand forecasting), and integrated infrastructure planning.^{2,43–46}

2.3.2. MLP

The MLP is a sociotechnical transitions framework that conceptualizes innovation as the result of interactions between three analytical levels:

- (i) Niches: Protected spaces where radical innovations emerge (e.g., early-stage Hydrogen Valleys)⁴⁷
- (ii) Regimens: Dominant sociotechnical configurations such as those underpinning fossil-fuel-based energy and transport systems⁴⁸
- (iii) Landscape: The broader exogenous environment, including climate change pressures, geopolitical shifts, and societal values.^{49–51}

Applying the MLP to Hydrogen Valleys reveals how they operate as niche environments designed to challenge incumbent carbon-intensive regimens by demonstrating integrated hydrogen solutions at scale. Their success is influenced by:

- (i) Landscape pressures: EU climate neutrality deadlines, rising carbon prices, and energy security imperatives
- (ii) Regimen resistance: Path dependencies in fossil-based infrastructure, entrenched market incumbents, and regulatory inertia

- (iii) Niche strengthening: Policy incentives, public-private partnerships, and experimental learning from operational projects.^{33,52}

The combination of SOI and MLP offers a complementary analytical approach: SOI focuses on the “content and direction” of innovation, while MLP explains the “dynamics and positioning” of Hydrogen Valleys within broader sociotechnical systems. This dual lens helps identify both the internal design factors (e.g., stakeholder governance, sustainability metrics) and external enabling conditions (e.g., market creation, policy harmonization) required to accelerate hydrogen transitions.^{10,53}

To integrate these perspectives, [Table 1](#) presents an SOI-MLP matrix that maps how sustainability dimensions manifest across different levels of the sociotechnical system. This framework underpins the subsequent analysis of European Hydrogen Valleys.

2.4. Knowledge gaps

Although Hydrogen Valleys are now a prominent feature of the EU's hydrogen policy and have been widely promoted in industry roadmaps, academic literature remains fragmented and limited in scope. Existing research ([Table 2](#)) tends to focus on the technical feasibility, economic viability, and policy and governance frameworks of hydrogen production.

These three strands—technical, economic, and governance—dominate the literature, but they fall short of capturing Hydrogen Valleys as integrated sociotechnical ecosystems. This gap motivates our focus on applying SOI and MLP frameworks, and three critical gaps are identified:

- (i) Lack of integrated sociotechnical analyses: The majority of studies treat Hydrogen Valleys primarily as technology deployment projects, neglecting their role as systemic innovation ecosystems. Few studies have explicitly analyzed how they interact with incumbent regimens or respond to broader landscape pressures—a perspective central to understanding their transformative potential.^{10,49}
- (ii) Limited application of SOI and MLP frameworks: Although SOI and MLP are well-established in sustainability transitions research, their combined application to Hydrogen Valleys is rare. This limits the ability to assess how sustainability objectives are embedded in innovation processes and how these projects evolve within multi-level sociotechnical systems.⁵⁸
- (iii) Insufficient comparative empirical evidence: Most of the available empirical work is based on single case studies or project-level evaluations. There is a lack of comparative analyses across multiple Hydrogen

Table 1. Integrated sustainability-oriented innovation and multi-level perspective framework for Hydrogen Valleys

Sustainability-oriented innovation dimension	Niches Hydrogen Valleys as pilot projects)	Regimens (energy, industry, mobility)	Landscape (climate, geopolitics, society)
Governance and inclusion	Local public-private partnership governance, municipal authorities	National certification, policy alignment	European Green Deal, Fit-for-55
Circularity and resource efficiency	Small-scale circular pilots (e.g., oxygen reuse)	Industrial symbiosis, cross-sector integration	Global resource flows, circular economy
Digitalization and smart integration	Basic digital tools, pilot demonstrations	Smart grids, digital twins	Digitalization trends, artificial intelligence, data governance
Social sustainability	Community acceptance, local employment	Workforce reskilling, equity in scaling	Societal values, energy justice

Table 2. Overview of research strands on EU Hydrogen Valleys

Main focus	Typical research topics	Representative studies	Limitations for Hydrogen Valley analysis
Technical feasibility	Electrolyzer performance, hydrogen storage, and infrastructure integration	Bhandari <i>et al.</i> ; ⁵⁴ Buttler and Spliethoff ⁵⁵	Reduces Hydrogen Valleys to technology pilots, overlooking sociotechnical dynamics and systemic integration
Economic viability	Levelized cost of hydrogen, investment risks, and supply-demand modeling	Glenk and Reichelstein; ⁵⁶ Ball and Wietschel ⁵⁷	Focuses on cost curves and investment, providing limited insight into governance, circularity, or social acceptance
Policy and governance frameworks	Funding mechanisms, regulatory barriers, and certification schemes	Wolf and Zander ¹³	Considers enabling conditions, but rarely connects to innovation ecosystems or systemic transition theory

Valleys, particularly those drawing on primary data and recent large-scale mapping efforts such as the EU Hydrogen Valleys Platform and CHJU datasets.²⁹

Addressing these gaps is essential for moving beyond technical and economic assessments toward a more comprehensive understanding of Hydrogen Valleys as strategic, policy-enabled innovation niches capable of shaping Europe's energy transition. This study responds to this need by integrating SOI and MLP lenses to analyze the current landscape of European Hydrogen Valleys, to identify systemic success factors and barriers, and to examine pathways for scaling both within and beyond the EU.

3. Methodology

3.1. Research design

This study employed a qualitative, hybrid analytical approach that integrated:

- (i) Broad mapping of all 76 European Hydrogen Valleys (based on the latest version of the EU Hydrogen Valleys Platform, August 2025) to identify macro-trends
- (ii) In-depth analysis of five strategically selected demonstration cases to examine sociotechnical dynamics through the SOI-MLP dual lens.

The dual-framework approach enables both descriptive mapping of Hydrogen Valley characteristics and

explanatory interpretation of their regimen-disrupting potential. Given the emerging nature of Hydrogen Valleys and the diversity of implementation models, a qualitative methodology is appropriate for generating theoretical insights and policy-relevant findings.⁵⁹

This dual-framework approach further facilitates descriptive mapping of current Hydrogen Valley initiatives and explanatory analysis of the drivers, barriers, and enablers that shape their evolution. The SOI-MLP integration supports the development of a structured typology that classifies Hydrogen Valleys as Pilot, Transitional, or Systemic, according to dimensions such as governance inclusivity, circularity, social performance metrics, infrastructure integration, and alignment with policy and market regimens.

3.2. Case selection

The analysis was conducted in two phases. First, an exploratory scan of all listed Hydrogen Valleys within the EU Hydrogen Valleys Platform and the CHJU database was performed to identify sectoral patterns, technological configurations, and spatial distributions. This broad scan helped establish a comparative landscape and inform the calibration of the analytical framework. Second, a focused subset of five Hydrogen Valleys was selected for deeper analysis based on the following criteria:

- (i) Relevance: Projects demonstrating a clear attempt at integrated value chains (e.g., production, distribution, and end use)

- (ii) Diversity: Inclusion of different national contexts, scales, and governance models
- (iii) Geographical scope: Projects located within the EU or associated countries
- (iv) Operational maturity: Valleys at an advanced planning stage, under construction, or already operational, as listed in the EU Hydrogen Valleys Platform and CHJU project database⁶⁰
- (v) Data availability: Access to publicly available reports, policy documents, technical briefs, and press releases.

Selected cases include NorthH2 (Netherlands), Green Hysland (Spain), Port of Antwerp (Belgium), H2 Energy Applications in Valley Environments for Northern Netherlands (Netherlands), and Hydrogen Valley South Tyrol (Italy). These cases were used to examine how Hydrogen Valleys align with—or fall short of—SOI and MLP principles in practice.

3.3. Data sources

The study was conducted using multiple secondary data sources to ensure triangulation:

- (i) Policy and strategy documents: European Commission communications, CHJU Annual Work Plan (2025), SRIA, and national hydrogen strategies⁷
- (ii) Industry reports and Hydrogen Valley databases: Clean Hydrogen Partnership annual reports,^{8,34,36} IEA Global Hydrogen Review (2024),² International Renewable Energy Agency report “International Trade and Green Hydrogen” (2023),²⁴ and International Renewable Energy Agency report “Global Hydrogen Trade to Meet the 1.5°C Climate Goal” (2022)¹⁴
- (iii) Academic literature: Peer-reviewed studies on SOI, MLP, and hydrogen ecosystem development
- (iv) Project documentation: Technical specifications, funding announcements, stakeholder presentations, and progress updates from individual Hydrogen Valley websites.

3.4. Analytical framework

The analysis applied theory-driven thematic coding based on the SOI and MLP frameworks:

- (i) SOI lens: Examined how sustainability goals were embedded within the design, governance, and expected impacts of each Hydrogen Valley
- (ii) MLP lens: Analyzed the positioning of Hydrogen Valleys within sociotechnical systems, including niche-regimen interactions and responses to landscape-level pressures.

The analytical process combined deductive coding based on SOI and MLP categories (e.g., niche-regimen interaction, circularity indicators) with inductive

refinements derived from emerging themes. Cases were classified using the SOI-MLP typology, and cross-case comparisons were conducted to identify success factors, bottlenecks, and policy implications.

3.5. Limitations

Three main limitations should be acknowledged:

- (i) Reliance on secondary data: This study relied primarily on publicly available sources, such as technical reports, project databases, and policy documents. Although suitable for comparative analysis, these sources may omit internal governance dynamics, unpublished challenges, or stakeholder perspectives
- (ii) Limited case application: While the study reviews the broader Hydrogen Valleys landscape, the SOI-MLP dual-lens framework is applied in-depth to only a subset of five demonstration cases. A more comprehensive application across the full spectrum of European Hydrogen Valleys would be necessary to validate and refine the typology and proposed scaling pathways
- (iii) Rapidly evolving policy and market context: Hydrogen-related policies, investments, and project statuses continue to evolve. The analysis reflects the state of knowledge as of August 2025 and may not capture the most recent developments, including new regulatory instruments, funding rounds, or cross-border initiatives.

Despite these limitations, the dual-framework methodology provides a novel and timely analytical foundation. It enables structured, theory-informed comparisons and generates actionable insights for advancing Hydrogen Valleys as systemic enablers of Europe’s energy transition. The selected cases maximize variation in valley maturity, geographical context, and sectoral focus, thereby supporting a nuanced analysis of sociotechnical transition dynamics.

4. Results

As of August 2025, the EU Hydrogen Valleys Platform has mapped 76 Hydrogen Valleys across Europe, ranging from early-stage planning to fully operational projects. These valleys represent over EUR 56.6 billion in public–private investment, with a reported average annual hydrogen production capacity of approximately 43,320 tons per year across projects with disclosed data.

The majority of the projects (58%) are regional-scale initiatives integrating multiple sectors, while 27% focus primarily on industrial applications, and 15% have a strong mobility orientation (e.g., hydrogen-powered buses, heavy-duty trucks, or maritime transport).²

Operational timelines vary, with most large-scale valleys targeting full commissioning between 2026 and 2029 to align with EU Fit-for-55 and REPowerEU milestones.

4.1. Governance and stakeholder configurations

Hydrogen Valleys in Europe display diverse governance structures that reflect regional industrial capacity, policy priorities, and stakeholder networks. Based on the analysis of 15 representative cases, three dominant governance models were identified:

- (i) Public-private partnerships: The most common governance structure, accounting for 63% of the examined cases. These combine municipal or regional authorities with industrial consortia to secure funding, coordinate permitting, and manage operations (e.g., Green Hysland [Spain])⁶¹
- (ii) Industry-led consortia: Representing approximately 27% of cases, these are typically driven by large energy and industrial companies, often located in port-based or heavy industrial clusters, with a primary focus on rapid commercialization (e.g., NorthH2 [Netherlands])⁶²
- (iii) Research-driven innovation clusters: Accounting for approximately 10% of projects, these are typically coordinated by universities or research institutes, focusing on demonstration activities, training, and advancing technology readiness (e.g., Hydrogen Valley South Tyrol [Italy]).⁶³

Across governance types, early involvement of offtake partners and the inclusion of multi-sectoral stakeholders correlate strongly with project resilience and the ability to secure long-term funding.

4.2. Technological integration and sector coupling

The updated dataset reveals that Hydrogen Valleys in Europe employ a multi-sectoral coupling strategy in more than half of the cases, integrating hydrogen production with multiple end-use applications to optimize demand. Common applications include:

- (i) Industrial feedstock substitution: Projects in Germany, Spain, and the Netherlands prioritize the decarbonization of steel, ammonia, and refinery production
- (ii) Mobility applications: Fuel-cell buses, heavy-duty trucks, and maritime vessels feature prominently in valleys in Portugal, France, and Greece, supported by dedicated refueling infrastructure
- (iii) Grid integration and storage: Seasonal hydrogen storage and power-to-gas are being piloted in Denmark, Finland, and Austria.²⁴

The average electrolyzer size among operational valleys is between 20 and 50 MW, with planned expansions up to

100–200 MW in large-scale flagship projects. Most projects utilize proton exchange membrane electrolyzers, even though alkaline and emerging solid oxide technologies are also represented.²

4.3. Success factors and persistent barriers

Based on the analysis of the selected Hydrogen Valleys, four recurring factors underpinning successful implementation were identified:

- (i) Policy alignment and funding continuity: The most successful valleys leverage both EU-level funding (e.g., Horizon Europe, Innovation Fund) and national subsidies to ensure stable, long-term financing⁶⁴
- (ii) Diversified offtake agreements: Securing cross-sectoral demand reduces market risk and improves bankability, thereby enabling early utilization of installed capacity
- (iii) Regional renewable resource endowment: Proximity to high-capacity wind or solar generation (e.g., North Sea, the Iberian Peninsula) lowers production costs and enhances project economics
- (iv) Cross-border collaboration: Valleys connected to transnational hydrogen corridors benefit from shared infrastructure and market access (e.g., AquaVentus, linking Germany to Denmark and the Netherlands) and demonstrate faster scaling potential.⁶⁵

Despite progress, several systemic barriers continue to limit the scale-up of Hydrogen Valleys:

- (i) High levelized cost of hydrogen: Averaging EUR 4–6/kg for renewable hydrogen in 2024, this cost remains above that of gray hydrogen, limiting competitiveness against fossil alternatives¹⁷
- (ii) Infrastructure bottlenecks: Hydrogen pipeline networks and large-scale storage remain underdeveloped in many countries, thereby restricting scaling potential
- (iii) Regulatory fragmentation: Differences in permitting procedures, safety codes, and certification schemes across member states slow deployment⁶⁶
- (iv) Green hydrogen for sustainable industrial development: Lack of a policy toolkit for developing countries
- (v) Workforce skills gap: Shortages of specialized hydrogen engineering, operations, and safety expertise persist across multiple valleys.¹⁷

4.4. Positioning within SOI and MLP frameworks

From an SOI perspective, Hydrogen Valleys exemplify mission-oriented innovation, with sustainability objectives embedded within governance structures, funding mechanisms, and evaluation metrics. From an MLP perspective, they function as protected niches actively

seeking to challenge incumbent fossil-based energy regimens. However, their niche strength varies significantly, with some valleys already integrated into broader hydrogen corridors (e.g., NorthH2, Green Hysland), while others remain isolated pilot projects without defined transition pathways. This divergence underscores the importance of policy support, market creation, and infrastructure integration in enabling the scaling of niche innovations into dominant sociotechnical regimens.^{37,50} As shown in Table 3, the SOI-MLP framework was applied to selected European Hydrogen Valleys to analyze their systemic characteristics, highlighting both sustainability integration (SOI) and transition dynamics (MLP).

4.5. Niche maturity matrix for Hydrogen Valleys

Although Hydrogen Valleys are often discussed as a unified policy instrument, their real-world systemic impact varies significantly. The Niche Maturity Matrix (Figure 1) applies SOI and MLP indicators to categorize valleys into Pilot, Transitional, or Systemic types, thereby revealing differences in design sophistication and regimen-level influence. This typology enables policymakers to tailor interventions according to the respective maturity stage, facilitating the identification of valleys that require protection, scaling support, or regimen integration.

In Table 4, a concrete application of niche market strategies to major European Hydrogen Valleys, analyzed through the SOI-MLP dual lens, is presented. These cases illustrate how valleys create protected spaces for innovation while strategically targeting early-adopter markets to disrupt incumbent regimens.

5. Discussion

The expansion to 76 Hydrogen Valleys by August 2025—surpassing the EU’s 2030 interim target—signals robust policy-investment alignment. However, this growth masks critical disparities in niche maturity and regimen impact, as revealed by the SOI-MLP analysis of five demonstration cases. This acceleration reflects strong political commitment, effective policy instruments, and growing industry confidence in green hydrogen as a viable decarbonization pathway.

These findings illustrate that Hydrogen Valleys occupy a dual role: both mission-driven sustainability experiments (SOI) and protected sociotechnical niches (MLP). Success factors highlight how effective policy-market alignment enables valleys to mature beyond pilot projects, while persistent barriers reflect systemic misalignments that hinder regimen integration. Embedding social sustainability

Table 3. Application of SOI-MLP dual lens to EU Hydrogen Valleys

SOI dimension	MLP lens	Applied insight from European Hydrogen Valley cases
Innovation purpose: Technology and social impact (e.g., climate, equity)	Niche formation: Early-stage protected spaces	Green Hysland and HEAVENN act as SOI pilots, with LCA-informed design, enabled by European Union funding niches through the Clean Hydrogen Joint Undertaking
Circularity: Valorization of excess heat, oxygen reuse, and water reuse	Regimen resistance: Fossil lock-in, infrastructure path-dependency	Circular use in Green Hysland faces limited scalability due to the existing centralized energy infrastructure and cost-competitive gas
Digitalization: Forecasting, smart grids, artificial intelligence-integrated load control	Landscape pressure: Climate goals, energy crises	Upper Rhine Valley uses digital twins to align with REPowerEU deadlines, though full regimen integration remains limited
Socioeconomic inclusion: Equity, workforce reskilling	Regimen dynamics: Social legitimacy and political momentum	Romanian Valley pilots highlight social gaps and labor skill mismatches; success depends on MLP regimen support, including skills funding
Funding orientation: Mission-oriented innovation (Horizon Europe, IPCEIs)	Windows for opportunity: Geopolitics, Fit-for-55	Hydrogen Bank and European Union missions are SOI-aligned but must be leveraged through MLP to achieve certification and corridor integration
Scaling tools: Modular replication of successful governance	Niche-regimen bridging: Valley-to-corridor transition	NorthH2 scales through infrastructure alignment with the European hydrogen backbone, showing effective niche-regimen coupling
Barriers: Levelized cost of hydrogen, fragmented regulation	Barriers: Infrastructure delays, policy misalignment	Romanian Valley shows that both cost innovation (SOI) and policy harmonization (MLP) are required for viability
Metrics for success: greenhouse gas savings, jobs, inclusion, system learning	Transition outcomes: Regimen transformation	Only valleys with multi-dimensional metrics (e.g., HEAVENN) demonstrate progression beyond demonstration toward systemic impact.

Abbreviations: HEAVENN: H2 Energy Applications in Valley Environments for Northern Netherlands; IPCEI: Important Projects of Common European Interest; LCA: Life cycle assessment; MLP: Multi-level perspective; SOI: Sustainability-oriented innovation.

Table 4. Application to selected European Hydrogen Valleys

Hydrogen Valley	Classification	Niche market focus	Key evidence	SOI-MLP rationale
H2 Valleys (Italy)	Pilot	Alpine mobility and microgrid resilience	(i) Research-driven (Eurac) (ii) Single application (alpine mobility) (iii) <5 MW electrolyzer	SOI: Lacks circularity or social KPIs MLP: Isolated from industrial regimens; no landscape leverage
Green Hysland (Spain)	Transitional	Tourism mobility and backup power	(i) Public-private partnership governance (ii) Tourism mobility and backup power (iii) 10 MW electrolyzer and six refueling stations	SOI: Multi-sector integration MLP: Exploits Island energy vulnerability (regimen friction)
HEAVENN (Netherlands)	Transitional	Heavy transport and green steel	(i) Industry consortium (ii) Steel and transport integration (iii) Public hydrogen network	SOI: Circular heat reuse MLP: Coopts Gasunie (regimen player); leverages gas phaseout
NorthH2 (Netherlands)	Systemic	Green ammonia for fertilizers and shipping	(i) Cross-border hydrogen corridor (DE, DK) (ii) Commoditized ammonia exports (iii) 4 GW electrolyzer by 2030	SOI: Embedded in EU taxonomy metrics MLP: Repurposes existing gas infrastructure; establishes EU-wide standards
Port of Antwerp (Belgium)	Systemic	Port logistics and chemical feedstock	(i) Hydrogen pricing linked to the TTF gas index (ii) Utilization of by-product oxygen in wastewater treatment (iii) Skills academy for workforce reskilling	SOI: Full circularity and social KPIs MLP: Redirects port logistics regimens; exploits EU taxonomy metrics

Abbreviations: DE: Germany; DK: Denmark; EU: European Union; HEAVENN: H2 Energy Applications in Valley Environments for Northern Netherlands; KPI: Key performance index; MLP: Multi-level perspective; SOI: Sustainability-oriented innovation; TTF: Title Transfer Facility.

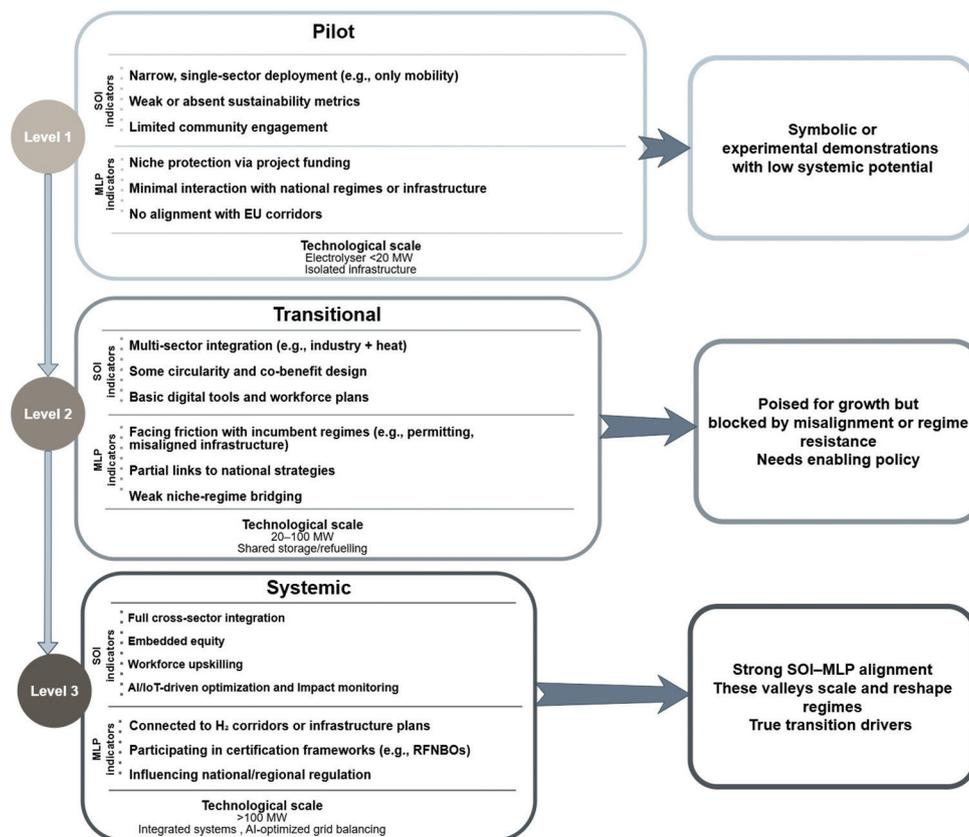


Figure 1. Niche maturity framework of European Hydrogen Valleys with integrated sustainability-oriented innovation-multi-level perspective diagnostics. Abbreviations: AI: Artificial intelligence; EU: European Union; IoT: Internet of Things; MLP: Multi-level perspective; RFNBO: Renewable fuels of non-biological origin; SOI: Sustainability-oriented innovation.

considerations and harmonizing regulatory frameworks are critical for unlocking scaling pathways.

5.1. SOI perspective: Mission-driven innovation at scale

From an SOI perspective, this growth illustrates the operationalization of mission-oriented policy at scale. Hydrogen Valleys function as living laboratories for sociotechnical experimentation, combining renewable hydrogen production with multi-sector applications and embedding sustainability goals into governance and evaluation frameworks. However, SOI implementation is uneven due to:

- (i) Advanced cases (e.g., NorthH2, Port of Antwerp) integrate cross-sectoral sustainability metrics such as carbon dioxide reduction and by-product valorization
- (ii) Lagging cases (e.g., South Tyrol) focus narrowly on technology demonstration while neglecting social equity and circularity.

European Union flagship initiatives and funding mechanisms have created the policy-investment nexus that enables these valleys to act as living laboratories.

5.2. MLP lens: The regimen integration divide

Through the MLP lens, the integration of valleys into the broader energy regimen remains uneven: systemic valleys, such as NorthH2 and Antwerp, leverage landscape pressures—including the REPowerEU plan and rising carbon prices—to connect with hydrogen corridors and repurpose fossil infrastructure, thereby reconfiguring elements of the regimen. In contrast, pilot and transitional valleys, such as South Tyrol and Green Hysland, remain niche-bound. Their progress is constrained by regulatory fragmentation, shortages of skilled labor, and weak connections to transnational infrastructure, which limit their ability to scale beyond local experimentation.

5.3. Pathways for scaling: Bridging SOI and MLP

Three main pathways have emerged to support the scaling of Hydrogen Valleys, with each requiring close synergy between SOI principles and MLP dynamics.

The first pathway involves the creation of networked macro-regions, where flagship projects such as NorthH2 anchor the North Sea hydrogen corridor. By pooling demand across multiple valleys and accessing shared infrastructure, these initiatives demonstrate how regional cooperation can accelerate regimen integration.

The second pathway centers on industrial cluster integration, exemplified by the Port of Antwerp. Here, hydrogen production is embedded within existing chemical and port ecosystems, creating circular synergies

while simultaneously leveraging logistics infrastructure to connect with broader regimens.

The third pathway is modular replication, where scalable design solutions enable transfer to new contexts. H2 Energy Applications in Valley Environments for Northern Netherlands, for example, developed standardized refueling modules that could be replicated in Eastern Europe, provided that harmonized regulatory frameworks and inclusive governance mechanisms are established.

International collaboration will be critical to advance these pathways, particularly in sharing best practices with hydrogen hubs in Asia, North America, and Australia, where progress in large-scale electrolysis and cost reduction can complement European initiatives.

At the same time, the geographic distribution of projects suggests the emergence of hydrogen “macro-regions.” Germany (17 projects), Spain (nine projects), and Portugal (five projects) lead in deployment, reflecting the interaction of industrial capacity, renewable resource availability, and proactive policy frameworks. While this clustering reinforces regional strengths, it also risks exacerbating spatial inequalities if lagging areas are not adequately supported.

5.4. Persistent barriers as SOI-MLP misalignments

Despite strong momentum, Hydrogen Valleys continue to face systemic barriers that constrain their evolution from protected innovation spaces to genuine regimen-transforming initiatives. The most pressing obstacles include elevated production costs (EUR 4–6/kg), limited transport and storage infrastructure, fragmented regulatory frameworks, and shortages of specialized skills.

These challenges can be understood as misalignments between SOI objectives and MLP dynamics (Figure 2). High costs reflect the absence of circular business models within valleys and the persistence of fossil fuel subsidies that entrench incumbent regimens. Skills shortages reveal weak workforce reskilling strategies, leaving niches without the capacity to disrupt existing regimens. Spatial inequalities further highlight the lack of equity in Hydrogen Valley governance and the absence of redistribution mechanisms to support lagging regions.

Nevertheless, Hydrogen Valleys demonstrate strong potential for cross-sector integration. By linking industrial, transport, and residential applications, they can optimize resource use, reduce waste, and enhance energy system flexibility. Local production of renewable hydrogen and the valorization of by-products, such as waste heat or oxygen, can further reinforce regional circular economies. However, social sustainability remains underdeveloped—workforce

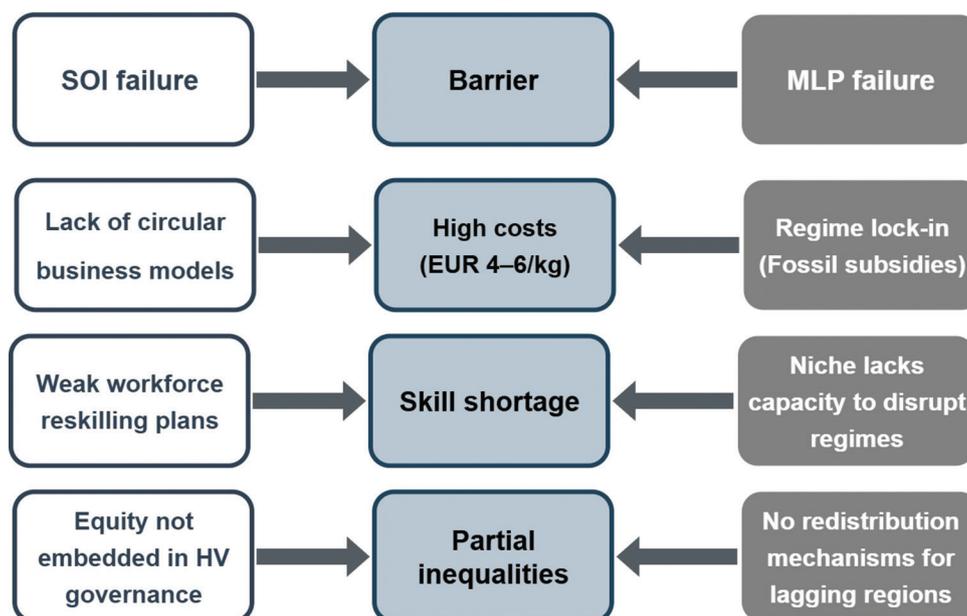


Figure 2. Persistent barriers to HV development interpreted as SOI-MLP misalignments
 Abbreviations: HV: Hydrogen Valley; MLP: Multi-level perspective; SOI: Sustainability-oriented innovation.

reskilling, community engagement, and equitable benefit-sharing mechanisms are often insufficient or missing. Without addressing these gaps, societal acceptance and long-term viability may be at risk.

Taken together, European Hydrogen Valleys emerge as both a policy success and a transition challenge. They have achieved scale in terms of numbers and investment, but the critical test now lies in delivering measurable decarbonization, enhancing market competitiveness, and achieving full integration into Europe’s evolving energy regimen.

6. Conclusion

6.1. From symbolic growth to regimen transformation

European Hydrogen Valleys demonstrate policy success in niche creation, achieving unprecedented scale (76 valleys, EUR 56 billion investment) through cross-sector integration that optimizes resource use, enhances circularity, and strengthens energy resilience. However, this momentum risks remaining symbolic if valleys persist as isolated experiments rather than drivers of systemic change.

The SOI-MLP lens reveals the critical gaps underlying this risk. On the SOI side, cross-sector integration is progressing, but social sustainability (e.g., workforce reskilling, community engagement, and equitable benefit-sharing) remains underdeveloped. On the MLP side,

high costs (EUR 4–6/kg), infrastructure bottlenecks, and regulatory fragmentation limit regimen integration, particularly for transitional valleys such as South Tyrol.

Achieving transformative impact therefore requires:

- (i) SOI rigor: Embed equity and circularity metrics into funding and evaluation
- (ii) MLP strategy: Fast-track hydrogen corridors and implement EU-wide certification
- (iii) Targeted maturation: Support pilots through demand aggregation and corridor connectivity.

Hydrogen Valleys thus embody both a decarbonization opportunity and a transition challenge. Their true potential lies in functioning as deliberately aligned sociotechnical experiments that translate niche successes into regimen-level reconfiguration.

6.2. Policy implications

To unlock this potential, policy interventions are needed across both niche and regimen levels:

- (i) Enhancing policy stability and funding predictability through long-term EU and national hydrogen strategies with reliable funding pipelines
- (ii) Investing in enabling infrastructure, particularly for transmission, storage, and refueling networks
- (iii) Harmonizing regulations through EU-wide certification, permitting, and safety standards
- (iv) Embedding social sustainability in project governance through workforce reskilling programs, community engagement, and benefit-sharing mechanisms

- (v) Fostering international collaboration with leading hydrogen hubs in Asia, North America, and Australia to accelerate cost reduction and scaling.

By embedding valleys within coherent frameworks and addressing systemic barriers, Europe can position them as blueprints for global hydrogen adoption.

6.3. Key synthesis from dual lens

The SOI-MLP framework clarifies the importance of Hydrogen Valleys. SOI provides the design logic (e.g., circularity, governance, and innovation) while MLP explains the dynamics of scaling niches into regimens under landscape pressure. Their transformative potential depends on aligning these two dimensions.

- (i) Transformative potential: Valleys serve as incubators of sustainable business models and as niches challenging incumbent regimens
- (ii) Scaling pathways: Modular replication (SOI-driven) and interconnected macro-regions (MLP-driven) provide viable routes for expansion
- (iii) Policy imperatives: Equity and circularity must be embedded in project assessment (SOI), while infrastructure and certification harmonization reduce regimen fragmentation (MLP)
- (iv) Risks: Without integration, valleys risk becoming “SOI showcases” without regimen impact, thereby reinforcing lock-in through social and infrastructure gaps.

Strategic nesting of SOI principles within MLP transition pathways is therefore essential. Frameworks such as Horizon Europe, the Hydrogen Bank, and Fit-for-55 must bridge innovation and regulation to enable valleys to fulfil their systemic role.

6.4. Future research directions

Future studies are recommended to:

- (i) Conduct longitudinal analyses of Hydrogen Valleys to track impacts and regimen integration over time
- (ii) Explore governance innovation, embedding social and environmental metrics (e.g., equity, jobs, circularity) into project design
- (iii) Assess global energy trade implications, focusing on transregional value chains and Europe’s role in connecting with emerging hydrogen exporters.

By situating Hydrogen Valleys within multi-scalar policy frameworks and addressing systemic misalignments, Europe can elevate them from regional pilots to global models. Their contribution lies not only in advancing clean hydrogen technologies but also in building integrated sociotechnical systems capable of reshaping energy, industry, and mobility regimens at scale.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

This study draws on publicly available secondary sources, including EU Hydrogen Valleys Platform and Clean Hydrogen Joint Undertaking databases, European Commission reports, and peer-reviewed literature. Additional information and supporting material can be obtained from the corresponding author upon reasonable request.

Further disclosure

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