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Hydrogen Hubs and ESG Sustainability: Best Practices and Governance Models for accelerating the adoption of Green Hydrogen by SMEs and Startups

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Abbreviations

Acronym	Description
AEL	Alkaline Electrolyser
AEM	Anion Exchange Membrane
AFIR	Alternative Fuels Infrastructure Regulation
AI	Artificial Intelligence
API	Application Programming Interface
ARCHES	Alliance for Renewable Clean Hydrogen Energy Systems
AREH	Asian Renewable Energy Hub (Australia)
BMC	Business Model Canvas
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CfD	Contract for Difference
CSR	Corporate Social Responsibility
DOE	Department of Energy (USA)
ENEA	National Agency for New Technologies, Energy and Sustainable Economic Development (Italy)
EPSRC	Engineering and Physical Sciences Research Council (UK)
ESG	Environmental, Social, and Governance
EU	European Union
EU ETS	European Union Emissions Trading System
FH2R	Fukushima Hydrogen Energy Research Field (Giappone)
FID	Final Investment Decision
GH2	Green Hydrogen Organization
GHES	Green Hydrogen Energy Systems
GHG	Greenhouse Gas
H2-Cluster Hamburg	Hamburg Hydrogen Cluster
H2IT	Italian Hydrogen and Fuel Cells Association e
H2Ports	Valencia Hydrogen Port Project
H2SHIFT	Hydrogen Smart Innovation and Future Technologies (EcoPark Torino)
H2START	Hydrogen Start-up Project (Bulgaria)
H2UB	Hydrogen Start-up Hub (Germania)
HaaS	Hydrogen as a Service
HECA	Hydrogen Energy California
HGHH	Hamburg Green Hydrogen Hub
ICT	Information and Communication Technology
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IRA	Inflation Reduction Act (USA)
IRENA	International Renewable Energy Agenc
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
LOHC	Liquid Organic Hydrogen Carrier
ML	Machine Learning
MOGC	Organization, Management and Control Model
NACE	Nomenclature of Economic Activities
NASEO	National Association of State Energy Officials
NLP	Natural Language Processing
OECD	Organization for Economic Co-operation and Development
OECDO	Organization for Economic Co-operation and Development Office
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PGM	Platinum Group Metals
PNRR	National Recovery and Resilience Plan
PPP	Public–Private Partnership
R&D	Research and Development
SDG	Sustainable Development Goal
SME	Small and Medium-sized Enterprise
SOEC	Solid Oxide Electrolyzer Cell
TRL	Technology Readiness Level
UAE	United Arab Emirates
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
WEF	World Economic Forum
WGEH	Western Green Energy Hub (Australia)

Abstract

This thesis analyzes the methods for adopting green hydrogen within the context of Hydrogen Hubs, and in particular examines governance models and commercial incentives necessary for involving small entities such as SMEs and startups in this framework. The research delves into how these factors can contribute to accelerating the adoption of green hydrogen while simultaneously pursuing Environmental, Social, and Governance (ESG) sustainability objectives. The analysis also highlights the fundamental role of effective governance and financial mechanisms supporting the participation of SMEs and startups, which are considered entities with a primary role in technological innovation. Furthermore, through the examination of best practices, international policies, and case studies of both active and failed hydrogen hubs, the thesis identifies the crucial factors that determine the success of these ecosystems, including stakeholder engagement, the definition of binding purchase contracts and a strong integration of ESG criteria. The results suggest that the combination of inclusive and transparent governance, targeted financial support, and a collaborative approach between the public and private sectors creates the essential mix for large-scale adoption of green hydrogen. The thesis concludes by proposing a framework for the creation of resilient, competitive, and sustainable hydrogen hubs, which contribute to the global energy transition while promoting local economic development and social cohesion.

Introduction

Over the past decades, the increasing urgency of addressing climate change and reducing dependence on fossil fuels has led the international community to promote a profound process of energy transition. Global agreements such as the Paris Agreement, together with the strategies advanced by the European Union, including the Green Deal and the Hydrogen Strategy, have charted a pathway towards a decarbonized and sustainable energy system to be achieved by 2050. In this context, green hydrogen is increasingly emerging as one of the technological and strategic pillars of the transition, thanks to its versatility and its potential to significantly reduce greenhouse gas emissions **(European Hydrogen Observatory, 2025,EU Green Deal).** Green hydrogen is widely recognized as one of the most promising solutions for the decarbonization of energy-intensive and hard-to-electrify sectors. Its ability to function as a flexible energy carrier and to promote integration across different energy systems makes it particularly strategic in advancing a just and sustainable transition **(European future energy forum,2025).**

Produced through electrolysis powered by renewable sources, green hydrogen offers tangible opportunities for integration with energy-intensive industries, storage systems, and low-emission mobility. An emerging concept gaining relevance in this regard is that of hydrogen valleys: territorial ecosystems where the production, distribution, and use of hydrogen are integrated locally, generating multiplier effects across economic, environmental, and social dimensions. **(European Commission-Clean Hydrogen Partnership,2025, Hydrogen Valleys).**

Scientific literature and industry reports have examined integrated green hydrogen systems not only from a technological perspective but also in terms of governance models, incentive policies, and sustainability criteria. Clean energy hubs, in particular, represent contexts in which the logic of ecological transition takes shape through synergistic projects that bring together public and private stakeholders **(Hydrogen Europe, 2023,Hydrogen Europe Research).** Within these hubs, the adoption of ESG (Environmental, Social, Governance) criteria becomes a key factor in assessing the effectiveness and long-term sustainability of initiatives, while the involvement of SMEs and startups proves essential in accelerating innovation and facilitating the diffusion of new technologies. **(H2IT, 2021)**.

Nevertheless, despite the growing momentum, several critical questions remain open. How should the governance of hydrogen hubs be structured to ensure efficiency and resilience? Which strategic models are most effective in fostering robust and sustainable supply chains? To what extent can financial support, both public and private, determine the long-term success of such projects? Above all, how decisive is the active participation of small and medium-sized enterprises (SMEs) and startups in stimulating innovation, diversifying technological solutions, and promoting the widespread adoption of green hydrogen across regions?

These questions form the starting point of this thesis, which seeks to explore the role of green hydrogen and hydrogen valleys as territorial hubs where production, distribution, and use converge through collaboration between public institutions, private companies, universities, and research organizations. Their integrated nature allows not only for the experimentation of new technological solutions but also for the creation of local ecosystems oriented around hydrogen, capable of delivering economic, environmental, and social benefits. From this perspective, hydrogen valleys assume a strategic role, functioning as incubators and accelerators of one of the most promising energy carriers for decarbonization and for achieving climate neutrality targets **(Edison Next, 2024)**.

Specifically, this research aims to investigate how different governance models and commercial incentive mechanisms implemented within hydrogen hubs can enable and support the active participation of SMEs and startups in the adoption of green hydrogen technologies, as well as to analyze the impacts generated in terms of positive outcomes on environmental, social, and governance (ESG) parameters.

Through a comparative analysis of international policies, best practices, and relevant case studies, the thesis seeks to provide a comprehensive framework of the dynamics governing the integration of green hydrogen into existing energy systems, highlighting the role of SMEs and startups as key innovation actors capable of generating flexible, scalable, and high-value-added solutions.

The ultimate objective is to identify effective governance strategies and targeted incentive tools that can foster the creation of hydrogen hubs that are competitive, inclusive, and sustainable. At the same time, the research aims to understand how these green innovation strategies may contribute to the achievement of ESG goals, thereby promoting not only environmental sustainability but also social cohesion, the creation of skilled employment opportunities, and greater transparency in decision-making processes. In conclusion, this thesis aspires to offer an original and concrete contribution to the academic and policy debate on the future of sustainable energy, highlighting the transformative potential of green hydrogen and the essential role of SMEs and startups as drivers of systemic change and responsible innovation.

The thesis begins by outlining the general context of the energy transition and the international policies shaping its development, before introducing the key concepts of green hydrogen and hydrogen valleys. These are presented not merely as technical solutions but as genuine instruments of economic and social transformation, capable of linking innovation, sustainability, and local development. This is followed by a review of the state of the art, which examines the main technologies currently available, the organizational models that support their adoption, and the application of ESG criteria as benchmarks for designing and evaluating sustainable initiatives. This step provides a solid theoretical foundation for the analysis of concrete cases that follow.

The discussion then focuses on the strategic and organizational dynamics that characterize hydrogen hubs and, on the role, played by SMEs and startups in this context, with particular attention to governance structures, long-term strategies, and the contribution of both public and private actors in building resilient and integrated infrastructures. Subsequently, the methodological approach adopted in the research is presented, clarifying the criteria for selecting case studies and the techniques used for data collection. The central part of the thesis is devoted to the case studies themselves, which are analyzed in detail to highlight their distinctive features, the challenges they faced, and the results achieved. The comparative analysis that follows emphasizes areas of convergence, significant differences, and potential critical success factors.

Finally, the thesis concludes with a synthesis of the findings, accompanied by operational recommendations addressed to businesses, institutions, and policymakers, as well as proposals for possible directions for future research and development.

1 Background

Growing energy demand and the needs associated with energy transition have a profound impact on the global economy, shaping the future of political relations worldwide. The harmful emissions released as a result of energy production and use from traditional sources (primarily fossil fuels) make a major contribution to the widespread phenomenon of climate change. The effects of climate change on the planet's balance, together with concerns related to energy security and the possible depletion of traditional energy resources, have significant repercussions on the global economy, involving the entire world production system. The urgent need to find effective strategies in a short timeframe also represents an important opportunity to develop alternative energy systems at the international level, enabling economic and social growth to return to levels compatible with the preservation of our planet while ensuring adequate energy supply for all countries of the international community, even in the event of shortages of traditional energy sources.

In this situation, the use of alternative energy sources and the introduction of energy efficiency and saving policies represent a major opportunity. The rapid growth of global energy demand makes it essential to take careful decisions that gradually lead to the abandonment of fossil fuels, so harmful to the health of our planet, and to the increase of both energy efficiency and the use of renewable energy worldwide.

Achieving the energy objectives that have been set requires substantial investments in the field of sustainable energy, coming from both public actors and private operators. These must be accompanied by adequate governmental incentive schemes to support research and the development of low-emission technologies, with positive effects also in terms of employment. As highlighted by the **World Economic Forum** in the report **Fostering Effective Energy Transition (2025),** the energy transition can be accelerated through an approach based on international cooperation and strong public–private synergy, in which industrial policies and incentive systems play a central role.

To respond adequately and quickly to this emergency, it is necessary to adopt an energy policy that goes beyond national borders and is extended to the international level. The foundations of a sustainable energy system must in fact be laid through the establishment of an international framework involving all actors in the energy sector and, above all, the organizations that most effectively represent the interests of the international community. Establishing such a regulatory system should also act as a strong incentive for the rapid creation of a sustainable global energy system ***(*Ahmed Elkhatat et al., 2024).**

The link between the fair evolution of the energy sector, environmental protection, and the socio-economic development of society is fully expressed in the concept of sustainable development. This principle requires economic growth to be compatible with the preservation of environmental resources, for the benefit of both present and future generations. Economic and technological progress is fundamental for human development, especially in less advanced regions, but equal importance must be given to the protection of the environmental heritage, which cannot be endangered by uncontrolled growth **(European Parliament, 2025, Environmental Policy: General Principles and Framework).**

According to the principle of sustainable development, technological processes in the long term should not have a negative impact on the natural environment. Applied to the energy sector, this means that economic development based on energy production that generates high greenhouse gas emissions and relies on the complete depletion of traditional resources (namely fossil fuels such as coal and oil) cannot be considered sustainable, since it produces a strong negative impact on the environment.

Ensuring the sustainable development of society therefore requires careful management of issues linked to the availability and exploitation of energy resources. It has become increasingly urgent to reverse the current course by developing and implementing, both internationally and nationally, regulatory tools that promote the use of alternative energy sources on several levels. Among these, renewable energy represents the safest choice for environmental protection, since its use involves minimal pollution and does not generate the same environmental damage associated with traditional energy sources, proving particularly advantageous in terms of sustainability.

Within this framework, green hydrogen can play an increasingly important role. However, its development requires policies that not only encourage its diffusion but also promote its integration into a broader and interconnected energy system. Indeed, it is precisely economic and regulatory decisions that determine both the sustainability and the pace of the energy transition.

1.1 International Policies as a Driver of the Transition to Green Energy

The energy transition represents the shift from an energy production model based on fossil fuels, like oil, natural gas, and coal, to a system based on renewable sources, such as wind and solar power. This change is driven not only by the finite nature of fossil resources but, more importantly, by the need to reduce environmental impact and carbon dioxide (CO_2) emissions, the primary cause of global warming and related phenomena, such as glacier melting, rising sea levels, desertification, and the intensification of extreme weather events, such as hurricanes and floods. To address these challenges and promote a path towards decarbonization, the European Union has outlined a series of strategic milestones aimed at transforming the continent into the first climate-neutral region, with the ambitious goal of achieving NET-ZERO by 2050 **(IEA, 2021, Report). (**Figure 1**)**

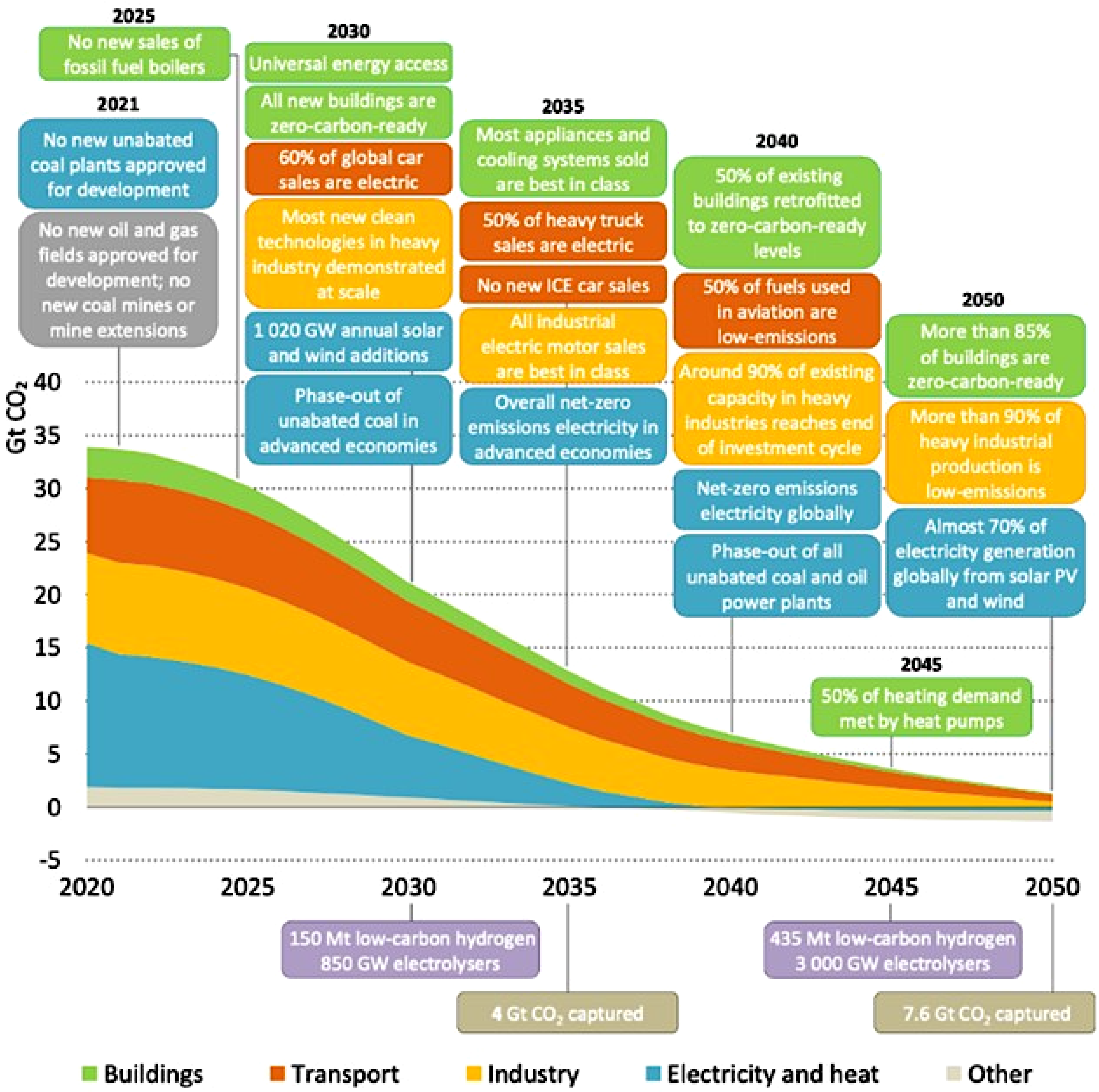


Figure 1: Key Steps in the Path to Achieve Net Zero Emissions by 2050 in Various Strategic Sectors (Source: IEA, 2021, Report Net Zero by 2050 - A Roadmap for the Global Energy Sector)

In this context, the growing interest in hydrogen must be framed. According to the International Energy Agency (IEA), hydrogen can play a significant role "in addressing many energy challenges and achieving the 2050 targets", both by integrating renewables and by helping decarbonize so called hard-to-abate sectors, such as the chemical and steel industries and heavy transport, where it is difficult to eliminate emissions through direct electrification and currently available technologies. With the transition of green hydrogen from a niche technology to a central component of the energy transition, public policies must go beyond merely promoting its spread and instead focus on facilitating its structural integration into the broader energy system. It is precisely economic and industrial policy decisions that determine the sustainability, speed, and scale of this transition. For green hydrogen to generate real value, it is crucial that both society and the industrial sector play an active role in its development. Only through widespread and informed participation will it be possible to create the conditions for a supportive ecosystem, capable of not only fostering the growth of the hydrogen sector but also driving the overall evolution of the energy and social systems in a sustainable direction.

In recent years, the international community has recognized hydrogen, particularly that produced from renewable sources (the so-called "green hydrogen"), as one of the most promising tools for accelerating the energy transition and reducing carbon emissions in energy-intensive sectors. The International Energy Agency (IEA) has played a leading role in this regard, publishing the report "**The Future of Hydrogen publication in June 2019**", which provided a detailed analytical framework for the potential of hydrogen as an energy carrier, highlighting its versatility in industrial applications, long-distance transport, and energy storage. The IEA has clearly emphasized that for hydrogen to play a systemic role in global decarbonization, it is necessary to lower the cost of green hydrogen production and develop adequate infrastructure for its production, storage, transport, and distribution. In this context, the report stresses the urgency of moving away from hydrogen forms with high carbon intensity (such as "grey" and "blue" hydrogen) and decisively shifting towards those with low or zero environmental impact.

To tackle these challenges, many international strategic initiatives have been established, combining research, multilateral cooperation, and the mobilization of financial resources to promote the development of renewable hydrogen. One of the most significant of these is *the* **Hydrogen Council,** a global coalition launched in 2017, which today includes around 150 large companies active in the energy, transport, and industrial sectors. The goal is to promote large-scale investments in green hydrogen to contribute to achieving the targets of the Paris Agreement. In parallel, the Clean Energy Ministerial Hydrogen Initiative **(Clean Energy Ministerial/Hydrogen Initiative (H2I), 2020)**, launched in 2019 and coordinated by the IEA, represents an intergovernmental initiative aimed at strengthening public policies and projects to support the commercialization of hydrogen technologies and fuel cells. This platform has enabled the creation of multilateral partnerships, fostering joint investments between governments and the private sector.

Another important coordination and support tool is the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE, 2023), **(U.S. Department of Energy and transportation, 2030)**. Today, IPHE involves 24 countries and plays a crucial role in aligning national policies and funding research and development programs. To support innovation and industrial competitiveness, the Mission Innovation platform, launched in 2015 during COP21, has set the target of reducing the cost of green hydrogen to $2 per kilogram by 2030 and building at least 100 "hydrogen valleys" worldwide, integrated areas where hydrogen production, consumption, and transport develop in a coordinated way **(Europe Union, 2021, Mission Innovation).**

In Europe, another example of a systemic approach is the European Clean Hydrogen Alliance, founded in 2020 **(European Commission, 2020,European Clean Hydrogen Alliance*)*** to foster the creation of a continental ecosystem for clean hydrogen, stimulating both public and private investments in large-scale industrial projects.

At the same time, IRENA's global strategy, the International Renewable Energy Agency, saw significant evolution in 2024. According to the document "***Green Hydrogen Strategy: A Guide to Design*** **(IRENA, 2024)** 46 countries have already adopted a national hydrogen strategy, with another 20 in the process of development. These strategies converge on three key drivers of development: i) decarbonization, ii) industrial development opportunities, and iii) energy security. To support these objectives, many countries have defined investment plans and direct incentives for the construction of electrolysis plants, storage infrastructures, and logistical networks for hydrogen transport.

The IEA's **Global Hydrogen Review 2023** highlighted a steady increase in both public and private investments in the hydrogen value chain, particularly for green hydrogen. Efforts are focused on scaling up electrolysis capacity, with the aim of reaching a global capacity of 117.4 GW by 2030 and over 370 GW by 2050. At the same time, green hydrogen demand is expected to grow to 27.6 million tons by 2030 and 164 million tons by 2050. To achieve these targets, national strategies outline gradual steps: from technological maturity to market penetration and eventually to large-scale commercial growth. This approach allows public policies to be adapted according to achieved results, progressively adjusting support mechanisms, evaluating the need for further fiscal incentives, public financing, or regulatory frameworks.

Another central aspect is the international consensus on the role of hydrogen in priority sectors such as heavy transport, aviation, public transport, and energy-intensive industries. Countries such as Japan, South Korea, Germany, and Australia have distinguished themselves by adopting particularly ambitious investment plans, integrating support for the national industry with bilateral agreements for importing green hydrogen from exporting countries **(World Energy Council, 2020, International Hydrogen Strategies)**. In fact, global hydrogen trade is increasingly seen as an opportunity to develop an international supply chain that balances production and demand across regions with different renewable resource availability.

In conclusion, the international context today appears strongly mobilized toward building a hydrogen economy, where targeted financing tools, public-private alliances, multilateral initiatives, and national strategies converge to promote the expansion of green hydrogen as a key driver for global decarbonization and future energy security.

Within the European context, hydrogen is now considered a fundamental pillar of strategies for the ecological transition, particularly for the decarbonization of energy-intensive industrial sectors and heavy transport, areas where traditional renewable technologies are often insufficient. In July 2020, following the economic and social crisis triggered by the COVID-19 pandemic, the European Union adopted **NextGenerationEU (NGEU)**, an extraordinary recovery and resilience plan with a total allocation of approximately €806.9 billion at current prices (European Commission, 2023). This temporary tool, operational from 2021 to 2026, is funded through the issuance of common debt securities by the Commission and is primarily structured within the Recovery and Resilience Facility (RRF), which accounts for around 90% of the total resources.

The strategic framework of NGEU is aligned with the objectives set by the ***European Green Deal***, adopted by the Commission on December 11, 2019, which aims to achieve climate neutrality by 2050 through a broad transformation of production, consumption, and energy models in a sustainable direction. In this sense, the implementing regulation of NGEU mandates that at least 37% of the resources allocated to each National Recovery and Resilience Plan (NRRP) be dedicated to green transition interventions, and at least 20% to digital transition, thus promoting a dual technological and environmental acceleration.

Among the priority initiatives supported by this financial framework, the European Hydrogen Strategy **(EU strategies on hydrogen and energy system integration, 2021)** published on July 8, 2020, plays a central role in building a climate-neutral economy. The strategy identifies renewable hydrogen, specifically green hydrogen produced through electrolysis powered by renewable sources, as a strategic energy carrier for decarbonizing energy-intensive industrial sectors and segments of transport that are difficult to electrify. The interaction between NGEU, the Green Deal European, and the Hydrogen Strategy thus forms an integrated political-financial architecture, aimed at mobilizing large-scale public and private investments to accelerate the energy transition and ensure the European industrial competitiveness in the context of decarbonization. The strategy has been strengthened by additional legislative and programmatic tools. Notably, with the **Fit-for-55** package in 2021, the Commission introduced a series of regulatory proposals to translate the strategy's goals into a binding legal framework, while with the **REPowerEU** plan in 2022, it reaffirmed renewable hydrogen as a key component to strengthen energy security and reduce dependency on Russian fossil fuels. REPowerEU set ambitious targets: to produce 10 million tons of renewable hydrogen annually within the EU and to import an equal amount by 2030.

To make these goals a reality, the European Union has implemented numerous financial and regulatory tools. Among the key support instruments are the Important Projects of Common European Interest **(IPCEI)** dedicated to hydrogen, which allow member states to financially support strategic industrial projects, even by derogating from the limits imposed by state aid rules. State aid approved, along with private investments planned for research and development in these integrated IPCEIs, amounts to over €92.2 billion. Of the eleven integrated IPCEIs approved so far (Figure 2), more than 22% of the participating companies are small and medium-sized enterprises (SMEs). Since the launch of the first integrated IPCEI in 2018, the participation rate of SMEs and the share of approved state aid for SMEs have consistently increased from 7% in IPCEI Microelectronics 1 to 64% in IPCEI Med4Cure in 2024 and 60% in IPCEI Tech4Cure in 2025.

Approved Integrated Important Projects of Common European Interest (IPCEI)

	Participating companies	Participating projects	State aid approved (EUR billion)	Expected private investments (EUR billion)	Participating Member States
First IPCEI on Microelectronics (2018)	29	43	1,9	6,5	
First IPCEI on Batteries (2019)	17	23	3,2	5	
Second IPCEI on Batteries – EuBatIn (2021)	42	46	2,9	9	
First Hydrogen IPCEI – Hy2Tech (2022)	35	41	5,4	8,8	
Second Hydrogen IPCEI – Hy2Use (2022)	29	35	5,2	7	+
Second IPCEI on Microelectronics and Communication Technologies (2023)	56	68	8,1	13,7	
IPCEI on Next Generation Cloud Infrastructure and Services (2023)	19	19	1,2	1,4	
Third Hydrogen IPCEI – Hy2Infra (2024)	32	33	6,9	5,4	
Fourth Hydrogen IPCEI – Hy2Move (2024)	11	13	1,4	3,3	
IPCEI Med4Cure (2024)	13	14	1	5,9	
IPCEI Tech4Cure (2025)	10	10	0,4	0,8	
Total	293 257*	345	37,6	66,8	23 Member States, UK and Norway participated in at least one IPCEI

*Excluding the companies that participated in more than one IPCEI

Figure 2: Important Projects of Common European Interest (IPCEI)
(Source: European Commission/2025)

Alongside the IPCEIs, a central role is played by the European Hydrogen Bank, established by the European Commission to support investments in the renewable hydrogen market. This bank operates on four pillars **(Communication on the European Hydrogen Bank, 2023)**: a domestic mechanism to connect supply and demand within the EU; public auctions to fund innovative projects (the first, concluded in April 2024, allocated €720 million to seven projects); an international platform to facilitate green hydrogen imports; and a coordination and transparency system to support market players and ensure the proper functioning of the ecosystem. These measures are complemented by the Innovation Fund, financed through the proceeds of the Emissions Trading System (ETS), which supports pioneering projects in low-emission technologies, including electrolyzes, fuel cells, and carbon capture and utilization.

Other financial instruments also contribute significantly to the development of hydrogen, including the Connecting Europe Facility, the Modernization Fund, the European Regional Development Fund, the Cohesion Fund, the Just Transition Fund, and LIFE projects **(European Hydrogen Observatory, 2024, Financial Tools and Incentives)**. Additionally, the Clean Hydrogen Partnership, a public-private partnership under the Horizon Europe program, funds research and demonstration across the entire hydrogen value chain: from production to logistics, from storage to end-use. The partnership also focuses on strategic aspects such as training, standardization, the creation of hydrogen valleys, and strengthening European supply chains **(European Union, 2021. Clean Hydrogen Joint Undertaking).**

At the regulatory level, the EU has strengthened the role of hydrogen with the adoption of the RED III Directive (2023/2413), which sets specific sub-targets for the use of renewable fuels of non-biological origin (RFNBO), including green hydrogen. According to the directive, by 2030, at least 42% of hydrogen used in industry must come from renewable sources, a percentage that will rise to 60% by 2035. In the transport sector, the share of renewable energy derived from RFNBO must reach at least 5.5% by 2030, with at least 1% produced from renewable hydrogen.

The new European regulation, approved on September 20, 2023, the **AFIR (Alternative Fuels Infrastructure Regulation, 2023)**, has introduced binding criteria for the development of hydrogen refueling infrastructure along the core TEN-T network. By 2030, all Member States must ensure a minimum infrastructure coverage, with publicly accessible stations every 200 km, a daily capacity of at least one ton of hydrogen, and a delivery pressure of 700 bar.

Finally, with the approval of the EU package for the decarbonization of gas and hydrogen **(Directive 2024/1788 and Regulation 2024/1789)**, part of the broader legislative framework Fit for 55, the EU has defined the framework for the gradual integration of renewable gases into energy markets. The new legislative tools, to be transposed by mid-2026, aim to ensure fair access to networks, promote the hydrogen market, guarantee supply security, and protect environmental sustainability.

Overall, the European approach to promoting hydrogen stands out for its integrated and multi-level vision: alongside the setting of ambitious quantitative targets, it combines concrete financial tools, technological partnerships, binding regulatory standards, and strong public-private cooperation. Green hydrogen thus emerges as a strategic pillar of European energy policy, essential both for decarbonization and for the sustainable reindustrialization of the continent.

In line with international and European trends, Italy has progressively consolidated its own strategic framework aimed at promoting hydrogen as a fundamental component in the energy transition and the decarbonization of the economic and industrial system. The National Hydrogen Strategy **(MASE/2024)**, as outlined by the Ministry of the Environment and Energy Security, includes a set of complementary measures aimed at facilitating the implementation of projects, including the introduction of incentive schemes to reduce the cost of hydrogen production, support for the entire value chain, from production to distribution, and the simplification of authorization processes, particularly regarding environmental and safety aspects.

The first formal steps in this direction date back to late 2020, when the Ministry of Economic Development published the Preliminary Guidelines for the National Hydrogen Strategy **(Minister of Economic Development, 2020)**, a document providing high-level guidance on the potential role of hydrogen in the country's future energy landscape. This document outlined a development trajectory that positioned renewable hydrogen at the core, especially in sectors that are difficult to electrify, heavy transport, and energy storage processes.

This vision was later reaffirmed and strengthened in the update of the **National Energy and Climate Plan (PNIEC), published in 2024**, which adopted European directives and the objectives of the **Repower EU** plan, defining a minimum development path for hydrogen. The Italian plan estimates a total consumption of approximately 0.25 million tons of renewable hydrogen per year by 2030, of which at least 70% should be produced domestically. This forecast reflects the ambition to promote a domestic hydrogen industrial supply chain, leveraging local renewable resources and fostering job creation and skill development in the sector.

Italy has structured its approach through a variety of investment and research support tools, many of which are included in the National Recovery and Resilience Plan (PNRR). In particular, Mission 2 called "Green Revolution and Ecological Transition," allocates significant investments to promote hydrogen, with over €3.6 billion earmarked for initiatives related to production, distribution, and end-use, especially in industry and transport **(MASE,2022, MISSIONE 2)**. Among the most notable measures are calls for the creation of hydrogen valleys, territorial districts where the production, use, and distribution of hydrogen develop in an integrated and synergistic way. These projects aim to create advanced technological hubs and generate a leverage effect on private investments, contributing to the strengthening of the national supply chain.

At the same time, Italy actively participates in European IPCEI projects already mentioned (Hy2Tech, Hy2Use, Hy2Infra, Hy2Move), with significant involvement from Italian companies and research centers in R&D projects, industrial production, and infrastructure development. Participation in IPCEIs not only allows Italy to access dedicated funding but also strengthens its position in the hydrogen value chain at the European level, positioning it as a key player in the development of technologies and innovative solutions ***(MASE, 2025,*****Investimento 3.1 Hydrogen Valleys).**

At the regulatory level, the transposition of the RED III directive and the new European regulations on the decarbonization of gas and hydrogen is expected by 2026. The Italian government has already initiated preparatory work to adapt the national legal framework, aiming to facilitate the integration of hydrogen into energy markets and ensure fair and transparent access to transport and distribution infrastructures. Additionally, the updated PNIEC (National Integrated Energy and Climate Plan) sets specific targets for the industrial and transport sectors, accompanied by support measures such as certification systems, purchase obligations, public financing schemes, and tax incentives to promote the *diffusion of hydrogen-related technologies.* In particular, Italy is one of the few member states to have outlined a detailed breakdown of renewable hydrogen consumption targets across different sectors, as well as an analysis of investment needs and a plan for the development of electrolysis capacity. The goal is to reach an installed capacity of 5 GW of electrolyzes by 2030 (**CESI Studies, 2021, Italian Hydrogen Strategy)**, with a theoretical production of approximately 0.9 million tons per year. Furthermore, evaluations are underway to establish bilateral agreements for importing green hydrogen from third countries, in line with the diversification goals of the REPowerEU plan.

Overall, the national strategic framework reaffirms Italy's intention to position itself competitively in the emerging hydrogen economy. The combination of financial tools, participation in European projects, infrastructure investments, and regulatory policies provides a solid foundation for promoting the adoption of green hydrogen in the coming years, with the aim of making a significant contribution to the decarbonization commitments made at the EU and global levels.

In light of the above initiatives, the evolution of the hydrogen market in Italy can be structured into three main time phases, each characterized by specific objectives, implementation tools, and operational challenges **(MASE, 2024, National Hydrogen Strategy)**. In the short term, from now until 2030, the launch of the first projects will largely be driven by European obligations introduced by the aforementioned RED III directive, which imposes minimum quotas for the use of renewable hydrogen in energy-intensive sectors, such as industry and transport. In this context, Italy, as mentioned earlier, has already initiated a structured path for the development of the national hydrogen market, particularly leveraging the National Recovery and Resilience Plan (PNRR).

During this initial phase, market development will mainly occur through the creation of Hydrogen Valleys, territorial ecosystems where hydrogen production and consumption are concentrated in specific areas, promoting synergies between different sectors, primarily mobility and industry. This will enable the activation of local value chains and promote the use of hydrogen types specified by European delegated acts, namely renewable hydrogen and low-carbon hydrogen. These initial volumes will be equipped with specific guarantees of origin to ensure traceability and compliance with EU regulations. Additionally, the development of local hydrogen transport and logistics infrastructures will begin, including the planning of production from renewable energy carriers such as ammonia and methanol. This will help increase the availability of Renewable Fuels of Non-Biological Origin (RFNBO), contributing to meeting the growing decarbonization needs **(The Preliminary Guidelines for the National Hydrogen Strategy, 2020).**

In the medium term, between 2030 and 2040, we will enter a scaling-up phase, where the goal will be to consolidate the hydrogen market, expanding it beyond the experimental phase and making it a structural component of the national economy. Public policies will aim to ensure continuity with the initiatives launched in the short term, focusing on the implementation of larger-scale projects capable of generating economies of scale and reducing operational costs. Growth will be driven not only by environmental targets but also by the increasing availability of H_2-ready technologies, which are ready to integrate hydrogen into existing energy systems. In this time frame, hydrogen demand is expected to rise in the most difficult sectors to decarbonize, such as maritime and aviation transport, high-temperature industry (HTA), as well as heavy-duty and long-range mobility. To this end, the development of an extensive infrastructure for hydrogen production and distribution will be crucial, not only to ensure supply but also to ensure that it is competitive and efficient.

Finally, in the long term, between 2040 and 2050, hydrogen could become a strategic component of the national energy mix, playing a central role in achieving climate neutrality (Net Zero) targets. The most credible estimates suggest a potential hydrogen penetration of 13-14% of final industrial HTA consumption and 30% of transport consumption (Figure 3). To make this evolution possible, it will be essential to have developed an advanced infrastructure network capable of linking large-scale production hubs with major consumption centers. In this mature phase, hydrogen may also be used in innovative sectors, previously less explored, such as grid balancing through Power-to-Gas (P2G) and Power-to-Power (P2P) solutions, as well as seasonal energy storage. Italy could also aim to become a strategic energy hub for Europe, facilitating the import and transit of hydrogen and its derivatives thanks to new interconnections with North Africa and leveraging its port network, both on the Tyrrhenian and Adriatic sides, as an entry point for energy carriers such as ammonia and methanol. This scenario paves the way for a profound transformation of the Italian energy system, with hydrogen at the center of a new industrial and infrastructural paradigm **(Gandiglio/Marocco, 2025).**

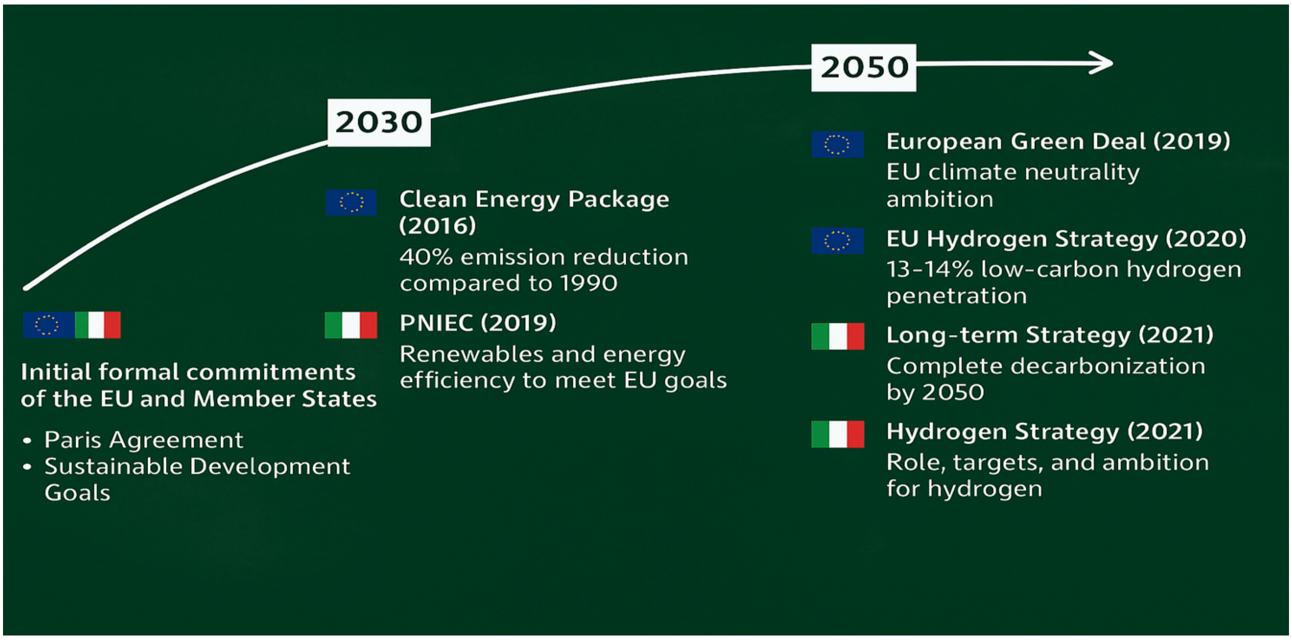


Figure 3: Main Environmental Milestones for the EU and Italy
(Source: Ministry of Economic Development, 2020, National Hydrogen Strategy)

Thus, hydrogen emerges as a key pillar of both national and international energy policies, with its development trajectory unfolding along interconnected strategic pathways, from the decarbonization of hard-to-abate (HtA) industrial sectors to the support of research and technological innovation.

1.2 Green Hydrogen: An Overview

Hydrogen, known as the first element in the periodic table, is also the lightest element. According to basic atomic chemistry, its atom has an extremely simple structure, consisting of a central nucleus containing a proton, around which a negatively charged electron orbits. In its elemental state, hydrogen primarily exists as a diatomic molecule (H_2), which, at atmospheric pressure and room temperature, manifests as a colorless, odorless, non-toxic, and highly flammable gas. Its density, lower than that of air, causes the gas to quickly rise upwards in case of leaks, as reported in key physical chemistry texts.

Among the most significant properties of hydrogen is its high energy density per unit of mass, accompanied by a relatively low volumetric energy density when compared to conventional hydrocarbons such as gasoline. This means that one kilogram of hydrogen can provide more energy than one kilogram of gasoline, but at the same time, it occupies a larger volume, making larger storage tanks necessary.

Moreover, hydrogen is the most abundant element in the observable universe, accounting for about 75% of its total mass. However, on Earth, it is practically absent in its molecular form. This scarcity is since hydrogen molecules are extremely light and therefore not retained by Earth's gravity, easily escaping into the atmosphere.

On Earth, hydrogen is found combined with other atoms, for example, with oxygen to form water, or with carbon in various hydrocarbons (the simplest being methane, CH_4), as well as in plants, animals, and other forms of life, as it is an essential component of organic molecules.

Hydrogen should not be considered a primary source of energy, but rather an energy carrier. In other words, it is not naturally available in an immediately usable form but must be produced from other energy sources. As an energy carrier, hydrogen can also play a significant role in integrating intermittent renewable sources, such as wind and solar power, into the energy system. It can act as a network balancer, storing excess electricity generated during peak periods and releasing it during times of higher demand or reduced availability of renewable resources.

In practice, as shown in Figure 4**,** surplus electricity generated from green sources can be converted into hydrogen through electrolysis and then stored in the form of H_2 molecules, creating a flexible energy reserve. The hydrogen thus stored can be used in various ways: as a clean fuel for heat production or in fuel cells to generate electricity efficiently and without direct CO_2 emissions. Fuel cells also have the potential to operate in reversible mode, allowing hydrogen to be produced when renewable energy is in excess and, at the same time, to convert stored hydrogen back into electricity when demand exceeds renewable production, ensuring continuity and flexibility to the energy system, even in the absence of wind or sunlight.

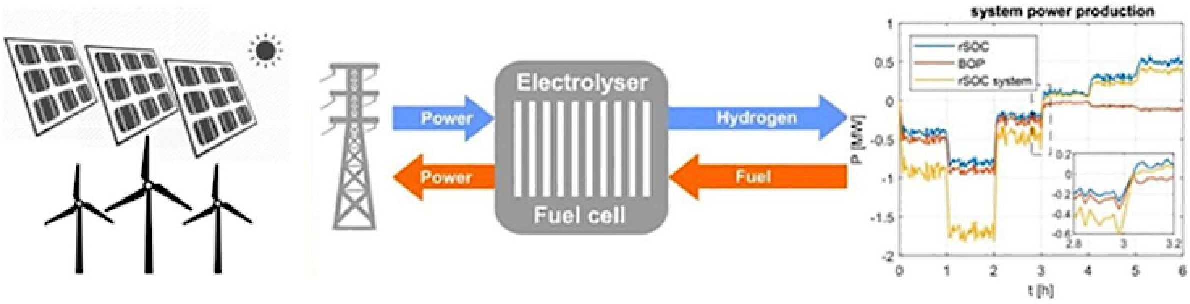


Figure 4: Schematic Representation of a Fuel Cell System for Grid Balancing
(Source: ENEA, 2021, Hydrogen, a 'Bridge' to the Renewable World)

Hydrogen can be classified as a renewable resource if its production utilizes renewable energy sources, such as solar, wind, or hydroelectric power. In summary, hydrogen represents a carrier capable of storing and transporting energy, and its value as a renewable resource depends largely on the type of energy source used in its production process.

Hydrogen is indeed one of the most versatile and flexible energy carriers. Its use will also play a crucial role in providing CO_2-free heat for the decarbonization of energy-intensive industries, such as the steel and glass sectors, which require large amounts of industrial heat for their production processes. Hydrogen will also play a significant role in the future of sustainable mobility, especially in heavy-duty and long-range transport, as described in the **National Hydrogen Mobility Development Plan, developed by the Italian Hydrogen and Fuel Cell Association (H2IT**). In particular, hydrogen can be essential in road transport, reducing CO_2 emissions while also improving air quality in urban environments. In the railway sector, cell-powered fuel locomotives are already competitive with current diesel-powered ones, both in terms of performance and service reliability.

In the context of the energy transition and the growing attention towards hydrogen as a low or zero-carbon emission carrier, it is essential to distinguish between the different types of hydrogen based on the production process and the energy source used. Internationally, several main categories are recognized. For this reason, it is incorrect to speak generically of "hydrogen": various forms exist, and not all have the same environmental impact. To facilitate their identification, the energy sector has adopted a classification system using color codes, which helps better understand their level of sustainability. The main categories are recognized internationally, as shown in Figure 5, and their main characteristics and production processes are illustrated below.

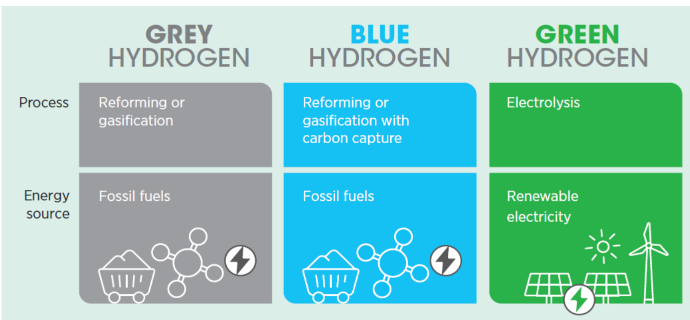


Figure 5: The Main Colors of Hydrogen
(Source: IRENA, 2024,Green Hydrogen Strategy: A Guide to Design)

1. **Grey Hydrogen**

Grey hydrogen is produced through conventional processes based on the use of fossil fuels, primarily via steam methane reforming (SMR) of methane or coal gasification. These processes, widely used globally, generate significant carbon dioxide (CO_2) emissions as they do not include carbon capture or storage systems **(IRENA,2024).** As a result, grey hydrogen is highly emissive and incompatible with long-term decarbonization goals. While it is a well-established and widely available industrial resource, its production relies on non-renewable fossil sources with a high environmental impact **(Hydrogen Council, 2023).**

2. **Blue Hydrogen**

Blue hydrogen represents an intermediate approach: it is produced from fossil sources but is associated with carbon capture and storage (CCS) technologies. This method allows for partial reduction of climate-altering emissions, with capture rates estimated between 85% and 95% ***(IRENA, 2024).*** Blue hydrogen can support the creation of a hydrogen market during the energy transition phase, utilizing existing infrastructure and ensuring stable supplies, particularly for energy-intensive industrial sectors (such as steel). However, this technology relies on fossil resources, involves additional costs for CCS infrastructure, and is associated with risks related to the management and storage of CO_2, as well as potential environmental and social challenges **(Hydrogen Council/2023).** Additionally, methane leaks in the supply chain contribute to a significant residual climate impact. For these reasons, blue hydrogen is considered a bridge tool towards the large-scale adoption of green hydrogen.

3. **Green Hydrogen**

Green hydrogen is produced through water electrolysis powered by renewable electricity (wind, solar, hydroelectric), with no direct greenhouse gas emissions **(Hydrogen Council, 2023)**. The electricity generated powers an electrolyzes that, through the process of electrolysis, splits water molecules (H_2O) into two fundamental elements: hydrogen (H_2) and oxygen (O_2). Specifically, the presence of a membrane and electrolyte allows for the selective separation of the gases produced. The hydrogen is then directed into storage tanks, while the oxygen can either be released into the environment or collected for other uses **(Haldor Topsoe A, 2020).**

From a storage perspective, hydrogen can be stored as a high-pressure gas (350–700 bar), as a cryogenic liquid at -253°C, or via adsorbent, absorbent, or metallic hydride materials. Ammonia, with its higher energy density and less stringent storage conditions (-33°C), is seen as the preferred carrier for large-scale transport and storage (Haldor Topsoe A/S Annual Report 2020). It represents the most sustainable solution in line with the climate neutrality targets set for mid-century **(BloombergNEF, 2024)**. This technology supports the integration and flexibility of energy systems, enabling sectors to coupling between electricity, industry, and mobility.

Although some alternative technologies for producing green hydrogen are still experimental, electrolysis remains the dominant and most mature method. A subcategory of green hydrogen is the so-called yellow hydrogen, which takes its name from the way it is produced by solar energy.

In summary, the three forms of hydrogen differ significantly in terms of energy source, environmental impact, technological maturity, and compatibility with decarbonization objectives:

- **Grey hydrogen**: widely used but incompatible with decarbonization, being highly emissive and based on non-renewable fossil sources.
- **Blue hydrogen**: offers partial emission reduction through CCS but remains dependent on fossil fuels and presents technical, economic, and environmental challenges; thus, it is a temporary solution.
- **Green hydrogen**: the only option fully aligned with climate neutrality, produced from renewable sources with no direct emissions, representing the most promising path for a sustainable, long-term energy transition.

There are, however, other types and/or colors of hydrogen beyond the more well-known ones. **(Belkhiri et al., 2025)** In particular, **black hydrogen** is produced using black or brown coal (lignite) through a process called gasification. Its production depends on fossil fuels, which is why it is considered a subcategory of grey hydrogen. There is also **pink hydrogen**, obtained from nuclear energy, which reduces emissions but involves challenges related to waste disposal and high water consumption. **Turquoise hydrogen**, on the other hand, is produced through methane pyrolysis, a process that generates solid carbon instead of CO_2, reducing environmental impact, although the technology is still in its early stages.

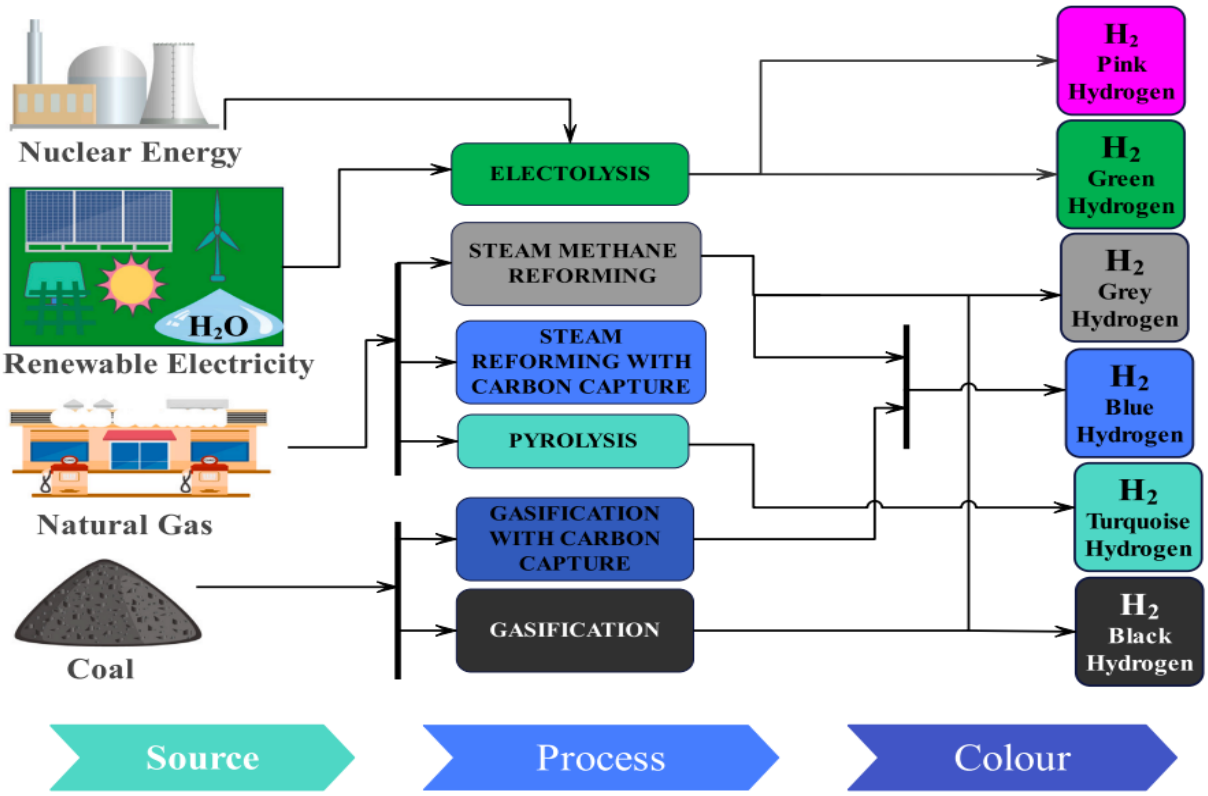


Figure 6: Hydrogen taxonomy according to the method of production (Source: Belkhiri et al., 2025)

1.3 Hydrogen Valley

As previously emphasized, hydrogen has been widely recognized as a central energy carrier in the decarbonization processes of numerous sectors, thanks to its unique characteristics. However, the development of green hydrogen still faces significant barriers that limit its full potential within the global energy transition, primarily due to infrastructure constraints, the limited scope of markets, and the high costs associated with production, storage, and distribution stages, as highlighted in the previous section. These challenges can be progressively overcome through the creation, management, and expansion of so-called Hydrogen Valleys, which are considered a strategic element for building an efficient and sustainable energy supply chain.

Hydrogen Valleys are recognized as integrated ecosystems where renewable energy production, hydrogen generation, storage, distribution, and usage converge synergistically **(Zhang et al., 2023)**, creating favorable conditions both for the large-scale adoption of innovative technologies and for testing sustainable business models (Figure 7).

Figure 7: Hydrogen ecosystem
(Source: Zhang et al., 2023)

Additionally, they serve as catalysts for cooperation between public institutions, the industrial sector, and the research community, accelerating energy transition processes and significantly contributing to the achievement of decarbonization goals at local, national, and international levels.

Thanks to their integrated approach, Hydrogen Valleys represent a crucial step toward the creation of localized hydrogen economies within specific geographical contexts. In this sense, they can be seen as true incubators and accelerators of one of the key vectors for decarbonization and the technologies necessary for its development. This phenomenon has now taken on a global dimension, as evidenced by the numerous integrated projects currently under development in different parts of the world.

The concept of a Hydrogen Valley refers to a project, or a coordinated set of initiatives, which involves the integration of different technologies and solutions across the entire hydrogen value chain, from production to storage and final uses, within a defined geographical area. Figure 8 illustrates this model schematically: renewable energy (solar, wind, hydroelectric) powers different types of electrolyzers (AEL alkaline, PEM-Proton Exchange Membrane, SOE-Solid Oxide Electrolysis Cells), which allow for hydrogen production. The hydrogen produced can be stored in its pure form (compressed gas or liquid) or converted into derivatives such as methanol, ammonia, or liquid organic carriers. Once stored, the hydrogen is transported to the points of use.

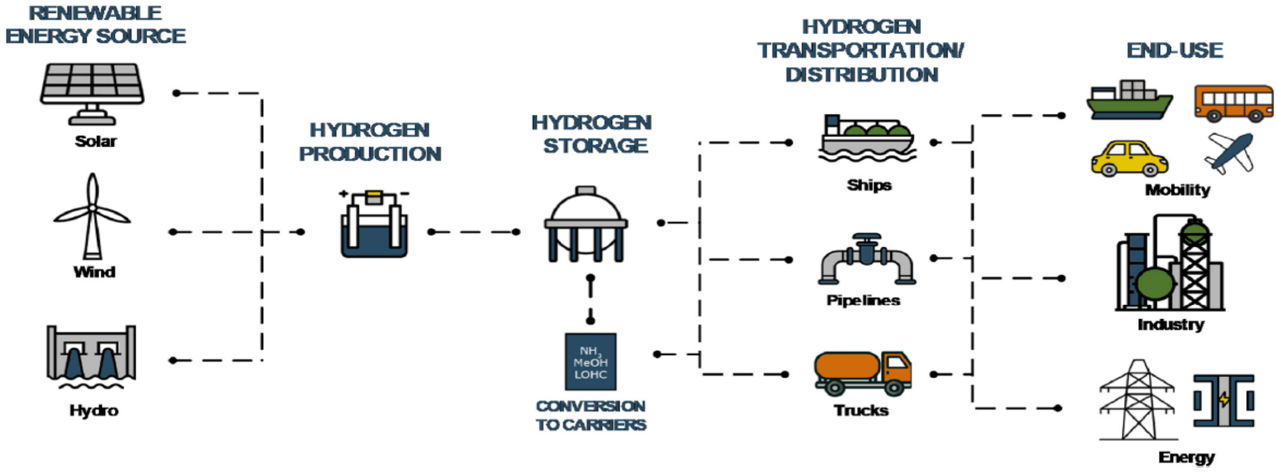


Figure 8: Overview of critical value chain aspects within the hydrogen valley concept (Source: Bampaou et al.,2025)

Hydrogen is transported to the points of use via pipelines, trucks, or ships, both in its pure form and as an energy carrier. It is then used in the energy, mobility, and industrial sectors, both within and outside the valley.

While Hydrogen Valleys exhibit heterogeneous characteristics, shaped by the specific technological processes and governance models adopted, they share some common features identified by the **Hydrogen Valley Platform**. Firstly, they are large-scale development initiatives that require significant investments and function as hubs capable of producing, distributing, and using hydrogen through integrated, systemic approaches. Secondly, they are characterized by a defined geographic area, designed in line with territorial peculiarities. These projects can be local or regional, such as in port areas and their surrounding regions, or can develop nationally or transnationally, as in transport corridors along strategic infrastructure axes. Another central element is the extension along the entire value chain: Hydrogen Valleys encompass not only hydrogen production, but also treatment, storage, and distribution stages, along with the integration of renewable energy production to power the electrolyzes. Additionally, they promote the diversification of end uses, as the hydrogen produced is destined for multiple sectors, from mobility to industry, with benefits in terms of shared infrastructure, cost reduction, and the activation of collaborative territorial models. Technical and economic feasibility is, finally, an essential criterion for selecting initiatives that are genuinely implementable and not merely speculative.

The benefits of Hydrogen Valleys are numerous and can facilitate the large- and small-scale spread of renewable hydrogen.

The main benefits include:

- Significant investment savings through shared infrastructure between various stakeholders;
- Creation of synergies between businesses, academic institutions, local authorities, and citizens, in line with Open Innovation principles, which encourage inter-sectoral cooperation and knowledge exchange;
- Gradual reduction in hydrogen production costs through economies of scale and technological learning mechanisms;

- Creation of new job opportunities and specialized training paths in the renewable hydrogen sector;
- Environmental and health benefits related to the replacement of fossil fuels with renewable, carbon-free sources;
- Promotion of new regulatory frameworks, with Hydrogen Valleys acting as true Open Innovation Test Beds (OITBs), experimental environments for testing emerging technologies, business models, and policy tools before their broader rollout **(Bampaou et al., 2025).**

In this context, Hydrogen Valleys are key tools within international initiatives such as Mission Innovation, which promotes cooperation between governments, industry, and research to accelerate the energy transition. Thanks to their role as collaborative and testing platforms, they not only strengthen the competitiveness and resilience of the sector but also serve as a catalyst for the establishment of renewable hydrogen as a pillar of long-term decarbonization.

A strong push for the spread of hydrogen also comes from Important Projects of Common European Interest (IPCEI, mentioned in paragraph 1.1), European cooperation projects where companies, member states, and the European Commission work together towards a common goal. In the hydrogen field, key projects include IPCEI Hy2Tech (2022) focused on technologies, IPCEI Hy2Use (2022) aimed at industrial applications, and IPCEI Hy2Infra (2024), which focuses on the development of regional hubs and a European hydrogen network. The latter project foresees €6.9 billion in public funding, the highest amount ever approved for hydrogen, triggering an additional €5.4 billion in private investments. These projects demonstrate how public support is crucial for the economic and operational sustainability of the hydrogen supply chain.

2 Literature Review

The transition to a low-carbon economy requires innovative energy solutions capable of overcoming the structural limitations of fossil fuels and ensuring security, sustainability, and resilience to energy systems **(Blohm, M., & Dettner, F., 2023)**. In this context, green hydrogen emerges as a flexible and strategic energy carrier, capable of facilitating the decarbonization of various sectors while integrating intermittent renewable sources, alleviating pressure on electrical grids, and promoting the development of more resilient energy systems. The growing attention to these systems is evidenced, as highlighted in the previous chapter, by the spread of Hydrogen Valleys, territorial ecosystems in which production, storage, distribution, and end-use applications of green hydrogen are integrated within an environmental and economic sustainability perspective. Hydrogen Valleys are not just technological hubs but also emerge as ecosystems of open innovation: according to the Quintuple Helix approach, they promote the exchange of expertise between universities, industry, governments, civil society, and the environment, fostering intersectoral collaboration that accelerates experimentation and industrial scalability **(Morea et al., 2024)** .

Recent literature indicates that green hydrogen systems go beyond a mere collection of technologies: they play a central role in integrating renewable energy sources and decarbonizing high-carbon sectors, thanks to their ability to store, transport, and convert energy into a coherent and efficient energy system **(Gomez e Castro, (2024).** The adoption of ecosystem thinking models and multilevel governance frameworks enables green hydrogen systems to address challenges posed by hard-to-abate sectors and support the creation of Hydrogen Valleys focused on sustainability, as highlighted by **Clean Hydrogen Mission (2024)** and by **Horizon Europe CP Portal (2024)**. These Hydrogen Valleys are emerging as energy hubs capable of promoting not only decarbonization but also local economic development, social innovation, and industrial competitiveness, aligning with global climate neutrality goals and ESG principles. A recent example is the Hydrogen Valley in Puglia, supported by a €370 million European funding, which aims at decarbonizing the steel industry and creating new energy infrastructures **(ANSA, 2024).**

In this context, this literature review aims to provide an overview of the main research and development trajectories concerning integrated green hydrogen systems. The analysis will be structured around four main dimensions: technologies, functions, and objectives of Green Hydrogen Systems; application contexts represented by Clean Energy Hubs and Hydrogen Valleys; the role of ESG criteria in defining sustainability standards and metrics; and finally, the contribution of SMEs and startups, key actors in open innovation and the global dissemination of green hydrogen solutions.

2.1 Green Hydrogen Energy Systems (GHES): Technologies, Functions, and Objectives

The global energy sector is currently undergoing a fundamental transformation, shifting from fossil fuels to renewable energy sources. Green hydrogen is one of the most promising energy carriers of the future in global efforts to reduce the carbon footprint of energy systems. The progress and adoption of green hydrogen technologies depend on various technological, environmental, and economic factors. In this section, a review of recent studies on Green Hydrogen Energy Systems (GHES) is conducted, highlighting the recent advancements in the various technologies for generating, storing, and utilizing green hydrogen. In recent years, GHES have taken a central role in the debate on the energy transition, positioning themselves as one of the key technologies for decarbonization and global energy security. As previously mentioned, green hydrogen, produced through water electrolysis powered exclusively by renewable electricity, emerges as an energy carrier capable of combining sustainability, versatility, and integration with existing infrastructure. Recent literature emphasizes that its potential goes beyond merely replacing "grey" or "blue" hydrogen; it primarily concerns providing storage, grid flexibility, and solutions for so-called hard-to-abate sectors that are difficult to electrify directly. It does not only represent an alternative to fossil fuels but also serves as a cross-cutting infrastructure capable of integrating energy, industrial, and transport sectors in an ecosystem thinking approach. In this sense, GHES should be interpreted as components of complex ecosystems, where technological innovation, public policies, industrial strategies, and market dynamics converge.

This chapter explores the different aspects that define GHES, focusing on three main dimensions: technology, functions and applications, and strategic objectives. These factors are crucial for understanding how green hydrogen can be used to reduce carbon emissions, improve energy efficiency, and support the transition to a more resilient and sustainable energy system.

2.1.1 Technological dimension

The technological dimension of Green Hydrogen Energy Systems (GHES) is at the heart of their operation and development. In this section, the main technologies involved in the production of green hydrogen will be analyzed, focusing on the different types of electrolyzes and the technological innovations that are determining their evolution. The benefits, challenges and advances of technological solutions will be explored, highlighting how research and innovation can contribute to improving the efficiency and competitiveness of green hydrogen in the global energy context.

From a technological perspective, the production of green hydrogen mainly relies on water electrolysis, a process in which renewable energy is used to split water molecules, generating hydrogen and oxygen. This process includes the stages of production, storage, transport, and utilization of hydrogen generated from renewable electricity. Regarding production, recent studies have identified four main types of electrolyzes: alkaline (AEL - Alkaline Electrolyze), proton exchange membrane (PEM), solid oxide electrolysis cells (SOEC), and anion exchange membrane (AEM), each with specific advantages, limitations, and technological maturity stages, currently at different stages of development and commercialization **(X. Wei et al., 2024)**. Alkaline electrolyzes (AEL) are the most established and widely used technology at the industrial scale (covering 70% of the global market). They are characterized by their relative simplicity, robustness, and low cost, elements that have favored their widespread adoption in large-scale industrial applications. However, these systems have a limited ability to quickly adjust production in response to fluctuations in renewable energy availability, a characteristic that can be a significant constraint in contexts where electricity comes from intermittent sources such as photovoltaics or wind **(H. Tüysüz, 2024)**. Proton exchange membrane (PEM) electrolyzers represent a more recent technological alternative, characterized by greater operational flexibility and faster response times to grid variations. This technology is particularly suited for integration with unstable or variable electrical systems, making it more suitable for scenarios where renewable production dominates the energy mix. Despite the higher initial cost, advances in material research and the reduction of precious metals used in electrodes are making PEM electrolyzers increasingly competitive **(J. Mao at al., 2024).**

In parallel, emerging technologies such as solid oxide electrolyzers (SOEC) and anion exchange membrane (AEM) electrolyzers are being studied and experimented. SOECs operate at high temperatures and promise superior thermodynamic efficiencies, allowing for the combined production of hydrogen and useful heat for integrated industrial applications **(Ferrete et al., 2025)**. AEM electrolyzers, on the other hand, offer the potential to reduce or eliminate the use of noble metals, contributing to lower costs and greater material sustainability. A crucial aspect in the development of GHES is progress in catalysts and membrane materials, both of which are key to efficiency, durability, and the overall cost of green hydrogen production. In recent years, research has focused on developing alternative catalysts to noble metals, such as those based on nickel, molybdenum, and complex carbides/oxides, which can offer high electrocatalytic activity while significantly reducing costs compared to platinum and iridium **(Dong et al., 2025)**. At the same time, advancements in AEM membranes have shown substantial improvements in chemical stability and ionic conductivity: recent polymer formulations have maintained stable performance for over 800 hours under severe operational conditions, bringing these solutions closer to the established performance of PEM membranes, but with lower production costs **(Liu, L., 2024).** Furthermore, studies focused on the catalyst layers of Anion Exchange Membrane Water Electrolyzers (AEMWE) demonstrate how material engineering and optimized ionomer distribution can increase current density up to 3 A/cm^2 while maintaining component durability for over 1,000 hours of operation **(Volk et al., 2024)**. Technological innovations, based on combined approaches to catalyst design and membrane polymer development, are essential drivers for reducing the life-cycle costs of GHES without sacrificing reliability, thereby strengthening the competitiveness of green hydrogen in the global energy market **(Fortin, A., 2025)**. The green hydrogen production process begins with the use of renewable energy sources, such as solar and wind energy, which, through photovoltaic panels and wind turbines, are converted into electricity for electrolyzers. These devices, powered by the generated electricity, initiate the electrolysis process, which splits water into hydrogen and oxygen through the action of a membrane and electrolyte. The hydrogen is then channeled into appropriate storage tanks, while the oxygen can either be released into the atmosphere or collected for further industrial uses **(IEA, 2025)**. In terms of energy, current plants require approximately 55 kWh to produce one kilogram of hydrogen, with prospects of reducing this to 45 kWh thanks to technological progress **(DOE, 2024)**. However, the installed capacity of electrolyzers remains limited: in 2023, it stood at 1.4 GW, with projections to grow to 5 GW by the end of 2024 **(IEA, 2025)**. The hydrogen produced can either be used directly or transformed. One option is the production of synthetic fuels, obtained by combining hydrogen with carbon dioxide captured from industrial processes or directly from the atmosphere. This family of fuels includes methanol, aviation fuels, methane, and other synthetic hydrocarbons, which can replace their fossil counterparts and potentially achieve net-zero carbon emissions, provided that the CO_2 used comes from sustainable sources. Another option is the synthesis of green ammonia, produced by combining hydrogen with atmospheric nitrogen through processes that replace fossil-derived hydrogen with that from electrolysis. Green ammonia, in addition to being used as a fertilizer, represents a valid option as a fuel and, especially, as an energy carrier for hydrogen transport and storage due to its energy density and ease of liquefaction compared to pure hydrogen **(Hossein et al., 2024)**. Ammonia emerges as a particularly promising carrier: with an energy density of 12.7 MJ/L, higher than that of liquid hydrogen (8.5 MJ/L), it requires less extreme storage conditions (-33 °C versus -253 °C) and benefits from an already widespread logistical infrastructure globally, with over 120 dedicated port terminals. However, the cost of green ammonia remains two to four times higher than its fossil counterpart, and various direct-use technologies, such as ammonia engines, are still in experimental stages.

A central aspect of GHES concerns the methods of hydrogen storage and transport. Regarding storage, the most established technologies are compression and liquefaction, both characterized by high energy demands. Compression, although the most widespread technique, involves high energy consumption due to the pressurization of gas. Liquefaction increases the energy density of hydrogen, making it easier to transport and store in smaller volumes, but incurs significantly higher energy and infrastructure costs. Solid material-based solutions, while promising greater safety and energy density, are still in advanced research and have not achieved significant commercial deployment. More innovative alternatives include the use of metal hydrides and Liquid Organic Hydrogen Carriers (LOHC), which offer greater energy density and safety, although with still limited overall efficiency **(Omotayo et al., 2025)**. In parallel, the literature highlights growing attention towards geological storage in salt caverns, which could guarantee long-duration storage at relatively competitive costs, especially in large-scale contexts **(Xiaojun et al., 2025)**. Each solution presents advantages and challenges in terms of cost, safety, and energy density. Hydrogen is highly flammable and requires strict safety protocols, including ventilation techniques, leak detection, and the use of materials resistant to hydrogen embrittlement. Furthermore, the establishment of appropriate infrastructure is hindered by high costs and regulations still being defined **(Khalili et al., 2025).**

Similarly, hydrogen transport can take place through multiple modes, each characterized by specific advantages and challenges. Dedicated hydrogen pipelines represent the most advanced and secure infrastructure option for large-scale transport **(Alssalehin et al., 2025)**. Alternatively, blending hydrogen with natural gas allows for the use of existing networks, but the percentage of hydrogen allowed in the flow is subject to specific technical limits. These limits are mainly related to safety and the compatibility of existing infrastructure, which must be adapted to manage the chemical properties of hydrogen without compromising pipeline integrity or system efficiency **(Erdener et al., 2023)**.

Emerging solutions for long-distance hydrogen transport, such as chemical carriers like ammonia (NH_3) and Liquid Organic Hydrogen Carriers (LOHC), such as methylcyclohexane (MCH), offer significant advantages in terms of stability and energy density. These compounds allow for transporting hydrogen in liquid form at ambient temperature or moderate pressures, reducing risks associated with managing pure molecular hydrogen **(Negro et al., 2023)**. However, the reconversion of hydrogen from chemical carriers requires energy-intensive processes. For ammonia, the dehydrogenation process results in an energy loss of 7-18%, while for LOHCs, dehydrogenation can require up to 35-40% of the energy contained in the hydrogen itself. These processes create a trade-off between greater transport safety and the overall system performance, influencing energy efficiency and the overall costs of the hydrogen value chain **(The ANZ Hydrogen Handbook 2.0, 2024).**

These aspects are central to the design and development of large-scale energy systems, as highlighted in recent analyses by Hydrogen Europe, which emphasize the importance of dedicated infrastructure, the adaptation of geological storage (e.g., salt caverns), and the selective use of LOHCs and ammonia to address logistical gaps, especially in international trade. Hydrogen blending in natural gas networks (H2 blending) remains a transitional solution, with its applicability varying based on local technical and economic conditions **(Hydrogen Europe, 2024, Hydrogen Infrastructure Report).**

In conclusion, understanding the design of hydrogen hubs requires focusing on specific technological aspects: from the efficiency of electrolyzers and the availability of renewable sources to the choice of the most suitable storage and transport solutions for the context. It is crucial to assess the maturity and flexibility of production technologies, also considering infrastructure and logistical requirements, such as the possibility of using geological storage, advanced systems based on metal hydrides or chemical carriers such as ammonia and LOHC. Only a conscious and innovative integration of these technological components makes it possible to design efficient, safe and scalable hubs, capable of maximizing the environmental and economic benefits of green hydrogen and accelerating the transition to a sustainable energy model.

The production of green hydrogen through electrolysis is a process that integrates various technologies, ranging from established solutions, such as alkaline electrolyzers (AEL), to emerging technologies, such as anion exchange membrane (AEM) systems and solid oxide electrolysis cells (SOEC). Each technology has specific advantages and challenges, but advancements in research are rapidly improving efficiency and reducing costs, making green hydrogen an increasingly competitive resource for the future.

2.1.2 Functions and Applications

In addition to the technological dimension, GHES offer a number of strategic applications that go far beyond the simple production of hydrogen. This section will explore the multifunctional functions of green hydrogen systems, including energy storage and management, decarbonisation of hard-to-electrify industrial sectors, and integration with other energy technologies. The benefits and challenges emerging from the large-scale adoption of these applications will also be examined, as well as their impact on the global energy system.

From a functional standpoint, integrated green hydrogen systems play a strategic and multifunctional role in reshaping contemporary energy architectures, positioning themselves as key elements for the transition to a low-carbon economy. Their function extends beyond the production phase. They play a crucial role in energy storage and balancing electrical systems, enabling the conversion of surplus electricity generated from intermittent renewable sources into a storable and reconvertible energy carrier. This mechanism helps ensure grid stability, reducing reliance on fossil peak power plants **(Kourougianni et al., 2024).** Green hydrogen is fundamental for the decarbonization of energy-intensive industrial sectors such as steelmaking, chemical production, and maritime and aviation transport, where direct electrification proves inefficient or impractical. For instance, the production of steel through direct reduction with hydrogen (H_2DRI) involves significantly higher emission reduction costs compared to other technologies, such as carbon capture, unless specific incentive policies are implemented **(Jordan et al., 2025)**.

In summary, Green Hydrogen Energy Systems (GHES) play several strategic functions in the context of the energy transition:

- **Energy storage and management:** Excess hydrogen produced during periods of high renewable energy generation can be stored and used later, contributing to the stability and flexibility of the electricity grid. The integration of advanced storage systems, such as those based on metal hydrides, can further improve storage efficiency and safety **(Kourougianni et al., 2024).**
- **Decarbonization of industrial sectors and transport:** Green hydrogen can replace fossil fuels in energy-intensive industrial processes, such as steel and cement production, as well as in heavy transport sectors like maritime and rail transport. Recent studies highlight the effectiveness of green hydrogen in reducing greenhouse gas emissions in these hard-to-electrify sectors **(Gómez/Castro, 2024).**
- **Integration with carbon capture technologies:** Integrating Direct Air Capture (DAC) systems with green hydrogen production offers both economic and environmental synergies. Recent studies suggest that adopting advanced DAC technologies could improve the overall system efficiency and reduce carbon capture costs **(Sunwoo et al., 2024).**

The functions of GHES also include (i) sector coupling between electricity and gas through power-to-hydrogen (P2H) to absorb renewable energy surpluses, reduce curtailment, and provide auxiliary services (demand flexibility, frequency regulation via electrolyzes); (ii) power-to-X for synthetic fuels (e-methanol, e-fuels); and (iii) decarbonization of hard-to-abate sectors. Recent evidence shows operational benefits: P2H integration can reduce overall system costs by up to 20% and halve renewable energy waste **(Algburi et al., 2025)**.

However, the use of hydrogen in these sectors presents significant challenges. The production of green hydrogen requires large amounts of renewable energy, with a conversion efficiency that can vary, and large-scale distribution requires complex and expensive infrastructure. The reconversion of hydrogen from chemical carriers requires energy-intensive processes, creating a compromise between increased transport safety and the overall system performance **(Franco, 2025).**

Its versatility is also evident in Power-to-X applications, which include the synthesis of methane, ammonia, and liquid fuels, thus creating interconnections between the energy sector and the chemical-industrial sector **(Gómez/Castro, 2024).**

GHES offer a number of strategic functions that go beyond hydrogen production. The integration of energy storage systems, the decarbonization of industrial sectors and the ability to support the flexibility of the electricity grid are just some of the crucial applications that make green hydrogen a central player in the context of the global energy transition.

2.1.3 Objectives and Systemic Dimension

The transition to a low-carbon economy requires the adoption of clear and consistent targets, which guide the development and implementation of GHES. In this section, the economic, environmental, and policy goals that define the future of green hydrogen will be discussed. The economic aspects related to the reduction of production costs, the environmental benefits deriving from its adoption and the political and regulatory dimensions that influence the diffusion of GHES will be analyzed. The importance of a systemic approach to overcome challenges and ensure a sustainable and inclusive energy transition will be emphasized.

Generally, the objectives guiding the development of integrated green hydrogen systems can be articulated on several levels, each reflecting a different but complementary strategic dimension of the energy transition. On the economic front, one of the main drives for the development of integrated green hydrogen systems concerns the progressive reduction of the Levelized Cost of Hydrogen (LCOH), a parameter that measures the average production cost of hydrogen over the lifetime of the plant. Currently, the LCOH ranges between 3 and 10 €/kg, values that make green hydrogen competitive only in specific industrial contexts or as a policy-driven decarbonization tool. Technological and industrial scaling scenarios foresee a significant cost reduction, with the aim of falling below 2 €/kg by 2030 and approaching around 1 €/kg by 2050, thanks to economies of scale, improvements in electrolyze efficiency, and optimization of renewable energy supply chains. Such an evolution would make green hydrogen a competitive energy resource on a large scale,

encouraging private investments and targeted support policies **(IEA – *Global Hydrogen Review 2024*)**. Moreover, the 2025 Review updates the cost curves, highlighting effectiveness and efficiency issues, especially for new Chinese offerings **(IEA, 2025).** Concurrently, the U.S. Department of Energy's Hydrogen Shot initiative **(DOE/2024)** provides details on the state of the art and the R&D needs for all four types of electrolyzes, emphasizing that further reductions in Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), as well as improvements in plant balance sheets, are prerequisites for aggressive cost targets. According to estimates by **BloombergNEF (2024,Five Energy Transition Lessons for 2025)**, the levelized cost of green hydrogen currently ranges between 3.74 and 11.70 dollars per kilogram, depending on location and conditions (electrolyzing costs, renewable energy availability, and other factors). In comparison, gray hydrogen costs between 1.11 and 2.35 dollars per kilogram. Even with the adoption of support policies, such as tax incentives in the U.S., the cost of green hydrogen remains high. For example, the U.S. Department of Energy has set a goal to reduce the cost of clean hydrogen to 1 dollar per kilogram by 2031, but this requires significant investments in research, development, and infrastructure **(BloombergNEF, 2024).**
Improving efficiency along the entire chain, from production to storage and final use, is another key goal. Several studies have shown that the lifespan and degradation of electrolyzes significantly impact the overall costs: a PEM electrolyzes, for example, can increase the production cost from 4.56 to over 6.50 dollars per kilogram if degradation is considered, highlighting the importance of more durable materials and processes **(Schofield-Paren, 2024).**
In addition to technological and economic aspects, the political-regulatory dimension strongly emerges. In the absence of clear regulatory frameworks and stable incentives, investments risk remaining fragmented. In China, for example, the lack of national standards for green hydrogen certification creates uncertainty for operators, a phenomenon similar to what was observed in Europe before the introduction of stricter rules for the classification of renewable sources **(S$P Global, 2025).**

From an environmental perspective, these systems are designed to achieve a drastic reduction in greenhouse gas emissions, significantly contributing to achieving climate neutrality. In particular, green hydrogen is a crucial tool for the decarbonization of energy-intensive industrial sectors, heavy mobility, and chemical production processes, sectors that traditionally rely on fossil fuels. This goal aligns with the United Nations Sustainable Development Goals (SDGs), particularly those related to clean and accessible energy (SDG 7), industrial innovation and sustainable infrastructures (SDG 9), and the fight against climate change (SDG 13). This outlines a framework where the mitigation of climate risks is closely linked to technological innovation and the transformation of energy models. The issue of overall sustainability also requires evaluating not only direct emissions but also indirect impacts, such as water consumption and the use of critical raw materials, factors often overlooked in traditional analyses but crucial for a life cycle assessment perspective **(Shaya- Glöser/Chahoud, 2024).**

Finally, a socio-economic and organizational systemic dimension emerges, emphasizing the importance of building collaborative ecosystems that accelerate innovation **McAvoy et al. (2024),** propose a systems thinking approach to rethink innovation models related to clean hydrogen. The authors highlight that the energy transition cannot be addressed solely with technological solutions but requires a systemic perspective that considers the interactions between technical, economic, social, and institutional dimensions. The article emphasizes the importance of collaborative ecosystems where businesses, research centers, startups, and public institutions cooperate through open innovation logic. This vision enables the management of the complexity of the hydrogen supply chain, addressing barriers such as high costs, insufficient infrastructure, and issues related to resources and materials. In this sense, green hydrogen is seen not just as a technology but as a catalyst for socio-technical transformations and a strategic element for building a sustainable and resilient energy system. However, recent literature highlights a gap between ambition and implementation. The **IEA (2024-2025)** reports that many projects are still in the early stages, and demand is still limited to traditional applications (refining/ammonia), with political and market signals not always aligned. The 2025 Review revises expectations for low-emission hydrogen production, reducing them by approximately 25% by 2030. Economic press and industry news from 2024–2025 report delays or downsizing (e.g., green steel in Europe) due to volatility in electricity and green H_2 prices, regulatory uncertainty, and capital costs (Financial Times, 2025). In conclusion, although GHES technologies are mature in many components (AEL/PEM, physical storage, ammonia as a carrier), scalability by 2030 will depend on the reduction of electrolyzes costs, the availability of low LCOE renewable electricity, dedicated infrastructure, and demand creation mechanisms (purchase standards, green procurement, CBAM, and similar measures).

The economic, environmental and policy objectives linked to GHES are complementary and interlinked. Reducing the production costs of green hydrogen, improving its efficiency and creating collaborative ecosystems are essential elements to ensure a fair and sustainable energy transition. Cooperation between the public, private and research sectors, combined with supportive policies, will be decisive in achieving sustainability and decarbonization goals.

In conclusion, the success of GHES will depend on the integration of these technological, functional and strategic aspects, which together will contribute to building a greener, more resilient and competitive energy system.

At the end of the section, in order to offer a clear and detailed overview of the topics addressed, the following Table 1 is proposed which summarizes in an integrated way the main technological, functional, economic, environmental and social aspects covered, highlighting the interconnections between the different solutions and showing how each contributes to the construction of a sustainable green hydrogen energy system, resilient and integrated.

Technology / Solution	Function / Usage	Economy	Environment	Social	Interconnections / Implications
AEL (Alkaline Electrolyser)	Large-scale green H_2 production	Low costs, industrial maturity, limited flexibility	Reduction of emissions if powered by renewables, water consumption	Industrial job creation, technical training	Strong impact on decarbonization, less suitable for flexible grids
PEM (Proton Exchange Membrane)	Green H_2 production, quick response	Higher costs, but falling with innovation	High efficiency, less use of critical materials than AEL	It fosters new skills, innovative supply chains	Ideal for integration with intermittent renewables
SOEC (Solid Oxide Electrolyzer Cells)	Combined production of H_2 and heat	Potential cost reduction when fully operational, more R&D	High efficiency, but high power consumption	Opportunities for integrated industrial districts	Synergies with hard-to-abate industrial processes
AEM (Anion Exchange Membrane)	H_2 production, reduction of the use of noble metals	Reduction of material costs, still under development	Better material sustainability, growing performance	Accessibility for SMEs/startups	Potential democratization of the H_2 supply chain
Storage: Compression/Liquefaction	Energy storage, grid balancing	High energy costs, high CAPEX/OPEX	Indirect emissions if energy is not green	Security, risk management	Essential for flexibility and energy security
Storage: Hydrides/LOHC/Ammonia	Long-term transport/storage	Variable costs, efficiency to be improved	Reduction of transport risks, but energy-intensive processes	New logistics chains, training	Key solutions for H_2 export/import
Transport: Dedicated pipelines	Large-scale H_2 distribution	High initial investment, economies of scale	Reduced transport emissions compared to trucks	Infrastructure development, territorial impact	Crucial for regional/national H_2 networks
Transportation: Natural Gas Blending	Transitional solution	Low costs, use of existing infrastructure	Reduced emissions compared to pure fossil gas	Social acceptance, gradual transition	Technical and regulatory limitations, bridging solution
Power-to-X (e-fuel, methanol, ammonia)	Synthesis of fuels, fertilizers	New markets, revenue diversification	Decarbonizing challenging sectors	New skills, supply chain development	Synergies between energy, chemistry and transport

Table 1: Technologies for the production, storage and transport of green hydrogen, with a focus on the economy, environment, social and related interconnections.

2.2 Clean Energy Hubs and Sustainability Ecosystems: Application Contexts for Green Hydrogen Systems

In the previous paragraph, we explored the key technologies and functions of Green Hydrogen Energy Systems (GHES), which, thanks to their versatility and ability to integrate with different sectors, provide a solid foundation for the transition to a sustainable energy system. However, the adoption of Green Hydrogen Energy Systems (GHES) reaches its full expression when placed within clean energy hubs and sustainability ecosystems, contexts where the synergy between green hydrogen, other renewable sources, and storage technologies allows for the full enhancement of this value chain. Green hydrogen, by integrating with electricity grids and industrial and transport sectors, acts as a strategic carrier for the flexibility and resilience of the energy system.

According to a report by the **International Renewable Energy Agency (IRENA, 2023)**, the integration of green hydrogen into energy hubs improves system efficiency, reducing the overall cost of energy infrastructure through the combined use of renewable sources and storage technologies. Green hydrogen plays a crucial role in addressing the fluctuation of renewable energy production, lowering operational costs and increasing the competitiveness of low-emission projects. Additionally, a report from **Hydrogen Europe in November 2024** estimates that the implementation of the National Green Hydrogen Mission (NGHM) could generate around 600,000 jobs by 2030. The creation of green

hydrogen infrastructure will stimulate the development of new economic sectors, creating opportunities in hydrogen production, storage system management, and distribution technologies.
The expansion of projects that integrate various renewable sources, such as solar and wind energy, with electrolysis and storage systems, demonstrates how green hydrogen can become a central element in the transition to a decarbonized and resilient energy system. In particular, the integration of green hydrogen as a means to store and transport energy is crucial to address the seasonality and intermittency typical of renewable sources, such as wind and solar. Hydrogen enables the storage of surplus energy for use during periods of low production, such as when demand is high or weather conditions do not favor renewable energy production, as highlighted by **Sakthimurugan et al. (2025)** in their study Green Hydrogen: Unleashing the Potential for Sustainable Energy Generation.
Indeed, the integration of green hydrogen into energy hubs can optimize the efficiency of distribution networks, improving the balance between supply and demand and reducing the need for fossil backup sources. Green hydrogen not only helps reduce the costs associated with using non-renewable energies, but also increases the flexibility of integrated energy systems, making the entire system more resilient to seasonal and daily fluctuations in energy production, as stated by **Adekola (2024)** in his study Electricity supply configurations for green hydrogen hubs.
However, in the short and medium term, global decarbonization requires the simultaneous use of both forms of hydrogen. Blue hydrogen, due to its technological maturity, currently allows for the start of large-scale and significant production, although the permitting process and the construction of CCS facilities may slow it down. Regions with access to low-cost natural gas and CCS capacity, such as the Middle East, Russia, and the United States, currently enjoy a competitive advantage in blue hydrogen exports. At the same time, countries with vast renewable energy availability at low cost, such as Australia, are leading in the development of green hydrogen, particularly for the markets of Northeast Asia, where geographical proximity reduces transport and conversion costs **(Wood MacKenzie, 2021).**
In summary, although blue hydrogen predominates today in the initial phase for reasons of cost and scalability, the strategic transition to green hydrogen is already underway, supported by public policies, industrial investments, and forward-looking prospects that position green hydrogen at the center of global energy transition.
In 2025, the production of green hydrogen is developing on multiple fronts, reflecting the diversification of energy sources and the geographic spread of related technologies. Globally, the production of green hydrogen continues to expand, supported by a wide range of projects that utilize various renewable sources to power the electrolyzes necessary for hydrogen production. This diversification reflects local energy availability conditions and national strategies for the energy transition. In Europe, the spread of photovoltaic plants has made countries like Spain particularly suitable for producing green hydrogen through solar-powered electrolysis. The abundant sunlight and incentive policies have fostered the development of numerous small and medium-scale electrolysis projects, with a positive impact on the green ammonia industry as well. **(Repubblica, 2024, Green hydrogen, Spain aims to become the first EU producer).**

In France, however, a significant role in low-carbon hydrogen production is played by nuclear energy, which represents a stable and low-carbon source. The country is positioning itself to develop electrolysis projects that use nuclear energy to produce hydrogen with extremely low emissions, laying the groundwork for a new generation of green ammonia plants **(RtE, 2020).**

In Finland, on February 12, 2025, the first industrial-scale green hydrogen plant was inaugurated in Harjavalta, built by P2X Solutions in collaboration with Sunfire. The plant, equipped with a 20 MW pressurized alkaline electrolyzes, uses renewable electricity, mainly wind, to produce green hydrogen, which can then be converted into synthetic methane via a methanation unit. This project represents the first replicable model of the national green hydrogen value chain **(Hydrogen Europe, 2025).**

In other parts of the world, particularly interesting projects are being implemented in Australia, where a mix of renewable sources is being tested. In Australia, initiatives combining solar and wind energy are being developed to ensure a stable and continuous supply of electricity for green ammonia production, aiming for 75% of electricity to come from these energy sources. **(Greenreport.it, 2025).**

Within the context of the Vision 2030 strategy, Saudi Arabia is developing the world's largest commercial green hydrogen plant: the NEOM Green Hydrogen Project, a joint venture between NEOM, Air Products, and ACWA Power. The project, valued at an estimated USD 8.4 billion, will integrate 3.9 GW of renewable energy (solar, wind, storage) and produce up to 600 tons of clean hydrogen per day, which will be converted into 1.2 million tons/year of green ammonia. The plant is expected to be operational by 2026. **(Renewable, 2025).**

According to the International Renewable Energy Agency **(IRENA 2023 World Energy Transitions Outlook**), by 2050, almost all of the world's hydrogen production, around 94%, will come from renewable sources. This gas is considered a fundamental component for reducing emissions and making energy systems more flexible. The study emphasizes that, thanks to more efficient technologies, increased renewable energy use, and new consumption behaviors, global energy demand could even decrease by 6% between 2020 and 2050. In particular, green hydrogen and biomass will play an increasingly important role: the demand for hydrogen produced from renewable sources could reach around 180 million tons per year. This will require massive investments. IRENA estimates that, to stay within the scenario that limits global warming to +1.5°C, $150 trillion will be needed by 2050, equivalent to over $5 trillion per year. Of this, about half will be allocated to end uses: $43 trillion for energy efficiency and savings, $16.6 trillion for electrification, $6 trillion for renewables, $4.7 trillion for the development of green hydrogen, and $3 trillion for CO_2 capture and removal technologies. Market numbers for hydrogen also confirm this trend. In recent years, the global hydrogen market has seen steady growth, expected to solidify in the next decade. According to data from Acumen Research and Consulting, the hydrogen industry was valued at approximately $182.4 billion in 2022; forecasts indicate an expansion to $303.5 billion by 2032, with a compound annual growth rate (CAGR) of 5.4% from 2023 to 2032 **(Acumen Research and Consulting, 2024).**

Similar projections are provided by other analysis firms, although with slightly different estimates. Zion Market Research, for example, calculates a market value of $150.45 billion in 2023, growing to $360.6

billion in 2032, with a CAGR of 10.2% **(Zion Market Research, 2023).** According to Mordor Intelligence, the hydrogen generation sector is expected to increase from $185.49 billion in 2025 to $226.55 billion in 2030, with a CAGR of 4.08% (**Mordor Intelligence, 2020).**
Despite the varying estimates, research agrees on a sustained growth outlook for the sector, supported by investments in innovative technologies and growing interest from the energy, transport, and heavy manufacturing sectors, which see hydrogen as a strategic solution for decarbonization and energy transition.

2.2.1 Challenges and Opportunities in the Adoption of Green Hydrogen: Technological, Infrastructural and Economic Barriers"

The success of these technologies will depend on the ability to overcome existing barriers, ensuring the alignment between scientific innovation, industrial investments, and the political and institutional support necessary for an effective energy transition. These obstacles can be divided into two main categories: on one hand, common barriers to all types of hydrogen, such as the lack of dedicated infrastructure; on the other hand, specific challenges related to the electrolysis production process, which affect only green hydrogen.
Among the common difficulties, the lack of infrastructure is particularly significant. Currently, the hydrogen transport and storage network is extremely limited. Globally, there are about 4,500 km of pipelines dedicated exclusively to hydrogen, of which about 1,600 km are in Europe. This figure is far below the millions of kilometers of natural gas networks in existence, confirming the strong scarcity of dedicated infrastructure. Similarly, the spread of hydrogen refueling stations remains very limited: as of December 31, 2024, there were about 1,160 hydrogen refueling stations operating globally. **(H2Stations, 2025).** The spread remains limited compared to the network of stations for fossil fuels, which counts tens of thousands of points in regions such as the United States and Europe. Although part of the existing natural gas infrastructure could be converted for hydrogen transport, this option is not feasible everywhere, limiting the expansion of the network.
The reuse of existing infrastructure, such as natural gas networks, is one of the most promising strategies to reduce the implementation costs of hydrogen hubs. Recent studies confirm that adapting existing natural gas pipelines for hydrogen transport can lead to significant cost savings and accelerate the transition to a low-emission energy system. This approach could speed up the transition to a more sustainable energy system by cutting costs compared to building new networks, significantly contributing to decarbonization goals. According to an analysis in 2023, the use of existing natural gas infrastructure for hydrogen transport could reduce infrastructure development costs by 26% in Europe, accelerating the transition to a low-emission energy system. In some regions, natural gas networks can be adapted to transport green hydrogen with minimal modifications, thus reducing initial costs for the creation of new transport facilities **(Lipiäinen, 2023)**. In other words, repurposing existing natural gas infrastructure is an economically and technologically feasible solution for hydrogen transport, although the technical specifications of some pipelines may limit their

adaptation potential **(Telessy et al., 2024)**. As for the specific challenges of green hydrogen, one of the most significant obstacles is the high production costs. Currently, green hydrogen produced via electrolysis powered by renewable sources has significantly higher costs than grey hydrogen derived from fossil fuels. The production cost of green hydrogen is, on average, over three times higher than that of blue hydrogen. According to a detailed study from 2025, green hydrogen costs between 3.5 and 6 USD/kg, while blue hydrogen is priced between 2.0 and 3.5 USD/kg, with grey hydrogen being the cheapest (1.5–2.5 USD/kg) (**Cornell University, 2025)**. This difference is also evident in the costs associated with the final uses of hydrogen, particularly in the transport sector. Fuel Cell Electric Vehicles (FCEVs), equipped with hydrogen tanks, have a significantly higher total lifecycle cost (Total Cost of Ownership) compared to conventional vehicles powered by fossil fuels. Some scenario analyses report costs up to ten times higher, depending on usage conditions, production volumes, and the infrastructure context. However, in more optimistic scenarios or with established economies of scale, this differential may be smaller but remains significant compared to traditional technologies. **(Burke-Zhao-Fulton, 2024)**.

Another obstacle to the widespread adoption of green hydrogen is the limited recognition of its environmental contribution within market mechanisms and pricing policies. Although green hydrogen represents a low-carbon solution, it still does not receive adequate recognition in terms of incentives, certifications, or market premiums that reflect the environmental benefits associated with its production and use. The absence of a uniform certification system for renewable origin or an explicit carbon price sufficient to close the economic gap with grey hydrogen makes it difficult for green hydrogen to compete economically, despite its clear sustainability advantages. (**IEA, 2023)**.

The sustainability of green hydrogen is tightly linked to the electricity source used for electrolysis. If the electrolyzes are directly powered by renewable energy plants, the hydrogen produced is certainly "green." However, if electrolysis is connected to the general electricity grid, the energy mix may include fossil fuel-derived energy, compromising the overall environmental sustainability. Therefore, it is crucial to consider the CO_2 emissions associated with the electricity consumed, which represents a significant barrier, especially in countries with an energy mix still heavily dependent on fossil sources. An analysis conducted in 2024 highlighted that the production of green hydrogen using wind energy resulted in the lowest emissions (0.6 kg CO_2 eq. per kg of H_2), while solar energy resulted in higher emissions (2.5 kg CO_2 eq. per kg of H_2). When the electricity grid is connected to both solar and wind in a 50:50 ratio, most of the emissions come from solar energy, with 1.2 kg CO_2 eq. per kg of H_2, while emissions from wind energy are lower, at 0.3 kg CO_2 eq. per kg of H_2. The total emissions for this combination amount to 1.5 kg CO_2 eq. per kg of H_2. These figures underline the importance of a renewable energy mix to ensure the sustainability of green hydrogen. **(Patel et al., 2024).**

From a technical perspective, one of the main challenges associated with green hydrogen is the energy losses along the entire production, distribution, and utilization chain. The process of water electrolysis, although representing a sustainable solution for the production of emission-free hydrogen, has limited efficiency: it is estimated that about 30–35% of the electrical energy used is lost during this phase. Further inefficiencies occur during the conversion of hydrogen into other energy carriers, such as ammonia, which is often used to facilitate long-distance transport and storage. In this process, energy losses range from 13% to 25%, depending on the technologies used. **(WEF, 2021).** Finally, the use of hydrogen in fuel cells, for example in the mobility sector, leads to an additional reduction in efficiency, with losses ranging from 40% to 50%, due to the thermodynamic nature of the conversion process. **(Opolot et al., 2025).**

Considering the entire chain, from production to final use, the overall efficiency of green hydrogen may be significantly lower compared to other technological solutions. This implies that, to meet a given final energy demand, a much higher initial input of renewable energy is required, making the system particularly demanding in terms of infrastructure and installed capacity. This aspect represents a significant challenge to the scalability of green hydrogen, especially in the context of increasing competition for the use of renewable sources.

Another critical aspect in evaluating the green hydrogen supply chain concerns transportation, which presents challenges both from a technical and economic perspective. The modes and costs of transport vary significantly depending on the volumes moved and the distances to cover, significantly influencing the overall competitiveness of the solution. In the case of small-scale transportation, such as trucks transporting compressed hydrogen over distances up to 500 km, the costs are estimated to range between 1 and 2 USD/kg **(Sovechea S., 2024).** However, for longer distances, such as 1,000 km, costs rise significantly, making this mode less competitive compared to other solutions. At low volumes, the cost of transporting compressed hydrogen for 1,000 km by truck is approximately 3.5 USD/kg. For large volumes, the shipping of green ammonia is the most cost-effective option, adding only 0.15 USD/kg of hydrogen (excluding conversion costs, i.e., dehydrogenation). Similarly, very low costs can be achieved using large pipelines (around 2,000 tons per day) over short distances. Hydrogen transportation via pipeline can cost one-tenth of the cost of transporting the same energy as electricity **(Lenntech/ Hydrogen/2023)**. Finally, for short to medium distances, transportation through dedicated hydrogen pipelines remains the most efficient solution. Although the existing infrastructure is still limited, the potential of these networks is significant. High-capacity infrastructures, designed to transport up to 2,000 tons of hydrogen per day, allow for substantial economies of scale, reducing unit transportation costs and increasing supply reliability. However, the construction of these networks requires significant upfront investment and long-term strategic planning, as well as full integration with the existing energy system (**IEA, 2023)**.

It is expected that the costs of green hydrogen will decrease significantly in the coming years due to technological improvements in electrolyzes efficiency and the declining cost of renewable electricity, particularly in favorable markets (e.g., Australasia, the Middle East).

Recent projections indicate a significant reduction in the cost of green hydrogen production in the coming decades. According to PwC (2025), by 2030, the cost could decrease by up to 50% in the most competitive markets, reaching between 1 and 2 €/kg, with a further gradual decrease by 2050 **(PWC, 2022).** Estimates from the International Renewable Energy Agency (IRENA) confirm this trend, forecasting values of 1.2 $/kg for production from solar sources and 0.95 $/kg from wind sources by mid-century, provided that all technological innovation goals, infrastructure optimization, and market development objectives are met. These advancements are critical for making hydrogen competitive: about 5 €/kgH_2 for the transportation sector and between 2 and 3 €/kgH_2 for the main industrial applications. **(Irena, 2019).**

This significant drop in costs will make the gradual shift from blue hydrogen to green hydrogen possible in the coming decades. However, it is crucial to emphasize that this trend will not be uniform: each market presents a unique combination of resources, infrastructure, regulations, and energy costs that will influence local trajectories of green hydrogen. **(PWC, 2022).**

In conclusion, despite the challenges related to the scarcity of infrastructure, high costs and technical inefficiencies, green hydrogen offers important opportunities. With technological improvement, optimization of existing infrastructure and appropriate policies, green hydrogen can become a pillar of the energy transition. Overcoming these barriers requires coordinated action between science, industry and policy to unlock its full potential in decarbonization.

2.3 ESG Criteria in the Context of Hydrogen Hubs

The growing interest in green hydrogen, particularly within energy hubs, raises questions about how this system aligns with ESG (Environmental, Social, and Governance) criteria. Hydrogen hubs represent a unique opportunity to integrate these three dimensions synergistically, creating not only a more sustainable energy system but also a driver of economic and social development. Green hydrogen hubs are, in fact, not only an opportunity to reduce greenhouse gas emissions but also to generate long-term socio-economic benefits, particularly in terms of employment and infrastructure development.

In recent years, the role of ESG criteria (Environmental, Social, and Governance) in the green hydrogen sector has garnered increasing attention from the international community, as highlighted by several recent publications in the field. In particular, hydrogen hubs emerge as strategic platforms capable of effectively integrating the three pillars of sustainability, addressing urgent environmental needs while also tackling the social and economic challenges that characterize the energy transition.

Several recent studies have explored these issues, proposing innovative solutions and strategies to reduce environmental impacts and promote long-term sustainability. The environmental aspects of hydrogen hubs are primarily related to the sustainable production and management of hydrogen. According to various authors **(Goodwin et al., 2024)**, renewable hydrogen certification plays a crucial role in ensuring that the hydrogen produced is indeed derived from renewable sources, minimizing the overall environmental impact. The integrated management of green certificates, energy, and carbon is seen as an effective strategy to promote the uptake of green energy and reduce greenhouse gas emissions. Recent studies suggest that strengthening the links between these markets can accelerate the transition to a sustainable energy system **(Xu Li et al., 2025)**. The integration of the management of green certificates can foster an effective transition towards the adoption of green hydrogen, accelerating the deployment of low-carbon technologies and stimulating investments in the necessary infrastructure. This approach contributes not only to the reduction of greenhouse gas emissions, but also to the improvement of the overall efficiency of the energy system, creating synergies between energy and sustainability markets **(Yang Jun et al., 2025)**

Furthermore, another study **(Yang Jun's 2025)** proposes a distributed dispatch approach for district-level multi-energy microgrids, integrating green certificate trading and carbon emissions management. Each microgrid can thus optimize the benefits of green certificate management, increase the overall efficiency of the energy system and significantly contribute to carbon emissions reduction. The green certificate trading approach, combined with carbon credit trading, facilitates the uptake of renewable energy within the system, encouraging energy production from renewable sources. In this way, the integration of green certificates not only incentivizes the use of clean energy but also ensures carbon neutrality, making the energy system more sustainable and promoting the transition to a low-carbon future.

Regarding sustainable hydrogen production strategies, an important area of interest involves producing green hydrogen through advanced technologies and efficient resource management. The study Innovative Sustainable Green Hydrogen Ecosystem **(Akdag O., 2025)** proposes an innovative ecosystem for green hydrogen production, focusing on technologies capable of significantly reducing environmental impacts. The adoption of these technologies not only optimizes energy efficiency but also contributes to reducing the resources consumed during production, thus improving the sustainability of the entire process. This study introduces the Hydrogen Dynamic Ecosystem Model (HDE-M), designed to support sustainable energy transitions in maritime transport. The model develops in six stages: Hydrogen Feedstock Supply, Production, Storage, Transport, Use in Hydrogen Refueling Stations (HFS), and Maritime Application. Technical, environmental, and cost analyses have been conducted using Balıkesir, Turkey, as a case study.

Another relevant aspect is the analysis of different hydrogen production methods and their environmental impact. The study Economic and environmental assessment of different hydrogen provision methods examines various hydrogen production methods, comparing the costs and environmental impacts associated with each technology. The comparison helps identify the most sustainable solutions in specific contexts, with the goal of minimizing the ecological footprint of hydrogen production ***(Sayer M. et al., 2024).*** The work analyzed a study that evaluated four main production chains and two transportation modes from North Africa to Europe, focusing on costs and environmental impacts. It concluded that both importing and locally producing green hydrogen are realistic solutions for decarbonizing the energy system. However, for emissions reduction to be effective, green hydrogen must be prioritized, while blue hydrogen, although useful as a bridge solution, presents the critical issue of methane emissions, which require careful monitoring. In conclusion, both importing and locally producing green hydrogen can support the energy transition, as long as carbon emissions containment and blue hydrogen risk management are given the highest priority.

An innovative approach to reducing the environmental impact of hydrogen hubs is the production of green hydrogen using offshore wind energy. The study *Offshore wind-driven green hydrogen* explores the environmental and economic implications of this model, highlighting both the potential benefits and the challenges of integrating wind energy into hydrogen production. The use of renewable natural resources in maritime areas significantly reduces the use of agricultural and industrial land, optimizing energy efficiency and minimizing ecological impact compared to land-based technologies **(*Guven D., 2024*).** This study analyzes the environmental and financial implications of a green hydrogen generation system powered by offshore wind energy, utilizing Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) methodologies. The analysis uses Global Climate Models (GCM) to predict wind speeds, which are crucial for sizing the electrolyzes based on wind energy production.

The study by **(*Nam Nghiep Tran et al., 2025*)**, explores the integration of ESG factors in the techno-economic analysis of decentralized ammonia production in Africa. The findings show how renewable technologies such as elevated thermal plasma and mini-Haber-Bosch can be effectively implemented, positively impacting the sustainability of supply chains. However, ESG metrics have not been fully integrated into the cost optimization model, limiting their strategic impact. Additionally, reliance on fixed assumptions and emerging technologies presents challenges for long-term scalability.

A recent article by **(J. Christopher Fisher et al., 2024)** proposes a method called H2Locate for selecting ideal locations for hydrogen production plants within a defined region. This approach analyzes crucial variables such as resource availability, access to energy, and social impacts to identify the most relevant factors for choosing a location for plant implementation. The illustrative example, using the Oklahoma area, shows how the counties in the region can be analyzed to identify suitable sub-regions. The method uses Excel-based software, the Probability of Hydrogen Implementation (PHI), which utilizes public data on resources, energy, and social variables to support location selection. For an alkaline electrolyze plant of 290 MW, the results indicate that the counties of Kay, Johnston, Caddo, and the surrounding ones are the most suitable for implementation based on the analyzed variables. Determining the optimal locations for green hydrogen production facilities remains a complex challenge, influenced by multiple technical, economic, logistical, and environmental factors. To address this challenge, a recent study by **(Denizhan/Özçelik, 2025)** proposes the CELO_GH algorithm (Optimization of Urban Locations for Green Hydrogen), a new heuristic approach that differs from traditional multi-criteria decision-making (MCDM) models. The algorithm dynamically evaluates cities based on various factors, including the renewable energy surplus available, proximity to industrial hydrogen demand, accessibility to infrastructures like ports and pipelines, and economic feasibility. A case study conducted in Turkey demonstrated the effectiveness of CELO_GH, identifying the optimal cities for green hydrogen production using real data on energy and infrastructure. Comparison with a genetic algorithm revealed that the proposed heuristic approach provides more cost-effective results for location selection. Additionally, the methodology is flexible in terms of geography, as the algorithm can be applied globally in regions with high renewable energy potential, ensuring scalability and adaptability to future energy transition strategies.

The sustainability of a hydrogen hub is not only dependent on the production process but also on the entire supply chain. The study "*Environmental assessment of a hydrogen supply chain*" **(Rey I., 2024)** examines the environmental impacts associated with hydrogen production and distribution, offering a comprehensive view of the sustainability of the supply chain. The analysis suggests that the long-term sustainability of hydrogen hubs depends on optimizing resources throughout the entire process, from production to distribution, integrating eco-friendly practices to reduce environmental impact. Another recent study analyzed the environmental impact of the hydrogen supply chain by applying life cycle assessment (LCA) to the synthesis of new low-concentration PGM (Platinum Group Metals) catalysts, an underexplored topic. The results highlighted that the dehydrogenation process is the most critical step environmentally, mainly due to the high heat consumption. Furthermore, the environmental footprint of platinum usage in catalyst production is significant, with considerable ecological impacts linked to its extraction and use. The research emphasizes the need to explore alternative solutions to rare metals to improve the sustainability of LOHC systems, encouraging broader adoption of these technologies in the long term. An another study **(Rangel et al., *2025)*** propose a new optimization approach to determine the optimal installed capacities of wind, solar, and hydrogen storage systems aimed at the continuous production of green hydrogen. The main focus of this approach is the "Real Hydrogen Cost" (Total Cost of Ownership /TCOH), a metric that combines both costs and environmental impacts over the life cycle, thus supporting decision-making and the design of energy projects. The study results show that optimizing the TCOH for costs and environmental impacts can reduce a wide range of environmental impact categories by up to 37%, while incurring an increase in costs of up to 0.23 €/kg H2. The work emphasizes that, despite the increase in costs, TCOH optimization allows for economically advantageous hydrogen production while contributing to mitigating the environmental impacts associated with green hydrogen production. This approach has the potential to strengthen current requirements for carbon footprint, leading to a transition towards a more sustainable energy path. The production of green hydrogen must be evaluated not only from an environmental perspective but also from an economic one. The study Techno-economic and environmental assessment of green hydrogen production **(Tushar et al., 2025)**, provides a detailed evaluation of green hydrogen production in an Australian energy hub, examining both the economic and environmental aspects. The research emphasizes how optimizing technologies and resources can significantly improve project sustainability, while reduce greenhouse gas emissions and improve system efficiency. The study examines green hydrogen production in Australia using an off-grid system based on renewable energy (60% solar, 40% wind) and different electrolyzes technologies (PEMEL, AEL, SOEL). The analysis shows that green hydrogen can reduce lifecycle emissions by up to 95% compared to grey hydrogen, also improving regional employment and the Human Development Index (HDI), especially in remote communities. From an economic perspective, the most influential factors were found to be solar capacity factor and electrolyze CAPEX.

In the context of the transition to a sustainable energy system, the adoption of circular economy practices along the hydrogen supply chain emerges as a key strategy to reduce environmental

impacts. An another study **(Aghajani et al., *2025)*** propose an innovative design for the hydrogen supply chain that integrates circular economy sustainability principles. This approach demonstrates how optimized resource management and material recycling can significantly reduce waste and improve overall efficiency, thus reducing environmental impacts associated with hydrogen production and distribution. However, its large-scale adoption is hindered by high costs and inefficient production utilization. In this context, the study proposes an innovative framework for producing bio-hydrogen from municipal solid waste (MSW) and dairy residues, integrating waste disposal centers, biorefineries, carbon capture and storage, and refueling infrastructures. This model foresees competition between hydrogen and oil producers, incentivized by government policies to promote green production, technology, and job creation, with a "Stackelberg leader" guiding the strategy. The price of hydrogen derived from this approach is integrated into a multi-objective linear programming model, focusing on market uncertainties to optimize production and distribution in a competitive market environment. Implemented in a case study in Finland, the framework demonstrates the potential to improve the efficiency and sustainability of bio-hydrogen production, making this resource a key part of a sustainable future energy system.
The study Towards greater circularity in the hydrogen technology value chain **(Axt et al, 2025)** explores how the circular economy can be applied to the hydrogen value chain. According to the authors, the integration of circular practices, such as material recycling and component reuse, can significantly reduce waste and improve resource efficiency, thereby increasing the long-term sustainability of hydrogen hubs. In parallel, (**Abdirahman et al., 2025)** emphasize that applying the circular economy in the renewable energy sector, including hydrogen hubs, offers significant benefits in terms of cost reduction and efficiency improvement. The authors highlight that the adoption of circular practices, such as material recycling and waste reduction, contributes to more sustainable resource management. This approach not only reduces the overall ecological impact but also improves the operational efficiency of plants, fostering a more resilient and sustainable energy system. However, the research points out the need for further studies to optimize the integration of circular practices and maximize both environmental and economic benefits. The evolution of hydrogen towards a circular economy model requires the use of advanced technologies capable of transforming waste into pure hydrogen, minimizing environmental impact. A recent review (**Ganesan Subbiah, 2025**) explored the advances in various techniques to produce hydrogen, analyzing the effectiveness, costs, and environmental impact of each. Catalytic techniques, such as systems using special materials to facilitate chemical reactions, have shown good results in hydrogen production but are still hindered by issues such as material efficiency loss over time and the difficulty of scaling up processes. Thermochemical techniques, which use heat to transform materials into hydrogen, are promising but require high initial costs and complex operations. Biochemical techniques, which use biological processes such as fermentation, have good potential but are limited by slow processes and challenges in preparing materials. Studies comparing the lifecycle and economic efficiency of different technologies suggest that combining thermochemical and

biochemical methods could be the best solution, reducing costs and environmental impact, thereby improving the sustainability of hydrogen production.

The adoption of the circular economy (CE) in businesses is emerging as a sustainable strategy, but its financial implications along the supply chain are still underexplored. A recent study **(Mingsen Wang et al., 2025)** analyzes how CE initiatives influence the financial performance of businesses and their partners along the supply chain, using data from the Chinese stock market and other sources between 2006 and 2021. The results show that CE practices improve business financial performance and provide indirect benefits to suppliers and customers. In particular, the benefits are more pronounced in sectors with high competition and supply chain concentration. Companies that adopt CE strategies tend to develop stronger relationships along the supply chain, improving efficiency and reducing costs. Centralized purchasing strategies within the circular economy also offer a competitive advantage. The study suggests that companies should promote CE initiatives not only internally but also among supply chain partners, generating collective advantages. The transition to a sustainable energy system involves not only technical and environmental aspects but also a profound social transformation. The adoption of green hydrogen could bring both opportunities and social challenges. On the one hand, it could create new jobs in the renewable energy sector, but on the other, it could cause job losses in traditional sectors, exacerbating regional inequalities. Furthermore, while some communities may economically benefit from the establishment of plants, others may face conflicts related to land use and resource management, undermining social cohesion. The distribution of benefits must be fair to avoid the exclusion of vulnerable groups who could be left behind in the transition. It is essential that energy policies include inclusive measures to promote equality and the well-being of all. Green hydrogen hubs, as key components in this process, offer significant opportunities for the welfare of local communities.

In particular, a recent study **(Rui A. dos Reis, 2024)** analyzed the social impacts of green hydrogen production using a social life cycle assessment (S-LCA) methodology. The analysis considered various stages of the green hydrogen production process, such as raw material extraction, component fabrication, and final production. The approach focused on four categories of social impacts: workers, value chain actors, society, and local communities. The results highlighted that the raw material extraction and processing stages for electrolyzes production were the main source of social impacts, negatively affecting workers and local communities, particularly in countries like China and South Africa. The study also found that electrolyzes production significantly impacted workers' rights, such as weekly working hours and union density, with Portugal contributing the most to these indicators. The study revealed differences between two databases used for the analysis, with one database distributing social impacts across various stages and countries, while the other showed more concentrated results.

The transition from high-carbon hydrogen production through methane reforming to low-carbon hydrogen production is critical for the decarbonization of the European industrial sector. However, the employment impact of this transition remains unclear. A recent study **(Ganter A. et al, 2024)** estimated that transitioning to an electrolyzes-based hydrogen sector could create about 40,000 jobs in the hydrogen sector by 2050, but the distribution of these jobs is not equitable. Western Europe would account for 40% of the new jobs, while some regions traditionally involved in hydrogen production could experience job losses. Even including renewable energy jobs related to the increased demand for electricity, the workforce for low-emission hydrogen would represent only 10% of the current fossil fuel workforce. The research suggests that due to regional inequalities, diversified transition plans for each sector are necessary.

Recent literature highlights the crucial role of Social Impact Assessment (SIA) in analyzing the effects of the transition to low-carbon industries, particularly the green hydrogen sector. While the shift to alternative energy sources brings widespread environmental and social benefits, tensions arise concerning the distribution of benefits and costs within communities and among stakeholders. A study **(*Yuwan Malakar et al., 2024*)** applied John Rawls' justice theory (focused on distributive justice, i.e., the fair distribution of benefits and risks among groups) to examine how to ensure a fair distribution of benefits and risks associated with green hydrogen production. The results showed that while the transition could create jobs and economic opportunities, it could also generate social inequalities. In a case study in Australia, tensions arose related to land use, income distribution, and social cohesion. In some regions, green hydrogen could drive economic growth, while in others, it could lead to job losses in traditional fossil fuel sectors. The study emphasizes that a just transition requires a systemic and inclusive vision that promotes the active participation of all involved parties, ensuring that negative impacts are mitigated, and benefits are equitably distributed. An inclusive SIA perspective is therefore crucial to promote a just transition toward a low-carbon economy.

A recent study **(Bindi, 2025)** developed a theoretical framework to assess the social impacts of green hydrogen deployment, integrating energy justice, human rights, and the capability approach. The framework provides an overview of potential social impacts, focusing on employment, well-being, health, social justice, and socio-economic inequalities. The main findings indicate that the introduction of green hydrogen could create new job opportunities but also cause losses in traditional sectors, leading to regional inequalities. The adoption of green technologies could improve well-being in some areas but also exacerbate socio-economic disparities. The framework emphasizes the importance of ensuring a fair distribution of benefits, integrating human rights into energy policies. As green hydrogen production is still in its early stages, the study suggests an ex-ante approach to predict social impacts, using plausible scenarios. An important next step in assessing social impacts is the adoption of mixed methodologies, combining qualitative research (such as interviews and focus groups) with quantitative research (such as surveys and data analysis). This integrated approach allows for capturing complex dynamics that might not be identified with purely quantitative methods, providing a more comprehensive assessment of social impacts. The triangulation of methodologies offers a broader view, useful for formulating energy policies that are not only economically driven but also socially informed.

The production and adoption of green hydrogen have significant social impacts that go beyond economic and technological efficiency. Some experts in the field **(*Boom/Dettner, 2023*)** emphasize how the integration of sustainability criteria across the entire value chain is essential to promote a fair and responsible energy transition, reducing the risk of social injustices and balancing the interests of all involved stakeholders. Focusing solely on economic costs can lead to partial decisions and the exclusion of vulnerable groups.

A theoretical framework is proposed, with 16 sustainability criteria organized into six impact categories (Figure 9), designed to guide decision-makers and stakeholders in evaluating green hydrogen projects.

Figure 9: Sustainability criteria (outer circle) and related impact categories (inner circle) (Source: Boom/Dettner, 2023)

The practical adoption of these criteria, such as through design checklists, promotes transparency, trust, and acceptance among local communities, helping to mitigate social conflicts and regional inequalities. Furthermore, these criteria are closely linked to smart energy systems, enabling the optimization of renewable energy use, improving efficiency, integrating hydrogen production into the power grid, and developing supporting policies based on techno-economic assessments.

The results emphasize that integrating the social dimension into the design and management of green hydrogen systems not only improves overall sustainability but also facilitates project implementation, promoting an inclusive, fair, and socially responsible transition. Therefore, the approach suggests that social sustainability should be considered an integral part of evaluating and planning green hydrogen projects, alongside environmental and technological aspects.

Governance represents a crucial element within ESG (Environmental, Social, Governance) practices in hydrogen hubs, as it ensures transparency, accountability, and stakeholder participation, directly influencing the effectiveness, sustainability, and social acceptance of projects. Recent studies highlight that adopting clear and accessible ESG transparency and reporting practices is essential for building trust among investors, local communities, and other stakeholders, ensuring that environmental, social, and economic impacts are responsibly monitored and managed.

MÁTÉ ZAVARKÓ's study (*2023*), *"The global ESG trend and adaptation opportunities in the emerging hydrogen economy: A corporate governance perspective",* has explored how global ESG trends influence business strategies, focusing on governance systems and adaptation opportunities to improve environmental, economic, and decision-making performance in the emerging higher education sector, with relevant implications for hydrogen hubs. The findings indicate that governance is a key factor for integrating ESG aspects into strategic decisions, influencing not only environmental sustainability but also the resilience and competitiveness of hydrogen-based energy sectors. The study identified 27 strategic and governance opportunities aimed at supporting environmental performance, suggesting that targeted regulatory policies, incentive systems, and responsible leadership can drive investments in green technologies, including solutions for large-scale production and use of green or low-carbon hydrogen (e.g., through power-to-X processes). Moreover, there is a reciprocal interaction between governance and ESG performance: effective governance can stimulate better environmental and social outcomes, while improving ESG performance helps strengthen the decision-making structure and organizational resilience. Integrating ESG into business strategies also enables coordination of top-down regulatory and business interventions, generating socio-economic and sectoral benefits, including promoting a more competitive and climate-neutral energy sector based on hydrogen. Despite promising findings, the study notes some limitations: the systematic analysis mainly focused on environmental and governance aspects, while the social dimensions have been less explored. Therefore, future empirical research could delve deeper into the role of governance systems in managing the social impacts of hydrogen hubs and in the technological diffusion of green energy.

The active involvement (Stakeholder Engagement and Community Participation) of local communities (Local Community Engagement, LCE) and listening to public opinion (Public Opinion, PO) are key elements in ensuring a fair distribution of social impacts in hydrogen hubs. Recent studies indicate that emerging industrial regions, such as some provinces in Indonesia, face difficulties in adopting Green Technological Innovation (GTI) due to infrastructure and regulatory limitations, while agricultural areas and those with indigenous populations may benefit from integrating local knowledge in resource management, improving resilience and social cohesion.

The research **(Asep Marfu et al., 2025)** also emphasizes that effective corporate governance (Good Corporate Governance, GCG), combined with transparency tools, incentives for sustainable investments, and public awareness campaigns, promotes sustainable practices and a fair distribution of economic and social benefits. These findings align with previous evidence on the importance of integrating the social dimension in hydrogen hub planning, confirming that participatory and transparent governance is a decisive factor for the success of projects and mitigating negative social impacts.

To address the lack of direct impacts from green technology innovation, targeted incentives need to be introduced for businesses to invest in eco-friendly technologies. National sustainability policies should promote good corporate governance, strengthening transparency and accountability among companies operating in the natural resources sectors. Moreover, public awareness campaigns on environmental responsibility can help bridge the gap between technological advances and community expectations, fostering a more conducive environment for growth driven by sustainability. The case of Morocco (**Mohammed Boulghalagh et al., 2025**) highlights that the creation of a clear legal and institutional framework, supported by public-private partnership (PPP) laws and dedicated governance bodies, is essential for mobilizing green investments and improving national energy resilience. Despite progress, regulatory and operational challenges persist fragmented standards, lack of a unified green taxonomy, and discrepancies in ESG reporting requirements increase the perceived risk for investors, limiting the speed and feasibility of projects. In this context, PPPs emerge as strategic tools, facilitating balanced risk-sharing, the integration of international standards, and active private sector participation. The literature also emphasizes the importance of strengthening the capacity of public and private actors through targeted training, digital monitoring tools, and streamlining administrative procedures to improve transparency, project management, and investor trust. Overall, Morocco's experience demonstrates that clear, inclusive, and strategically integrated governance can facilitate the mobilization of green capital, promote a fair distribution of benefits, and support economic growth, green job creation, and climate resilience. The report "***Scaling Hydrogen Financing for Development***" ***(*****2023, The World Bank*****)*** highlights that the lack of a consolidated market for clean hydrogen is one of the main obstacles to the development of hydrogen hubs and the mobilization of private investment. Despite the announcement of global subsidies between $100 billion and $300 billion, many clean hydrogen projects have not yet reached the final investment decision stage due to high costs and significant perceived risks (ScienceDirect). In this context, governance emerges as a crucial factor: predictable regulations, simplified procedures, and clear regulatory frameworks are essential to reduce uncertainties and increase investor confidence. Studies highlight the importance of integrated policy packages that consider the entire hydrogen value chain, from supply to demand, and connect energy infrastructure with end uses. Targeted incentives are a key tool in governance: public subsidies, tax breaks, and financial instruments dedicated to risk mitigation can stimulate private investments, foster the development of pilot projects and large-scale plants, and attract private participation in emerging markets. In developing countries and emerging economies (EMDC), early involvement of governments and the private sector can strengthen the international hydrogen value chain, optimize local socio-economic benefits, and promote climate justice. Governments' willingness to share and absorb risks, combined with the participation of multilateral institutions such as development banks (MDBs), fosters the diffusion of knowledge, stimulates technological innovation, and consolidates a more resilient international hydrogen market. In summary, the report emphasizes that adopting solid and transparent governance, alongside strategic incentives and targeted financial instruments, is

essential to accelerate the creation and diffusion of green hydrogen hubs, optimize the value chain, attract private investments, and promote a sustainable, inclusive, and fair energy transition.
From a governance perspective, integrating assessment tools and integrated methodologies represents a strategic element in the decision-making process of Hydrogen Hubs. The adoption of social analysis methodologies, both qualitative and quantitative, allows public and private decision-makers to transparently monitor and manage impacts on local communities, ensuring stakeholder participation and information sharing across the entire value chain. In particular, tools like Social Life Cycle Assessment (S-LCA) and participatory impact assessments promote continuous dialogue with local communities and greater social legitimacy of projects, thereby enhancing organizational resilience and the ability of hubs to respond to emerging needs.
For instance, **Tabandeh et al. (2024)** propose a planning framework for hydrogen hubs capable of integrating net-zero goals with technical-economic constraints and Life Cycle Assessment (LCA) indicators (emissions, water/soil use), showing in a case study how the reconfiguration of the electric mix and end uses enables a significant reduction in overall emissions compared to business-as-usual scenarios. In this context **Ajeeb et al. (2024)** summarize LCA findings for green hydrogen via electrolysis, clarifying that climate benefits are truly realized only with additional or very low-carbon electricity, while also quantifying trade-offs on water consumption, materials, and scalability of the supply chain, which are crucial for the localization and design of hubs.
Regarding systemic and environmental risks, **Karplus et al. (2024)** warn that investments in hubs may not generate deep greenhouse gas (GHG) reductions, or even compromise them due to leakage and lock-in, recommending renewable additivity, prioritizing hard-to-abate uses, and robust monitoring (PMC). This approach aligns with the U.S. institutional framework: the Department of Energy (DOE) initiated NEPA (National Environmental Policy Act) Environmental Impact Statement processes for regional hubs (e.g., Pacific Northwest, Appalachian) in December 2024, formalizing the evaluation of impacts on emissions, energy and water consumption, and other local externalities as a requirement for fund allocation **(The Department of Energy's Energy.gov, 2024)**.
The review by **Osman et al. (2024)** summarizes evidence across the entire value chain (production, storage, distribution, end uses), confirming that the greatest climate benefits are achieved when green hydrogen replaces fossil fuels in industrial processes that are energy-intensive and hard to electrify directly, reiterating the importance of the electric mix and additionality to maintain a low overall GHG footprint for hubs. The review also highlights the essential role of LCA in guiding the hydrogen economy towards a low-carbon future, positioning hydrogen as a versatile energy carrier with significant potential (Figure 10).

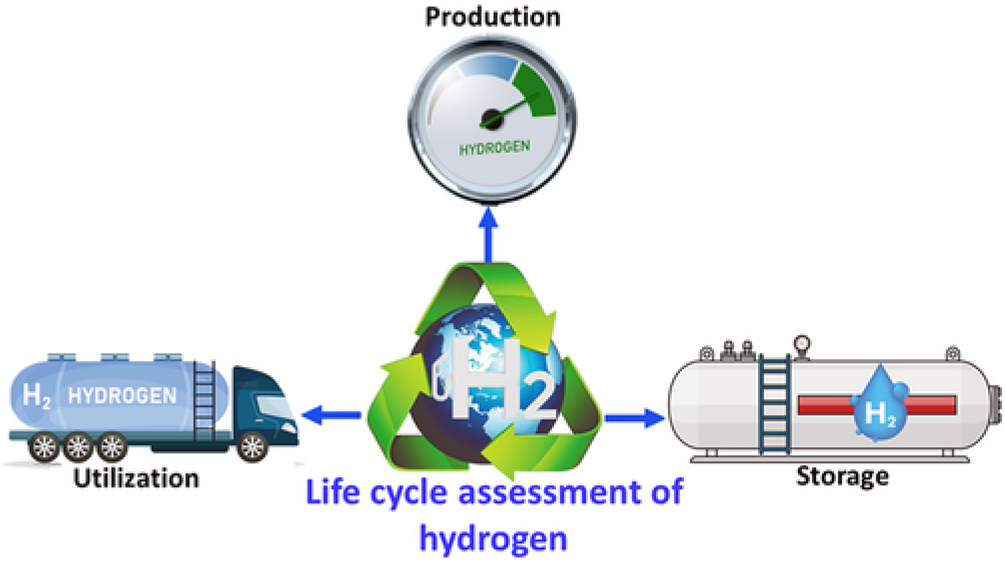


Figure 10: Life cycle assessment of hydrogen. (Source: Osman et al., 2024)

Furthermore, the IRENA report (2023) provides a global perspective on energy transition strategies, highlighting the central role of green hydrogen in achieving climate goals and promoting sustainable energy practices (**IRENA, 2023,Hydrogen: A renewable energy perspective). The European Hydrogen Backbone Initiative (2023)** complements this analysis, showing how the expansion of hydrogen hubs can further reduce dependence on fossil fuels, accelerating the transition toward a fully decarbonized energy system. Supporting this evidence, BloombergNEF (2024) reports a 35% global increase in green hydrogen investments over the past year alone, alongside significant growth in production capacity in Europe and Asia **(Hydrogen Market Outlook, BloombergNEF, 1Q2024)**.
Additionally, the recent analysis by Hydrogen Council and McKinsey (2025) emphasizes that adopting advanced ESG standards and digital monitoring systems has become critical for securing financing and scaling projects. The **"Global Hydrogen Compass 2025"** (Hydrogen Council) report also highlights increasing attention to environmental and social impacts across the entire value chain, with a growing number of projects incorporating independent audits and transparent Life Cycle Assessment (LCA) procedures.

2.4 The Role of SMEs and Startups in Hydrogen Adoption

Startups and small and medium-sized enterprises (SMEs) represent two complementary actors in the transition to green hydrogen, capable of driving innovation while ensuring the industrial diffusion of new technologies. Startups are the engine of radical innovation: in Europe, most of the venture capital in the hydrogen sector (about 97%) is directed toward hardware solutions, electrolyzes, production plants, and storage systems, reflecting the highly technological nature of the sector. Iconic examples like H2 Green Steel in Sweden show the ability of emerging companies to impact energy-intensive supply chains **(OECDO, 2025)**, while in the United States, companies like Electric

Hydrogen have raised record funds from global investors to develop large-scale electrolyzes **(H2UB, 2024).**

Alongside these, SMEs play a crucial role as a "bridge" between research and the market, thanks to consolidated technical expertise and the ability to integrate innovative solutions into existing production processes. SMEs can act as transition actors, facilitating the adoption of hydrogen in traditional sectors and contributing to the creation of regional hubs through networks of collaboration with universities, large enterprises, and institutions. A recent study by **Mousavi et al. (2025)** examined the role of Dutch SMEs in promoting a green hydrogen economy, using interviews with SMEs, industrial associations, and ecosystem facilitators. The results reveal that SMEs are not merely niche players, but market-oriented innovators and system integrators, significantly contributing to the diversification of energy transition pathways. However, SMEs face several obstacles, including the "innovation-market gap," which manifests financial barriers, regulatory blocks, and the lack of market formation mechanisms that limit the adoption of new technologies like green hydrogen. Despite these challenges, SMEs develop dynamic capabilities, such as entrepreneurial spirit and strategic flexibility, enabling them to navigate limited resources and respond agilely to market needs. Finally, the study suggests that to fully realize the potential of SMEs in the green hydrogen transition, a shift in support policies is necessary. Policies should evolve from "project-based" support to an "ecosystem-based" model, promoting strategic industrial policies that encourage alternative transition pathways and developing financial instruments like patient capital to align with the long development times of SMEs' technologies **(Mousavi et al., 2025)**.

The central role of SMEs globally is recognized in the report "Advancing the green transition of Smes Insights for SME development agencies to support sustainability practices and reporting" **(2024, Economic and Social Commission for Asia and Pacific**-**ESCAP**), where it is confirmed that SMEs represent a significant part of the global economy (90% of global businesses), with several challenges to face in integrating sustainability into their operations, such as lack of awareness, limited financial resources, and insufficient technical skills. However, the adoption of ESG practices can bring numerous benefits to SMEs, including cost savings, access to new markets, and improvements in competitiveness. The document explores various approaches to overcome these challenges, such as promoting awareness through roadshows, awards, and digital platforms; building skills through training courses and technical assistance; offering practical tools for implementing and monitoring ESG practices; and providing access to green finance, which is essential for supporting the transition. Several examples of initiatives in various ASEAN countries are presented, such as the "SMILEES Roadshow" in the Philippines, the ESG Academy in Thailand, and the "Cambodia Green Industry Award."

Similarly, the fundamental role of SMEs in the United States in the transition to green energy emerges from a recent analysis by **Ogunyemi and Ishola (2024)**, which highlights that SMEs represent over 99% of businesses and are a crucial engine for economic and employment growth. Despite the benefits, SMEs continue to face significant barriers, such as a lack of awareness about funding options, difficulties in meeting the requirements necessary to access green funds, and a perception of high financial risks. In conclusion, the combination of sustainable financing and specialized consulting proves to be a key factor in overcoming difficulties in the ecological transition, helping to achieve global sustainability goals and strengthening the competitiveness of SMEs in the U.S.

Meanwhile, the role of startups is decisive in the low-carbon energy technology (LCET) ecosystem, emphasizing how these companies are essential drivers for decarbonization thanks to their flexibility, innovative capacity, and rapid adaptability in a fast-evolving market **(Harilal Krishna et al.,2022)**. Startups, particularly in the renewable energy and mobility sectors (with a focus on electric vehicles), have benefited from significant inflows of investment, favored by government policies aimed at the development of green technologies. In these areas, mobility startups stand out for their intense patent activity, highlighting a strong orientation towards technological innovation, while renewable energy startups tend to improve already established technologies through practical experience. However, startups active in more complex sectors, such as advanced materials and chemicals, face greater difficulties in accessing resources and funding, signaling the need for more targeted support policies. In general, although significant progress has been made in the sector, startups in the renewable energy and mobility fields seem to benefit more from existing market policies, while those operating in more complex sectors face greater challenges.

A recent review also highlights the key role of startups in the renewable energy sector, dividing them into technological, community, and rural types. Technological startups lead the innovation toward decarbonization but face significant financial and regulatory obstacles. Community startups promote local energy justice, although they must overcome resource limitations and social resistance, while rural startups improve energy access in isolated areas despite funding difficulties and political support challenges **(Bendig et. al., 2025)**. The success of these ventures depends on their ability to adapt to local conditions, raise capital, and overcome technical, financial, and social barriers.

Small and medium-sized enterprises (SMEs) and startups are often more agile and willing to experiment with new technologies compared to large corporations. For example, startups like H2Pro (Israel) and Enapter (Germany) are developing modular electrolyzes and innovative storage solutions, contributing to reducing costs and improving the efficiency of green hydrogen production. H2Pro has developed a water-splitting technology called E-TAC, which promises a more cost-effective hydrogen production compatible with renewable energies. According to an article published in the New Atlas, H2Pro's E-TAC process is described as "the first technology to offer 95% energy efficiency," compared to the 70% of traditional electrolysis. Moreover, H2Pro aims to reduce the cost of hydrogen to less than $1 per kilogram by the end of the decade, making it the cheapest in the world **(Loz Blain, 2021)**. On the other hand, Enapter has developed modular electrolyzes based on AEM (Anion Exchange Membrane) technology, combining the advantages of alkaline electrolysis and proton-exchange membrane electrolysis. This solution appears promising for green hydrogen production due to its operational efficiency and lower costs **(Bernat et al., 2024).** Additionally, Enapter recently introduced the world's first megawatt-class electrolyzes, capable of producing about 450 kilograms of green hydrogen per day with 99.999% purity. This development marks a

significant step toward large-scale green hydrogen production, with applications in various sectors, including energy, mobility, and industry **(Andrea Potestà, 2024)**.
This agility is often attributed to their streamlined structure and willingness to experiment with new ideas. In fact, SMEs and startups are increasingly adopting advanced digital technologies, such as artificial intelligence (AI), to improve operational efficiency and stimulate innovation. A recent analysis has shown that the adoption of AI can reduce operational costs by up to 30% and save over 20 hours per month, thus contributing to the sustainable growth of SMEs **(Oluwatosin Agbaakin, 2025).**
In the report "Hydrogen Hubs Engagement Workshop Outcome Report" prepared by EPSRC and Innovate UK, SMEs are recognized as key players in the hydrogen sector, helping to reduce the risks associated with the technologies developed by startups and transforming them into concrete and reliable solutions through testing and validation infrastructures. In particular, SMEs play a fundamental role in de-risking emerging innovations, facilitating their transformation into safe and market-ready proof-of-concepts. This process occurs through the creation of test and validation infrastructures that allow technologies to be verified and optimized in controlled environments before their large-scale deployment. The involvement of SMEs in these stages is crucial to overcoming the technical and financial barriers that often hinder the adoption of new technologies in the green hydrogen sector. Their ability to integrate innovations into real-world contexts and adapt them to specific market needs significantly contributes to the maturation and scalability of the solutions proposed by startups. **(EPSRC – Innovate UK, 2022, Hydrogen Hubs Engagement Workshop Outcome Report)**.
To achieve net-zero emissions and environmental goals, it is essential to invest in decarbonization and innovation, supported by a banking system focused on sustainability. Despite growing attention to green finance and regulatory and consumer pressures, the necessary investment levels have not yet been reached. SMEs and startups play a key role in adopting sustainable models due to their agility, but challenges remain in accessing financing and protecting intellectual property. The experience in India shows how specific policies and financial instruments, such as green bonds and ESG loans, can facilitate this transition, although further strengthening collaboration between governments, investors, and businesses is needed (The Indian banking sector has seen a significant increase in green bonds and ESG loans, raising about $7 billion in 2021, compared to $1 billion in 2020) **(Mukul Bhatnagar et al., 2022)**. Allocating financial resources to eco-friendly practices allows SMEs to improve transparency and communicate their sustainability initiatives more effectively. A key aspect emerging from a recent study is that the pro-environmental behavior of SMEs partially mediates the relationship between green financing and sustainability reporting: financial support for green initiatives promotes greater attention to environmental issues, which is directly reflected in reporting practices. Furthermore, digitalization is a moderating factor in the relationship between pro-environmental behavior and sustainability reporting. SMEs that implement digital technologies, such as blockchain and solutions for digital business process management, tend to further improve the quality and frequency of sustainability reporting, especially when adopting pro-environmental behaviors. Empirical results, obtained through SEM methodologies and rigorous validation of analytical tools, confirm the robustness of these mechanisms.

From a practical standpoint, the study suggests that SMEs should allocate dedicated budgets for ecological practices and invest in sustainable financial instruments such as green bonds. Managers are encouraged to establish policies that direct funds to environmentally responsible projects, thereby promoting innovation in green products and services and the adoption of processes related to the circular economy **(Elias Appiah-Kubi et al., 2024).**

To achieve significant and sustainable impact over time, it is essential that startups adopt scalable business models, which are capable of promoting growth without a proportional increase in operational costs. Scalability allows startups to address typical sector challenges, such as high capital needs, regulatory complexity, and market uncertainty, making them more competitive and flexible. Among the most effective strategies for scalability, the adoption of technologies like Geographic Information Systems (GIS) has proven fundamental. GIS enables advanced spatial analyses for site selection, resource assessment, and infrastructure planning, optimizing the supply chain and identifying areas with the highest market potential. This allows startups to reduce costs, improve efficiency, and make more informed decisions. However, implementing GIS involves technical and financial challenges, such as the need for training, integration with existing systems, and data accuracy. Despite these challenges, the advantages outweigh the obstacles: with GIS, startups can mitigate risks, accelerate growth, and strengthen their competitive position **(Oguanobi & Joel, 2024).** Success stories like Sunrun and Ørsted demonstrate that integrating GIS and scalable models fosters rapid expansion and sustainable growth. The evolution of emerging technologies such as artificial intelligence (AI), machine learning, IoT, and cloud computing, integrated with GIS, opens further opportunities to optimize resource management and improve operational efficiency, making startups more resilient and ready to seize new trends in the global market.

In the context of emerging technologies, artificial intelligence (AI) and quantum computing (QC) are rapidly transforming the energy sector. Startups developing solutions based on these technologies are playing a fundamental role in improving energy efficiency, optimizing smart grid management, and facilitating the integration of renewable energies. The adoption of AI, with tools like Machine Learning and predictive analytics, enables more accurate energy demand management, real-time monitoring of operations, and decision automation, leading to superior operational efficiency and greater sustainability **(Lanbaran et al., 2024)** Meanwhile, quantum computing, still in its early stages, offers enormous potential to solve complex challenges that traditional systems cannot address, such as optimizing electrical grids and energy storage. The combination of AI and QC is accelerating innovation in the sector, tackling intricate issues like renewable resource management and grid stabilization. Startups operating in this field, many of which are funded by significant investments, are at the center of this technological revolution, with an increasing impact on improving the reliability and resilience of energy infrastructure.

To promote the adoption of green hydrogen by SMEs, it is essential to implement supportive policies that reduce risks and encourage innovation. Crucial measures include tax incentives and research and development grants, which can help businesses address the financial and technological challenges of the transition. The regulatory framework, as discussed in previous sections, provides a foundation to guide investments in emerging technologies such as green hydrogen, but direct support for SMEs remains crucial. Such policies not only incentivize SMEs to enter the market but also help reduce uncertainties associated with investing in sectors still under development. Collaboration between SMEs, startups, research institutions, and governments is essential to create an ecosystem that facilitates the adoption of green hydrogen. Specifically, partnership models between SMEs and startups can accelerate the transition to clean energy by combining innovative technological expertise with strong market experience. SMEs can benefit from the startups' ability to develop advanced technological solutions, while startups can leverage the network and established skills of SMEs to penetrate markets and achieve greater scalability. In this context, the interaction between all actors becomes crucial to overcoming economic and technological barriers, fostering the adoption of sustainable solutions, and promoting competitiveness.

In this context, the study by **Schwappach et al. (2025)** proposes an ecosystemic approach to analyzing the transition to green hydrogen, considering the need to integrate technological, organizational, and socio-political dimensions. The authors highlight how creating joint value within the green hydrogen ecosystem (GHE) depends not only on technological scalability and cost reduction but also on the coordination among heterogeneous actors, governments, companies, technology providers, and research institutions. Key triggers for the emergence of the GHE are identified, such as political goals (Paris Agreement, national strategies), the willingness to decarbonize, and economic competitiveness compared to fossil fuels. The authors further emphasize the importance of multilevel governance and coherent public policies to transform the innovative ecosystem into a stable entrepreneurial ecosystem, capable of reducing risks and ensuring continuity in the transition.

From this perspective, the GHE is not just a set of technologies but a complex socio-technical system that integrates technological, regulatory, and market factors, acting as a catalyst for new forms of cooperation and sustainable development.

The collaboration between SMEs and startups in the clean energy sector is gaining attention due to the rise of green finance and impact investments that support projects with both environmental sustainability and financial return. Governments can incentivize this cooperation through public-private partnerships (PPPs), offering grants, tax incentives, and technical support, thus facilitating the adoption of innovative technologies. However, SMEs and startups face significant obstacles, such as difficulties accessing funding and managing intellectual property (IP), which can lead to disputes and undermine trust in collaborations. Despite these challenges, strategic partnerships between SMEs and startups are crucial for accessing new markets and promoting the transition to more sustainable energy, especially in emerging markets **(Soyombo et al., 2024).**

3 Strategy and Governance in Hydrogen Hubs

The considerations regarding the role of startups and SMEs in green hydrogen adoption integrate seamlessly with studies dedicated to hub strategy and governance, which are fundamental elements for creating an environment conducive to innovation and sustainability. In this context, effective governance, combined with industry's best practices, is crucial for the success of hydrogen hubs, as it ensures cooperation among various actors, promotes the integration of emerging technologies, and facilitates the development of a robust and competitive supply chain.

Understanding governance models in the energy sector involves analyzing an articulated network of decisions involving governments, companies, and citizens, who are engaged in balancing control requirements, environmental issues, and economic conditions. In essence, energy governance translates into the definition of rules, policies, and structures that determine how energy is generated, distributed, and used. Energy governance consists of the set of decisions, rules, and instruments that regulate the management of energy resources, involving public and private actors at various levels (governments, companies, citizens, and international organizations). It accounts for diverse energy sources (fossil, renewable, nuclear), decision timeframes (from short to long term), geographical scopes (local, national, international), and the instruments adopted (incentives, markets, treaties).

This complex system aims to ensure the efficient and sustainable use of energy, balancing the immediate needs of society with future sustainability goals. Energy governance requires collaboration among multiple actors to manage production, distribution, and consumption, addressing challenges such as security, justice, equity, and social development. To be effective, it must be able to reconcile diverse interests, adapt to technological and geopolitical changes, and promote community participation **(Energy Governance Models By Sustainability Directory, 2025).**

3.1 Governance Structure and Best Practices in the Energy Sector

Recent academic literature highlights that effective governance in the energy sector must be characterized by participatory approaches, decisional transparency, and the integration of sustainability principles, including Environmental, Social, and Governance (ESG) aspects. Studies explore various governance models, emphasizing how these can facilitate the transition to renewable energy sources while simultaneously reducing risks and economic barriers for smaller actors in the sector, such as SMEs and startups.

Within this framework are the contributions of **Lentschig et al. (2025),** which offer complementary perspectives on energy governance. **Lentschig et al. (2025)** propose a multilateral governance model, stressing the importance of international and local cooperation and the need for coordinated agreements and policies between countries to foster the development of the global hydrogen economy and the growth of Hydrogen Hubs. According to the authors, synergy between public and private actors at a transnational level is fundamental to overcoming regulatory barriers and incentivizing investments in the green hydrogen sector.

Similarly, **Araujo-Vizuete e Robalino-López (2025)**, propose a hybrid governance model that combines top-down approaches, decided by governments, with bottom-up ones, originating from local communities and SMEs. Their study demonstrates that integrating national policies and community participation is fundamental to addressing energy transition challenges, such as fossil fuel dependency and the need for sustainable solutions adapted to the local context. These authors, despite operating in different contexts, agree that hybrid governance represents a bridge between global needs and local specificities. Lentschig's multilateral approach is reinforced by the participatory dimension highlighted by Araujo-Vizuete and Robalino-López, suggesting that only through collaboration between governance levels and heterogeneous actors is it possible to build resilient, inclusive, and sustainable energy systems. In summary, both contributions demonstrate that the combination of top-down and bottom-up strategies, united with effective international cooperation, forms the basis of the most advanced governance models in the hydrogen and energy transition sector.

In the case of Namibia **(Klagge, 2025)**, the top-down governance focused on the Hyphen project accelerated the transition from "governance of expectations" to "governance by expectation," with the national government playing a crucial role in supporting the project's realization (see Chapter 5). This centralized approach reduced conflicts among the involved actors by prioritizing a single project, but it raised concerns, particularly regarding the transparency of decision-making processes and potential social and environmental implications, critical issues highlighted by civil society.

According to **H2UB (2024),** the integration of public, private, and technological actors within participatory processes is a cornerstone for fostering the growth of green hydrogen, particularly through the active involvement of SMEs and startups. Similarly, **Algburi et al. (2025)** emphasize that the centrality of green hydrogen in the global energy transition depends on the ability of governance structures to integrate heterogeneous actors. Meanwhile, the Organization for Economic Co-operation and Development **(OECD, 2024),** highlights the need for financial and regulatory instruments that ensure the effective participation of smaller firms in sector projects. Analysis of regional cases **(Karplus et al., 2024)** shows that clarity in decision-making processes can reduce conflicts between actors with different bargaining power.

Regarding good governance in the energy sector, understood as the creation of systems that ensure transparency, accountability, and inclusivity in policy and corporate decisions, **(Zander et al. (2024)**, emphasize that transparency in energy megaproject decisions is essential for gaining public approval and fostering active participation from local communities. Their study on governance approaches in the renewable energy industry highlights that transparent project management, combined with citizen participation, is a decisive factor in minimizing social resistance and increasing project effectiveness. Inclusivity in energy policies thus translates into governance that allows collaboration between private and public sectors, reducing conflicts and improving the long-term impact of policies.

In this perspective, reports such as that from the **Rocky Mountain Institute (RMI, 2024)** stress that H2Hub governance requires projects to be inclusive, transparent, and capable of responding to the specific needs of local communities, with particular attention to social and economic justice issues. At the same time, the **National Association of State Energy Officials (2024)** notes the role of public commitment and the direct involvement of small businesses in state-level clean hydrogen initiatives. Several authors agree on the effectiveness of multi-stakeholder approaches, wherein cooperation among governments, industries, and financial institutions translates into environments favorable to collaboration and innovation **(Bade et al., 2024)** e **(Tabandeh et al., 2024).**

Best practices in the energy sector, as highlighted by **Zatonatska et al. (2024)** in their study "*A Comprehensive Analysis of the Best Practices in Applying Environmental, Social, and Governance Criteria within the Energy Sector*", show how the Netherlands, Sweden, and Finland, examples of advanced governance, have implemented national policies such as the Climate Act and Roadmap 2050. These policies set concrete goals for emissions reduction and renewable energy adoption. Another central element of these best practices concerns corporate governance practices, which impose sustainability reporting obligations, incentivizing companies to measure and communicate their environmental and social impact. Furthermore, these countries have promoted renewable energy use through feed-in tariffs and subsidies, stimulating technological innovation to reduce CO2 emissions. Incentivizing tax policies and the creation of transparent legal frameworks have accelerated the adoption of sustainable energy solutions, making these countries reference models for others.

Another innovative approach in energy governance is that of "energy communities", which represent decentralized and inclusive management models. **Karameros et al. (2025)** propose a governance model for community energy projects, based on including local communities in decision-making processes and creating support ecosystems for renewable energy projects. This approach aims to remove regulatory barriers and facilitate the adoption of renewable technologies through local policies that encourage direct citizen involvement. Their analysis shows that effective management of energy communities must be characterized by a strong capacity to adapt to the specific needs of the territory, involving consumers, producers, and other key actors in an integrated manner to promote efficiency and sustainability in energy projects.

Another innovative perspective in governance management is proposed by **Hasan e Fuentes (2025),** who explore how energy markets can influence governance in the hydrogen sector, particularly regarding infrastructure access and price transparency. Their study suggests that to create a competitive and open green hydrogen market, governance must ensure fair prices and quality standards that are understandable to all involved actors. The creation of transparent and non-discriminatory markets is fundamental to ensuring that SMEs and startups can access resources without facing unfair practices or inaccessible prices. In this sense, solid governance must balance access to resources and costs for all actors, fostering a more competitive and inclusive market.

Several recent studies also explore how energy governance, through targeted policies and de-risking tools, can reduce economic barriers and stimulate investment, particularly for SMEs and startups, which are frequently exposed to risks associated with introducing capital-intensive technologies. Both **Cleantech for Europe (2024) and the Green Deal Industrial Plan (2023)** emphasize that instruments such as de-risking mechanisms, public financing, and financial guarantees represent fundamental levers for overcoming the economic obstacles that limit SME participation.

Scholvin et al. (2025) stress that energy governance must be able to confront the challenges posed by political and economic instability, given that renewable technologies like green hydrogen involve high levels of risk, especially in developing countries. To mitigate these risks and incentivize investments, de-risking tools such as off-take guarantees, tax incentives, and political risk insurance are essential. Analyzing the cases of Chile and South Africa, the authors highlight how the adoption of de-risking policies, including Contracts for Difference (CfD), is fostering the growth of green hydrogen demand by guaranteeing a minimum price for locally produced hydrogen. This mechanism creates favorable conditions for investors by reducing uncertainty about economic returns.

The effectiveness of de-risking policies is maximized when based on international coordination between public and private entities, as also indicated by the OECD (2024). International cooperation thus appears essential for integrating financial instruments and technical expertise, thereby addressing the challenges of the energy transition and facilitating the development of the infrastructure needed for hydrogen production and distribution. Specifically, the **OECD (2024)** underscores that the introduction of off-take guarantees and tax breaks represents a key lever for attracting private capital to green hydrogen projects, as they provide greater security and reduce investors' risk perception.

Furthermore, to address economic barriers in emerging markets, energy governance must integrate public and private policies, offering specific support to SMEs and startups **(Jerzyniak (2024)**. In this perspective, favorable tax policies and public-private partnerships are essential tools for mitigating economic risks and stimulating the growth of the global green hydrogen market. According to Jerzyniak, de-risking policies must be structured to bridge the inequalities between large industrial actors and small business entities, thus allowing for more balanced and inclusive participation. The integration of tax incentives for technological innovation and the creation of regulated markets represent key levers to support SME access to the hydrogen market.

Similarly, Just Energy Transition Partnerships (JETPs), as described by the **Institute For Energy Economics and Financial Analysis (IEEFA, 2025)** prove fundamental for ensuring an equitable approach to green hydrogen governance. These partnerships promote access to financing and foster the integration of emerging technologies into local markets, thereby helping to reduce economic risks, especially in the most vulnerable countries. In this context, the adoption of de-risking tools, targeted incentives, and the creation of transparent, regulated markets emerge as central elements for effective, inclusive, and innovation-oriented governance in the green hydrogen sector.

3.2 Supply Chain Development and Support for Hydrogen Hubs

The hydrogen supply chain encompasses all necessary activities, from production and storage to transport, and ultimately distribution and final consumption in the industrial, transport, and power generation sectors. Hydrogen hubs play a central role in making this supply chain efficient, creating an integrated ecosystem that synergistically connects the different stages of the process. These ecosystem models, which cover the production, distribution, and use of hydrogen, are considered optimal solutions for addressing the scalability and sustainability challenges of hydrogen technologies **(M. Bampaou , K.D. Panopoulos, 2025)**. To develop and utilize hydrogen as an energy carrier, it is therefore essential to establish dedicated supply chains and commercialization pathways that include production, storage, and transport. Figure 1 illustrates an example of a hydrogen supply chain superstructure, offering an overview of the main steps from the energy source to the final use (Figure 11).

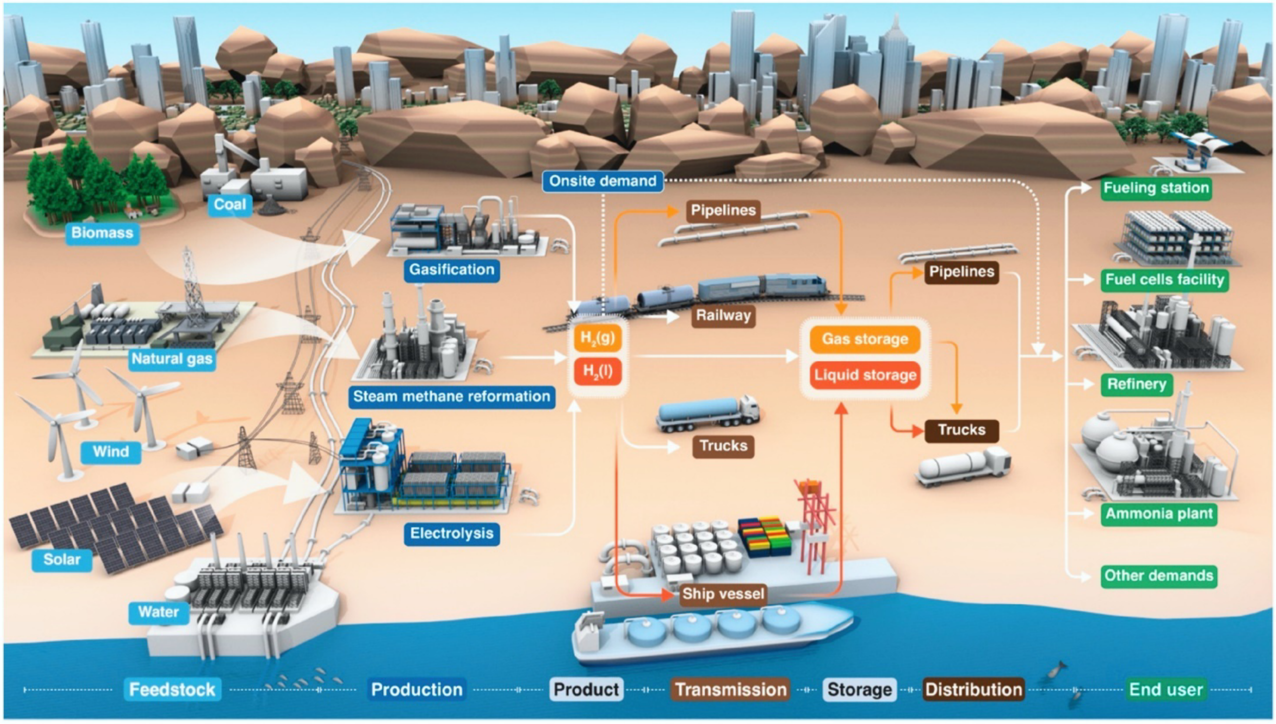


Figure 11: Different Types of Hydrogen supply chain
(Source: Xie et al. 2025)

3.2.1 The Role of Hydrogen Hubs in Supply Chain Development

In recent years, studies have emphasized the importance of structuring this chain through hydrogen hubs, which act as central nodes for production, storage, and distribution, creating a scalable and sustainable infrastructure at a regional level. Hydrogen hubs thus represent a strategic solution for overcoming the logistical and infrastructural challenges associated with the supply chain, enabling centralized and optimized resource management.

One of the most significant approaches is the optimization of hydrogen production and distribution through mathematical models. In particular, **Anasrul e Sopha (2025),** propose an innovative approach to optimize hydrogen production and distribution in urban areas. They focus on supply chain optimization via advanced mathematical models, aiming to foster the transition to hydrogen mobility. A central element of their study is the creation of regional hydrogen hubs, conceived as strategic nodes capable of supporting production, storage, and distribution in a sustainable and

economically efficient manner. These hubs help reduce both operational costs and emissions by optimizing the overall efficiency of the hydrogen supply chain.
Specifically, the mathematical model they developed integrates hydrogen production and distribution through a network of Hydrogen Refueling Stations (HRS), applying a combination of a gravitational model for site selection and Mixed-Integer Linear Programming (MILP) to optimize costs and logistics. The analysis results highlight how careful resource management within the hubs can support urban hydrogen mobility while simultaneously strengthening the sustainability of the entire city energy system. This research confirms the relevance of an optimized supply chain and the integration of hydrogen hubs in urban areas, demonstrating that such strategies can significantly reduce the ecological footprint of transport and increase distribution efficiency in cities.
Similarly, **Efthymiadou et al. (2025)** proposed a stochastic optimization framework for planning hydrogen infrastructure, systematically addressing the uncertainty tied to key supply chain parameters. This model is also based on a two-stage Mixed-Integer Linear Programming (MILP) approach, which optimizes investments in hydrogen production, storage, and transmission. It integrates the variability of demand, technological costs, availability of biomass and renewable sources, as well as gas prices. A distinctive element of the framework is its use of scenario reduction techniques, which facilitate the management of computational complexity without sacrificing analytical accuracy.
The study underscores the importance of dynamic and flexible infrastructure design, highlighting that hydrogen hub planning must account for both the spatial and temporal distribution of demand and the need for decentralized storage solutions. The innovative contribution of this approach lies in its ability to incorporate technological and market uncertainties into a single optimization model, thus offering a strategic tool for planning hydrogen hubs and managing resources efficiently on the path to decarbonization.
The works of Anasrul/Sopha and Efthymiadou are closely linked from a methodological and application standpoint. Both approaches aim to max amaze the efficiency of the hydrogen supply chain through advanced mathematical models. In essence, both contributions show how the integration of optimization tools, both deterministic and stochastic, is fundamental for planning and developing resilient, efficient, and sustainable hydrogen infrastructures, demonstrating the complementarity between models focused on the urban context and more general ones that address uncertainty at a systemic level.
The study by **Sizaire et al. (2024)** aligns with the same perspective, proposing a multi-modal optimization model for the hydrogen supply chain, focusing on the Texas and Louisiana regions. Its main contribution lies in developing a linear programming model that optimizes hydrogen production from electrolysis, powered by renewable sources (wind and solar) and natural gas, on an hourly scale and over a wide geographical area, with projections up to 2050. The model integrates the joint assessment of electrical and hydrogen transmission networks, allowing a comparison between transporting energy as electrons and as chemical carriers. A strength of the analysis is the

centrality given to advanced hydrogen storage (using salt caverns, liquid, and compressed tanks), which is essential for balancing production variability with constant industrial demand.
In practice, the model also optimizes hydrogen distribution and storage, identifying the creation of regional hubs in the most suitable areas of Texas and Louisiana, with an efficient pipeline transport system to demand zones along the coast. According to projections for 2050, the model forecasts an annual demand of 276 TWh of hydrogen, the need for 62 GW of electrolyzes, 102 GW of onshore wind capacity, and 32 GW of solar, with a progressive reduction in the cost of hydrogen from $5.6-6.3/kg in 2025 to $3.2-3.5/kg in 2050. In summary, the study provides a reference basis for designing resilient and sustainable hydrogen supply chains, offering an integrated vision that includes production technologies, transmission, storage, and support policies, and identifying the creation of regional hubs as a fundamental strategy for the energy transition.
The importance of integrating renewable energy into hydrogen hubs was also highlighted by **Cutore et al. (2024)**, who studied the integration of wind energy and hydrogen production in Sicily. In this case, regional hydrogen hubs play a fundamental role in optimizing the distribution of hydrogen produced from renewable sources. Their spatial optimization model demonstrates how the co-location of hydrogen production plants and wind resources can reduce operational costs and improve supply chain sustainability, making the hubs focal points for a stable energy supply.
A recent study by **Aguirre-García et al. (2025)** analyzed the current state of hydrogen supply chain network design (HSCND), focusing on export-oriented configurations, with the intent to improve efficiency and reduce costs through an integrated approach that includes technical, economic, and policy aspects. The study's main findings highlight that hydrogen supply chain design must be conceived by considering the entire cycle, from production and transport to final distribution. According to the study, hydrogen hubs in ports represent a fundamental component in the global supply chain. Ports are not just places for loading and unloading hydrogen; they can also serve as strategic centers for the production, storage, and distribution of its derivatives. However, the design of port infrastructure, which includes tanks, pipelines, and conversion units for hydrogen derivatives like ammonia (NH3) and methanol (MeOH), is still insufficient. This aspect, if underestimated, could increase capital and operational costs (CAPEX and OPEX) and delay the full exploitation of international hydrogen trade. In particular, the retrofitting of existing infrastructure to handle these derivatives represents a significant gap, with potential implications for the long-term efficiency of transport and storage systems. The study also highlights several research gaps that must be addressed to improve HSC design for international export. One of the main deficiencies is the lack of models that integrate the different aspects of the supply chain, such as production, transport, storage, and distribution, with cost and demand uncertainty.
In this context, the analysis by **Riera et al. (2023)** provides an in-depth overview of the design and optimization of hydrogen supply chains (HSC) and production processes, with a particular focus on the role of hydrogen hubs. The study's distinctive element lies in the adoption of advanced models for optimizing the entire supply chain, from production to storage, transport, and distribution, integrating renewable sources and innovative technologies like electrolysis and carbon capture

(CCS). Another innovative aspect is the design of supply chain superstructures that allow for the selection of the most efficient and sustainable configuration from various feedstock, production, and transport alternatives, based on local resources and needs. Finally, the integration of hydrogen hubs with both local and global energy systems is identified as an enabling factor for energy security and economic sustainability. In summary, the research proposes a model that promotes synergy between renewable energy, technological innovation, and infrastructure, accelerating the transition to a low-carbon economy and strengthening the resilience of hydrogen supply chains.

An innovative view comes from the **National Renewable Energy Laboratory (2024),** which, with its SERA (Scenario Evaluation and Regionalization Analysis) optimization model, proposes a new approach to planning and deploying the necessary infrastructure for the hydrogen supply chain. The SERA model integrates various factors, such as hydrogen demand, production and storage capacities, and distribution technologies, to optimize the network of regional hubs. In this sense, the authors suggest that hubs can serve as platforms for testing and implementing advanced production and distribution solutions, increasing the system's overall capacity to respond to growing demand. The SERA model thus allows for the optimization of the hydrogen supply chain through integrated planning of production, storage, and distribution infrastructure. Specifically, it allows for the strategic positioning of regional hubs and refueling stations, reducing costs and improving reliability. It also favors the choice of sustainable technologies, the integration of renewable energy, and system resilience to demand variations.

Another crucial aspect for supply chain success is storage management, as suggested **Baghirov et al. (2024).** They analyze the efficiency and CO2 intensity of the hydrogen supply chain, with particular attention to the Underground Hydrogen Storage (UHS) process. In this context, hydrogen hubs play a crucial role as storage centers, contributing significantly to the energy network's stability and security, especially during seasonal fluctuations. The article highlights how hubs, thanks to their capacity for long-term hydrogen storage in geological formations like salt caverns or saline aquifers, can reduce costs associated with maintaining inventories and meet seasonal energy demand. The use of underground storage solutions to accumulate hydrogen makes it possible to address the variability of renewable energy production, ensuring a constant supply even during periods of low production. In summary, hydrogen hubs, as central nodes in the supply chain, are essential not only for accumulation and management of seasonal hydrogen demand but also for optimizing energy efficiency and reducing the environmental impact of hydrogen production and distribution.

A different approach comes from **Jeje et al. (2024)** who analyzed the economic and infrastructural challenges in the hydrogen supply chain, proposing the adoption of advanced production and storage technologies to reduce costs and improve efficiency. Their research confirms that hydrogen hubs, as centers integrating various technologies, could represent a practical solution for centralizing production and optimizing distribution. The integration of innovative systems within hubs can reduce capital and operational costs, facilitating the global spread of hydrogen. In summary, the article argues that hydrogen hubs could address the infrastructural and economic challenges of the supply chain by centralizing production and reducing the risk of logistical inefficiencies.

In recent years, the topic of hydrogen supply chain development has gained growing relevance in international literature, with particular attention to SME involvement and technological innovation as enabling factors for an efficient and resilient supply chain. Recent studies emphasize that the value of hydrogen hubs is fully realized only if small and medium-sized enterprises are actively integrated into the supply network creation processes, thus fostering the adoption of niche technological solutions and the emergence of new business models **(Hydrogen Integration For Accelerated Energy transitions, 2025, Hydrogen Supply Chain Availability Report)**. From this perspective, hubs are not just physical centers for production and storage; they act as "catalysts for building an interconnected supply chain" capable of aligning the various actors in the chain, from production and distribution to the valorization of advanced storage technologies **(H2UB, 2024)**. A study by **Vankayala et al. (2025)** analyzes global trends and opportunities in the green hydrogen value chain, underscoring how hydrogen hubs can reduce operational costs and improve efficiency through the integration of resources among different actors (public and private). An innovative aspect of their approach is the emphasis on economies of scale achieved when multiple local actors collaborate to share infrastructure, such as production and storage facilities. The article also highlights the importance of collaborative and integrated models, which allow local communities to benefit from renewable resources, reducing dependence on fossil fuels and stimulating green employment.

Finally, the systematic review by **Yi et al. (2024)** on the collaborative planning of integrated hydrogen energy chain-multi-energy systems (HEC-MES) is noteworthy. It reveals that hydrogen hubs represent central nodes in the energy chain, as they facilitate the interconnection between the different stages of the supply chain, which include hydrogen production, storage, transport, and application. The hubs are not limited to simplifying logistics; they play a strategic role in improving energy resource management, enabling the optimal spatial and temporal distribution of hydrogen. This ability to adapt to the variability of renewable energy sources is particularly important, as it allows for an efficient balancing of supply and demand.

Furthermore, hydrogen hubs are essential for managing the seasonality of resources, as they allow excess hydrogen produced during periods of high generation to be stored and used when demand is higher or when renewable energy production is insufficient. This storage and its subsequent distribution through advanced transport networks make it possible to overcome geographical and temporal limitations, ensuring a continuous and stable supply. **Yi et al. (2024)** also stress that integrating hubs into a multi-energy system (MES) allows for optimizing resource use, reducing operational costs, and improving the overall efficiency of the energy system, while fostering the transition to a low-carbon economy. The integration of hubs into a multi-energy system (MES) allows for optimizing resource use, reducing operational costs, and improving the overall efficiency of the energy system, while fostering the transition to a low-carbon economy. Therefore, hydrogen hubs not only facilitate logistics and operational efficiency but are also crucial for ensuring the flexibility, energy security, and reliability of the future energy system, making them an indispensable element in the evolution of the hydrogen supply chain. The study explores various aspects of the hydrogen supply chain (HSC), highlighting how the hydrogen energy chain (HEC) can optimize the allocation of energy resources in complex scenarios, with particular attention to emerging technologies and future challenges.

Based on the above, it is confirmed that hydrogen hubs can be configured as indispensable pillars for building a resilient, efficient, and sustainable supply chain. They not only enable the centralization and optimization of resources but also foster operational flexibility, the management of uncertainties, and the integration of renewable energy, thus responding to the challenges posed by the energy transition.

Thanks to the active involvement of SMEs and the adoption of collaborative models, hubs become true catalysts for innovation, promoting synergies among the different actors in the supply chain and facilitating the emergence of new business models. From this perspective, the role of hydrogen hubs extends far beyond the infrastructural dimension: they represent the beating heart of an interconnected supply chain, capable of adapting to technological and market changes and of guiding the decarbonization of energy systems at local and global levels. Only through integrated planning and inclusive governance will it be possible to fully valorize the potential of hubs, transforming them into engines of sustainable development and competitiveness for the hydrogen economy of the future.

3.2.2 Support from Public and Private Investors

Support from public and private investors is a fundamental driver for green hydrogen adoption. Government policies, combined with private investments, are crucial for reducing production costs and creating resilient and sustainable infrastructure. In particular, public-private partnerships are emerging as a key strategy for financing hydrogen technologies, fostering an environment of innovation that supports the decarbonization of the industrial and transport sectors.

Recent literature has highlighted the role of governance strategies and advanced financial instruments in supporting hydrogen hubs, with particular emphasis on risk reduction for SMEs and startups and the alignment of public and private investment. Studies such as those by **Bhat et al., (2024, Rocky Mountain Institute)** identify four key strategies to accelerate hydrogen hub financing: i) adopting blended finance instruments, ii) promoting public-private partnerships, iii) creating regulated and transparent markets, and iv) utilizing de-risking mechanisms. These strategies are particularly effective in mitigating economic barriers and fostering the scalability of innovative solutions developed by small firms.

Furthermore, the report suggests developing creative capital syndicates to better distribute risks among various types of investors. These syndicates could include strategic investors, original equipment manufacturers (OEMs), and public financiers willing to offer performance guarantees. Moreover, the use of innovative capital stacks, combining public funds, philanthropic donations, and low-risk financing, could foster broader access to capital for green hydrogen projects.

According to the **Plug and Play Tech Center (2025, Annual Hydrogen Report),** investment trends show growing attention toward technology startups in the hydrogen sector. However, the success of these startups depends heavily on the support of robust governance that reduces the risks associated with scaling emerging technologies. Difficulties in large-scale growth are among the main obstacles these projects face. A solid governance structure, which includes risk mitigation mechanisms and promotes transparency, is essential for attracting investment and enabling the rapid diffusion of innovative solutions, particularly for SMEs developing cutting-edge technologies in the hydrogen sector.

In line with these considerations, the "Unlocking Opportunities: A Framework for Assessing Green Hydrogen Potential in Emerging Markets" of International Finance Corporation stresses that although green hydrogen has significant potential for decarbonizing "hard-to-abate" sectors, its cost remains higher than that of fossil-fuel-based hydrogen. In this scenario, fostering an adequate investment context to support the sector's development becomes fundamental **(IFC, 2025).**

Globally, numerous governments have developed policies to stimulate the green hydrogen market, introducing targeted incentives and subsidies. For example, Chile established a $1 billion fund to incentivize green hydrogen projects, while Egypt and India have allocated $50 million and $1.59 billion, respectively, for low-emission hydrogen production (IFC, 2025). On the other hand, the private sector has responded positively to these stimuli, recognizing green hydrogen as a long-term decarbonization opportunity. Companies are investing in partnerships along the entire value chain, aiming to reduce production costs and increase technological efficiency. Private sector involvement is not limited to direct investment but extends to R&D of new technological and infrastructural solutions (IFC, 2025).

Furthermore, public-private collaborations have become an established practice for accelerating project implementation. An emblematic example is the RenewStable Barbados project, which received technical and financial support from the International Finance Corporation. In this case, public support encouraged private investor participation and facilitated the green hydrogen project's development.

An original approach to the topic is offered by **Ahang et al. (2025).** This study contributes innovatively to the analysis of public and private support in the hydrogen sector by providing a stochastic model of the European power system, the European Model for Power System Investment with Renewable Energy (EMPIRE). This approach allows for the simulation of long-term scenarios that reflect energy price variability and uncertainties related to hydrogen demand. A distinctive aspect of the Ahang et al. approach is the analysis of long-term hydrogen prices, a key factor in determining the competitiveness of hydrogen production technologies. Their study suggests that, with adequate government support and policies favoring external demand, green hydrogen will become economically advantageous for system flexibility, reducing the "curtailment" of renewable energy production. In particular, the introduction of incentive policies, such as subsidies, tax breaks, and R&D investments, emerges as a fundamental element for overcoming initial investment barriers, thereby attracting private capital to the sector. In summary, the innovative contribution of this study lies in its ability to model the interaction between the hydrogen market and the European power system, highlighting the strategic role of public and private investment in making hydrogen a key component of the energy transition. Several studies, such as those by **Shipalana (2024)** and **Imasiku et al. (2025),**

emphasize the importance of innovative financing mechanisms to support the transition to green hydrogen, particularly through the use of resources from both the public and private sectors.
Shipalana's article explores emerging financing mechanisms in developing countries, with a particular focus on Africa. The author highlights the importance of adequate policies to facilitate access to private capital by creating a stable regulatory environment. Among the financial instruments mentioned are green bonds, favorable-rate public loans, and public-private partnerships (PPPs). Shipalana suggests that to overcome the risks associated with green hydrogen investments, which are accentuated by political instability and limited infrastructure, tax incentives and support from multilateral financiers, such as the African Development Bank (AfDB) and the Green Climate Fund (GCF), are necessary. Furthermore, the author underscores the importance of aligning national policies with international standards to ensure market coherence and transparency, thereby attracting private investment and stimulating green economic growth. Imasiku et al.'s (2025) article, while also addressing financing mechanisms, proposes a more practical and specific approach for green hydrogen adoption in Sub-Saharan Africa. Imasiku likewise identifies various financing tools to support green hydrogen development, including green bonds, venture capital, public and private loans, and multilateral and bilateral funds. However, a distinctive aspect of this study is its analysis of the financial risks associated with green hydrogen investments, estimating an investment risk factor of 35% stemming from infrastructural, political, and technological issues. Imasiku argues that a hybrid financing model, combining public and private resources, is essential to reduce these risks. The author suggests that, in addition to direct investments, off-take agreements are necessary to guarantee stable demand and reduce market uncertainty. Both articles stress that innovative financing mechanisms and cooperation between multilateral/bilateral resources and public-private partnerships are essential to foster green hydrogen adoption in Africa. However, Shipalana emphasizes regulatory policies, tax incentives, and alignment with international standards to attract private investment (a political approach). In contrast, Imasiku focuses on practical financial instruments and the management of technological and infrastructural risks through hybrid models and off-take agreements (a financial approach). Together, the two approaches are complementary and, if integrated, could facilitate the reduction of financial barriers and promote a sustainable energy transition in Sub-Saharan Africa. In light of these considerations on innovative financing strategies and the centrality of public-private collaboration, the theme of "bankability" in green hydrogen projects emerges forcefully. This concept extends beyond a project's simple ability to obtain loans, encompassing the proactive management of financial, technical, operational, and regulatory risks. The "bankability" of a project refers to its capacity to attract investment thanks to the forecast for stable returns and the reduction of associated risks, making it attractive to financiers.
In this regard, the report **"Unraveling the myth of bankability for green hydrogen projects" (DEKRA/Hydrogen Europe, 2025)** underscores the importance of a structured approach to ensure the bankability of green hydrogen projects. This approach includes a comprehensive assessment of risks, such as market, technical, and regulatory risks, and the adoption of preventive measures to mitigate them. A fundamental element is the collaboration among all involved actors: developers, financiers,

component suppliers, and regulators. The creation of a bankability management system that integrates all these aspects is seen as key to facilitating access to financing. An innovative aspect proposed in the report is the introduction of a "Bankability Seal," a standardized certification guaranteeing that a project meets the requirements demanded by financial institutions. The adoption of this seal could simplify risk assessment and accelerate financing approval, creating greater confidence among public and private investors. This approach has the potential to reduce regulatory and technical uncertainties, helping to ensure the financial sustainability of projects. Regarding public support, the report highlights that although government policies, such as tax incentives and risk-sharing mechanisms, are fundamental for stimulating investor interest, they are not sufficient on their own. Public policies must align with a clear risk management system, like the Bankability Seal, which reduces perceived risk and facilitates the adoption of green hydrogen projects. In this way, hydrogen projects can be seen not only as technically feasible but also as financially sustainable, increasing investor confidence and the flow of capital toward this emerging sector. In light of the preceding considerations, which highlight that a synergy between innovative financial instruments and public-private collaboration is fundamental to overcoming investment barriers in green hydrogen, it is appropriate to further explore the role risk management plays in attracting capital and facilitating this strategic sector's growth. A key element facilitating private investor involvement, particularly in the green hydrogen context, is the ability to reduce uncertainty tied to operational and environmental risks, which can significantly impact project profitability.

In this context, the article by **Nwafor e Al Hooti (2025)** provides an innovative contribution by developing an artificial intelligence (AI)-based Maintenance Pressure Index (MPI). This index is capable of predicting the maintenance needs of green hydrogen infrastructure in extreme climatic environments, such as that of Duqm, Oman. This tool leverages public meteorological data to analyze environmental risks linked to factors like extreme temperatures, atmospheric dust, and humidity, which influence the durability and reliability of the technologies used in green hydrogen production. The article's contribution is particularly relevant for investors, as using AI to generate accurate forecasts on operational maintenance and environmental risks allows for more efficient planning and reduced uncertainty tied to unforeseen climatic factors. Specifically, adopting this type of tool helps public and private investors make more informed decisions regarding project selection by integrating artificial intelligence into risk assessment models. The proposed predictive models, such as XGBoost and the Prophet model, can make long-term forecasts on environmental conditions and maintenance needs, supporting operational management and reducing costs associated with sudden failures. This approach increases investor confidence, as they can now base their decisions on quantitative risk indicators, leading to benefits in reduced insurance premiums and improved financing conditions. In summary, integrating AI for operational and environmental risk assessment, as proposed by Nwafor and Al Hooti, offers a competitive advantage to green hydrogen investors by enabling better prediction and management of environmental risk factors.

The theme of financing and public-private support for the growth of the green hydrogen market represents one of the crucial challenges for the energy transition, as highlighted in-depth in a **2023**

Deloitte study ("Catalyzing the clean hydrogen economy using business model innovation"). Deloitte highlights that public support, through a stable regulatory and financial framework, is fundamental to reducing this gap, but real success also depends on the direct and active commitment of the private sector in market development. In particular, the study proposes innovative business models aimed at making investments safer and more predictable. Among these is the "Take or Pay" model, which involves contracts between buyers and sellers to ensure predictable cash flows. In this type of contract, the buyer commits to purchasing a predetermined quantity of hydrogen, regardless of whether they actually consume it or not. This model, which also finds application in sectors like natural gas, can foster greater revenue predictability for producers and greater security for buyers, thus helping to reduce market uncertainty and make private investment more attractive. Another innovative financing strategy is represented by Contracts for Difference (CfD), which establishes a guaranteed minimum price for the produced hydrogen. This instrument protects producers from market price fluctuations, providing them with a stable cash flow that facilitates attracting investments (Figure 12). CfDs have already been adopted in the renewable energy sector, as in the case of offshore wind. Applying this model to the hydrogen market could represent a solution for mitigating risk and making hydrogen more competitive against traditional alternatives.

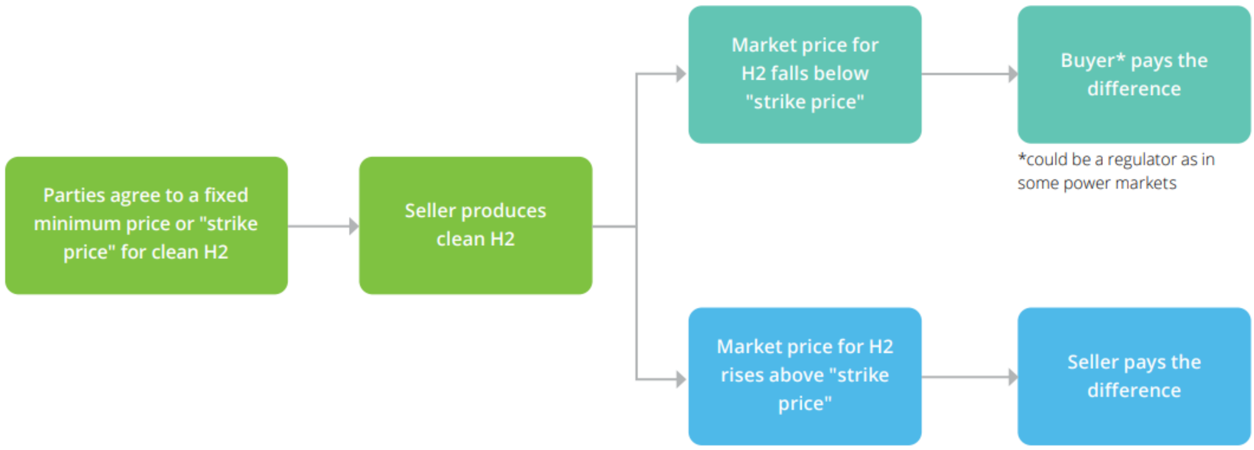


Figure 12: Example: Contract for Difference (CfD)
(Source: GOV UK, 2023, Government explores major reform to flagship renewables scheme to improve energy security and drive investment)

The "Book and Claim" model (Figure 13), which allows companies to purchase hydrogen certificates without physically receiving the product, offers a further innovative approach to foster hydrogen demand. In this system, companies that do not have direct access to hydrogen infrastructure can still benefit from the carbon credits associated with its use, further incentivizing demand without having to face the logistical challenges related to the physical distribution of the fuel. This model, already adopted in the aviation sector for fuel decarbonization, could be extended to the hydrogen market to facilitate the creation of a global network of carbon certificates, while simultaneously reducing costs for producers.

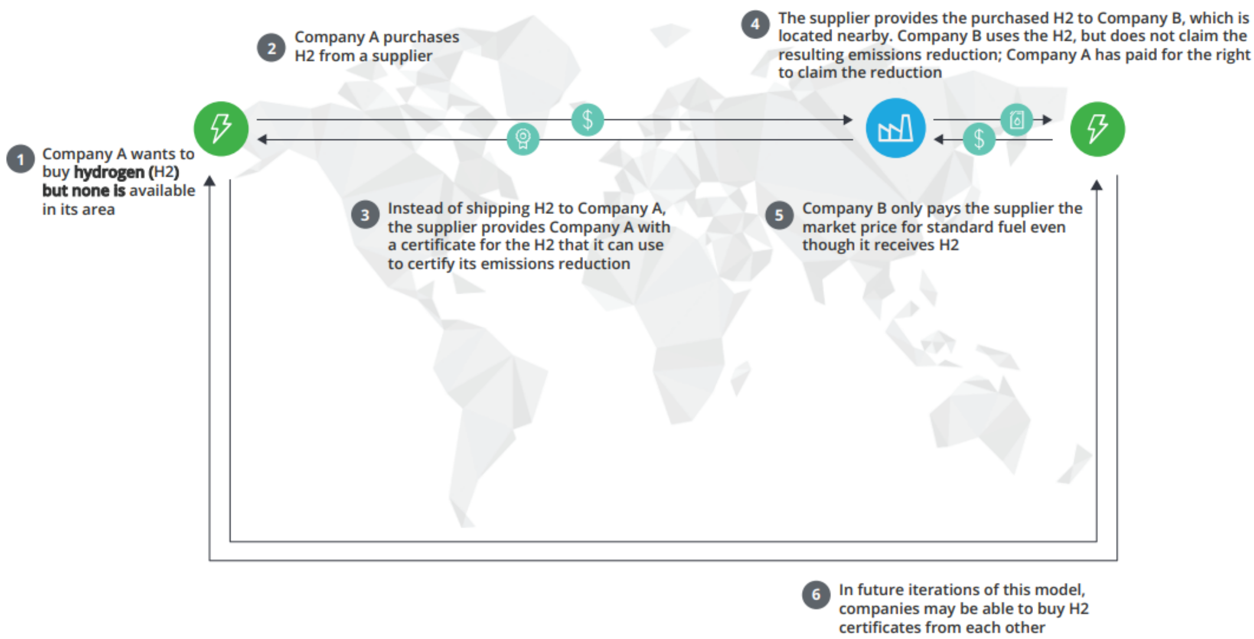


Figure 13: Example: Book and Claim
(Source: Roundtable on Sustainable Biomaterials Association (RSB), 2025, Book & Claim Program)

Another innovative aspect of public and private support is the concept of "co-opetition" (cooperation among competitors) (Figure 14). This approach, which promotes collaboration between competing actors to develop shared infrastructure, exemplifies the regional hydrogen hub model. Such regional hubs, through cooperation among private actors and the support of public policies, could accelerate the global diffusion of hydrogen.

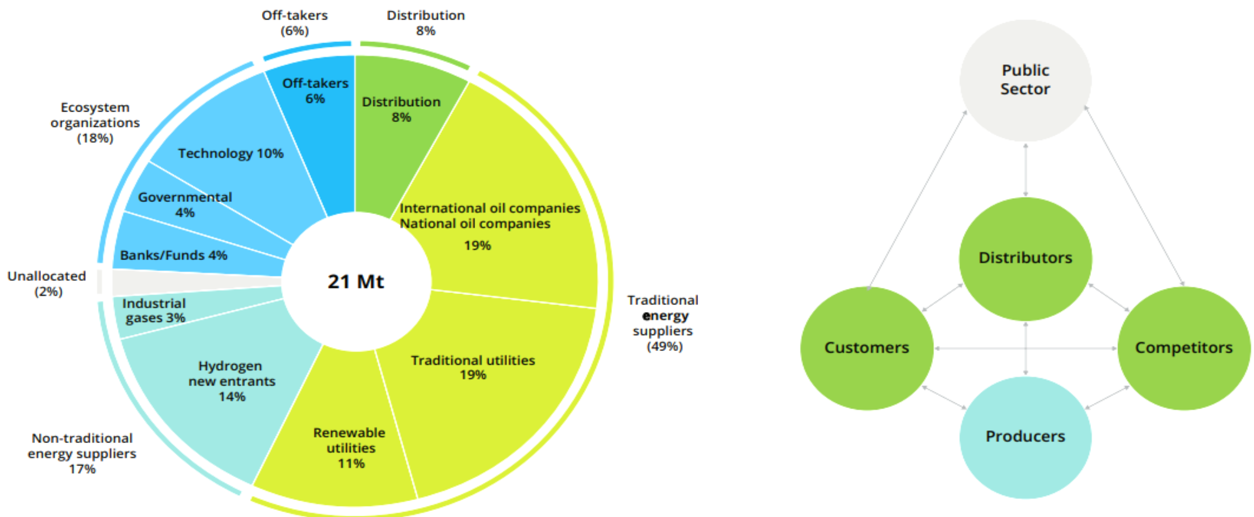


Figure 14: Example: "Co-opetition" through targeted partnerships.
(Source: Deloitte Energy Transition Monitor", 2025)

Finally, the "Hydrogen as a Service" (HaaS) model, which allows companies to access hydrogen storage and refueling infrastructure without facing initial costs, represents another example of how innovation can solve the "first-mover" dilemma in the hydrogen sector. The HaaS model allows end-users to gain access to advanced technologies without the burden of initial investment, while simultaneously creating a stable revenue source for hydrogen producers.

In summary, public and private support for clean hydrogen must be seen as a joint effort combining favorable public policies and innovative business models. The creation of a stable financial environment, the adoption of risk mitigation tools like CfDs, the use of flexible contracts like the "Take or Pay" model, and the promotion of collaborative solutions like "co-opetition" and HaaS are all key strategies to incentivize the investments needed to scale the hydrogen market. The integration of such models, accompanied by public policies, can help overcome industry uncertainties and foster the large-scale adoption of clean hydrogen. (**Deloitte, 2023)**

3.3 Public and Private Financing Mechanisms

In light of the points discussed regarding innovative strategies and models to support the diffusion of green hydrogen, it is now useful to briefly focus on the primary public and private financing mechanisms that are driving the growth of this sector. This completes the picture of the solutions available to overcome economic barriers and accelerate the energy transition.

Within the scope of public financing mechanisms, one of the most utilized tools by governments is direct subsidies and tax incentives. These instruments reduce the initial investment risk and stimulate research and development. For example, in the United States, the Inflation Reduction Act (IRA) introduced incentives for green hydrogen production with a production subsidy of up to $3/kg, intended to incentivize producers to invest in low-carbon hydrogen plants. This type of incentive is a fundamental part of reducing costs and improving the competitiveness of green hydrogen in the international market **energy.gov, 2024).**

In Europe, the European Commission, under the Green Deal Industrial Plan, has created tax incentives and financing for hydrogen projects, focusing on creating an infrastructure that supports the production and use of green hydrogen. These incentives foster not only research and innovation but also the creation of an industrial supply chain and a transport network for renewable hydrogen **(Clean Hydrogen Partnership, 2024).**

Furthermore, development banks play a fundamental role in supporting the transition to green hydrogen by offering loans at advantageous, low-interest conditions to finance low-environmental-impact infrastructure. A significant example comes from Germany, where the KfW (Kreditanstalt für Wiederaufbau) and the European Investment Bank (EIB) have allocated €24 billion to build a hydrogen transport network. This strategic investment aims to integrate hydrogen into the national energy system, lowering production costs and increasing this source's competitiveness against traditional fuels. Public banks are, therefore, decisive in mobilizing large-scale infrastructure investments. **(Reuters, nov 2024).**

Another pillar of financing involves public-private collaboration through partnerships (PPPs), which are indispensable tools for realizing complex projects that require large financial resources, such as those related to green hydrogen. A concrete example is the aforementioned Green Hydrogen Valley in Puglia, which received a €370 million contribution from the European Commission. This initiative involves companies like Edison, Saipem, and Snam, engaged in building plants for green hydrogen production and storage. The goal is to reduce emissions in the most energy-intensive industrial sectors, such as steel production. Through public-private partnerships, a virtuous combination of stable public funds and private sector innovation capacity is achieved **(Reuters, feb 2024).**

In the private financing landscape, green bonds are playing an increasingly relevant role. These are debt instruments that allow both public and private entities to raise capital earmarked for projects with a high positive environmental impact. Green bonds have established themselves as one of the main channels for supporting green hydrogen growth: one need only consider the $700 million green bond issuance by **Corporations Multi Inversiones (CMI) Energy (2022)**, a Guatemalan company, to finance renewable energy initiatives, including hydrogen production. (Corporations Multi Inversiones, 2021, CMI Energy places $700 million in green bonds).

Alongside bonds, venture capital provides precious resources to technology startups developing innovative solutions for the green hydrogen supply chain. An emblematic case is Hysata, a company specializing in electrolyzes, which raised $111 million thanks to support from investors like BP and Posco **(The Wall Street Journal, 2024).**

To mitigate the risks typical of emerging or unstable markets, as already mentioned in this section, both public and private investors resort to instruments like guarantees and Contracts for Difference (CfDs). The latter fix a guaranteed minimum price for hydrogen production, ensuring revenue stability and reducing uncertainty for investors. In contexts characterized by high regulatory or political volatility, instruments of this type become particularly valuable. For example, in Asia and Africa, GDF Suez has used innovative financial solutions to build green hydrogen plants, thereby addressing the economic and political risks present in these areas. **(Imasiku et. al., 2025).**

Finally, blended finance, which combines public and private funds, remains fundamental for overcoming financial obstacles and increasing the effectiveness of green hydrogen projects. Organizations like the World Bank and the Asian Development Bank promote initiatives where concessional loans and public guarantees attract private capital, thus fostering the development of a sustainable production and distribution network, even in emerging markets. This model not inly facilitates resource mobilization but also helps consolidate a global green hydrogen supply chain. **(Green Hydrogen Organization/GH2, 2022).**

In summary, this review highlights how the variety of governance models and the richness of commercial incentive tools adopted in Hydrogen Hubs are decisive in fostering the participation of SMEs and startups in the green hydrogen ecosystem.

The analysis has revealed that multi-level, hybrid, and inclusive governance models, combined with collaborative and transparent practices, create the conditions for the active involvement of smaller actors, lowering entry barriers and stimulating innovation. The incentive mechanisms, from Contracts for Difference to off-take guarantees, from public-private partnerships to blended finance models, have proven crucial for mitigating risks, attracting capital, and making projects bankable. This has positive effects on the scalability of technological solutions and the competitiveness of SMEs.

The review has also shown how these dynamics translate into tangible progress on the ESG sustainability front, like Inclusive and transparent governance fosters social justice and community acceptance (Social), the integration of incentives and innovative financial tools accelerates decarbonization and environmental efficiency (Environmental) the participation of SMEs and startups fuels the diffusion of responsible practices and sustainable business models (Governance & Social). This work also highlights, from a multidisciplinary perspective, the interactions between governance, incentives, and SME participation, offering a theoretical-operational framework useful for both future research and the definition of policy and industrial strategies. It emerges that only a governance structure capable of integrating collaborative models and targeted incentive tools can transform Hydrogen Hubs into true engines of innovation, inclusion, and sustainability, solidifying the role of SMEs and startups as protagonists of the energy transition.

4 Case Study Selection Methodology

The starting point of this research was the creation of a suitable and comprehensive database. This database gathers the most significant case studies illustrating concrete models of green Hydrogen Hubs and Hydrogen Valleys.

The selection process analyzed the integrated solutions and challenges of these cases, placing greater attention on projects that included SMEs and startups and their role within ESG factors. This focus ensures the selected cases are representative of the thesis's central theme.

The methodological approach used to achieve this result was based on a structured process of collecting and selecting case studies. This process harmonized diverse information sources, including online resources, scientific articles, and reports from international organizations (such as IRENA, the International Energy Agency - IEA, and Hydrogen Europe) and institutional bodies, particularly at the European level.

4.1 Identification of Case Studies

The research involved several sequential work phases, which included cross-referencing and documentary analysis of international and institutional agencies. As a preliminary step, internet consultations were conducted to identify green hydrogen adoption projects located worldwide that, based on an initial survey, appeared to meet the requirements for the analysis. These checks allowed for the acquisition of initial information on ongoing initiatives, pilot projects, and strategies for green hydrogen development. This data was then supplemented with further details acquired by consulting papers from international/institutional organizations, such as IRENA (International Renewable Energy Agency) and the European Union, which provided additional details on regional policies and initiatives. This process established an initial data panel on which to base subsequent detection and selection phases.

Initially, approximately 40 case studies were identified that seemed to meet our objective's requirements, with a selection that included projects in Italy, Europe, and around the world. The research conducted in the Italian context used projects linked to the PNRR (National Recovery and Resilience Plan) and the REPowerEU plan as a starting point, two strategic initiatives for the energy transition and the development of green hydrogen technologies. The selected Italian cases reflect a variety of approaches, with a particular focus on the involvement of SMEs and startups, promoting integrated local solutions for hydrogen production and distribution in line with decarbonization goals. Subsequently, the analysis expanded to Europe, referencing projects that benefit from European public funding through the IPCEI (Important Projects of Common European Interest) plan. In this phase, significant cases were chosen in countries like Germany, France, and the Netherlands, where hydrogen integration into local grids is incentivized through environmental sustainability policies and public-private collaboration.

Finally, the global analysis involved countries on other continents, such as Australia, the United States, Africa, and Asia, where green hydrogen is considered a strategic element for the energy transition.

These international cases were chosen to compare different approaches, focusing on technological innovation, common challenges, and financing policies that stimulate the adoption of sustainable energy solutions.

In summary, the 40 selected cases reflect the variety of approaches and governance models in the green hydrogen sector. The selection was based on their relevance to the thesis topic, considering their consistency with sustainability objectives and the involvement of key actors such as SMEs, startups, and governments, based on the specific requirements of the research question.

4.2 Defining the Analysis Sample

Once the preliminary collection was complete, it became essential to refine the selection process, focusing on specific distinctive features to ensure the quality and relevance of the cases considered. Therefore, to define the final sample for this study, in addition to prioritizing cases that met the research objectives, further rigorous selection criteria were applied. These criteria focused on fundamental aspects to provide a complete and comprehensive analysis, including:

- **Global Coverage:** Selecting case studies that ensure global geographical coverage, including projects from all five continents. This ensures a diversity of hydrogen policies and strategies adopted in different regions of the world.
- **Archetype Distinction:** Dividing the case studies based on different project archetypes, such as territorial ecosystems, R&D hubs, infrastructural hubs, and national policy strategies. This structure serves as the foundation for the subsequent data analysis phase. This *modus operandi* allows for highlighting the different project approaches adopted globally and enables a coherent comparison of entities belonging to the same cluster.
- **International and Local Policies:** Considering case studies that are representative of various hydrogen management policies, such as those defined by the European Union and other international organizations, or by local authorities that influence the creation and operation of hydrogen hubs and valleys.

Following a scrupulous screening of the approximately 40 cases initially identified, twenty-two active projects were selected that reflect the defined inclusion criteria. These cases represent a variety of approaches and governance models related to the production, distribution, and use of green hydrogen, originating from Italy, Europe, and other countries, representing all continents.

Additionally, case studies of failed projects were randomly selected. This was done to investigate the causes behind their failure to achieve their objectives, which ultimately led to the suspension or abandonment of the project.

4.3 Data Analysis

Once the study sample was defined, a comparative analysis of the identified cases was conducted. The goal was to identify adopted best practices, differences, and opportunities for optimizing green hydrogen adoption, while also offering deductive recommendations based on the results obtained.

This analysis was also conducted in relation to the failed project case studies, highlighting and comparing the aspects that led to their failure.

For the purposes of simplification and standardization, this comparative analysis was performed using a series of 19 Key Performance Indicators (KPIs). These KPIs assess the projects according to strategic, economic, and operational parameters, as listed below:

1. **Short- and Long-term Objectives:** The short- and long-term strategic and operational objectives of each project, including production milestones and economic impacts.
2. **Target Market and Customer Needs:** Identification of target market segments and specific customer needs, particularly for SMEs and startups.
3. **Business Model/Governance Model:** Study of the business models and governance structures adopted by each project.
4. **Services Description:** Description of the services offered by the projects and the methods by which they are delivered.
5. **Competitive Analysis (Regulatory Environment):** Analysis of the competition and the regulatory environment, with particular attention to hubs outside the European Union.
6. **Access to Services:** Assessment of the accessibility of the services offered, with a focus on SMEs and startups.
7. **Revenue Streams:** Identification of revenue streams, particularly those financed by European or government projects.
8. **Pricing Strategy (also future):** Analysis of pricing strategies, including future developments and planned approaches for economic sustainability.
9. **Marketing Strategy and Sales Plan:** Evaluation of marketing strategies and sales plans, including approaches to attract new participants and stakeholders.
10. **Customer Acquisition Costs/Strategies:** Analysis of the costs and strategies for acquiring new customers, particularly SMEs, startups, and other relevant stakeholders.
11. **Retention Strategies:** Strategies adopted to maintain and retain customers and users over the long term.
12. **Operations Plan and Organizational Structure:** Analysis of the operations plan and organizational structure, focusing on necessary resources and internal processes.
13. **Facilities, Equipment, and Technology Requirements:** Identification of necessary resources, including facilities, equipment, and technologies used, with details on size and specifications.
14. **Organizational Information:** Information on the project's organization and management, including key teams and roles.
15. **Supply Chain Management:** Study of supply chain management, including analysis of suppliers, logistics, and material flows.
16. **Financial Plan:** Financial plan, including projected costs, cash flows, and financial projections.
17. **Test Line Costs:** Costs related to the project's testing and development phase, including those for prototyping and feasibility trials.
18. **Break-Even Analysis:** Break-even analysis and investment payback period.

19. **Social/Environmental Spillovers:** Analysis of the social and environmental impacts of the projects, including positive effects on local communities, employment, and sustainability.

The structured analysis using these indicators allowed for a uniform and comprehensive comparative overview of the selected projects. This made it possible to highlight the different strategies adopted and the main difficulties encountered in implementing project activities, as well as to present practical guidance for a more effective deployment of green hydrogen.

4.4 Integration with the Triple Layer Business Model Canvas

As specified above, the case study selection process also accounted for the ESG factor impacts of the various project entities.

For this reason, to supplement the analyses conducted, the "Triple Layer Business Model Canvas" (TLBMC) was developed for two of the selected case studies. This tool was applied in combination with Eric Ries's Lean Startup principles as an evolution of the classic "Business Model Canvas." The goal was to schematically, effectively, and immediately illustrate the strategic management model of these two green hydrogen entities from the triple "Economic," "Environmental," and "Social" perspective.

Each phase of this methodology was designed to answer the research question defined in this thesis's introduction. To reiterate, this question addressed how different governance models and commercial incentive mechanisms in Hydrogen Hubs and Hydrogen Valleys might favor the participation of SMEs and startups in adopting green hydrogen technologies, and with what effects in terms of environmental, social, and governance (ESG) sustainability.

5 Summary Statistics

Below is a summary that highlights the main characteristics of the 19 KPIs analyzed, in relation to the case studies examined:

1. ***Short-term objectives*** for green hydrogen projects primarily focus on creating basic infrastructure and validating technologies. Projects like the Trentino Hydrogen Valley and H2SHIFT aim to build pilot plants. Other projects, such as the Fukushima Hydrogen Energy Research Field and the Hyundai HTWO Innovation Centre, focus on experimenting with advanced electrolysis and storage technologies on a small scale, preparing for larger-scale development. Looking at the **long term**, the objectives shift to scalability and commercialization. Projects like Hyundai HTWO and Fukushima aim to expand their production capacity. Meanwhile, initiatives like H2SHIFT and the Trentino Hydrogen Valley aim to move beyond the pilot phase and increase production.
2. ***The target market*** for most green hydrogen projects includes both the industrial and energy sectors. Projects like the Andalusia Green Hydrogen Valley and Ulsan Green Hydrogen Town aim to serve large customers in the energy sector, including utilities and industrial companies that require green hydrogen to reduce their carbon emissions. Projects like the Fukushima Hydrogen Energy Research Field and the California Hydrogen Hub focus on a broader market that also includes the automotive and mobility sectors, aiming to meet the demand for hydrogen-fueled vehicles and other industrial applications.
3. *The* ***services Description*** offered by green hydrogen projects primarily include the production and distribution of low-carbon hydrogen. Projects like the Trentino Hydrogen Valley and H2SHIFT focus on research and technological innovation, providing consulting and support services for adopting green hydrogen technologies. Other projects, such as the Hyundai HTWO Innovation Centre, are oriented toward large-scale hydrogen production and providing industrial solutions for hydrogen-based energy and mobility.
4. ***Access to the services*** offered by green hydrogen projects depends on the project's phase. For projects like H2SHIFT and the Trentino Hydrogen Valley, access is provided through public-private partnerships and collaborations with research institutes. Other projects, such as the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field, offer services directly to industrial companies and utilities, using an access model geared toward long-term hydrogen supply.
5. ***Revenue streams*** for green hydrogen projects are primarily derived from the sale of green hydrogen and the provision of technological solutions and consulting services. Projects like the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field generate revenue through long-term hydrogen supply contracts with industries and utilities. Other projects, such as H2SHIFT and the Andalusia Green Hydrogen Valley, generate revenue streams mainly through public funding and collaborations with research institutes and universities.
6. ***The pricing strategy*** is influenced by public policies and production costs. Projects like the Fukushima Hydrogen Energy Research Field and the Hyundai HTWO Innovation Centre set prices

based on production costs, taking public incentives into account. Other projects, such as the Trentino Hydrogen Valley and the Andalusia Green Hydrogen Valley, do not adopt direct pricing strategies but instead focus on experimentation and cost optimization.

7. ***The marketing strategy and Sales Plan*** focus on sustainability and technological innovation. Projects like the Andalusia Green Hydrogen Valley and H2SHIFT are building strong reputations as research hubs for green hydrogen, aiming to attract investment and industrial partners. Other projects, such as the Fukushima Hydrogen Energy Research Field, have an industry-oriented strategy, aiming to collaborate with companies in the energy and utility sectors for green hydrogen supply.
8. ***Customer acquisition costs/strategies*** are generally based on long-term contracts and industrial collaborations. The costs to acquire customers are high, considering the development and research expenses. Projects like H2SHIFT and the California Hydrogen Hub focus on acquisition through contracts with large companies and local governments, while projects like the Hyundai HTWO Innovation Centre aim for collaborations with companies in the automotive and industrial sectors.
9. ***Retention strategies*** focus on creating long-term relationships with industrial partners. In many cases, green hydrogen projects retain customers through the quality of their technologies and continuous innovation. The Fukushima Hydrogen Energy Research Field and the Hyundai HTWO Innovation Centre seek to build customer loyalty through long-term hydrogen supply contracts.
10. *The* ***Operations Plan and Organizational Structure*** depend on the project's size and phase. Many projects, such as H2SHIFT and the Trentino Hydrogen Valley, are focused on research and development, so the structure is generally more collaborative. In projects like the Fukushima Hydrogen Energy Research Field and the Hyundai HTWO Innovation Centre, the operational structure is more centralized, with direct management of large-scale H_2 production and distribution.
11. ***Facilities, Equipment, and Technology Requirements*** vary significantly depending on the project's phase. Projects like H2SHIFT and the Trentino Hydrogen Valley require pilot plants and equipment for experimenting with hydrogen production technologies. Larger projects, such as the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field, require advanced industrial infrastructure, including electrolyzes plants, hydrogen refueling stations, and renewable energy production facilities.
12. *The* ***organizational Information*** for green hydrogen projects depends on the project's structure. Most projects, such as H2SHIFT and the Andalusia Green Hydrogen Valley, have a collaborative structure involving government bodies, universities, SMEs, and large companies. Projects like the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field have a more centralized structure, with leadership oriented toward large-scale industrial production.
13. ***Supply Chain Management*** is crucial for ensuring the availability of the technologies needed for green hydrogen production. Projects like H2SHIFT and the Andalusia Green Hydrogen Valley focus on a supply chain that integrates suppliers of hydrogen production technologies, such as

electrolyzers, and resources for renewable energy generation. Other projects, like the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field, manage a more complex supply chain that includes hydrogen distribution, industrial plant construction, and natural resource management.

14. ***The Financial Plan*** for green hydrogen projects is mainly based on public and private investments. Projects like the Trentino Hydrogen Valley and H2SHIFT are financed by public contributions from European and national funds. In contrast, projects like the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field require significant private investment, with financial plans that anticipate a long-term return on investment thanks to large-scale hydrogen production.
15. ***Test line costs*** depend on the project's size and the complexity of the technologies used. Projects like H2SHIFT and the Trentino Hydrogen Valley have relatively low test line costs, which involve pilot plants and small-scale testing. Conversely, more industrialized projects like the Fukushima Hydrogen Energy Research Field and the Hyundai HTWO Innovation Centre require large-scale test lines, with development costs that can exceed €50 million.
16. *The* ***Break-Even point*** for green hydrogen projects depends on their size and operational costs. Projects like H2SHIFT and the Trentino Hydrogen Valley can reach break-even more quickly thanks to public support and low initial costs. In contrast, projects like the Hyundai HTWO Innovation Centre and the Fukushima Hydrogen Energy Research Field may take longer to reach break-even due to high initial costs and longer amortization periods.
17. *The* ***Competitive and Regulatory Analysis*** for green hydrogen projects varies depending on the country and regulatory context. Projects like the Trentino Hydrogen Valley and the Andalusia Green Hydrogen Valley operate in a favorable European regulatory environment, with policies and incentives to promote green hydrogen adoption. In Japan, the Fukushima Hydrogen Energy Research Field benefits from national government policies for renewable energy. Meanwhile, projects like Hyphen Hydrogen Energy in Namibia are still in the regulatory development phase but are supported by favorable national policies.
18. *The* ***Business and Governance Models*** of green hydrogen projects vary, but they are generally public-private models. Projects like H2SHIFT and the Andalusia Green Hydrogen Valley are managed through consortiums that unite universities, government bodies, and private companies. Other projects, like the Fukushima Hydrogen Energy Research Field and the Hyundai HTWO Innovation Centre, follow a centralized structure with strong government and industrial involvement, focusing on large-scale hydrogen production.
19. *The* ***Social and Environmental Spillover*** impacts are positive for almost all green hydrogen projects. The creation of local jobs, training in the energy sector, and technological innovation are common aspects. Projects like the Trentino Hydrogen Valley and the Lolland Hydrogen Community help stimulate the local economy. The environmental impact includes the reduction of CO_2 emissions and the promotion of renewable energy as solutions for the energy transition.

6 Case Study Analysis and Results

6.1 Overview of the Selected Hydrogen Hubs

This chapter follows the delineation of the methodological process that allowed us to identify the reference material. It aims to offer an in-depth analysis of the case studies which, despite their heterogeneity, share the ambition of configuring themselves as territorial models for hydrogen development. The objective is not to validate or refute individual hypotheses, but rather to construct a critical reading of the project trajectories, highlighting the conditions that favored their consolidation or, conversely, led to their discontinuation.

The analysis is based on a comparative perspective that considers Hydrogen Valleys and Hydrogen Hubs not as isolated entities, but as complex constructs, situated at the intersection of energy policies, industrial and territorial dynamics, and innovation processes. In this sense, the comparison between active experiences and failed projects arises from the need to compare various dimensions, including: the coherence between objectives and instruments, the capacity for contextual adaptation, the degree of local stakeholder involvement, economic and environmental sustainability, and the robustness of governance networks.

The decision to include both completed projects and ongoing initiatives in the sample allows for broadening the scope of observation, avoiding a selective or celebratory reading. Failed cases, in particular, offer a unique vantage point from which to examine the structural weaknesses that can undermine even the most ambitious initiatives. At the same time, active projects allow for the real-time observation of the evolution of different operational models, highlighting the strategies that have enabled them to overcome initial challenges and build resilient configurations.

The chapter is not limited to describing the characteristics of individual projects; it aims to identify recurring patterns, significant discontinuities, and enabling factors. The analysis is developed through an interpretive framework that integrates technical, economic, institutional, and territorial variables, with particular attention to the ESG dimension, considered a cross-cutting indicator of project maturity. The objective is to build a reasoned taxonomy of Hydrogen Valley models, useful not only for understanding current dynamics but also for guiding future design.

Within this framework, the comparison assumes a heuristic function: it is not a matter of identifying an ideal model, but of exploring the variety of possible configurations, analyzing their conditions for effectiveness, emerging criticalities, and potential for evolution. The chapter thus serves as a space for empirical and theoretical reflection, where concrete experiences are examined in light of the questions posed by the energy transition, industrial transformation, and the redefinition of territorial policies.

6.2 Hydrogen Hubs and Valleys: A Conceptual Clarification

Before proceeding to the case-study analysis, it is useful to briefly address a preliminary reflection on the definitions of Hydrogen Hub and Hydrogen Valley. This step is necessary as, in both literature and project practice, no clear line of demarcation exists between the two concepts. Their interpretations vary significantly depending on the specific geographical, economic, and institutional context.

Conventionally, a Hydrogen Hub tends to be identified as a facility focused on a specific segment of the hydrogen value chain, often functioning as a technology incubator or industrial accelerator. In this sense, the hub does not cover the entire hydrogen cycle but concentrates on one or more aspects such as production, transport, or distribution in a specialized and centralized manner.

Conversely, the term Hydrogen Valley, as already highlighted in the previous chapter 1.3, is generally used to describe an integrated territorial ecosystem capable of coordinating all phases of the value chain: from initial design and infrastructure implementation to the production, use, and, in some cases, the commercialization of green hydrogen. The valley is distinguished by its local integration, the involvement of a plurality of public and private stakeholders, and its multi-sectoral scope, which includes industry, mobility, research, and the community. It is important to emphasize that, due to the absence of a unique definition, similar projects may be classified as hubs or valleys depending on the context in which they develop, generating interpretative ambiguity.

In this study, an effort has been made to maintain a perspective consistent with the European approach, which tends to prioritize territorial integration, the community dimension, and functional integration. To clarify this distinction, two emblematic examples can be cited. On one hand, the Andalusia Green Hydrogen Valley **(moeve, 2024)**, which represents a true valley: a complete ecosystem that integrates the production, distribution, and local use of hydrogen, actively involving SMEs, universities, industrial clusters, and public institutions. In this case, the value chain is fully developed and interconnected.

On the other hand, the Hamburg Port Hydrogen Project **(HydroNews, 2022)** is configured as an authentic hub: a centralized infrastructure dedicated to large-scale production and distribution, with import/export terminals and industrial contracts, but lacking direct hydrogen use within the territory where it is produced. The absence of a local and multi-sectoral dimension confirms its nature as a logistics-industrial node rather than a territorial ecosystem.

6.3 Learning from Failure: Structural Weaknesses and Missed Opportunities

In the course of analyzing Hydrogen Valleys and Hydrogen Hubs, it was deemed appropriate to dedicate a specific section to case studies that, despite being initiated with ambitious objectives and significant resources, failed to reach a consolidation or operational phase. The inclusion of these examples does not stem from a desire to contrast successful and unsuccessful projects, but rather from the need to build a critical foundation useful for comparison with initiatives currently in effect.

The objective is to observe, at a later stage, whether and how active projects have addressed the problems that emerged in the failed cases, and in what ways they have sought to overcome them. In this sense, failures are not treated as marginal exceptions, but as fundamental elements for understanding the sector's evolution and the maturation of project models.

The six failed cases analyzed in this section (Table 2) represent heterogeneous experiences in terms of geographical context, project scale, and strategic aims, but they share the commonality of not having reached full maturation. Some were interrupted in the preliminary phase; others failed to overcome the economic, environmental, or social barriers hindering their implementation. Their analysis is not intended to highlight what was missing, but rather to offer a useful perspective for evaluating, in the subsequent comparison, whether active projects have successfully learned from these experiences and transformed past criticalities into strengths.

In this regard, failures are not treated as anomalies, but as an integral part of the sector's evolutionary process. Their observation allows for the construction of an interpretive framework that will then be applied to current cases, aiming to identify potential discontinuities, improvements, or repetitions. Only through this step is it possible to understand whether the hydrogen sector is genuinely progressing toward more robust and sustainable models, or if structural weaknesses that limit its scalability persist.

	Projects	Locality	Total Capacity Target	Hydrogen production
1	**Western Green Energy Hub (WGEH)**	Nullarbor Plain, Australia	70 GW (wind + solar)	Phase 1: 500,000 t/year; Final phase: 3.5 million t/year
2	**Australian Renewable Energy Hub (AREH)**	Pilbara, Australia	26 GW (wind + solar)	1.6 million t/year
3	**Port Pirie Hydrogen Project**	South Australia, Australia	440 MW (electrolyzers)	100 t/day (36,500 t/year)
4	**Hunter Valley Hydrogen Hub**	New South Wales, Australia	55 MW (electrolyzers)	~4,700 t/year~1 million t/year
5	**Hydrogen Energy California (HECA)**	Kern County, USA	390 MW (combined cycle power plant)	~1 million t/year
6	**Fusina Hydrogen Power Station**	Fusina, Italia	12 MW (electrolyzers)	~~60,000 MWh/year

Table 2: Failed Cases

6.3.1 Lack Stakeholder and Community Engagement: A Criticality Intertwined with Environmental and Territorial Impacts

One of the most recurring themes in the failed case studies is the weakness, if not the absence, of a structured process for territorial stakeholder engagement. In more than one project, the lack of consultation with local communities generated opposing cultural and environmental conflicts, ultimately compromising the very feasibility of the initiative. This aspect does not only concern the social dimension but also directly impacts the political, environmental, and operational sustainability of the project, highlighting that territorial acceptability is an indispensable condition for success.

The comparative analysis also reveals a systematic link between the lack of engagement and *perceived* environmental and territorial impacts. Specifically, where communities were not involved, the strongest opposition also emerged, related to:

- Expropriation or forced transformation of the land, even in the absence of significant "technical" environmental impacts;
- Loss of local control over natural resources and landscapes;
- Disruption of identity-based and cultural ties to the territory.

In the case of the Western Green Energy Hub, located in the Nullarbor Plain (Australia), the opposition from the Mirning Indigenous people took on not only environmental but also identity and cultural significance. The lack of consultation generated a profound conflict with the local communities, who reported the risk of losing sacred lands and a new form of "energy colonialism." Although the project planned for the use of renewable sources and low-impact technologies, the symbolic and material expropriation of the territory was perceived as an unacceptable violation. The Western Green Energy Hub is the only one of the six cases considered that is not officially closed; in fact, it has been stalled for over a year pending an environmental impact assessment by the Australian government **(HyResource, 2025).**

A similar situation occurred with the Asian Renewable Energy Hub in the Pilbara region (Australia). Despite its technological and industrial ambition, the absence of effective dialogue with local stakeholders contributed to the negative assessment by environmental authorities. The project was deemed "clearly unacceptable" by the federal government, partly due to risks to migratory wildlife and wetlands. However, it was precisely the failure to integrate territorial concerns that prevented the emergence of shared solutions and fueled the perception of an external invasion **(ABC NEWS, 2021)**.

In other cases, such as the Port Pirie Hydrogen Project **(S$P Global, 2025)** and the Hunter Valley Hydrogen Hub **(Orica Knowledge Sharing Report, 2025),** the involvement of local communities and SMEs was marginal or absent. Although environmental issues were not as central in these contexts, the disconnect between the project and the local socio-economic fabric reduced the capacity to build consensus and activate local synergies. This lack of trust contributed to a loss of legitimacy and a reluctance from local actors to participate.

Finally, in the case of Hydrogen Energy California (HECA), environmental opposition was particularly intense, with protests related to emissions and the use of agricultural land. Although the project was aimed at producing green hydrogen, the massive use of coal alarmed the community due to fears of worsening air quality. Furthermore, the project involved the consumption of large quantities of water in an area severely affected by drought, fueling the concerns of citizens and farmers. Here too, the project's governance demonstrated a poor capacity for dialogue with local communities, contributing to a climate of mistrust and opposition **(Sierra Club, 2016).**

This recurrence suggests that territorial engagement cannot be considered an optional component but must be integrated from the earliest design phases. Building an energy ecosystem requires not only infrastructure and investments but also relationships, trust, and legitimacy. Moreover, active community participation can serve as a safeguard for environmental and territorial sustainability, helping to identify risks at an early stage and develop shared solutions.

From the analysis of issues related to environmental aspects, the concept of "energy injustice" emerges with increasing clarity. The territories and populations affected by the development and construction of Hydrogen Hubs or Valleys do not always actively participate in the distribution of the benefits they generate. This disparity only strains relations between the local population and large investors, fueling protests and discontent. For this very reason, the need for cooperation among the various stakeholders, to work jointly toward a common goal and common good, is increasingly evident.

6.3.2 Lack of Binding Off-take Agreements and SME Engagement: Challenges in an Emerging Market

A recurring theme in the failed case studies, though one that cannot be attributed as a direct responsibility to the Hubs or Valleys considered, is the uncertainty tied to the development speed of the hydrogen market (especially for green hydrogen) and the associated risk of capital-intensive development.

This macro-issue generates a series of consequences that have undermined, and continue to undermine, the implementation of many projects. The lack of an established market creates significant difficulties in finding potential clients with whom to sign binding off-take agreements, that is, commercial agreements that guarantee the purchase of the hydrogen produced by stable and reliable customers (cf. Chapter 3). In the absence of such instruments, projects are exposed to high market uncertainty, which compromises their bankability and discourages the entry of private investors. Advanced technology or an ambitious industrial plan is not sufficient unless accompanied by structured demand and solid contractual relationships.

Envisioning these issues as a chain, it is precisely the lack of a market, and thus of off-take contracts, that ultimately affects SMEs and startups. These enterprises perceive the projects as too risky and lacking concrete prospects for economic returns, thereby disincentivizing their involvement **(The Oxford Institute for Energy Studies, 2025)**.

This situation generates a dangerous combination: the absence of binding contracts and weak local entrepreneurial participation, which constitutes a structural fragility that has compromised the construction of resilient and locally integrated ecosystems. Without guaranteed buyers, SMEs and startups do not invest; without SMEs and startups, the project loses its capacity for adaptation, innovation, and territorial legitimacy.

Considering the cases under analysis, the Hunter Valley Hydrogen Hub demonstrated significant vulnerability in this regard: the project was abandoned due to the lack of a market willing to pay a premium price for green hydrogen, and without long-term contracts to ensure its economic sustainability. Local SMEs and startups were excluded from the decision-making process and the value chain, further reducing local integration **(SkyNews, 2024).**

A similar situation occurred with the Port Pirie Hydrogen Project, where the project's financing company, Trafigura, in collaboration with the Australian government, decided to suspend development precisely because of the difficulties encountered in entering the new green hydrogen industry. Local SMEs and startups, initially interested, progressively lost confidence in the project, seeing no concrete prospects for economic return **(Klean Industries, 2025).**

Finally, the Hydrogen Energy California (HECA) case highlights how, even with a significant federal grant, the lack of stable commercial agreements and structured demand rendered the project uncompetitive and unbackable. In addition to failing to identify secure buyers for the produced hydrogen, their strategy for collecting and subsequently reselling emitted CO_2 did not yield the expected results (**Carbon Capture and Sequestration Technologies, 2016)**. Here too, the involvement of local businesses was weak, partly due to the technologically complex nature of the project and partly due to the economic uncertainty that discouraged startups.

In all these cases, the dual challenge of missing off-take agreements and the lack of SME/startup engagement represented a structural limitation, making the projects vulnerable to market fluctuations and investor reluctance. The following paragraphs will analyze whether and how currently active projects have addressed this dual criticality, and what tools they have adopted to ensure commercial stability and territorial inclusion.

6.3.3 Weaknesses in Governance Models

A further cross-cutting element that emerged from the analysis of failed case studies pertains to structural weaknesses in the governance models adopted. In more than one project, governance proved to be fragmented, insufficiently inclusive, or incapable of effectively managing territorial and industrial complexity. This generated conflicts among partners, exclusion of local stakeholders, and difficulties in operational coordination. Specifically, three recurring types of critical issues are observed:

- **Centralized and non-inclusive governance In projects like the Asian Renewable Energy Hub and, especially**, the Western Green Energy Hub, the centralized management of the project raised concerns regarding the genuine inclusion of local communities in the decision-making process. Despite declarations of intent, the lack of participatory governance limited the effectiveness of integrating Indigenous communities **(TIME World Sustainability, 2021).**
- **Conflicts between industrial partners and institutions**
  The Hunter Valley Hydrogen Hub suffered from divergences among the parties involved, slowing the plan's execution and creating strategic uncertainty. In fact, the project stalled when Origin Energy, the main industrial partner, decided to withdraw from its commitments. A lack of strong cohesion between the involved actors (Origin Energy and the government) to mitigate the difficulties of entering such a challenging and uncertain sector made the difference between the project's success and its closure **(Energy and Resources Knowledge Hub, 2024).**
- **Absence of multi-level coordination**
  The Hydrogen Energy California (HECA) project highlighted a governance structure unable to integrate different decision-making scales (federal, state, local), resulting in a dispersion of responsibilities and inefficiency in managing permits and funding. Disagreements between the federal agencies, which largely financed the project, and California legislators regarding rules for tax credits and project eligibility created an operational bottleneck that compromised the entire project's advancement **(Decarbonfuse, 2025)**.

These critical issues demonstrate that governance cannot be considered a technical or secondary element; rather, it represents a strategic component for a project's success. An effective governance model should ideally be structured to be:

- **Multi-level**, capable of coordinating public and private actors at the local, regional, and national scales;
- **Inclusive**, able to involve SMEs, startups, communities, and territorial institutions;
- **Flexible**, to adapt to regulatory, technological, and market evolutions.

Obviously, achieving and establishing such a governance model is not always possible or easily feasible; however, striving toward a similar model increases the developing project's chances of survival.

6.3.4 High Costs and Financing Difficulties

The analysis has highlighted another dual challenge, one as predictable as it is difficult to address: high production costs and the difficulty in securing stable and sufficient financing. In many cases, even with promising technologies and initial institutional support, the economic model proved unsustainable, discouraging private investors and compromising the project's bankability.

This criticality manifests in various forms:

- **Excessively high operational and infrastructure costs**, often linked to the project's scale, technological complexity, or the need for complementary infrastructure (e.g., desalination, transport, storage);
- **Absence of structural incentives** that could have offset the gap between costs and revenues;
- **Lack of guaranteed buyers**, making it difficult to build a credible business model;
- **Perceived risk being too high**, which deters investors and industrial partners.

Examining the analyzed case studies in detail, it can be observed that in the case of the Port Pirie Hydrogen Project, although the lead partner Trafigura had decided to invest approximately $750 million and had already initiated the design and engineering process, it decided to suspend the project entirely. This was due to the prohibitive construction and hydrogen production costs. This decision was also made in anticipation of limited interest from buyers, who still consider the price of green hydrogen excessive **(The Australian, 2025**).

The Hunter Valley Hydrogen Hub followed a similar trajectory: the project was abandoned in 2024 due to demand uncertainty and the inability to guarantee a competitive price for green hydrogen. Market growth forecasts were insufficient to justify the investment, and divergences among industrial partners further weakened the financial governance **(Reuters, 2024)**.

The case of Hydrogen Energy California (HECA) is emblematic given its scale and ambition: despite a $408 million federal grant, the project was canceled in 2016. The gasification and CO_2 capture technology proved too costly and complex, and the lack of guarantees on economic returns prevented it from attracting private capital **(Industry Dive, 2015).**

These cases, the Hunter Valley Hydrogen Hub and Hydrogen Energy California, illustrate how high production costs and low customer willingness-to-pay are apparently irreconcilable with current solutions.

The Fusina Hydrogen Power Station represents an example of economic failure in a European context. The electricity produced was 5–6 times more expensive than conventional electricity, rendering the project uncompetitive. In this case as well, high costs and the absence of a market willing to pay a premium price led to the plant's decommissioning **(Gorina et Al., 2021).**

The following table provides a concise overview of the common challenges faced by these green hydrogen projects, highlighting, in summary, how economic sustainability, governance, and territorial engagement are crucial factors for the success of such initiatives:

These cases demonstrate that, beyond technological promises, economic sustainability is an indispensable condition for a project's success. Without a framework of favorable policies, without guaranteed customers, and without risk mitigation tools, even the most advanced initiatives can fail. Below is a summary Table 3 of the cases analyzed:

	Projects	Start Date	End Date/Corrent Status	Main Critical Issues and Causes of Failure
1	**Western Green Energy Hub (WGEH)**	2021	Standby (blocked for over a year)	Conflicts with local communities (Mirning indigenous peoples); Lack of territorial involvement and environmental criticism.
2	**Australian Renewable Energy Hub (AREH)**	2014	2021 - Abandoned planning	Lack of involvement of local communities, risks for migratory fauna, negative assessment by the federal government.
3	**Port Pirie Hydrogen Project**	2021	2025 - Cancelled	High construction costs, difficulty in attracting customers and investors, marginalization of local SMEs.
4	**Hunter Valley Hydrogen Hub**	2021	On Standby (abandoned in 2024)	Uncertainty about demand, difficulty in establishing off-take contracts, exclusion of local SMEs.
5	**Hydrogen Energy California (HECA)**	2008	2016 - Abandoned	Too high costs, lack of off-take contracts, poor governance and opposition from local communities.
6	**Fusina Hydrogen Power Station**	2008	2018 - Decommissioned	High production costs (5–6 times higher than conventional production), difficulty in finding a market willing to pay.

Table 3: Summary of Hydrogen Hub Failure causes

The following paragraphs will analyze the strategies adopted by active projects to address these criticalities and build more robust and resilient financial models.

6.4 Analysis of Currently Active Ecosystem Case Studies

Following the analysis of cases defined as failed or stalled, the focus shifted, after a careful selection process, to twenty-two currently active cases/projects/strategies for Hub or Valley development aimed at the adoption of green hydrogen. An in-depth study of their main characteristics was conducted, highlighting points of commonality and/or divergence within the sample analyzed, also in relation to the examples previously discussed.

As stated in the methodology, the objective was set to identify and include at least one project per continent within the reference sample. The analyzed sample includes the following projects (Table 4), organized by continent; among these are the numerous examples in Europe and America that were previously discussed:

Table 4: Case studies analysed

Ensuring the widest possible territorial differentiation was deemed essential and highly valuable. This approach makes it possible both to understand the development level of the green hydrogen transition in different geographical contexts, and to identify potential technological differences, which may also arise from cultural and financial variations.

The large-scale presence of projects for green hydrogen production and use attests to the collective commitment to the energy transition at a global level. Before proceeding with the comparative analysis itself, it is important to re-emphasize (see Section 3.2.2) that it currently remains very difficult for private entities to launch green hydrogen projects entirely independently. The scale of investment, the challenging technological development, an immature market, and uncertainty regarding an acceptable pricing strategy for customers necessitate public support (whether national or supranational). This support takes the form of grants (non-repayable funding), auctions, guarantees, or State aid schemes.

Therefore, analyzing the global incentive landscape, various initiatives can be identified. In the European Union, the majority of incentives derive from the instrument known as IPCEI (Important

Projects of Common European Interest) for the hydrogen chain. This allows Member States to finance flagship projects along the entire value chain, integrating technology, industrial applications, infrastructure, and mobility **(European Commission, 2021).**

6.4.1 Interpretive Framework and Archetypal Clustering of Green H_2 Projects

To pursue the analytical goals of this work, the cases under observation were suitably clustered into four functional archetypes. This choice stemmed from the need to compare each initiative with others in the same domain, possessing a similar structure and analogous objectives, thereby avoiding cross-comparisons between ecosystems that are entirely different from one another.

In this regard, the division was made into the following four macro-categories, distinguished by the objectives, management models, and economic impacts of each category:

i. Territorial ecosystem / hydrogen hub
ii. Research and development (R&D) hub.
iii. Infrastructural / industrial platform
iv. National strategic frameworks and enabling policies.

The following Table 5, "Mapping of Projects by Archetype (A–D)," summarizes this classification and serves as an interpretive key for the relative comparison between the different entities.

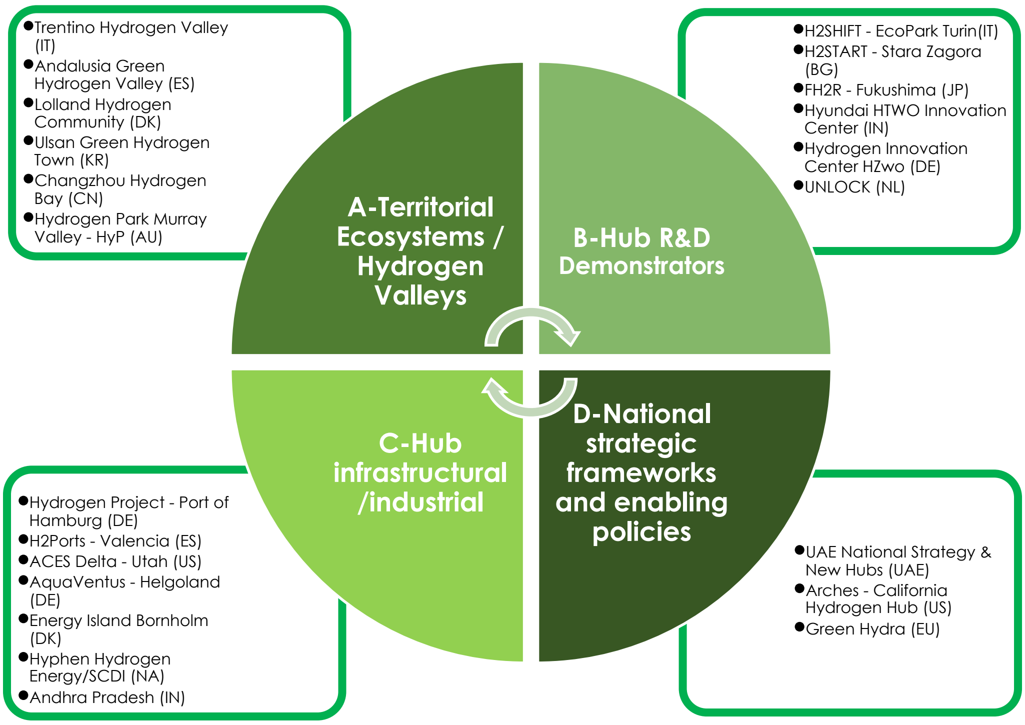


Table 5: Project mapping by archetipe

In particular, in the section:

A) Territorial Ecosystems / Hydrogen Valley

This category includes projects initiated with predominantly public and territorial objectives: the primary goal of these initiatives is to build local capacity, expertise, applied R&D, initial limited-scale applications, and strengthen local supply chains. This is the case for the Trentino Hydrogen Valley **(Invest in Trentino, 2023)**, the Andalusia Green Hydrogen Valley **(Moeve, 2022)**, the Lolland Hydrogen Community **(Nami et al., 2025)** , the Ulsan Green Hydrogen Town **(InvestKorea, 2019)**, the Changzhou Hydrogen Bay **(International Climate Initiative, 2020)**, and the Hydrogen Park Murray Valley **(Australia Government, 2024).**

In all these contexts, the trajectory is mission-driven impact is measured in terms of firms involved, qualified personnel, technological spillovers, and CO_2 reductions within the local perimeter, while revenues, when present, are ancillary (e.g., access fees, services). This section includes projects like Ulsan Green Hydrogen and Andalusia Green Hydrogen which, despite currently having characteristics associated with Hydrogen Valleys, could scale up toward industrial production in the future. Should off-take agreements and pricing models mature, they could be considered true industrial hubs; however, their current prevailing function is capacity building and local ecosystem activation.

B) R&D Hubs and Demonstrators

This category includes all structures whose main purpose hydrogen production per se is not, but the development of validated knowledge: test lines, protocols, experimental results, and technology transfer. Examples include H2SHIFT at EcoPark Torino **(H2Shift, 2025),** H2START in Stara Zagora **(H2START, 2024)**, the Fukushima Hydrogen Energy Research Field (FH2R) **(The Government of Japan, 2021)**, Hyundai's HTWO Innovation Centre **(Indian Institute of Technology Madras,2025)**, the Hydrogen Innovation Center HZwo **(Hzwo, 2025)**, and the UNLOCK project in the Netherlands **(Interreg Europe, 2025).**

The decision to place them here stems from the fact that the risk addressed is primarily technical: these hubs reduce uncertainty regarding technologies (electrolysis, fuel cells, compression, storage), standardize tests, and allow companies (often SMEs and startups) to approach higher TRLs (Technology Readiness Levels) by working collaboratively. Although the FH2R project has a significant scale and grid-balancing functions, it maintains a demonstrative and testing framework, not oriented toward stable sales; for this reason, it was deemed appropriate to include it among the examples in this section. Even when some activities generate revenue (laboratory or service fees), their economic role remains instrumental to the R&D mandate.

C) Infrastructural and Industrial Hubs

Here we observe projects of an industrial or logistical nature which, by definition, are measured by capacity, contracts, and bankability: production, transport, storage, port usage, and grid integration. The Port of Hamburg **(HGHH, 2025)**, H2Ports in Valencia **(H2Ports, 2025)**, ACES Delta in Utah **(ACES DELTA, 2023)**, AquaVentus in Helgoland **(AquaVentuS, 2025)**, the Bornholm Energy Island **(BORNHOLM ENERGY ISLAND, 2025)**, Hyphen in Namibia **(HYPHEN Hydrogen Energy, 2025)**, and Andhra Pradesh (India) **(Energetica India Magazine, 2025)**, are placed in this section because they operate (or aim to operate) with typical market metrics: volumes, off-take contracts, cost structure, payback forecasts, and material infrastructure such as pipelines, salt caverns, or port systems.

For Hamburg, the classification is straightforward, given the strong IPCEI framework and dedicated local network; for H2Ports, despite originating as a demonstrator, its operational dimension within a real port context carries weight, moving it closer to operational infrastructure; for Bornholm, the choice reflects its function as a system platform, more an energy island than a local project; and for Hyphen, the GW-scale export orientation makes the logic clearly market-driven. In summary, in this section, the dominant factor is not experimentation but the ability to sustain contracts and prices amid demand risk and energy costs. The risks associated with an emerging market come strongly into play.

D) Policy Frameworks and Enabling Strategies

The final section includes elements that are not industrial projects or test hubs, but rather the overarching structure that allows the others to exist: national strategies, federal programs, and policy improvement initiatives. The UAE National Strategy **(HydrogenNews, 2023)**, the Californian ARCHES program **(Arches H2, 2025)**, which entails multiple hubs spread across Californian territory, and the European Green Hydra project **(HYDRA, 2025)** are here because they define objectives, standards, financial instruments, and access methods, creating conditions for bankability and coordination that private actors alone would struggle to achieve.

ARCHES, as a whole, also includes downstream project components, but for comparative analysis, it is more accurate to interpret it as an enabling framework, dependent on federal support and its continuity, rather than as a single industrial asset. Finally, Green Hydra is a policy improvement initiative at the European interregional level: for methodological consistency, it would be misleading to evaluate it using commercial metrics (pricing, payback), which are not applicable here. In all these cases, the main contribution is not direct production but rather systemic risk reduction and stakeholder alignment, a necessary prerequisite for archetypes A, B, and especially C to develop effectively. Very often, these policies replace and/or support private actors who are discouraged from investing in such an uncertain and unpredictable sector.

6.4.2 Analysis of the Archetypes

A) Territorial Ecosystems / Hydrogen Valleys: How They Are Organized, What They Do, Why They Matter

Hydrogen Valleys, or territorial ecosystems, originate with a distinctly public purpose: the ultimate goal is to build local capacity, technological, organizational, and industrial, that enables the territory to experiment, learn, and eventually scale up the use of green H_2. Unlike traditional companies, they can be considered coordination platforms, acting as a meeting point for universities, businesses, utilities, public administrations, and training operators. The underlying logic is mission-driven: to reduce barriers to adoption (technical, regulatory, and informational), create credible initial demand, and foster the emergence of local supply chains capable of engaging with these programs.

From an organizational standpoint, governance is almost always multi-level. At the center is a steering committee (a region or metropolitan city, sometimes a development agency or technology cluster) with orchestration tasks: it defines objectives, ensures project coherence, guarantees transparent access to shared infrastructure, and oversees links to national/EU funding calls. Surrounding this committee are the technical-scientific partners (universities, R&D centers), local industrial actors (utilities, manufacturing, ports, public transport), business associations, and, where relevant, the owners of the utility networks (gas, electricity, water). Effective governance is recognizable by three traits: clear roles, codified procedures for accessing services, and periodic progress reporting.

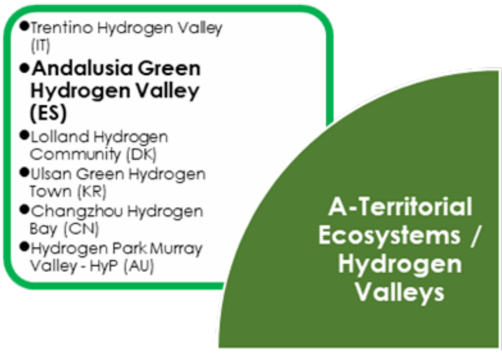
Operationally, a valley provides a catalog of services covering the entire territorial learning cycle. In the initial phase, activities such as mapping local demand (mobility, industrial heat, hard-to-abate processes), feasibility studies, and small-scale experiments (small-sized electrolyzers, pilot refueling stations, gas grid blending where permitted) prevail. These are complemented by testing and demonstration services for SMEs (component testing, interoperability, safety), training initiatives for technicians and operators, and, increasingly, assistance with authorization processes to streamline permits and connections. As the ecosystem matures, elements of infrastructure integration (connections to the renewable electricity grid, water management, potential logistics for hydrogen and derivatives) and embryonic forms of demand coordination (framework agreements with public fleets, local utilities, large consumers) appear.

The economic model of a valley is deliberately hybrid. The backbone consists of public funds (regional, national, or European), which finance the common platform (laboratories, small demonstration plants, training, coordination). Downstream, companies pay fees for the use of infrastructure and services or co-finance pilot projects. The focus is not on profit-making, but rather on enabling additional private investment and creating bankability for future market initiatives. For this reason, in performance evaluations, the platform's accounting break-even point has limited or no weight; attention is focused more on impact indicators such as companies involved, personnel trained, tons of CO_2 avoided within the local perimeter, technological maturation (TRL), and the ability to attract further funding.

On the risk front, territorial ecosystems primarily face coordination risks (many actors, administrative timelines), risks to the continuity of support due to changing political cycles, technical risks typical of the demonstration phase, and, not least, risks of insufficient demand if credible end-uses are not built in parallel. The best-functioning valleys mitigate these risks with a balanced project portfolio and a transparent roadmap outlining phases and milestones.

In summary, the territorial ecosystem is an institutional accelerator: it does not compete with the market but prepares the ground so that the market can take root. Should circumstances permit (i.e., the signing of off-take contracts and the large-scale availability of dedicated infrastructure), many cases analyzed would readily embrace a progressive evolution toward an industrial logic (Section C). Obviously, these are long-term possibilities that will be analyzed later, but in the current phase, the objective is to set learning, trust, and capacity in motion.

Focus: Andalusia Green Hydrogen Valley (Spagna)



To provide the reader with a complete view of a prototype Hydrogen Valley, the Andalusia Green Hydrogen Valley is taken as an exemplary case for this purpose. This ecosystem has a fragmented yet extremely cohesive structure. The setup is explicitly multi-node; in fact, the project's core is situated between the industrial poles of greatest critical mass, such as the Huelva and Campo de Gibraltar areas. It engages with major energy actors and port authorities within a programming framework that leverages national instruments (PERTE ERHA) **(FCW.H2, 2021)** and, for specific components, also IPCEI frameworks. This design, which splits the initiative into multiple sub-projects, allows for risk diversification and enables different components (production, industrial uses, mobility, port services) to advance with timelines that are coherent yet not dependent on one another.

From an institutional perspective, the valley is configured as a coordination platform: the *Junta de Andalucía* (regional government) plays the public steering role, while energy operators, startups, SMEs, industrial firms, and ports feed the pipeline of initiatives. Universities and regional technology centers ensure scientific oversight and training, with particular attention to the technical skills, electrolysis, safety, maintenance, power-to-X system management, necessary to support adoption. This structure allows for the alignment of authorization, connection, and commissioning times for the various projects, avoiding the typical bottlenecks that occur when each entity proceeds in isolation.

Operationally, the offering is structured along four main tracks that mutually reinforce one another. The first concerns experimentation and demonstration: small-scale plants to produce green H_2 from local renewables, with uses close to the point of production (public mobility and logistics, industrial heat, blending where regulated). The second is demand preparation: framework agreements with end-users, trials on fleets and port services, and progressive supply contracts that act as a "ladder" to increase volumes without abrupt scaling jumps. The third is training: dedicated programs for technicians and operators, competency certifications, and support for SMEs in the supply chain to access opportunities. The fourth is infrastructure integration: connecting to the renewable electricity grid and port infrastructure, while also exploring connections with national/European energy corridors, thus not enclosing the perimeter within regional borders.

The economic model reflects its nature as a territorial ecosystem. Common components (coordination, cross-cutting services, and training) are primarily supported by public funds (national and, where relevant, European instruments). Individual "vertical" projects, for example, a pilot plant at an industrial site or a port application, combine public co-financing with private resources from the involved operators. In some cases, individual components fall under European schemes like IPCEI: this occurs when the project has supply chain relevance and exceeds the local dimension. It is important to stress that the valley, as a whole, is not synonymous with a single IPCEI: the IPCEI is *one component*; the valley is the architecture that holds these diverse components together, making them complementary **(IPCEI HYDROGEN, 2024).**

The organization of activities favors a progression through clearly identifiable phases. Phase 1 consolidates governance, implements the first demonstrators, and deploys training, aiming to validate processes and operational standards in real-world conditions. Phase 2 aims to increase volumes and complexity, introducing more structured contracts with users and deeper infrastructural integrations. Phase 3 opens the door to interoperability with extra-regional hubs and, where maturity allows, to the export of services and supply chain components. This "ramp-up" design reduces the risk of premature investments on an unsustainable scale and allows for the effectiveness of choices to be measured along the way.

On the KPI front, the Andalusian valley is evaluated using a set of metrics coherent with its nature: number of local firms and SMEs activated, training hours delivered and qualifications issued, number and quality of pilot projects launched, CO_2 reductions achieved in demonstration applications, and the ability to attract additional investment and link to national/EU programs. Where projects closer to market logic appear, it becomes relevant to monitor elements like off-take agreements, utilization factors, Levelized Cost of Hydrogen (LCOH), and economic sustainability in realistic energy scenarios. These latter metrics, however, should be read as properties of the *individual component* and not as the objective of the platform as a whole.

Regarding risks, the valley must manage at least three. The first is permitting and connection risk, which can slow even mature initiatives: the response is a single interface with competent bodies and planning with shared time slots and milestones. The second is demand risk, typical of transitioning technologies: this is mitigated by building off-take contracts and anchoring initial volumes to stable local uses (public transport, port logistics, industrial heat). The third is fragmentation risk: in a "mosaic" ecosystem, it is essential to prevent components from proceeding in parallel without synergy; thus, a common roadmap, prioritization criteria, and shared learning mechanisms (ex-post evaluations, standardization of procedures and metrics) are crucial.

In perspective, the strength of the Andalusia Green Hydrogen Valley lies in the connection between locational advantages (renewable resources, strategic ports, existing industrial bases) and an institutional architecture capable of sequencing, prioritizing, and giving coherence to the interventions. The choice to maintain the valley as a coordinated framework, rather than a random sum of projects, allows for the enhancement of both the components closest to local use and those that, by characteristics and scale, can engage with European instruments like IPCEI. In this sense, the valley acts as a *director*: it selects where it makes sense to push for pure territorial learning and where, instead, to initiate industrialization paths capable of connecting the regional ecosystem to broader supply chains and markets.

The Andalusian Green Hydrogen Valley represents a true revolution. In terms of employment, the project will have a significant impact, with the creation of approximately 10,000 jobs during the construction phase and 1,000 permanent roles in operations, engineering, and maintenance. This growth not only stimulates employment but also opens opportunities for a specialized workforce in the energy transition, fostering sustainable evolution in the region.

A crucial aspect of the project is the inclusion of over 400 SMEs and freelancers, who will benefit from contracts for supplies, services, and logistics, thereby consolidating the local ecosystem and contributing to innovation. SMEs will play a fundamental role in diversifying activities, bringing advanced technologies, logistics solutions, and key products to the project. At the same time, the retrofitting of existing infrastructure, such as pipelines, storage tanks, and grid connections, will optimize the use of resources already available in Andalusia's energy parks, reducing implementation costs and accelerating timelines.

On the skills and research front, the project involves strong collaboration with local universities and research centers. They will help strengthen technical training and R&D for advanced technologies like electrolyzers, fuel cell systems, and safety protocols. This synergistic approach between academia and industry will ensure a highly qualified workforce ready to meet the challenges of green hydrogen.

Furthermore, the project is not limited to job creation; it aims to modernize entire heavy industry sectors, steering the region toward sustainable growth and progressively reducing dependence on fossil fuels. In this way, the Andalusian Green Hydrogen Valley not only boosts the local economy but also establishes itself as a model for green development that, thanks to technology, training, and inclusion, guides the region toward a concrete energy transition that is well-rooted in the territory.

When the platform is clear, roles are defined, access to services is established, and the roadmap and indicators are set, projects grow more effectively, risks are reduced, and the territory accumulates human and organizational capital. It is this capital, more than individual announcements, which determines a valley's ability to attract investment, link up with national and European programs, and, if and when the time is right, make the leap toward industrial-scale initiatives.

B) R&D Hubs and Demonstrators: What They Are, How They Function, Why They Are Needed

R&D hubs and demonstrators serve as the "cognitive infrastructure" of the hydrogen transition: they are shared laboratories, test lines, and controlled environments where technologies, components, and processes are developed, tested, and advanced in Technology Readiness Level (TRL) under conditions as close to operational reality as possible. Unlike industrial platforms, the "product" here is not tons of hydrogen or sales revenue, but validated knowledge: performance curves, safety protocols, interoperability, certified data, and, above all, the reduction of technical risk for the companies that will invest later.

From an organizational standpoint, these hubs are almost always established as consortiums: universities and research centers oversee methodology and metrology; technology companies and system integrators bring use cases and real-world constraints; public entities or regional agencies ensure steering and alignment with higher-level programs. Effective governance is recognizable by several recurring elements: a single, transparent access point for SMEs and large enterprises; a clearly described service catalog (testing, inspections, data analysis, certifications, training); a prioritization process that allocates laboratory time without conflicts of interest; and a legal framework for intellectual property and confidentiality that allows systemic knowledge to be published while protecting sensitive individual results.

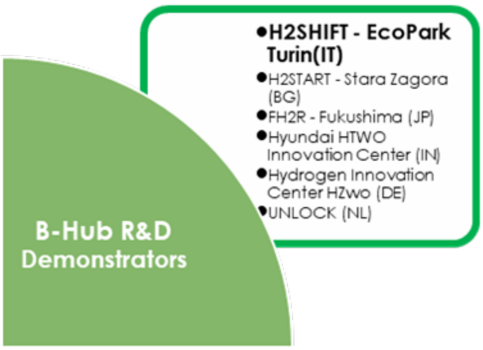
Operationally, these hubs function in "modules." The first is the test line: test benches and pilot plants to verify performance, degradation, efficiency, safety, material compatibility, and response to operational cycles. The second is metrology: sensors, protocols, and data quality; without reliable measurements, results are not transferable. The third is safety (EHS): procedures, validations, and training to reduce risk in critical phases (pressurization, ventilation, leak management). The fourth is transferability: interoperability standards, compliance checklists, and technical documents drafted specifically for investors that bridge the gap between the laboratory and the plant. Increasingly, there is also a digital module (data room, digital twin, test libraries) to reuse evidence and shorten new experimentation timelines.

The economic model is deliberately hybrid. The structure is supported by competitive grants and public co-financing (European or national programs), while users contribute through access fees for services (machine time, testing packages, engineering support). The goal is not to generate profit from these fees but to maximize the platform's use and industrial impact: the more projects that enter, the more the territory accumulates capacity, and the more the information asymmetry that otherwise blocks investment is reduced. Therefore, the metrics that matter include the utilization rate of the test lines, the number of companies served (especially SMEs), the variety of tests performed, the laboratory days delivered, and the instances where testing actually unlocked a subsequent investment or industrial partnership.

The potential risks are well-defined. Among them, we can analyze underutilization: an excellent but empty test line generates no impact; access must be simple, timelines certain, and the value proposition clear. The second is obsolescence risk: in rapidly evolving technologies, the hub must update equipment and protocols; this requires planned investment cycles and constant dialogue with the industry. The third is the risk of capture by a few dominant actors: governance must preserve technical neutrality and openness. Finally, there is the risk of "paper compliance": perfect reports that transfer nothing to the field. Mitigation involves focusing on outcome metrics (projects scaled, contracts signed post-testing, TRL progression times) and a shared learning curve (standards, guidelines, public manuals where possible).

Fundamentally, R&D hubs and demonstrators perform the function of a structural and knowledge bridge between research and industry. Their true capacity and economic utility should not be interpreted based on the quantity of hydrogen produced, but rather on the technological advancement they foster.

Focus: H2SHIFT – EcoPark Torino (IT)



The H2SHIFT project is the Italian implementation of the Open Innovation Test Bed model dedicated to hydrogen, operationally based at the EcoPark in Turin and supported by a network of scientific and industrial partners. The objective is clear: to offer companies and research centers a neutral and qualified testing environment for technologies along the H_2 value chain and their key components, thereby reducing technical risk and shortening transfer times.

The project's governance is organized in a consortium model: technical-scientific partners ensure data quality and define testing methods, while industrial partners contribute application requirements and collaborate on test plan design. Coordination, including scheduling, priorities, and reporting, is entrusted to the steering body. Access to testing occurs through a system of calls and dedicated channels ("doors"). Interested companies express their interest, define the test plan, estimate necessary resources (lab days, instrumentation, personnel), establish agreements on intellectual property and confidentiality, and finally initiate the tests following a tracked protocol. An "assisted track" is available for SMEs, providing support in defining the plan, thus removing potential barriers related to technical language or planning capacity.

The core of the H2SHIFT project is its testing activity. This includes performance and efficiency verification, characterization under variable operating conditions, stress cycles and durability trials, degradation and failure analysis, compatibility tests between materials and components (such as seals, valves, and sensors), as well as functional safety and the validation of EHS procedures. Complementing these tests are metrology and data quality services, such as sensor calibration, management of measurement uncertainties, and the definition of acquisition protocols. The services also cover the analysis of interoperability between systems, interfaces, and standards. Furthermore, technical documentation is provided (ready for audits by funders and insurers), alongside training for plant technicians. When necessary, the pathway continues with technology transfer assistance, including support for defining scaling specifications, managing permits, and conducting preliminary assessments of operational risks and infrastructural needs (e.g., energy, water, ventilation, and fire safety).

The H2SHIFT economic model relies on a combination of public funding and service access fees, aiming to maximize impact rather than profit margins. Test packages are modular and transparent, allowing companies to purchase single slots or multi-month programs. Partners who co-finance specific lines or test benches receive privileged access, but neutral access is always guaranteed for the remaining capacity. H2SHIFT's effectiveness is not measured in kWh consumed, but through milestones that enable progress: such as the TRL (Technology Readiness Level) increase of technologies or companies, reduction in time-to-pilot, the number of SMEs served, the utilization rate of test lines, instances where tests led to investments or contracts, and the production of manuals and standards that can be reused by the community. At an organizational level, the focus is on the punctuality of test windows, the quality of reporting, and the repeatability of results.

Key risks include the under-utilization of test lines, which can stem from access difficulties or unclear service packages for SMEs. To mitigate this, a proactive channel has been activated, providing examples of standard test plans and clear communication on what is learned, the cost, and the timeframe. Another risk is equipment obsolescence, which is addressed through scheduled upgrade cycles and a technical committee that periodically reviews protocols and priorities. A further risk involves information asymmetry among partners, mitigated by transparent rules on intellectual property and confidentiality, data quality audits, and, where possible, the publication of general guidelines. Finally, to prevent results from remaining confined to the laboratory, H2SHIFT must maintain solid operational relationships with utilities, industrial sites, and local authorities to facilitate the transition to pilot projects outside the test bed.

Although H2SHIFT may generate commercial services, the project is best understood as a testing and technology transfer hub, not a production plant or logistics infrastructure. H2SHIFT's success is tied to reducing technical risk and its ability to enable investments by others, making this project a highly functional demonstrator. Located in an area with a solid industrial base and an ecosystem of SMEs active in mechanics, components, and electronics, H2SHIFT acts as a multiplier: it standardizes technical language, lowers learning costs, builds trust among actors inexperienced with hydrogen, and makes technological maturation traceable. In the future, this function will prove fundamental for evolving territorial initiatives on solid foundations and for providing industrial projects with verified data upon which to build business cases and contracts.

C) Hub infrastrutturali e industriali: natura, organizzazione, logiche operative

Infrastructural/industrial hubs are the operational manifestation of the transition: here, hydrogen is no longer a test subject, but a commodity or a service integrated into supply chains, energy systems, and industrial processes. The identity is clearly market-driven capacity is designed, long-term contracts are secured, price and quality rules are established, and physical connections (pipelines, storage, port connections) and interfaces with electrical and gas grids are built. The objective is no longer to *demonstrate* feasibility, but to make the process bankable and repeatable.

Institutionally, governance is almost always consortium-based but with an industrial backbone: project developers and utilities lead the investment; network operators, port authorities, and large off-takers (steel, chemicals, heavy mobility) are on board to guarantee demand, interconnections, and coherent authorization procedures. The public administration is present not so much as an *executor*, but as an enabler: it issues permits, coordinates environmental assessments, aligns support instruments (auctions, CfDs, guarantees, CAPEX incentives), and, above all, provides regulatory certainty.

Industrial hydrogen hubs function through a well-defined chain. They begin with renewable energy supply and power contracts (PPAs, market hedging), which feed the electrolysis process. At the heart of the hub, process assets are designed and built, such as electrolyzers, compression plants, purification, and conversion into derivatives, with availability targets and load factors that meet demand requirements. Downstream, the focus is on logistics, which includes internal pipelines, ship loading/unloading, transport, and blending (when necessary and regulated), as well as delivery points and quality rules (purity, pressure, supply continuity). Surrounding all this are the enabling services, such as advanced environmental, health, and safety (EHS) management, cybersecurity for operational systems, control systems, predictive maintenance, and, when useful, storage in salt caverns or tanks to manage volatility in both electricity production and hydrogen demand.

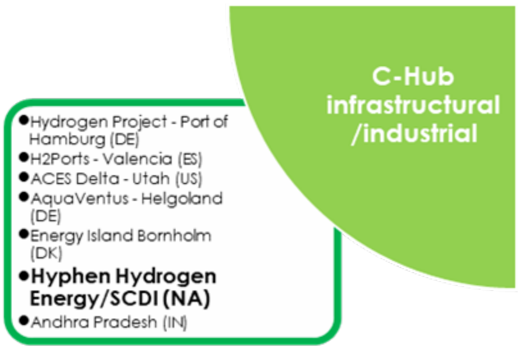
The economic model is what most differentiates these hubs from models A and B. Creating the business case starts with fundamental questions: Who are the buyers? What volumes will they purchase, for how long, and at what price? From this, pricing choices are determined (indexed to energy, fixed with escalators, floor/ceiling prices), along with contractual structures (multi-year purchase agreements, tolerances, penalties, take-or-pay clauses), and the use of risk mitigation tools (such as public Contracts for Difference (CfDs) on H_2/derivatives, loan guarantees, and technology insurance). In this phase, technological risk gives way to market-related risks, such as demand, competition from other low-carbon alternatives, energy risk (the spread between electricity cost and revenue), permitting risk, and supply chain risk (delivery times, critical components). The hub's bankability is the synthesis of all these variables: if the revenue model can cover fixed costs (CAPEX and OPEX) with a realistic safety margin, the hub has the potential to evolve; otherwise, it remains just a project on paper.

Crucial metrics in this model relate to installed and available capacity, the utilization factor, the Levelized Cost of Hydrogen (LCOH) (or derivatives) and its uncertainty, the contractual coverage of volumes (how much production is sold via long-term contracts), commissioning times, incident rates and availability of main assets, as well as losses and efficiency along the production chain. Beyond these, compliance plays a fundamental role: certificates of origin, emissions traceability, customs rules for export/import, and compatibility with industry standards required by customers (e.g., for green steel, fertilizers, shipping).

The risks associated with industrial hubs are non-trivial and include slowly forming (and potentially shifting) demand, volatile energy costs, permits requiring coordination among different bodies, critical supplies with long lead times (like electrolyzers, compressors, membranes), and potential bottlenecks in electrical and water grids. Mitigation strategies for these risks are known but must be carefully orchestrated: sequenced investments (with modular phases and gradual demand ramp-up), coherent energy and off-take contracts, use of storage to decouple production from delivery, procurement plans with local content and dual sourcing, and early dialogue with authorities to avoid surprises during permitting. Furthermore, public instruments like Contracts for Difference (CfDs), auctions, and guarantees are effective tools for reducing the cost of capital and mitigating cash flow volatility.

In summary, the industrial hub is where technology and contractual discipline meet. It is no longer measured just in terms of electrolytic cell efficiency or the COP (Coefficient Performance) of compressors, but by the robustness of the overall system: guaranteed physical flows, clear rules, aligned contracts, and an equitable distribution of risks. When these factors are combined correctly, the hub becomes a long-term platform, capable of attracting investment, both from customers who are decarbonizing and suppliers who choose to co-locate production.

Focus: Hyphen Hydrogen Energy/SCDI (Namibia)



The Hyphen project originates in a context where Namibia, driven by its energy transition policies, is positioning itself as a regional leader in renewable energy and green hydrogen. The country, with its abundant solar and wind resources, is investing significantly to become a central player in low-carbon hydrogen production, in line with global decarbonization and sustainability goals. Government policies, which offer incentives for renewable energy production, infrastructure improvement, and investment attraction, favor the development of projects like Hyphen, which aims to develop an industrial hub oriented toward the export of green hydrogen and its derivatives.

Hyphen is not conceived as a project oriented toward internal consumption, but as an industrial infrastructure capable of connecting Namibia with global markets. The project integrates renewable energy production (solar and wind), electrolysis for green hydrogen production, and its conversion into derivatives such as green ammonia, creating a system capable of responding to growing international needs. In this framework, Hyphen aligns perfectly with national policies that incentivize sustainability and the use of local resources for clean energy production, thus contributing to the global energy transition and the country's economic growth.

The project's governance is based on collaboration between industrial developers, Namibian public authorities, and, when necessary, commercial partners in the destination markets. The public role is crucial in defining the regulatory framework, which includes permits, land use, environmental standards, and support for the certifications necessary for export. National incentive policies provide the necessary support to facilitate access to natural resources and infrastructure, fostering a system that respects environmental regulations and the demands of foreign markets.

Technically, the project is structured in four main areas: renewable energy generation via long-term Power Purchase Agreements (PPAs); modular electrolysis to ensure scalability and maintenance; a downstream section for compression, purification, and synthesis of transportable derivatives; and finally, export logistics, including docks, tanks, and loading systems. The design focuses on modularity and redundancy of critical assets, aiming to ensure reliable operations and service continuity. Maintenance contracts with specific SLAs (Service Level Agreements) and the creation of strategic inventories for components with long lead times are essential for the project's success, in line with national policies promoting operational safety and reliability.

Hyphen's business model is built around a contract-centric strategy. The demand for green hydrogen and derivatives is not abstract but constructed through multi-year contracts with foreign partners, who are incentivized by the country's sustainability policies. The pricing strategy balances indexing to variables (like energy and shipping costs) with price stabilization mechanisms. On the cost side, access to competitively priced renewable energy, favored by public incentives, is a key element. The use of public and multilateral instruments, such as Contracts for Difference (CfDs) and loan guarantees, helps mitigate project risks, lower the cost of capital and improve bankability.

Regarding regulation and certifications, the project must meet rigorous standards that guarantee emissions traceability along the production chain, sustainability in water consumption, and the site's social and environmental suitability. Namibian public policies that favor traceability and the recognition of international certifications simplify the compliance process and reduce commercial uncertainty, facilitating access to foreign markets.

Finally, the main risks the project faces relate to infrastructure, the supply chain, and the market. Mitigating these risks relies on timely agreements with authorities to ensure infrastructure adequacy, a dual sourcing strategy to reduce dependence on external suppliers, and binding contracts to ensure stable demand. National support policies, such as public mechanisms to cover the gap between production costs and market price, are fundamental to reducing uncertainty and ensuring the project's success.

In summary, Hyphen represents an integrated industrial development model that not only addresses global sustainability and decarbonization needs but also contributes to Namibia's economic growth. National incentive policies, which favor the use of local resources and the creation of a sustainable industrial ecosystem, make the project a concrete example of how Namibia can position itself as a leader in green hydrogen production internationally.

D) Quadri strategici nazionali e politiche abilitanti

National or regional policies and strategies are not designed to produce hydrogen or directly manage test beds. Rather, they create the conditions that allow local ecosystems, R&D hubs, and industrial platforms to emerge, grow, and, above all, reach their economic equilibrium. These policies define a framework of rules, instruments, and governance that reduces uncertainty, clearly allocates risks, and guides development. They ensure that institutional capacity is built first, followed by pilot projects, and finally, the capacity to produce volumes on a contractual basis. Without this foundation, private actors face a combination of technological, regulatory, and market risks that often block investments.

A good policy is distinguished by three main characteristics. First, clear governance with well-defined responsibilities: who decides, who coordinates, and who monitors. Second, a portfolio of instruments that support the objectives, such as funding for R&D and demonstration projects, Contracts for Difference (CfDs) to cover the green hydrogen premium, guarantees to reduce the cost of capital, standards and certifications to make the product marketable, and support for permitting and infrastructure planning. Finally, it is crucial that credible demand signals are sent, such as framework agreements, sectoral targets, and "green content" standards, which provide multi-year visibility to potential buyers.

For the strategy to work, it is important to build a clear pathway. Initially, administrative capacity must be strengthened, featuring one-stop shops, clear guidelines, and reliable timelines. In parallel, demonstration projects and shared infrastructures are funded. When actors and applications are ready, market mechanisms (CfDs, auctions, green PPAs) are activated, and standardization (guarantees of origin, sustainability certifications, interoperability) is facilitated. This sequence prevents projects from having to "test everything for the first time" and reduces the risk of failure.

The economic model of a policy cannot be reduced to a simple income statement. It is, rather, a complex systemic balance, where public instruments do not replace the market but reduce risks in areas where the market cannot operate autonomously, such as energy price volatility or demand uncertainty. To evaluate its effectiveness, one looks not only at the immediate economic return but also at indicators of additionality (how much private investment is activated), timeliness (how quickly the investment phase is reached), quality (long-term contracts, standards adopted), equity (SME access), and persistence (how long the effects last, even in the event of economic changes).

The risks associated with these strategies are well known. They can include political or financial discontinuity that interrupts the project flow, regulatory capture (where instruments are designed only for a few large actors), and fragmentation among ministries or government agencies. Furthermore, excessive bureaucracy can slow processes rather than accelerate them. Mitigations for these risks are not straightforward but must include transparent and stable criteria, a multi-year calendar for calls and auctions, public monitoring with key indicators, and learning mechanisms to correct the course when necessary. Additionally, where useful, sunset clauses should be included for measures intended to be temporary.

Policy strategies operate at different levels, with complementary aims. National policies, like those of the UAE, set the direction and generate credibility. Regional or federal programs, like ARCHES in

California, coordinate actors and projects. Finally, policy improvement initiatives, like Green Hydra in Europe, focus on administrative capacity and SME access, without which even the best instruments risk being under-utilized. The quality of the transition depends on how these levels integrate and operate together.

Focus: ARCHES – California

ARCHES (Alliance for Renewable Clean Hydrogen Energy Systems) is a governance platform designed for California, operating within the federal US hydrogen hubs program. The objective of ARCHES is to transform a series of projects into a coordinated pipeline by aligning hydrogen production, its end-uses (in industry, mobility, and networks), and the enablers (such as training, standards, and permits). It is not a single plant or laboratory, but rather a system that unites public and private actors with common objectives and shared eligibility criteria, creating a steering framework that prevents projects from stalling due to organizational bottlenecks.

The governance of ARCHES is based on a decision-making core that manages strategy, priorities, and monitoring, supplemented by technical-sectoral tables for production, transport, hard-to-abate industry, safety, and the workforce. This approach allows diverse actors, such as the State, agencies, utilities, large buyers, and academia, to integrate, leading to direct collaboration among those who authorize, those who invest, those who train the workforce, and those who define demand. In this way, ARCHES provides a coordination model that prevents projects from remaining stalled, even if technically ready, due to a lack of institutional or organizational support.

To achieve its objectives, ARCHES mobilizes several operational tools, including support for studies and permits, standards definition, and safety management. The program also establishes common eligibility criteria for projects, in addition to guaranteeing access to federal financial instruments, such as grants and cooperative agreements. A crucial aspect of ARCHES is the sequencing of activities: it begins with projects of high readiness and high systemic impact, maintains windows for demonstration and training, and consolidates relationships with large users to build demand as production capacity grows.

The successes of ARCHES are measured using system-level indicators. Key indicators include the reduction in average authorization times, the number and quality of FIDs (Final Investment Decisions) achieved, the volume of private investment leveraged, and the long-term contracts signed. The quality of the human capital trained is another fundamental indicator, reflecting the effectiveness of workforce development and training programs. Another important result concerns the reduction in

the *perceived* cost of capital for projects, thanks to clear rules, predictable timelines, and instruments that cover risks not insurable by the market.
However, this enabling nature carries an inherent vulnerability: continuity. If federal support or regulatory coherence were to be interrupted or change suddenly, the entire system could suffer. This is not because the projects lack technical value, but because the balance of risks upon which the projects' bankability rests would be compromised. The main lesson is clear: a policy framework must be evaluated not only for its design and promises but also for its resilience to political changes and fluctuations in the economic context, such as changes in energy prices or supply chains.
It can be defined as the prototype for Archetype D, as its function is that of a policy platform. It does not replace industrial actors but *coordinates* them, *reduces risks* where possible, and *makes possible* what would otherwise remain stalled, many motivated actors, but few truly ready projects. This is its analytical strength, making it fundamental for comparison with other archetypes: local ecosystems (A) thrive if D supports them; R&D hubs (B) transfer value thanks to D's support; industrial plants (C) can only secure long-term contracts if D provides the rules and instruments capable of guaranteeing stable investments.

For the sake of completeness, the cases of the United Arab Emirates (UAE) and the Green Hydra program in Europe must be mentioned. The UAE's national strategy represents an example of country-level steering, with clear objectives, quality standards, and off-take contracts that reduce perceived risks, creating credibility for export-oriented projects. Green Hydra, meanwhile, is a European program working on policy improvement, focusing on institutional capital and SME access, two fundamental aspects needed to translate even the best instruments (like grants and auctions) into reality.

In conclusion, policies and strategies are not a mere *background* to the energy transition process: they are the foundation upon which all other efforts rest. Where these frameworks function well, local ecosystems develop faster, R&D hubs transfer the necessary value, and industrial plants can finalize long-term contracts. Where these frameworks are weak or discontinuous, the adoption curve becomes too steep, and promising projects risk remaining incomplete.

To facilitate the reader's understanding of the main distinctive characteristics of each archetype, a Table 7 is provided below. It highlights the various key aspects, including organizational structure, technological innovation, governance model, operational management, economic sustainability, risk management, operating model, and financial strategy. This summary allows for the display of the differences and specificities of each archetype, offering a clear and comparative view of the different green hydrogen adoption structures.

Aspects	Archetypes			
	Territorial Ecosystems (Hydrogen Valleys)	R &D Hubs and Demonstrators	Infrastructure and Industrial Hubs	National Strategic Frameworks and Enabling Policies
Governance Model	Multilevel governance with control room (regional, metropolitan city, technological clusters). Coordination platforms for universities, SMEs, local operators. Clear roles and regular reporting.	Consortia of universities, research centers, technology companies. Centralized one-stop-shop management for SMEs and industries.	Consortium governance with industrial backbones (utilities, network operators, port authorities). Industrial governance with defined roles for grid operators, utilities, and buyers.	Coordination between public administration, agencies and industry, creation of frameworks and incentives. National strategic plan with support and coordination tools between public and private sectors.
Technology	Local experimentation and innovation (e.g. small plant sizes).	Technologies in the testing and development phase, focus on security and interoperability.	Production and use of hydrogen on an industrial scale, with a focus on efficiency and business continuity	Not directly applicable; support for the evolution of technologies with a focus on R&D and standardization.
Financial Strategy	Public funds as a backbone, private co-financing, focus on environmental and social impact.	Hybrid: public co-financing, access fees to services, focus on technological progress.	Market-oriented model: long-term contracts (off take), established pricing, search for bankability.	Public support policies (CFDs, risk reduction tools, guarantees, subsidies), capital guarantees, incentives for private investments, and tools to reduce risks.
Risk Management	Coordination risks, technical risks, insufficient demand risks.	Risk of under-use of test lines, obsolescence of technologies.	Slowly growing demand risk, competition risk, supply chain and authorization risks.	Risk of political discontinuity, institutional fragmentation, and ineffectiveness of support tools.
Business Model	hybrid, with a focus on activating private investment and creating credible local demand.	Testing, certification, technical risk reduction for industry.	Supply contracts, established pricing, focus on long-term bankability.	Support local actors, creation of favorable conditions for the emergence of industrial ecosystems and R&D hubs.

Table 7: Specific characteristics of each archetype

7 Results: KPI Benchmarking and Comparison

Regarding the results of the analysis conducted, Appendix A provides a clear summary of the comparison carried out, offering a representative example for each identified archetype in order to simplify the exposition. This approach, being illustrative rather than exhaustive, is considered sufficient to convey the complexity and significance of the analysis performed, taking into account the 19 KPIs used to compare the 22 case studies examined.

Especially, building on the previous sections' extensive exploration of production methods, this analysis now examines the specific technologies adopted in the projects under review. This allows us to understand how these technologies are implemented in specific contexts, highlighting the key differences between the various approaches.

Among the production methods, the most commercially oriented is that used by the Hydrogen Project at the Port of Hamburg (specifically the Hamburg Green Hydrogen Hub - HGHH). This facility is not based on methane gasification (which produces grey or blue hydrogen with CCS), but on a large-scale electrolyzes for green hydrogen production, with a potential production capacity of 100 MW **(HGHH, 2025).** The objective of this project is clearly commercial: the hydrogen produced will be supplied to local heavy industry, particularly for ArcelorMittal's green steel production, and to the logistics and maritime transport sectors **(ArcelorMittal/Press Release).**

In contrast, projects belonging to R&D hubs focus primarily on technological innovation and experimentation. An emblematic example is the Fukushima Hydrogen Energy Research Field (FH2R)

in Japan. This project uses a 10 MW electrolyzes powered by an on-site 20 MW solar park, as well as by the power grid **(FH2R).** Its main purpose is not large-scale commercial sale, but research, experimentation, and the testing of energy management systems to balance the electrical grid using hydrogen **(Toshiba ESS).**
Similarly, H2SHIFT at EcoPark Torino focuses on pilot-scale experimentation. This project, funded by the PNRR (Italian National Recovery and Resilience Plan), does not aim to become an industrial ecosystem but serves as a "living lab." It uses electrolyzers powered by renewable sources to test and optimize hydrogen use specifically in the logistics and freight handling sector (e.g., forklifts) within the technology park, directly involving partner SMEs **(Environment Park H2SHIFT).**
Despite the differences in their final objectives, all projects examined remain dynamic. The rapid evolution of the sector, especially in electrolyzes efficiency and costs (such as PEM, Alkaline, or emerging SOEC technologies), makes the introduction of new production methods or technological upgrades likely **(Hydrogen Council, 2023, Hydrogen Insights).**

In conclusion, the variety of approaches reflects the diversity of strategies: while industrial projects like Hamburg are geared toward large-scale production and commercialization for immediate decarbonization, R&D hubs like FH2R and H2SHIFT play a crucial role in developing, testing, and optimizing the technologies that will ensure a faster and more sustainable global energy transition.

7.1 Local Community and Stakeholder Engagement

Local community and stakeholder engagement, a concept often defined as "Social License to Operate" (SLO),is one of the crucial aspects determining the success or failure of green hydrogen projects **(WEF, 2023, Fostering Effective Energy Transition)**. Its importance has become even more evident in light of experiences in related energy sectors, where many projects (e.g., wind or storage) failed to consolidate due to insufficient engagement of local populations and non-transparent communication (**IEA, 2024, Global Hydrogen Review 2024)**.The analysis of these cases highlights the need to develop more inclusive and participatory approaches from the earliest stages to foster social acceptance and ensure long-term sustainability (**Hydrogen Council, 2023, Hydrogen Insights).**
This chapter focuses on analyzing the engagement strategies adopted in four distinct projects, highlighting the ways in which local communities and stakeholders were included in the design, implementation, and management of the projects. Through examining the different practices of public consultation, transparent communication, and active participation, we will analyze how these projects addressed the challenge of engaging all actors.
In the case of the Trentino Hydrogen Valley (part of the broader "Brenner Green Hydrogen Valley" project), the engagement of local SMEs and the community was designed as a central aspect from the outset. The project, funded by the Italian PNRR, aims to decarbonize the strategic "A22" motorway and local public transport **(Autonomous Province of Trento, 2025).** The approach was not limited to informing but actively involved key local actors such as the Bruno Kessler Foundation (FBK) for research and the utility Alperia for production and distribution **(Fondazione Bruno Kessler, 2021).**

Public consultations and informational meetings were used to strengthen the bond between the project and the community, allowing the population to understand the benefits and implications. The involvement of SMEs was designed to stimulate innovation and local economic growth, creating a development model perceived as co-created by the territory **(Alperia, 2023, Going green: the key role of hydrogen).**

Similarly, Energy Island Bornholm (Denmark) based much of its success on the direct engagement of local communities. Being an island, the project saw the community as a crucial partner for its "Bright Green Island" strategy (which aims for carbon neutrality) **(Bornholm's Bright Green Island Strategy).** Consultations were not limited to formal meetings but included educational programs and thematic workshops (like the "House of Sustainability") that actively involved schools and citizens **(State of Green Denmark, 2019)**. This helped build a strong sense of community ownership of the project. Furthermore, great emphasis was placed on the equitable distribution of economic benefits derived from local resources (such as offshore wind) between the population and investors, reducing social tensions **(Baltic Energy Areas, 2019, A Planning Perspective).**

In the Hamburg Port Hydrogen Project (HGHH at Moorburg), the stakeholder engagement approach was more directed toward the industrial sector, focusing on commercial and logistics actors who serve as the main off-takers (buyers), such as ArcelorMittal **(HGHH).** Although the local community played a less active role in the industrial design, transparent communication channels were created through periodic reports and discussion forums, where local stakeholders and environmental associations had the opportunity to express their opinions and monitor the project's impacts **(H2-Cluster Hamburg).**

Finally, the case of H2SHIFT at EcoPark Torino is distinguished by its academic and scientific engagement. The project is hosted by Environment Park, a technology park whose mission is precisely to connect research, industry, and public administration **(Environment Park Torino- Mission. H2SHIFT)**. Universities and research centers, such as the Politecnico di Torino, were involved from the early stages, bringing technological innovation that benefited from the support of the scientific community **(Polytechnic University of Turin - PNRR Projects).** Although the main focus was research and application in logistics, public consultations and events (like Envipark's "Open Doors") were organized to ensure transparency and discuss environmental and economic impacts with the local community (**Environment Park Turin - Events).**

These examples highlight how, compared to failed projects of the past, current projects have succeeded in integrating local communities and stakeholders more effectively. The importance of active engagement management and continuous participation, not just a one-off event, has proven to be a decisive factor for success. The key to success lies in ensuring that all voices (industrial, academic, public, and civil) are heard and that the project is seen as a shared opportunity for all, rather than as an external initiative imposed upon the community.

7.2 Binding Off-take Agreements and SME/Startup Engagement

A rapidly growing and intrinsically unstable market, such as that of green hydrogen, presents significant challenges in project design and development **(IEA, 2024, Global Hydrogen Review 2024).** The sector is characterized by high capital intensity and uncertainty regarding both future production costs and final demand **(S&P Global Insights).** In this scenario, the financial management of off-take agreements and the integration of SMEs are the pillars for economic stability and innovation. Sector analyses show that the absence of clear, long-term purchase agreements (off-take) is one of the main obstacles to the **"bankability"** (see Section 3.2.2) of projects, preventing them from achieving a solid financial and market position **(Hydrogen Council, 2023)**.

It is essential to examine how projects currently in development address these aspects. Binding, long-term off-take agreements are used to guarantee stable demand, mitigating financial risks for investors and providing the necessary foundation for infrastructure investment (**Norton Rose Fulbright/Energy Transition/Hydrogen, 2023)**. However, the effectiveness of such contracts depends not only on their duration but also on the project's ability to integrate smaller, more dynamic actors, such as SMEs and startups. These actors contribute innovative technological solutions and operational flexibility in a market that is still maturing **(European Commission, 2020, A hydrogen strategy for a climate-neutral Europe).**

The green hydrogen projects we are analyzing show different approaches to balancing contractual stability and innovation.

In the Hamburg Port Hydrogen Project (HGHH at Moorburg), the approach is geared toward large-scale industrial stability. Binding off-take agreements have been established with large industrial companies and transport sector actors, such as the ArcelorMittal steelworks, to ensure stable demand for the hydrogen produced by its electrolyzes **(ArcelorMittal/Press Release).** This strategy, supported by founding partners like Vattenfall, is fundamental for reducing financial risks. However, the partnership model focuses primarily on large industrial suppliers, with more limited strategic involvement of innovative SMEs and startups in the project's core **(HGHH).**

Conversely, the H2SHIFT Project at EcoPark Torino represents a pilot model focused on supply chain innovation and, from a financial standpoint, relies on full public support from the PNRR (Italian National Recovery and Resilience Plan). The project is not focused on mass production but on testing hydrogen use in logistics and sector coupling **(Environment Park Torino - H2SHIFT).** Consequently, agreements with partners (which include the local utility Iren) are structured to ensure flexible demand that is open to innovation. The Environment Park's approach is, by its nature, centered on the active integration of SMEs and startups as technological partners, using the hub to develop and implement innovative solutions **(Environment Park Torino - Mission).**

Finally, the Trentino Hydrogen Valley (part of the Brenner Green Hydrogen Valley) is designed to stimulate the local ecosystem. Also supported by the PNRR, the project aims to guarantee demand for the hydrogen produced through targeted off-take agreements, specifically, as previously

mentioned, to decarbonize the strategic A22 motorway and local public transport managed by the utility Alperia.
In conclusion, the analysis of these approaches highlights a fundamental point: the importance of binding off-take agreements lies in their effect of mitigating financial risk and unlocking investments, acting as an anchor of stability. At the same time, the importance of engaging SMEs and startups lies in their capacity to act as an engine of innovation. Their effect is to provide the agility and advanced technological solutions necessary to ensure the project's long-term competitiveness and adaptability. In summary, off-take agreements ensure the project can survive economically, while the integration of innovation ensures it can thrive technologically.

7.3 The Evolution of Governance: Cohesion and Multi-level Coordination

If the failed cases highlighted how governance fragility can lead to a project's collapse, the initiatives currently under development have clearly learned this lesson. In sharp contrast to the centralized, conflict-ridden, or fragmented models of the past, the new hubs are designed from the outset with resilient governance structures, intended as a strategic tool for risk management and stakeholder alignment.
The analysis of the following cases shows how attempts are being made to overcome emerging criticalities by building more inclusive, cohesive, and coordinated models.
In the same state where HECA collapsed due to disagreements between federal agencies and Californian legislators, the new ARCHES hub has been structured to prevent this failure. Its governance is a multi-level public-private partnership (PPP) (ARCHES LLC) specifically created to act as a bridge. Its structure integrates the California Governor's Office, state agencies, universities (the UC system), national laboratories, and local communities. The explicit goal of this governance is to align federal funding (DOE funds) with stringent state regulations, ensuring the very multi-level coordination that doomed HECA **(ARCHES H2).**
In contrast to the "top-down" governance that, in cases like the Western Green Energy Hub, struggled to include Indigenous communities, Energy Island Bornholm represents a model of inclusive governance. The project is deeply rooted in the "Bright Green Island" community strategy. Governance is not imposed from the outside; it is a partnership that views the Bornholm Municipality and its citizens as key actors, promoting a model of energy democracy. Social acceptance is not an "add-on" but the very foundation of the project, eliminating the risk of local stakeholder exclusion at its root **(State of Green, 2019).**
R&D projects have also adapted their governance. While commercial projects can fail due to economic conflicts of interest (like Hunter Valley), R&D hubs risk failure due to research fragmentation. The Fukushima Hydrogen Energy Research Field (FH2R) in Japan overcomes this obstacle with a consortium governance model under clear public strategic leadership. It is a consortium led by NEDO (Japan's governmental R&D agency), which defines the national goal (testing grid balancing), and key industrial partners (like Toshiba and Tohoku Electric Power) who

provide the technological expertise. This structure aligns all actors toward a goal of shared knowledge, rather than individual profit **(FH2R).**

Finally, to avoid collapse due to partner conflicts, such as the one that caused the Hunter Valley Hydrogen Hub to fail after Origin Energy's withdrawal, industrial hubs like the Hamburg Port Hydrogen Project (HGHH) rely on binding consortium governance. Instead of a generic alliance, HGHH is a structured joint venture. The partners (like Hamburger Energiewerke and Luxcara) are not just participants but shareholders with defined financial commitments. This structure ensures industrial cohesion and makes a unilateral step-back much more difficult **(HGHH).**

The indication emerging from these cases is clear: governance is no longer seen as an administrative superstructure, but as the fundamental mechanism for mitigating the *specific* risks of each project. The evolution of governance models shows a targeted adaptation:

- To manage political and regulatory risk, large national hubs (ARCHES) adopt formal, multi-level PPPs.
- To manage social and acceptance risk, territorial projects (Bornholm) lean toward energy democracy.
- To manage research fragmentation risk, R&D hubs (FH2R) rely on public-led consortiums.
- To manage partnership and commercial conflict risk (which doomed Hunter Valley), industrial hubs (Hamburg) use binding joint ventures.

  In summary, effective governance is not standardized; it must be flexible, multi-level, and custom-designed to neutralize the main fragilities that led to past failures.

7.4 Analysis of Pricing Strategy and Financial Plans

Defining a pricing strategy and revenue streams represents one of the most critical and fluid aspects in the development of Hydrogen Hubs and Valleys. Currently, most projects do not have a fixed selling price for hydrogen. They are operating with limited foresight, relying on Levelized Cost of Hydrogen (LCOH) estimates and long-term forecasts **(IEA, 2024, Global Hydrogen Review 2024).** The common objective is clear: to reduce future costs through scaling and technological efficiency.

This uncertainty is particularly evident in R&D hubs (Archetype B). Their mission is not immediate sales. Their financial plan is not based on a traditional return on investment (ROI), but on funding streams from public and private research funds (such as the European calls for tenders for **Clean Hydrogen Partnership**. These funds do not finance a *product*, but a *purpose*: technological optimization, intellectual property (IP) valorization, and the development of crucial services, such as balancing the electrical grid.

A striking example of how a public financial plan is used to shape future prices comes from India and its National Green Hydrogen Mission, of which the Andhra Pradesh hub is a pillar. The aggressive national goal is to achieve a cost of approximately $2/kg by 2030. To reach this milestone, the Indian government has allocated a specific financial plan, with a program (SIGHT) that includes a budget

of approximately $2.1 billion. These funds are intended to directly subsidize electrolyze manufacturing and the purchase of renewable energy. This funding does not constitute generic subsidies; rather, it is a targeted instrument aimed at reducing the two primary costs (CAPEX and OPEX) **(The Economic Times, "India's green hydrogen mission targets), (Ministry of New and Renewable Energy, India).**
In other contexts, cost competitiveness stems not from subsidies, but from structural advantages. This is the case with the Douglas County PUD (USA), a local experiment cited for informational purposes, which produces hydrogen at an estimated cost of $2.75 to $3.50/kg. This highly competitive price is not the result of an incentive plan, but of the very low cost of local hydroelectric power (approximately $0.03/kWh). This demonstrates that an H2 project's financial plan is, first and foremost, an energy procurement plan. **(National Renewable Energy Laboratory-NREL, Hydrogen Production Cost from Low-Cost Electrolysis).**
Analyzing the different archetypes, we see how financial plans are allocated for different purposes:

- Ulsan Hydrogen Hub (Archetype A - Territorial): In Ulsan, South Korea, the financial plan is commensurate with the vision of a "Hydrogen Leading City," with public and private investments estimated at approximately $5.6 billion (6.7 trillion KRW) by **(Ulsan Metropolitan City, Hydrogen Leading City Plan).** These funds are earmarked for building the entire infrastructure (pipelines, stations) based on certain industrial demand, led by Hyundai Motors. Future captive revenues are already defined, making the financial plan more secure **(H2Korea).**
- Fukushima Hydrogen Energy Research Field (FH2R) (Archetype B - R&D): No traditional business plan aimed at sales exists. The "revenue" is the know-how generated from testing electrical grid balancing, a strategic national objective **(FH2R), (Toshiba ESS -Partner)**.
- AquaVentus (Archetype C - Infrastructural): This 10 GW German project represents a financial plan of immense scale, estimated in the tens of billions of euros. As a long-term vision, its revenue streams will come from direct sales to industries (Thyssenkrupp, RWE). However, a plan of this magnitude is not privately "bankable." The consortium therefore relies on European and German funds (such as IPCEI and H2Global). This initial public financing serves to cover development costs and de-risk the capital expenditures (infrastructure CAPEX), allowing the plan to achieve the necessary scale **(AquaVentuse), (RWE, Partner).**

In conclusion, the pricing strategy for green hydrogen is currently a direct consequence of its financing model. Future prices are poised to fall only because of these interventions: R&D funds (as with FH2R) finance technological efficiency, while large-scale infrastructure investment plans (like AquaVentus, supported by IPCEI) or production subsidies (like SIGHT in India) finance economies of scale, reducing costs at the source.

7.5 Overcoming High Costs and Financing Difficulties

The analysis of failed projects highlighted the absence of guaranteed buyers and an excessively high perceived risk; current projects, by contrast, are built around risk mitigation instruments.
To overcome the problems that caused the collapse of the Hunter Valley Hydrogen Hub and Port Pirie, demand uncertainty and prohibitive costs for a private actor, new European hubs rely on

strategic partnerships. The Andalusia Green Hydrogen Valley, for example, is led by an energy giant, Cepsa, which acts simultaneously as both producer and primary off taker, planning to use the hydrogen to decarbonize its own refineries **(Cepsa, Andalusian Green Hydrogen Valley).** To reduce the initial costs (CAPEX) of such a vast plant (2 GW), the project was designated as an IPCEI (Important Project of Common European Interest). This unlocked access to substantial public funds (Spanish and European) that serve as leverage for private investors, covering the initial cost gap **(European Commission, IPCEI Hy2).**

This blended finance approach marks a significant evolution from cases like HECA, which failed despite a federal grant. New projects utilize more mature financial instruments: the Advanced Clean Energy Storage (ACES Delta) in Utah, for example, did not rely on a simple subsidy but obtained a $504.4 million loan guarantee from the Department of Energy (DOE) **(U.S. Department of Energy, Loan Programs Office).** This guarantee is not a disbursement but a state-backed insurance that eliminates the risk for private investors (such as Chevron and Mitsubishi), making a project "bankable" that would otherwise have been perceived as too risky.

Furthermore, new projects address operational costs (OPEX) more structurally, learning from the lesson of the Fusina Power Station, whose production costs were uncompetitive. The Energy Island Bornholm project in Denmark illustrates this shift: instead of subsidizing a costly hydrogen plant downstream, the Danish state, through the grid operator Energinet, is investing massively upstream. It is building the offshore wind hub **(Energinet, Energy Islands),** thereby guaranteeing private hydrogen producers (such as Ørsted and CIP) access to renewable energy at a radically lower and predictable cost. The intervention targets the source of the cost (electricity), not the symptom (the final hydrogen price).

In summary, the adaptation over time is evident. The failures of Port Pirie and Hunter Valley taught the market that green hydrogen is not, at present, a conventional business. The economic sustainability of new projects is no longer based on the *hope* of future competitiveness, but on the *active construction* of robust financial models: there has been a shift from grants (HECA) to loan guarantees (ACES Delta); from isolated private initiatives (Port Pirie) to co-financed strategic partnerships (Andalusia/IPCEI); and from downstream subsidies (necessary for Fusina) to upstream infrastructure investments (Bornholm).

7.6 Business Model: The Challenges of an Emerging Market

As emphasized by the European Commission in its "Competitiveness Compass," and in line with the insights of the "Draghi Report," Europe must urgently address its "European Innovation Gap." To prosper and compete globally, Europe needs its startups to succeed. Over the last fifteen years, we have witnessed how startups, even those born small, have evolved into "unicorns" capable of transforming entire markets **(Hydrogen Europe, 2025, The Hydrogen Europe Quarterly).**

Europe, being a continent rich in Research and Development (R&D) and Intellectual Property (IP), possesses the ideal foundation to generate successful startups in this field. However, this requires the creation of an adequate support ecosystem, one that is not limited to funding R&D but that actively promotes an entrepreneurial mindset within research itself. In this context, Collaboration and Open Innovation emerge as key factors.

An emblematic case study is H2SITE. Originating as a spin-off from the collaboration between research centers (Tecnalia, TU-Eindhoven) and grown thanks to strategic investors (ENGIE, Hy24), it demonstrates how a startup can scale a niche technology (membrane reactors) only thanks to a supportive ecosystem **(Hydrogen Europe, 2025, The Hydrogen Europe Quarterly).** This strategic collaboration model is the true engine of the sector, and the analysis of European projects shows how these synergies take different forms, all of which are fundamental.

Some hubs are specifically designed to facilitate collaboration between research and startups. The Hydrogen Innovation Center HZwo in Germany is a prime example. It is not just a research center, but a platform where startups and local SMEs actively collaborate with TU Chemnitz. HZwo provides the testing infrastructure (test benches, laboratories) that allows a small company to validate its technology, transforming academic research into a market-ready industrial product, in an R&D-enterprise symbiosis (Hzwo, 2022).

Other projects create "living labs" where collaboration is operational and aimed at co-development. At the EcoPark in Torino, the H2SHIFT project does not just host companies; it makes them technological partners. Innovative startups and SMEs, such as the Politecnico spin-off Hysytech, collaborate directly with end-users within the park to develop, test, and refine their solutions (e.g., reactors, forklifts) in a real-world logistics environment, accelerating the time-to-market **(Environment Park Torino - H2SHIFT).**

This logic of collaboration extends to complex industrial challenges. The H2Ports project in Valencia is a "client-pilot" collaboration model. The port (the end-user) did not develop the technology itself; instead, it collaborated with technology suppliers (often specialized SMEs in the supply chain of larger players) by presenting a real operational challenge. The SMEs provided the innovative solution (the hydrogen-powered reach stacker), and the port provided the most rigorous test bed: an operational container terminal **(H2Ports).**

Finally, collaboration is not only technological but also social and economic. Projects like the Lolland Hydrogen Community in Denmark pioneered technology-community collaboration, where SMEs developing micro-co-generators worked with residents to test the technology in their homes case **(State of Green Denmark).**

This leads to the supply chain collaboration model, such as that of the Trentino Hydrogen Valley. Here, large "anchor" players (Alperia, A22) collaborate actively with the Bruno Kessler Foundation (FBK) **(FBK-Projects H2)** for a specific goal: to transfer technology, know-how, and contracts to local SMEs, actively engaging them to build a durable local supply chain **(Hydrogen News, 2025).**

In summary, the analysis of these cases demonstrates that success does not stem from individual actors, but from their ability to collaborate. Whether it involves R&D-enterprise synergies (HZwo), co-development in living labs (H2SHIFT), client-pilot partnerships (H2Ports), or the construction of local supply chains (Trentino), these collaborations are the true engine of the hydrogen ecosystem.

7.7 The Energy Transition and the Chicken-and-Egg Problem

The path toward a green hydrogen economy is currently defined by a central paradox: despite near-universal consensus on its potential, the sector is paralyzed by profound uncertainty. This uncertainty is not just technological, but primarily economic and strategic. As highlighted by an analysis from Regen Strategic, green hydrogen is "expensive to get right" **(Regen Strategic, 2025).**

This high cost creates a classic "*chicken-and-egg problem*", which generates a market stalemate. Producers will not invest billions in large-scale plants without the certainty of long-term buyers. On the other hand, large buyers (off takers), such as steel mills or the chemical industry, will not face the colossal costs of converting their production processes without the guarantee of a stable, secure, and predictably priced supply.

This paralysis is uncertainty in its purest form. It is here that the "recent project failures" mentioned by Regen Strategic become not a death knell for the sector, but crucial lessons in risk management.

It is precisely to break this stalemate that the strategies analyzed previously become the fundamental pillars for the "*bankability*" of any project.

1. Binding Off-take Agreements: As seen in the analysis of Hamburg, Torino, and Trentino, an off-take agreement is not just a commercial deal; it is the primary tool for destroying demand uncertainty. By guaranteeing a buyer (whether it be an industrial hub like ArcelorMittal in Hamburg or a local utility like Alperia in Trentino), the project becomes financeable. It transforms from a visionary idea into an asset with a predictable cash flow.
2. Stakeholder Engagement: Uncertainty is not only financial but also social. The Regen Strategic analysis calls for a "transparent pathway that brings the public along." This is exactly the role of active community engagement seen in Bornholm or the Trentino Valley. Building a "social license to operate" mitigates the risk of local opposition, delays, and political failures.
3. The Ecosystem of SMEs and Startups: Finally, technological uncertainty (the risk of obsolescence) is mitigated by Open Innovation. As demonstrated by H2SITE, HZwo, and the EcoPark in Torino, an ecosystem of agile startups and SMEs is not an accessory, but an insurance policy on future competitiveness. It allows the project to adapt, innovate, and remain relevant.

In conclusion, uncertainty is the unavoidable starting condition for green hydrogen, not a sign of failure. The market, on its own, cannot solve the chicken-and-egg paradox.

Success, therefore, does not depend on "*picking winners*", as the Regen Strategic analysis rightly points out, but on building resilient ecosystems capable of managing and absorbing these different types of uncertainty. The projects that succeed will not be those with the best technology at a given moment, but those with the most solid risk mitigation strategy: binding off-take contracts to manage market risk, community engagement to manage social risk, and an open innovation ecosystem to manage technological risk.

7.8 Sustainable Business Models

The preceding chapters have explored the implications and connections of the various ESG (Environmental, Social, and Governance) factors in the green hydrogen adoption process. It has become evident that the motivations driving the complex energy transition, particularly in the green hydrogen sector, are no longer exclusively economic. On the contrary, environmental and social aspects have assumed an equally significant role, becoming indispensable factors for evaluating a project's long-term sustainability and viability. An initiative that maximizes profit while ignoring its impact on the local community or the ecosystem is no longer considered a successful model in the current context.

To analyze this complex interaction between different forms of value, this thesis integrates the multidimensional "Triple Layer Business Model Canvas" (TLBMC) framework. This tool was introduced by Alexandre Joyce and Raymond Paquin in 2016. Their insight stemmed from a specific observation: the original Business Model Canvas, developed by Alexander Osterwalder and Yves Pigneur (2010), was an excellent tool for describing a firm's economic logic, but it completely overlooked the dimensions of sustainability. The objective of Joyce and Paquin was thus to extend the traditional model, creating a tool that required designers, entrepreneurs, and managers to think holistically, by literally superimposing two other distinct layers onto the original economic canvas:

1. The Environmental (or Ecological) Layer: A canvas based on the principles of Life Cycle Assessment (LCA), which analyzes the business model's impact on the environment (resource consumption, emissions, waste).
2. The Social Layer: A canvas based on stakeholder management, which maps the activity's impact on people (employees, local communities, customers, and society at large).

The adoption of the TLBMC in this analysis is therefore intentional. It allows us to move beyond a narrow perspective and evaluate two projects under review (the Port of Hamburg and Energy Island Bornholm) not only for their financial feasibility, but for their actual capacity to generate (or destroy) value across all three dimensions: economic, social, and environmental. It is the ideal tool for understanding whether a hydrogen project is truly "sustainable" in the most complete sense of the term.

7.8.1 Hamburg Green Hydrogen Hub (HGHH)

Business Model Canvas - Economic Layer

Key Partners	Key Activities	Value Proposition	Customer Relationships	Customer Segments
•Luxcara: manages investments in renewable energy •Hamburger Energiewerke (HEW): manages local energy infrastructure •Siemens Energy: provides and installs a 100 MW electrolyzer •Gasnetz Hamburg: manages the hydrogen distribution network (HH-WIN) •Shell, Mitsubishi Heavy Industries, Vattenfall: involved in earlier stages of the project	•Production of green hydrogen through electrolysis •Distribution through the HH-WIN hydrogen network •Development of infrastructure for transport and logistics.	•Supplying green hydrogen to industry, mobility and heating •Decarbonisation of the port and industrial economy. •Efficient use of waste heat to improve energy efficiency •Contribution to the Hamburg climate goals	•Long-term supply contracts •Collaborations for the integration of hydrogen into industrial operations •Technical support and advice for hydrogen adoption	•Industrial sector (steel, chemical, plastics) •Transport sector (buses, trucks, ships) •District heating networks • Local companies and institutions
	Key Resources		**Channels**	
	•100MW PEM electrolyzer •Direct connection to the 380 kV and 110 kV mains • Access to wind and renewable solar energy •Existing port and industrial infrastructure		•HH-WIN Pipeline (phase 1: 40 km, phase 2: 60 km) •Hydrogen refuelling stations • District heating distribution network	

Cost Structure	Revenue Streams
•High CAPEX for plants and pipelines, O&M, ESG compliance, training programs •Electrolyzer Construction and Maintenance Costs •Operating costs for managing pipelines and filling stations •Energy costs for electrolyzer power supply •Project management and administration costs	• H_2 sales, IPCEI European funds, public incentives, green premium.

Business Model Canvas - Environmental layer

Supplies & Outsourcing	Production	Environmental Value	End-of-life	Use Phase
• Renewable energy: Green hydrogen is produced using renewable energy from offshore wind and photovoltaics. • ESG-certified suppliers: Energy and material suppliers are selected based on ESG criteria.	• Technology: Electrolysis with reduced water impact, integrated into the Port of Hamburg.	• Decarbonization: The project aims to decarbonize hard-to-abate sectors (steel, chemicals, transport) by replacing grey hydrogen with green hydrogen. • Component recycling: Recycling programs for electrolyzer components, such as membranes and other critical materials.	• Component recycling: Recycling programs for electrolyzer components, such as membranes and other critical materials.	• Consumption sectors: The hydrogen produced is used directly in steel mills, aerospace, and the chemical sector, resulting in significant CO_2 reductions.
	Materials		**Distribution**	
	• Critical raw materials: The project depends on the use of critical materials such as platinum and iridium, managed through sustainable practices to reduce environmental impact.		• Pipeline and port: Hydrogen is distributed via local pipelines and from the Port of Hamburg, with lower emissions compared to transport methods by ship.	

Environmental Costs	Environmental Benefits
• High demand for renewable energy: Green hydrogen production requires large quantities of renewable energy, leading to a dependency on critical materials (e.g., platinum).	• CO_2 emissions reduction: Over 95% CO_2 reduction thanks to the use of green hydrogen, improvement in urban air quality, and contribution to EU climate goals.

<table>
<tr><th colspan="5">Business Model Canvas – Social Layer</th></tr>
<tr><th>Local Communities</th><th>Governance</th><th>Social Value</th><th>Social Culture</th><th>Customer Segments</th></tr>
<tr>
<td rowspan="3">• Direct benefits for the Hamburg community; creation of new jobs, improvement of air quality, reduction of emissions.
• Involvement in policy decisions thanks to the transparent and inclusive governance model.</td>
<td>• Multilevel public-private governance model (City of Hamburg, Vattenfall, industries, SMEs, universities).
• Decision-making transparency and active participation of local SMEs, aiming to create long-term sustainability.</td>
<td rowspan="3">• Supply of clean energy to large industries and local SMEs, reducing emissions and improving competitiveness of local businesses.
• Creation of social value through sustainable jobs and improved air quality.</td>
<td>• Hamburg as an example of sustainable innovation, a city at the fore front of the energy transition.
• Promotion of a green culture in local businesses, with clear commitments to sustainability.</td>
<td rowspan="3">• Large industries (steel, aviation), local utilities, SMEs in the logistics and service sectors.
• Hard-to-abate sectors that benefit from the long-term supply of green hydrogen</td>
</tr>
<tr><th>Employees</th><th>Scale of Outreach</th></tr>
<tr>
<td>• Training and reskilling for green competencies (hydrogen, renewable energy).
• High safety standards for employees in new hydrogen and advanced technologies.
• Creation of local jobs in industry and support services (logistics, maintenance, innovation).</td>
<td>• Benefits do not stop at the city of Hamburg but extend regionally thanks to the creation of a network of SMEs involved in the project.
• Increased scalability of green hydrogen production, with possible European-level expansions.</td>
</tr>
<tr><th colspan="3">Social Impact</th><th colspan="2">Social Benefits</th></tr>
<tr>
<td colspan="3">• Social and labor inclusion for local residents, with new opportunities in the green sector.
• Improved social cohesion thanks to active involvement of local communities in decision-making.</td>
<td colspan="2">• Creation of skilled jobs, new competencies for the ecological transition.
• Direct economic benefits for SMEs and local communities participating in the value chain.</td>
</tr>
</table>

The Hamburg Green Hydrogen Hub (HGHH) project is envisioned as a cornerstone of the city's energy transition, with positive impacts that transcend mere energy production. The environmental focus is at the heart of the initiative: the primary goal is the decarbonization of the port economy **(Ramboll, 2025**). At the social and occupational level, the impact is measured not so much in the creation of a vast number of *new* jobs, but in the transformation and safeguarding of existing industrial jobs (in steel, chemicals), which would be at risk without decarbonization.

However, the project does create new skilled jobs for the management of the 100 MW electrolyzes and the new HH-WIN hydrogen pipeline (**HGHH**). The most direct and quantifiable social impact is heat recovery: the electrolysis will generate approximately 13 MW of waste heat, which will be fed into the local district heating network, supplying thermal energy for about 6,000 households and improving the system's energy efficiency (**HGHH**).

7.8.2 Energy Island Bornholm

Business Model Canvas - Economic Layer

Key Partners	Key Activities	Value Proposition	Customer Relationships	Customer Segments
• Energinet (Danish national electricity operator) – responsible for the infrastructure and offshore grid connection. • Ørsted and Copenhagen Infrastructure Partners (CIP) – main developers of the offshore wind project connected to the energy island. • European Energy – strategic partner for hydrogen production and Power-to-X technologies. • Municipalities and Danish technical universities (DTU Aalborg) – university for research, training, and local training programs.	• H_2 production and distribution, maintenance, innovation with startups and research centers. **Key Resources** • 100 MW electrolyzers, port infrastructure, human capital, SME/startup cluster, technical know-how.	• Supply of green hydrogen to hard-to-abate sectors (steel, aviation, chemicals) and local SMEs, ensuring decarbonization and new industrial competitiveness.	• Long-term relationships with offtake agreements and public-private partnerships. **Channels** • Local pipelines, port terminals, urban refueling stations.	• Large energy-intensive industries (ArcelorMittal, Aurubis, Lufthansal), local utilities, and logistics SMEs.

Cost Structure	Revenue Streams
• High CAPEX for plants and pipelines, O&M, ESG compliance, training programs.	• H_2 sales, European IPCEI funds, public incentives, green premium.

Business Model Canvas - Environmental layer

Supplies & Outsourcing	Production	Environmental Value	End-of-life	Use Phase
• Offshore wind energy, suppliers of sustainable components.	• Energy from offshore wind farms (100 MW electrolyzers). • Power-to-X plants to produce synthetic fuels with low CO_2 emissions. **Materials** • Use of critical materials, research for sustainable alternatives.	• Green hydrogen from renewable energy for hard-to-abate sectors (steel, chemicals, aviation). • Replacement of fossil fuels with green hydrogen to reduce CO_2 emissions.	• Component recycling: Recycling programs for electrolyzer components, such as membranes and other critical materials. **Distribution** • Port of Rønne and pipeline-optimized logistics, lower emissions.	• Direct consumption in the shipping sector (Maersk) and local applications.

Environmental Costs	Environmental Benefits
• High demand for renewable electricity, balancing challenges.	• Strong reduction in maritime emissions, contribution to EU and IMO (International Maritime Organization) goals.

<table>
<tr><th colspan="5">Business Model Canvas – Social Layer</th></tr>
<tr><th>Local Communities</th><th>Governance</th><th>Social Value</th><th>Social Culture</th><th>Customer Segments</th></tr>
<tr>
<td rowspan="3">• Creation of local jobs thanks to the direct involvement of communities in the installation and management of green hydrogen projects.
• Sustainability at a local level, with a strong connection with the Bornholm community.</td>
<td>• Central and transparent governance: The Danish state leads the project, but the local community has a strong voice in decisions.
• Energy democracy model, where the community has control over energy developments.</td>
<td rowspan="3">• Supply of green energy with benefits for maritime transport and local industries, strengthening energy self-sufficiency.
• Creation of a sustainable energy ecosystem that can be replicated on other islands or in remote areas.</td>
<td>• Energy democracy as a fundamental value: the community has a direct role in participating in energy governance.
• Enhanced collaboration within the community to foster a strong spirit of cooperation fou substainability</td>
<td rowspan="3">• Maritime sector (Maersk), local industries, regional utilities.
• Small and medium-sized enterprises participating in the project's value chain, as suppliers or innovators.</td>
</tr>
<tr><th>Employees</th><th>Scale of Outreach</th></tr>
<tr>
<td>• Training programs for youth and local workers, with skills in hydrogen, renewable energy, and energy management.
• Direct jobs in the installation, maintenance, and management of the H_2 system.</td>
<td>• Scalability is a key element, with the project serving as a replicable model for other islands and European territories.
• Expansion beyond Europe, extending to the global marittime market.</td>
</tr>
<tr><th colspan="3">Social Impact</th><th colspan="2">Social Benefits</th></tr>
<tr>
<td colspan="3">• Creation of a sustainable society, improvement of the quality of life in the local community.
• Positive impacts on the educational sector, with new skills in green technologies.</td>
<td colspan="2">• Integration of SMEs and local communities into the energy value chain.
• Very high social acceptance due to the commitment to energy self-sufficiency and sustainability.
• Local economic benefits through the involvement of small businesses and the strengthening of local industry.</td>
</tr>
</table>

The Energy Island Bornholm project is distinguished by its deep integration of environmental goals and local community development. The environmental focus is absolute, as the island (population approx. 40,000) bases its strategy on the "Bright Green Island" vision, which aims for carbon neutrality and a "zero waste" society by 2032 **(Bornholm).** The energy island will harness 3 GW of offshore wind to supply clean energy to Denmark and Germany **(Energinet).**

This massive infrastructure investment generates a significant and quantifiable positive social impact. While final data for the 3 GW project is not consolidated, socio-economic studies on similar-scale (1 GW) Danish offshore wind projects estimate the creation of 600-1,000 direct and induced jobs (FTEs) during the installation phase and 60-80 stable FTEs per year for the 25-year operations and maintenance (O&M) phase **(QBIS, 2020)** Social engagement is actively managed through the "Ready for Energy Island Bornholm" program, which funds the reskilling of the local workforce. To date, 24 local residents have completed the GWO (Basic Safety Training) certification and 12 people have completed GWO Slinger training, which are specific skills required by the wind industry to ensure the occupational benefits remain on the island **(Offshore Center Bornholm).**

8 Conclusion

The research conducted in this thesis aimed to answer a central question: How can different governance models and commercial incentive mechanisms within Hydrogen Hubs foster the participation of SMEs and startups in the adoption of green hydrogen technologies, and what effects might these dynamics have in terms of environmental, social, and governance (ESG) sustainability?

The analysis revealed that governance models within green hydrogen hubs play a crucial role in determining project inclusivity. Projects that adopt integrated governance, involving both public and private actors, proved more inclined to favor the participation of SMEs and startups. A clear example is H2SHIFT, which created a platform where small businesses can easily access green hydrogen technologies, reduce economic barriers and make the sector more inclusive. This approach has fostered sustainable local ecosystems, with tangible benefits for social and environmental sustainability.

On the other hand, projects like the Port of Hamburg Hydrogen Project and Hyphen Hydrogen Energy/SCDI feature more centralized governance models. While efficient for large-scale management, these models can be difficult for SMEs to penetrate, thus limiting their participation. The governance of these hubs tends to focus more on the needs of large industrial firms, which require large-scale green hydrogen production and long-term contracts, rather than on local innovation or access for small businesses.

Commercial incentive mechanisms are another fundamental factor determining the successful integration of SMEs into the green hydrogen market. Economic incentives, such as subsidized financing, public grants, and discounts on installation costs, are essential to make these technologies accessible to small companies, which otherwise could not afford the highly required initial investments. In many of the analyzed projects, like H2SHIFT and H2START, a competitive pricing strategy for facility access was adopted, allowing SMEs to more easily adopt green hydrogen as an energy solution.

The comparison of the different green hydrogen hubs also highlighted diverse market dimensions and regional trends. In Europe, green hydrogen demand is growing strongly thanks to the European Commission's decarbonization policies, which have incentivized projects like the Trentino Hydrogen Valley and the Andalusia Green Hydrogen Valley. These hubs operate in an already consolidated and growing market, where hydrogen demand is supported by strong public incentives. In other regions, such as Namibia or California, demand is still developing, but export opportunities are high due to abundant renewable resources and lower hydrogen production costs.

A key aspect emerging from this analysis is how sustainable business models are decisive for long-term success. Projects like Hyphen Hydrogen Energy and Hydrogen Park Murray Valley aim to develop scalable, long-term infrastructure, with the goal of becoming global benchmarks for green hydrogen production and distribution. These projects require significant initial investments but have the potential to generate positive impacts in terms of environmental and social sustainability by creating jobs, stimulating innovation, and contributing to the global energy transition.

Conversely, some failed projects could not guarantee SME participation due to centralized governance models or a lack of adequate commercial incentives. The case of the Fukushima Hydrogen Energy Research Field is emblematic: despite technological advancements, the project failed to create sufficient local demand and struggled to attract investment due to insufficient governance and support policies. Similarly, projects like the California Hydrogen Hub faced difficulties related to regulatory uncertainty and a lack of adequate financial support, hindering SME entry and slowing technology adoption. This highlights the importance of a clear regulatory framework and a well-designed incentive system capable of including small businesses.

In general, the main difference between active and failed projects lies in how commercial incentive mechanisms and SME involvement were managed. Active projects, like the Trentino Hydrogen Valley and Lolland Hydrogen Community, developed a collaborative ecosystem that promotes innovation and SME engagement. In contrast, failed projects often ignored the specific needs of SMEs, focusing on solutions better suited to large industrial actors. Furthermore, the more inclusive projects showed positive impacts in terms of social and economic sustainability by generating local jobs and skills, while the failed projects had limited impact due to a lack of strong public support and incentive policies.

8.1 Limitations and Future Research

However, despite the extensive preliminary research, the study encountered a major limitation related to the availability and consistency of data. The initial landscape analysis identified a large number of Hydrogen Hubs and Valleys worldwide, and from these, around forty of the most relevant cases were selected based on defined inclusion criteria.

Yet, even within this refined group, the information available was highly uneven. Many projects lack consolidated documentation, publicly accessible datasets, or detailed technical reports. In several cases, only high-level descriptions were available, with no reliable data on governance models, technological choices, financial architecture, stakeholder involvement, or project progress.

This fragmentation made it impossible to construct a complete and homogeneous overview of each initiative. As a result, the comparative framework could not rely on a fully aligned set of indicators, limiting the depth and robustness of the cross-case analysis. This constraint ultimately prevented the development of a comprehensive, data-driven understanding of the global ecosystem of Hydrogen Hubs and Valleys.

Looking ahead, once the green hydrogen market has consolidated and these developing technologies become more mature, it will be possible to conduct more quantitative analyses. An important next step could be conducting structured interviews with key actors and stakeholders, particularly with hard-to-abate industries, to gather direct data on perceived barriers and the incentive strategies that best support the adoption of green technologies.

In conclusion, this thesis highlights how governance models and commercial incentive mechanisms are decisive for SME participation in adopting green hydrogen technologies. Despite some difficulties related to inclusiveness and economic barriers, projects that adopt a collaborative and inclusive approach are more effective in fostering the transition to a sustainable energy system. Green hydrogen offers enormous opportunities, and with the right support, SMEs can become key actors in this decarbonization process.

Appendix A - KPI benchmarking excerpt

Archetype	Case studies	KPI			
		1	2	3	4
		short- and long-term objectives	Target Market and Customer Needs	Business Model/Governance Model	Services description
A	**Andalusia Green Hydrogen Valley SPAGNA**	Short-term (2024–2027): development of 2 GW of electrolysis divided between Huelva (1 GW) and San Roque (1 GW), with commissioning between 2026–2027. Long-term (by 2030): production of 300,000 t/year of green hydrogen (+6 million tCO_2 avoided/year)	Heavy industries located in ports (chemicals, fertilizers, steel) in search of clean energy sources. Heavy mobility sector (road, maritime, rail transport). Production of derivatives such as ammonia and green methanol	Public-private model with the involvement of local authorities, energy companies and research institutes, focused on the production and distribution of hydrogen.	Green H_2 production via electrolysis integrated with renewables. Production of ammonia and green methanol. Port infrastructure for export (corridors with Rotterdam, Singapore)
B	**Fukushima Hydrogen Energy Research Field (FH2R) JAPAN**	Short-term (2020–2022): Launch a 10 MW alkaline electrolyser powered by 20 MW of photovoltaics, to test flexible green H_2 production and dynamic management with the power grid Long-term(2023–2030): Become a leading green hydrogen hub in Asia-Pacific, with business model development, scalability to 100 MW and urban/industrial integration	Utilities (e.g. Tohoku Electric) need network flexibility and P2G tools. Local communities (Namie) and residential environments are looking for decarbonization solutions and secure energy supply. H_2 mobility: people and fleet managers need renewable sources for FCVs and buses	Collaboration between public and private entities, with a business model oriented towards advanced research and large-scale hydrogen production.	Green H_2 production through solar energy electrolysis and grid. Dynamic production/storage management for grid balancing (without batteries). Mixed distribution for residential, public and mobility use
C	**Hydrogen Project-Port of Hamburg (Germany)**	Short term (2025–2027): Construction and start-up of the 100 MW electrolyser at the site of the former Moorburg coal-fired power plant, with a target of 10,000 t/year of green H_2. Long-term (until 2035): expand capacity to 800 MW, integrate port H_2 network (HH-WIN) and develop import terminals for green ammonia.	Port industry (steel mills, chemicals, refineries): replacement of natural gas and grey hydrogen. Logistics and shipping: fuel for trucks, port vehicles, H_2/ammonia ships. Local utilities: blending into energy grids to reduce CO_2.	Collaboration between public bodies, port companies and research institutes, with a business model based on the production and consumption of hydrogen in the port sector.	Production and supply of green hydrogen. Distribution via HH-WIN port network (60 km dedicated pipelines). Terminal for import/export of green ammonia. Support for pilot projects for shipping and aviation fuels..
D	**UAE National Strategy & New National Hubs (we are not talking about a valley or a hub but it is a country-strategy)**	Short term (2024–2031): create at least 2 "hydrogen oases" (regional clusters) to produce 1.4 Mtpa of hydrogen (green and blue). Long-term (until 2050): expansion to 5 national hubs, capacity up to 15 Mtpa, position the UAE among the top 10 global exporters.	Domestic: decarbonising heavy industry (aluminium, steel, fertilisers). International: European and Asian customers (e.g. Germany, Japan, Korea) interested in importing H_2/green ammonia.	The governance model is public-private, with the involvement of entities such as Masdar, ADNOC and the Ministry of Energy and Infrastructure. The strategy aims to integrate hydrogen into key sectors such as industry, mobility and energy production, promoting international collaborations and investments in the sector.	Production and supply of green H_2 (electrolysis powered by solar/wind). Production of blue H_2 (gas + CCS) as stepping stone. Export via green ammonia, pipeline, and LOHC. Integrated services: storage, gas-H_2 blending, certifications.

Archetype	Case studies	KPI			
		5	6	7	8
		Competitive Analysis (Regulatory Environment	Access to Services	Revenue Streams (sarebbe anche fondi recepiti)	Pricing Strategy
A	Andalusia Green Hydrogen Valley SPAGNA	Supported by European and Spanish national policies for the energy transition, with incentives for the production of green hydrogen.	Part of the project is managed by Cepsa and Iberdrola, involving companies, universities and SMEs through IPCEI calls	Sale H_2, ammonia, methanol. Electrolyzer Export, Storage, Manufacturing Services	Competitive price thanks to very low electricity cost (wind/photovoltaic). Economic support with IPCEI auctions and subsidies.
B	Fukushima Hydrogen Energy Research Field (FH2R) JAPAN	Supported by Japanese government policies for the promotion of hydrogen as an energy source, with a strong public commitment to research and development.	Direct access through public-private consortium (NEDO, Toshiba, TEP, Iwatani). It is not an open test-bed: not accessible for startups or external SMEs.	Sale of green H_2 to communities, FCVs, local industries. Development of P2G business models useful for balancing the network	Market price influenced by government subsidies and wholesale cost of renewable energy. Focus on demand-driven production with bind-to-grid pricing.
C	Hydrogen Project-Port of Hamburg (Germany)	Supported by German and European policies for the energy transition, with incentives for innovation in the field of hydrogen.	Industries: direct connection via port pipeline. Transport: refuelling stations in the port for trucks and heavy vehicles. External partners: Access through supply contracts and import MoUs.	Green H_2 sales to industries and logistics. Network rates for HH-WIN. EU funds: IPCEI projects + co-financing by the city of Hamburg and Bundesnetzagentur.	Initial prices above market, covered by EU/DE incentives (IPCEI). Medium-term target: <5 €/kg thanks to economies of scale and imports (green ammonia).
D	UAE National Strategy & New National Hubs (we are not talking about a valley or a hub but it is a country-strategy)	The UAE has developed a National Hydrogen Strategy with the aim of becoming a global leader in the production and export of low-carbon hydrogen by 2050. The strategy envisages the creation of "hydrogen oases" and dedicated research centres, with strong regulatory and financial support from the government.	Local industries: through direct contracts with production clusters. Overseas customers: Access through Abu Dhabi and Fujairah port terminals. Global utilities: MoUs with energy companies (ENBW, Uniper, JERA).	Sale of H_2 and ammonia to foreign customers. UAE public funding (Sovereign Wealth Fund, ADNOC, Masdar). Partnership with international institutions (BEIS UK, EU).	Competitiveness linked to very low solar costs in the UAE (<15 \$/MWh). Strategy: Deliver green H_2 at ~\$1.5–2.0/kg by 2030, but also integrate blue H_2 at lower costs to enter the market sooner.

Archetype	Case studies	KPI			
		9	10	11	12
		Marketing Strategy and Sales Plan	"Customer" Acquisition Costs/strategies	Retention Strategies	Operations Plan and organizational structure
A	**Andalusia Green Hydrogen Valley SPAGNA**	Communication through sponsors (Cepsa, Iberdrola), regional government and the EU. International partnerships (e.g. Port of Rotterdam) and participation in trade fairs such as H2Valleys/Hydrogen Week	Development through industrial and public agreements; marketing costs for tenders and business networks. Direct involvement of the "Puerta de Europa" cluster (over 80 companies)	Multi-year contracts with H_2 users (chemicals, fertilizers, transport). Training and ongoing involvement of SMEs/academia	Coordination between Cepsa (lead partner), Iberdrola, regional Andalusia, ports, SMEs, universities. Multi-level governance with dedicated project units
B	**Fukushima Hydrogen Energy Research Field (FH2R) JAPAN**	Communication via the Japanese Government, NEDO, METI and Toshiba; Presence at Forum Energy. Live demos at public facilities (restaurants, residential areas)	Acquisitions on a government basis, through NEDO and utility contracts. Zero cost for commercial part, government support covers OPEX.	Long-term contracts with TEP and Iwatani. Support through technology upgrades and capacity increases.	Collab. NEDO and Fuji Power System: fully integrated piping. Roles: Toshiba (EPC+management), TEP (grid), Iwatani (storage & H_2 logistics)
C	**Hydrogen Project-Port of Hamburg (Germany)**	Branding Hamburg as "Gateway Hydrogen Europe". Agreements with shipping companies and steel mills for guaranteed offtake. Promotion through Hydrogen Hamburg and H2Global clusters.	Low CACs: the port itself concentrates industrial customers. Strategies: Multi-year MoUs with key companies (Aurubis, ArcelorMittal, Lufthansa).	Long-term supply contracts (10–15 years). Additional services (green H_2 certification, customized blending). Integrated import/export offer for global customers.	Operator: Vattenfall consortium, Shell, Mitsubishi Heavy Industries and the City of Hamburg. PPP structure with shared governance (public-private).
D	**UAE National Strategy & New National Hubs (we are not talking about a valley or a hub but it is a country-strategy)**	Branding of the UAE as "Hydrogen Superpower". Bilateral agreements (e.g. with Germany, Japan, Korea) to ensure offtake. Participation in global forums (COP28, Hydrogen Council).	Low CACs thanks to government MoUs that already guarantee customers. Economic diplomacy and joint investments reduce customer acquisition costs.	Long-term supply contracts (10–20 years). "Green/blue" certificates of origin to ensure traceability. Integrated industrial partnerships (Masdar + European utilities).	Lead agencies: Ministry of Energy and Infrastructure + ADNOC + Masdar. Multi-level governance: federal entities + emirates (Abu Dhabi, Dubai).

Archetype	Case studies	KPI			
		13	14	15	16
		Facilities, Equipment, and Technology Requirements	Organizational Information	Supply Chain Management	Financial Plan
A	Andalusia Green Hydrogen Valley SPAGNA	2 GW electrolysers (Huelva + San Roque). Integration with wind/photovoltaic farms (≈7 GW). Export, storage and production infrastructure for e-derivatives	Lead partner: Cepsa-Moeve, supported by Iberdrola and Hygreen. Extensive network of industrial and institutional stakeholders	Supply of electrolysers (also local via Hygreen), compressors, chemical plants for ammonia/methanol. Logistics with ports, renewable supply, participation of SMEs (400+)	CapEx: towards €3 billion, with €303 million initial. OpEx: plant operations, O&M, energy costs. Expected revenues: H_2 sales, green products and logistics services.
B	Fukushima Hydrogen Energy Research Field (FH2R) JAPAN	10 MW alkaline electrolyzer (Asahi Kasei Aqualyzer), 20 MW photovoltaic, compressed storage (tanks + trailers) Grid control systems (EMS/SCADA) for dynamic balancing	Joint venture: NEDO, Toshiba ESS, Tohoku Electric, Iwatani. Inaugurated by PM Abe and METI, it is coordinated as a national project	Procurement: solar modules, electrolytic membranes, compressors, H_2 vehicles. Logistics: trailer replenishment, on-site distribution	CapEx: about $200 M (NEDO + industrial) OpEx: O&M electrolysis, solar, storage. Revenues: H_2 sales, P2G services, network balancing.
C	Hydrogen Project-Port of Hamburg (Germany)	Electrolysers 100–800 MW (PEM/Alkaline technology). HH-WIN pipeline 60 km. Ammonia port terminal + cracking unit.	HGHH consortium management based in Hamburg.	Upstream: electricity from renewables (offshore wind in the North Sea). Midstream: electrolysis, compression, pipeline. Downstream: industry, shipping, logistics.	CAPEX phase 1: ~€500 mln (100 MW). CAPEX phase 2: up to €2–3 bn (800 MW + terminal import). Sources: EU (IPCEI), German government, private investors (Vattenfall, Shell).
D	UAE National Strategy & New National Hubs (we are not talking about a valley or a hub but it is a country-strategy)	GW-scale electrolyzers (powered by solar PV and wind). Steam methane reforming + CCS systems for blue H_2. Ammonia and LOHC export terminals.	Coordination via Hydrogen Leadership Roadmap UAE. Implementation delegated to consortia (ADNOC, Masdar, Mubadala).	Upstream: natural gas + renewables. Midstream: electrolysers, CCS systems, compression and storage. Downstream: export via ports, ammonia shipping, blending in gas networks.	Estimated investments: $>40 billion by 2031. Sources: sovereign wealth funds (ADIA, Mubadala), ADNOC/Masdar, joint ventures with global utilities. Risks: volatility, global demand, competition (Saudi Arabia, Australia).

Archetype	Case studies	KPI		
		17	18	19
		Test Line Costs	Break even point	Spillover Sociali/Ambientali
A	Andalusia Green Hydrogen Valley SPAGNA	Electrolysis 1 GW costs about 600 M€–1 G€ (modular scale-up). Ammonia/methanol plants million. Port infrastructure, pipelines, storage: hundreds of millions.	There is no official break-even date. With falling electricity costs and CfDs, break-even expected after 2030..	Creation of local jobs, promotion of environmental sustainability and reduction of CO_2 emissions
B	Fukushima Hydrogen Energy Research Field (FH2R) JAPAN	10 MW + 20 MW PV plant: >$50 M. Upgrade to 100 MW in pipeline: new alkaline unit with costs >$500 M	NO	Contribution to post-Fukushima energy diversification, job creation and promotion of environmental sustainability.
C	Hydrogen Project-Port of Hamburg (Germany)	Pilot distribution lines already started (HH-WIN). Costs: pipeline test ~€10 mln/km, demo electrolyzer funded in part by IPCEI grants.	There is no single official figure, but IPCEI sources and stakeholders indicate that the project is aiming for break-even in the late 2030s. Heavily dependent on CFDs and offtakes with steel mills (ArcelorMittal), Lufthansa (aviation) and Aurubis (copper).	Promotion of environmental sustainability in the port sector, job creation and reduction of CO_2 emissions.
D	UAE National Strategy & New National Hubs (we are not talking about a valley or a hub but it is a country-strategy)	Small-scale pilot phase (100–200 MW) in Abu Dhabi and Fujairah. Prototype costs largely covered by ADNOC and Masdar.	A forecast has not yet been made	The strategy envisages the creation of new jobs in the hydrogen sector, the development of local skills and the promotion of environmental sustainability through the reduction of CO_2 emissions. In addition, the Emirates aim to diversify its economy, reducing dependence on oil and promoting technological innovation.

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