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# Green Hydrogen as a Key Vector of Industrial Decarbonization: Analysis of Business Models, Governance Structures and Strategic Dynamics across Global Hydrogen Hubs and Valleys

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# ABSTRACT

The aim of this thesis is to present the emerging role of the green hydrogen technology, intended as a low-carbon and sustainable alternative to fossil fuels, within the context of the global challenge to achieve carbon neutrality by 2050. A detailed overview of the subject of green hydrogen is provided, including its main characteristics, supply chain, policy framework and market position, with particular emphasis on supply-demand mismatch and barriers.

The research highlights the fundamental aspects and increasing development of new ecosystems such as Hydrogen Hubs and Hydrogen Valleys, which could be described as regional industrial clusters where research, innovation and infrastructure converge to advance the deployment of green hydrogen. Essentially, these configurations are facilitated through collaborative mechanisms involving multiple stakeholders from both the public and private sectors, whose combined efforts can support the large-scale adoption of green hydrogen. By analyzing the different ways in which these hubs operate in terms of business models and governance structures, the thesis identifies how these elements contribute to their growth and development, while encouraging stakeholders' participation. The findings underscore that there is no standardized business structure that prevails, instead successful hubs rely on a combination effective governance, dedicated financial support and strong collaboration between the public and private sectors. Hydrogen hubs are therefore examined not only as infrastructure solutions for green hydrogen production, but also as collaborative entities capable of reducing high-investment risks and fostering demand creation in hard-to-abate sectors.

# INTRODUCTION

One of the most complex and urgent matters in the transition towards climate neutrality is perhaps the decarbonization of industry. Human activities, such as urbanization and industrialization, emit every day large quantities of greenhouse gas (GHG) emissions, especially carbon dioxide ($CO_2$), into the atmosphere, thereby contributing to climate change and negatively impacting the environment. This issue not only threatens the Earth's health and biodiversity, but generates other global externalities impacting world's economy and society. Decarbonization targets have already been set during the Paris Agreement (2015), and later emphasized at COP26, highlighting the necessity for technological solutions to reduce emissions in hard-to-abate sectors (Roque et al, 2025). Although great progress and achievements have been made in the field of renewable electricity, some industries still depend on fossil fuels as their primary source of power due to their process temperature demands, chemical feedstock needs and energy density limitations. These include industries such as steel, cement, chemicals and fertilizers, as well as long-distance transport segments like aviation, shipping and road transport modes. Nevertheless, renewable energy sources (RESs) remain a clear path to take. According to the International Energy Agency's (IEA) *Global Hydrogen Review 2025*, the continued rapid adoption of clean energy technologies is limiting emissions growth, avoiding 2.6 billion tons of additional CO2 emissions per year. Under these circumstances, among renewable energy sources, green hydrogen has become an emerging and promising key solution for industrial decarbonization. Global-scale green hydrogen production could indeed satisfy up to 24% of global energy needs by 2050, resulting in the abatement of 6% of total cumulative $CO_2$ emission reductions (M. Jayachandran et al, 2024). Generated by electrolysis using renewable energy, it offers a low-carbon alternative used both as a fuel and as a feedstock. Green hydrogen possesses important properties that makes it particularly relevant: for instance, it can function as a long-term energy storage and it can be converted into, and utilized, in its derivatives, such as ammonia, methanol and synthetic fuels, thus enabling decarbonization in areas where electrification is technically or economically constrained. The development and use of green hydrogen, however, are not only a technological challenge. It is also a challenge to develop production capacity, specific infrastructure for transport and storage, and demand from industrial users simultaneously. Such interdependencies demand coordinated efforts and actions among stakeholders and sectors. Initiatives and innovations in the hydrogen industry are in fact shaped by the current technological, economic and political landscape. Its successful integration into energy systems requires also both supportive policy frameworks that address economic and infrastructure barriers (Angelico et al, 2025) and innovative organizational configurations capable of deploying green hydrogen technologies at scale and accelerating market adoption.

Increasing attention has been given to the creation of integrated hydrogen ecosystems, also known as hydrogen hubs or hydrogen valleys, which is recognized in this context as a key enabler for the systemic use of hydrogen. They are conceived as spatially concentrated ecosystems covering a specific geography ranging from local or regional focus (e.g. industrial cluster, ports, airports, etc.) to specific national or international regions (e.g. cross border hydrogen corridors) (Clean Hydrogen Partnership, *Hydrogen Valleys*, European Commission) where production, storage, transport, distribution, application, research and public sector activities are strategically located. Their strengths consist in concentrating production and consumption within proximity, so the need for long-distance transport is significantly reduced, while shared infrastructure, knowledge exchange and collaborative research and development efforts can significantly lower costs and accelerate technological advancements (Thekkethil et al, 2024). Hydrogen valleys showcase the versatility of hydrogen by supplying several sectors in their geography such as mobility, industry and energy end uses, and provide a replicable organizational framework for collaboration among industrial firms, energy providers, technology developers, infrastructure operators, research institutions and public authorities. Hydrogen hubs can increasingly be understood not only in terms of infrastructure development but also in terms of "governance" and "business model" experimentation in the development of complex hydrogen value chains. They have been identified in the RePowerEU plan (May 2022) as essential promoters of scaling up Europe's hydrogen economy (Clean Hydrogen Partnership, *Hydrogen Valleys*, European Commission).

The growing emergence of hydrogen hubs is directly related to the increasing policy support for clean hydrogen at the national and supranational level. During the last decade, many governments have developed and implemented specific hydrogen strategies, normally combined with public funding programs, regulatory frameworks and market incentives to stimulate both demand and supply. For this reason, the role of public intervention is especially important in the early stages of the development of the hydrogen market, where there are high capital costs, uncertainty about demand and rapidly developing technologies.

The objective of this thesis is to examine the way a number of hydrogen hubs and valleys operate in the green hydrogen context, in terms of business model, governance structure and strategic approaches, and how these elements contribute to accelerating green hydrogen's development and deployment into the industry. Focusing on a carefully selected database of case studies, the first step of the analysis will be to identify the major trends among these hydrogen hubs. These include economic and financial objectives, private and public stakeholders' participation and role, supply chain management and the types of demand they serve, with specific reference to end-use applications and customer segments. In a second phase, the research will adopt a more in-depth approach by focusing on a smaller sample of cases. The aim will be to understand how different organizational forms of business within hubs manage or intend to successfully implement and scale green hydrogen, which partnership they established and where financial support is coming from.

# 1 - BACKGROUND

## 1.1 A First Look into Green Hydrogen

### 1.1.1 Chemical Characteristics of Hydrogen

Hydrogen ($H_2$) is the first and simplest element of the periodic table and arguably the most essential one of them all. As a matter of fact, it is most abundant element in the universe, accounting for approximately 75% of all known and visible matter, and nearly 99% when helium is included. However, only small quantities of pure hydrogen (in the form of $H_2$ molecules) are found on Earth, as it's usually bonded with other elements, most importantly oxygen to form water. Being the lightest element, with an atomic weight of 1.008u[1], hydrogen presents a relatively simple atomic structure, comprehending a single electron and proton. It is odorless, colorless, and the extremely weak London dispersion forces[2], determine an extremely low melting and boiling temperatures: -259°C and -253°C, respectively.

Hydrogen possesses several important advantageous properties: a high calorific value, which refers to the amount of energy released per unit mass during combustion (in simpler words, hydrogen releases a large amount of heat when burned); a high reaction rate, the speed at which a reaction happens when interacting with other substances; flexibility: it can be used in various applications and in different forms such as gas, liquid or combined with other materials; availability from multiple sources (water, hydrocarbons, renewable resources, etc.). All these properties contribute to hydrogen's most significant feature for our research: the capacity to generate clean energy and enable efficient energy storage. As a matter of fact, hydrogen currently has the most significant potential to be a viable alternative to conventional energy sources a promising solution for the decarbonization of the global economy.

### 1.1.2 "Green Hydrogen" Definition and Comparative Position Towards Grey and Blue Alternatives

*Green hydrogen* is known as the cleanest form of hydrogen-based energy, as no $CO_2$ emissions are released during its production. The term, along with the other color-coded alternatives, all which constitute the so called "hydrogen rainbow", does not have a single and universally recognized inventor. Instead, these labels emerged due to an inevitable necessity to distinguish the types of hydrogen, assigning different color names based on three main criteria: the source of its molecules: water, biomass, natural gas and different types of coal; the processes used for its extraction: electrolysis[3], steam methane reforming[4], gasification, thermochemical, photochemical, biochemical and biological processes; the energy sources required to produce electrical energy (input to the electrolysis process) when there is no involvement of fossil fuels, and consequently no $CO_2$-associated emissions: renewable energy sources (RES) and nuclear energy (Incer-Valverde et al, 2023).

As hydrogen notoriety and practical utility is facing a rapid growth in the global energy transition, this classification has become a helpful tool for researchers, scientists, industry stakeholders and policymakers.

The three most relevant and referenced colors are the following,

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[1] 1 u (or 1 amu) = 1/12 of the mass of a carbon-12 atom, which is approximately $1.66054 \times 10^{-27}$ kg.

[2] The *dispersion force*, or *London force* (named after the German physicist Fritz London, who was the first to explain the quantum mechanical basis of the attraction), is the main intermolecular force responsible for the condensed states of nonpolar substances. These forces are extremely weak, but they can occur between any particles. In particular, they are the dominant intermolecular force between identical molecules.

[3] Electrolysis (of water) is the process of using electricity to split water into two gases, hydrogen and oxygen. The reaction takes place in a unit called an electrolyser. Further information will be given in 1.5.1 Sourcing and Production.

[4] Steam Methane Reforming (MSR) is a process in which methane, from natural gas, is heated with steam, usually with a catalyst, to produce hydrogen ad carbon monoxide as a by-product, representing the most cost-efficient method for hydrogen production from fossil fuels.

- *Green Hydrogen*, the focus of this research, refers to the hydrogen produced without direct $CO_2$ emissions. It is typically generated through water electrolysis powered by renewable sources such as wind, solar or hydro.
- *Gray Hydrogen* refers to the hydrogen coming from natural gas, especially from steam methane reforming (SMR), which results in a significant emission of $CO_2$.
- *Blue Hydrogen* refers to the hydrogen also produced from fossil fuels, usually through SMR, but incorporates CCUS technologies, enabling a little or almost no $CO_2$ emissions.

CCUS stands for Carbon Capture, Utilization, and Storage, and includes a range of technologies and infrastructures useful for capturing $CO_2$, either for storage or for reuse.

Other relevant color designations also exist, including black, turquoise, yellow, purple (*Figure 1*Figure 1). Minor ones are white, gold and red.

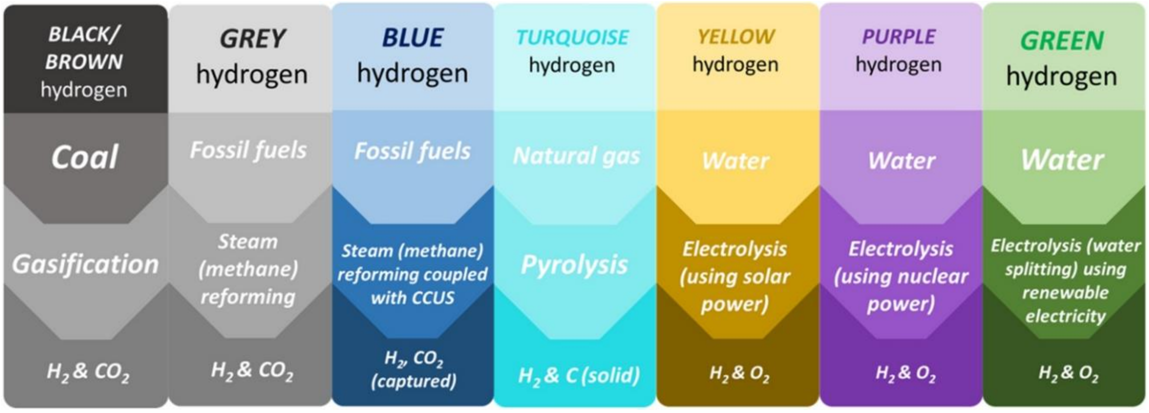

*Figure 1: $H_2$ rainbow highlighting the feedstock, conversion process and output for each category (Skillen et al, 2022)*

Despite continuous efforts by scientists and institutions trying to standardize and consolidate the terminology, inconsistencies persist. Some organizations may use, in their reports, other names to denote green hydrogen. For instance, the International Energy Agency (IEA) uses *renewable hydrogen* to describe the one produced though renewable electricity or via biomass-based routes. The IEA also defines *low-emission* or *low-carbon hydrogen* as the one produced through low-emission energy sources (renewable or nuclear), biomass, or fossil fuels with CCUS (Incer-Valverde et al, 2023). Even though there still isn't a universal agreement on hydrogen color code or definition, for the purpose of this thesis, the term green hydrogen will consistently indicate the hydrogen produced without carbon emissions, aligning with the definition used in most renewable energy and sustainability literature.

### 1.2 The Evolution of Hydrogen Economy in the Global Energy Transition

The process of hydrogen being utilized as an energy carrier across multiple sectors is commonly referred to as the *hydrogen economy*. The term was first coined by John Bockris in 1972 to describe a future in which hydrogen serves as an alternative to fossil fuels. Since that initial conceptualization, the historical evolution of this phenomenon has proven to be both complex and subject to a shifting evolution, shaped by technological, economic and environmental factors, where periods of high expectations, the so called "hydrogen booms", alternate with periods of investment and deployment shutdowns.

In the past five decades, global concerns over environmental degradation, climate change and the growing interest in clean energy systems, have drawn increasing attention from policymakers, researchers, the media and industry toward the green hydrogen economy. Studies show that despite a growing research activity and multiple attempts to drive a global hydrogen economy, strategies were inconsistent and no significant results had arisen.

Early contributors like Veziroğlu and Bockris both recognized the turbulent progress but emphasized its long-term potential, though writing at different points in the hydrogen economy's development: Veziroğlu in 2000 during a rising wave of interest, while Bockris in 2013 after that enthusiasm had declined. Other researchers, such as Hultman and Nordlund, used historical analysis of media and government documents (1990–2005) to explore fuel cell expectations. Solomon and Banerjee reviewed policy and industry documents (1998–2005) and found that hydrogen plans were often vague. El-Emam and Özcan analyzed hydrogen production costs in 170 journal papers, while McDowall and Eames compared 40 case studies and found no unified vision among stakeholders (Yap and McLellan, 2023). In more recent studies, to better understand the changing in interest in hydrogen economy, Yap and McLellan, in 2023, combined bibliometric with qualitative analysis to provide a comprehensive and historical evolution of the hydrogen economy literature from 1972 to 2020. As predicted, from their results, it appears a fluctuating yet growing interest over these past five decades, spread into three chronological phases: slow growth phase (1972–1979); stagnant growth phase (1980–1999); rapid growth phase (2000-2019). This reflects on real life events. In 1974, hydrogen interest peaked with the establishment of institutions like the IEA and International Association for Hydrogen Energy (IAHE), with the main purpose of responding to the global energy crises. Low oil prices and the 1986 Chernobyl disaster, which reduced interest in nuclear-based hydrogen. In the 1990s, global climate initiatives such as the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and 1997 Kyoto Protocol[5] renewed focus on clean energy. In the 2000s, increased R&D and the promotion of Fuel Cell Electric Vehicles (FCEVs) created initial consumer focus on the hydrogen economy and notability as a global solution for energy storage. These development paths, supported by policy initiatives, technological advances and growing climate concerns, set the starting point of an innovative period, positioning hydrogen as a key player in the evolving landscape of clean energy solutions.

During the last five years, interest in the green hydrogen economy has evolved from a niche enthusiasm to a dominant strategic priority. If at first it was seen as a long-term decarbonization tool, green hydrogen gained significant relevance after 2020, due to growing climate concerns and the need for immediate clean energy storage solutions, which led to the European Union's Hydrogen Strategy (2020)[6], followed by more than thirty nations launching their Hydrogen National Plan, Strategies or Roadmaps. Some of the most relevant countries participating are Japan, South Korea, India and Australia. As a consequence, investments increased, also driven by post-COVID recovery plans and rising fossil fuel instability after the 2022 energy crisis. Between 2021 and 2023, hydrogen's role across industry, mobility and power sectors announcements rose, mainly because of large-scale projects initiatives, international trade corridors creation and electrolyser manufacturing growth. By 2024–2025, the concept of using hydrogen as a source of energy began to become a reality: while excitement remained high, governments and investors started analyzing project feasibility and infrastructure readiness, keeping an eye to cost competitiveness. Overall, the green hydrogen economy has moved from

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[5] *Kyoto Protocol* operationalizes the United Nations Framework Convention on Climate Change by committing industrialized countries and economies in transition to limit and reduce greenhouse gases (GHG) emissions in accordance with agreed individual targets. The Convention itself only asks those countries to adopt policies and measures on mitigation and to report periodically.
United Nations Framework Convention on Climate Change, *Kyoto Protocol*, UNFCCC; https://unfccc.int/kyoto_protocol.

[6] "The *EU Hydrogen Strategy* will give a boost to clean hydrogen production in Europe. To become climate-neutral by 2050, Europe needs to transform its energy system, which accounts for 75% of the EU's greenhouse gas emissions. Hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications which would reduce greenhouse gas emissions across industry, transport, power and buildings sectors. Green hydrogen is expected to play a key role in the decarbonization of sectors where other alternatives might not be feasible or be more expensive". H2GreenTECH, *A Hydrogen Strategy for a Climate-Neutral Europe*; https://www.h2greentech.eu/a-hydrogen-strategy-for-a-climate-neutral-europe/

conceptual vision to an emerging industrial ecosystem, even though multiple challenges in scale-up, regulation and market formation are still to be faced.

### 1.3 Role of Hydrogen within Global Sustainability Goals

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, "is a plan of action for people, planet and prosperity"[7], as it provides a shared strategy and common willingness to build a world where "everyone has the chance to live in an environmentally, socially, economically and socially sustainable world"[8], now and into the future. The core concepts are the 17 Sustainable Development Goals (SDGs) (*Figure 2**Error! Reference source not found.***), which represent "an urgent call for action by all countries, developed and developing, in a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth, all while tackling climate change and working to preserve our oceans and forests"[9] One of the critical pathways to achieving these goals, particularly those related to climate action and clean energy, is the reduction in the cost of renewable energy technologies.

In this context, green hydrogen can significantly contribute to reaching net-zero emissions and global decarbonization by 2050 because, as already stated, it offers a cleaner alternative to fossil fuels. By enhancing investments in infrastructures building, improving production and technical efficiency, while reducing associated costs, green hydrogen can play a crucial role in climate change mitigation strategies and in reaching sustainable global targets.

*Figure 2: The Sustainable Development Goals (United Nations, Communications materials, Sustainable Development Goals)*

According to Maka et al, contributions of green hydrogen to sustainable development include:

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[7] United Nations General Assembly, *Transforming Our World: The 2030 Agenda for Sustainable Development*, United Nations, 2015; https://sdgs.un.org/2030agenda

[8] Agenzia per la Coesione Territoriale, *The UN Agenda 2030 for Sustainable Development*; https://www.agenziacoesione.gov.it/comunicazione/agenda-2030-per-lo-sviluppo-sostenibile/?lang=en

[9] United Nations, *The 17 Sustainable Development Goals (SDGs)*, SDG Knowledge Platform, https://sdgs.un.org/goals

- SDG 6: Clean Water and Sanitation

  Objective: ensure availability and sustainable management of clean water and sanitation for all.

  Green hydrogen can support this goal by increasing desalination capacity, boosting freshwater availability for residents in producing regions. Additionally, electrolysis, the key process in green hydrogen production, can generate potable water as a byproduct, through treatment techniques.

- SDG 7: Affordable and Clean Energy

  Objective: ensure access to affordable, reliable, sustainable and modern energy for all.

  Hydrogen, produced from renewable sources like solar, wind and biomass, can help achieve this by offering a clean and reliable energy option. Furthermore, the expansion of energy from renewable sources, other than supporting climate goals by reducing greenhouse gas (GHG) emissions, can lower energy costs and improve electricity access, especially in developing countries.

- SDG 8: Decent Work and Economic Growth

  Objective: promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

  Green hydrogen initiatives encourage industry innovation, support technical advancements and promote economic diversity, which can impact the sector in generating millions of new jobs in areas such as electrolyser manufacturing, system installation, maintenance and infrastructure development.

- SDG 9: Industry, Innovation, and Infrastructure

  Objective: build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

  The green hydrogen industry will stimulate development in modern technologies like ammonia conversion, electrolysers and low-emission industrial processes. It can also promote industrial and clean infrastructure growth in underdeveloped nations.

- SDG 11: Sustainable Cities and Communities

  Objective: make cities and human settlements inclusive, safe, resilient and sustainable.

  Using hydrogen in urban transport and power generation can improve cities' air quality, enhancing public health and urban sustainability.

- SDG 13: Climate Action

  Objective: take urgent action to combat climate change and its impact.

  Green hydrogen plays an important role in enabling the creation of a zero-emission energy supply chain, as it significantly reduces greenhouse gas (GHG) emissions across sectors. To maximize its climate benefits, rigorous guidelines and rules are required to guarantee the lowest possible related emissions throughout the value chain for hydrogen.

Contributing to 6 out of 17 sustainable goals, green hydrogen has strong potential to support a sustainable and carbon-neutral future, aligned with the UN's SDGs of achieving net-zero emissions by 2050. However, to achieve such ambitious prospect, continued investments are required, as well as supportive policies, international cooperation and technological advancement. Also, collaborations among governments, businesses and international organization must be encouraged in order to overcome challenges related to infrastructure, costs and innovation.

## 1.4 Strategic, Legal and Policy Frameworks for Green Hydrogen in the EU and Beyond

The European Union has put into action a complex but ambitious regulatory framework to guide the development of green hydrogen, categorized as part of the Renewable Fuels of Non-Biological Origin (RFNBOs). At the heart of this regulatory system, these are most significant.

### 1.4.1 International Climate Agreements

Kyoto Protocol (1997)

The Kyoto Protocol was the first legally binding international agreement that committed 37 industrialized countries, including the European Union to help reduce greenhouse gas (GHG) emissions in line with agreed targets outlined in Annex B. The Protocol was implemented by the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 and later became effective in 2005. The Protocol focused, other than low-carbon transition, on technological innovation and the establishment of a legal and political culture that embraces new forms of clean energy as feasible solutions. While the Kyoto Protocol did not explicitly address green hydrogen as one of them, it laid the ground for future climate policy mechanisms that now support its development.

*"Research on, and promotion, development and increased use of,* new and renewable forms of energy*, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies."*[10]

Paris Agreement (2015)

Another important international agreement is the Paris Agreement, adopted on 2015 at the UN Climate Change Conference (COP21) in Paris, whose goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels". The Agreement entered into force a year later, in 2016, reflecting the urgency and shared consensus for an immediate global climate action. Since then, the Agreement has driven significant progress: nearly every country is now a member and climate finance exceeded $100 billion per year as of 2022. It has also accelerated the global expansion of renewable energy while encouraging innovation in low-carbon technologies, although it does not mention them explicitly, and hydrogen usage specifically. However, its climate targets have created strong incentives for countries and industries to invest in zero-emission solutions to decarbonize hard-to-abate sectors like steel, transport and chemicals, and green hydrogen has been increasingly seen as a key technology for such achievements. Many governments, including the EU, have integrated green hydrogen into their climate strategies as a direct response to Paris related commitments.

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[10] *Kyoto Protocol*, 1997, Art. 2, par. 1(a)(iv)

*"All Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies, mindful of Article 2 taking into account their common but differentiated responsibilities and respective capabilities, in the light of different national circumstances."*[11]

COP28 (2023)

COP28 was the 28th annual United Nations (UN) climate meeting, where each year governments of member States gather to discuss how to limit and deal with future climate change. The meeting took place in Dubai in 2023 and counted a total of 85,000 participant, including more than 150 Heads of State and Government, representatives of national delegations, civil society, business, Indigenous peoples, youth, philanthropy and international organizations. COP28 hosted the first "global stock take" of the world's efforts to address climate change under the Paris Agreement, revealing however the insufficient progress of limiting global warming to 1.5°C. In response to the 2019 levels, Parties agreed to reduce global greenhouse gas emissions by 43% by 2030. One of the most relevant outcomes of COP28 was the official recognition to transition away from fossil fuels: countries committed to tripling renewable energy capacity and doubling energy efficiency by 2030. These actions drove significant attention to green hydrogen, which led to a global push to expand infrastructure creating favorable conditions for scaling up electrolyser deployment, improving grid integration and investing in hydrogen storage and transport systems.

*"Accelerating zero- and low-emission technologies, including, inter alia, renewables, nuclear, abatement and removal technologies such as carbon capture and utilization and storage, particularly in hard-to-abate sectors, and low-carbon hydrogen production."*[12]

### 1.4.2 EU-Level Strategic Frameworks and Policy Initiatives

European Green Deal (2019)

The European Green Deal is the EU's growth strategy, launched in 2019, consisting in policy initiatives that aim to achieve climate neutrality by 2050, aligning with the Paris Agreement. Some key issues were climate change, biodiversity loss, pollution and resource overuse, while key goals, other than climate neutrality, include circular economy, healthier environments, more sustainable farming, climate justice and fairness. Green hydrogen again plays a critical role in this and by supporting its development through investments, regulations and infrastructure planning, the Green Deal seeks to enhance the EU's energy independence and industrial leadership in a future global clean energy economy.

*"EU industry needs 'climate and resource frontrunners' to develop the first commercial applications of breakthrough technologies in key industrial sectors by 2030. Priority areas include* clean hydrogen*, fuel cells and other alternative fuels, energy storage, and carbon capture, storage and utilisation."*[13]

EU Hydrogen Strategy (2020)

In July 2020, the European Commission proposed and adopted the EU Hydrogen Strategy as part of the Green Deal implementation. The aim is to accelerate the development of renewable (green) hydrogen. The plan consists in three phases:

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[11] *Paris Agreement*, 2015, Art. 4, par. 19

[12] UNFCCC, *Outcome of the first global stocktake*, 2023, par. 28(e)

[13] *Communication on the European Green Deal*, 2019

- First phase, 2020-2024: install at least 6 GW of renewable hydrogen electrolysers in the EU and produce up to 1 million tons of renewable hydrogen. The key point to be achieved are: decarbonize existing hydrogen production, especially in the chemical industry, and expanding hydrogen into new application areas, such as industrial processes and transport.
- Second phase, 2025-2030: install at least 40 GW of renewable hydrogen electrolysers by 3020 and produce up to 10 million tons of renewable hydrogen in the EU. This phase, which is probably the most relevant from the perspective of this thesis, hydrogen becomes a core part of the EU's integrated energy system, supporting steelmaking, heavy transport, electricity storage and grid balancing. Local hydrogen ecosystems (the so called "Hydrogen Valleys") will emerge, and hydrogen infrastructures will be planned, including refueling stations, storage and cross-border pipelines. The EU also aims to establish a competitive hydrogen market and develop international trade routes, especially with neighboring regions.
- Third phase, 2030-2050: make the hydrogen technologies reach maturity and deploy them at large scale to reach all hard-to-decarbonize sectors. Hydrogen and synthetic fuels derived from it will play a growing role in areas such as aviation, shipping, heavy industry and commercial buildings, expecting by 2050 that around 25% of renewable electricity may be used for hydrogen production.

Fit for 55 Package (2021)

Aimed at reducing EU greenhouse gas emission by at least 55% by 2030, the Fit for 55 Package is a set of laws, supporting the transition towards climate neutrality by 2050. It was presented by the European Commission in 2021, as part of the Green Deal. The package ensures a just and socially fair transition, maintaining and strengthening innovation and competitiveness of EU industry, while reinforcing the EU's position as leading actor in the global fight against climate change. The Fit for 55 package is essential for green hydrogen because it creates strong incentives to shift away from fossil fuels by reducing emissions and increasing carbon pricing and promoting hydrogen use in heavy transport and industry through stricter $CO_2$ standards.

### 1.4.3 Regulations and Directives in EU

TEN-E Regulation (2022)

The Trans-European Networks for Energy, better known as TEN-E, took effect in June 2022, aligning with the European Green Deal and Fit for 55 climate targets. Under TEN-E, PCIs (Projects of Common Interest) and PMIs (Projects of Mutual Interest with non-EU partners) must now meet mandatory sustainability standards. Fossil fuels and oil infrastructures have now lost eligibility, while priorities became hydrogen networks development, large electrolysers construction, offshore electricity grids, smart electricity systems and $CO_2$ transport and storage.

Directive (EU) 2023/2413 of the European Parliament and of the Council (2023)

Directive (EU) 2023/2413, known as RED III was adopted and published in 2023. It revised the previous Renewable Energy Directive, RED II, and updates and amends EU's renewable energy framework, aligning with the European Green Deal and Fit-for-55 package, to raise attention across sectors and promote renewable fuels such as green hydrogen and other RFNBOs. It sets some ambitious targets: at least 42.5% of energy must come from renewable sources by 2030, and 42% of clean hydrogen is required to be used in industry by 2030 (and 35% by 2028). The directive also extends the use of RFNBOs beyond transport to industry, power and heating, reinforcing the role of green hydrogen in the EU energy system.

<u>Hydrogen and Decarbonized Gas Market Package (2024)</u>

It consists in two legal documents, Directive (EU) 2024/1788 and Regulation (EU) 2024/1789, which were adopted in May 2024. Part of the Fit for 55, the Package revises and defines new and firm norms for integrating renewable and low-carbon gases into the energy market. It introduces rules especially for hydrogen, regarding infrastructures, certifications, consumer rights and market access. A new body, the European Network of Network Operators for Hydrogen (ENNOH), will manage the cooperation of EU hydrogen networks. Key targets include 10 Mt of renewable hydrogen production and 10 Mt of imports by 2030, along with reaching 40 GW of electrolyser capacity. The Hydrogen Bank Mechanism, launched in September 2025, will match supply and demand to stimulate market growth.

## 1.5 The Hydrogen Supply Chain

In this section of this thesis, we will focus on the green hydrogen supply chain (HSC). It appears as a multifaceted system comprising interconnected stages, each shaped by technical, economic and environmental constraints: those are feedstock (the sourcing), production, storage, distribution and end application (*Figure 3*). Because this innovative technology is still emerging, high uncertainty remains throughout the entire supply chain. For instance, green hydrogen production depends on renewable electricity sources such as solar, wind, hydro and geothermal, and so their geographic availability, performance and distribution must be carefully considered. Decisions made in production, such as scale, geographic location or type of applications, directly influence storage forms and thus logistics transportation means (Sgarbossa et al, 2023). Storage can be used strategically to shift demand and supply across season, but also as a buffer for smoothing short-term supply and demand mismatches due to operational uncertainty (Sgarbossa et al, 2023).

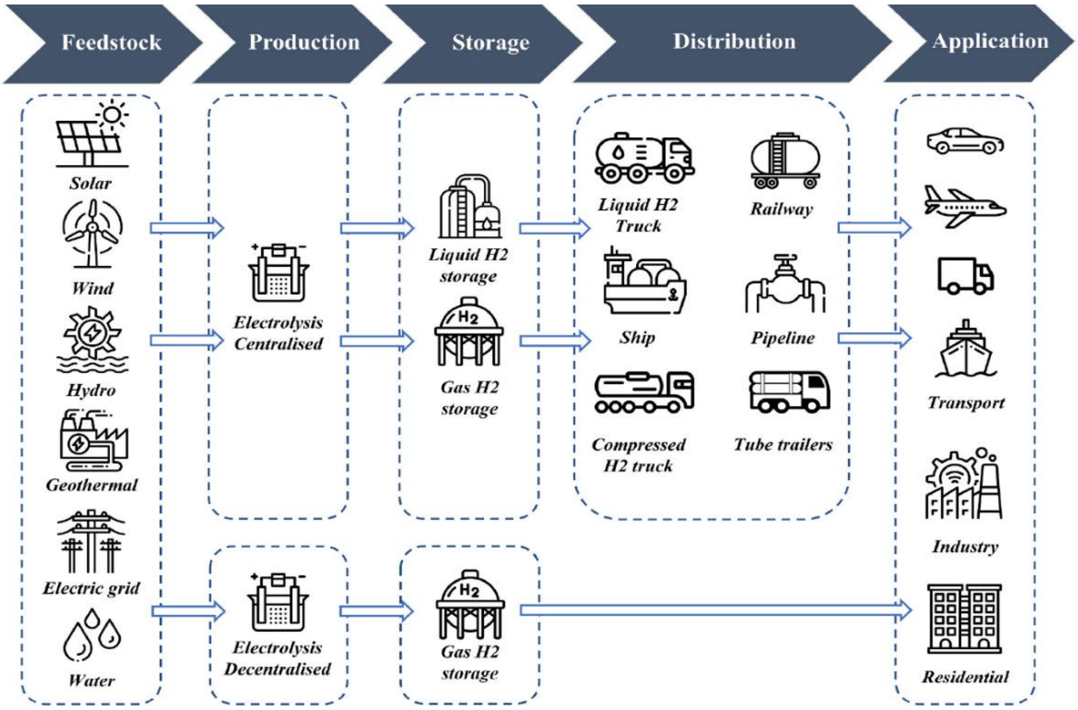

*Figure 3: Superstructure of renewable hydrogen supply chain (Sgarbarossa et al, 2023)*

Similarly, distribution must align with both production capacity and storage formats to ensure a reliable and cost-effective supply. These interdependencies between the HSC's phases show the high complexity of the process, due to its the potential diversity and extensions (scaling of the supply chains and integration with other supply chains) (Sgarbossa et al, 2023). It also highlights that no stage can be optimized alone; instead, to balance cost, efficiency, safety and sustainability, coordinated planning is essential. Furthermore, the design, operation and performance of the supply chain also depend on market development and technology choices, and vice versa. Since technologies used for feedstock, production, storage and distribution have different maturity levels (TRLs[14]), adoption and market development are affected. Existing integrated renewable hydrogen supply chains are often used for pilot and demonstration purposes, in particular configurations called hydrogen hub or valleys, whereas scale-up renewable HSCs are rare but imminent (Sgarbossa et al, 2023). To accelerate technology readiness and enable large-scale adoption, policymakers have been funding R&D since the early 2020s, aiming for stable market growth and maturity, with a time horizon between 2020 and 2050. Understanding these complexities is important for developing robust green hydrogen systems, which must be clearly defined in order to support the technology expansion and enhance international cooperation. The following paragraphs will be dedicated to examine each stage in detail (Sgarbarossa et al, 2023).

### 1.5.1 Sourcing and Production

In order to produce clean hydrogen, water needs to be split into its two molecules, hydrogen and oxygen. Because different processes may be used for this matter, colors have been adopted to indicate the source and the production method of $H_2$. As already stated, the most relevant colors are grey, produced by fossil fuels; blue, produced by fossil fuels while using carbon capture, utilization and storage; and green, produced from water electrolysis using RESs. Although most of the world's hydrogen production today is being produced through a more $CO_2$ intensive process called Steam Methane Reforming (SMR) (Iberdola, *Hydrogen Production*), the preferred production method is in fact water electrolysis, a specific and innovative electrochemical process known for its emission-free characteristics. Sourcing green hydrogen for production though electrolysis involves converting renewable energy inputs such as solar, wind, hydro and geothermal, into electricity. Given the limited availability of these resources, selecting the most cost-effective feedstock requires a careful and prior assessment of their quantity and their potential integration with existing energy systems, including the possibility of imports from other grids. Moreover, the decision of whether to locate hydrogen production facilities near feedstocks or not, leads to different outcomes: proximity to renewable resources allows for more efficient delivery to end-users, whereas greater distances necessitate the development of complex distribution networks. RESs provide a clean and sustainable base for manufacturing processes, preventing the release of greenhouse gases linked to conventional methods of hydrogen production (Sebbagh et al., 2024). However, this is only true for the operational phase (gate-to-gate). A cradle-to-gate view, which includes raw material extraction and electrolyzer manufacturing, reveals emissions from mining, processing, and production. To achieve truly zero emissions, the entire supply chain must reduce its carbon footprint, including more sustainable material sourcing and manufacturing. The electrolysis of water involves splitting water molecules into $H_2$ and $O_2$, when a certain voltage is applied. It comprises two electrodes, an anode and a cathode, immersed in an electrolyte and interacting with it. When the required voltage is applied, specific reactions occur at each

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[14] *Technology Readiness Levels* (TRL) is an agreed and standardized way to assess, in a qualitative way, the maturity of a specific technology or innovation. The hypothesis behind TRL is that the technology development is a progressive process that can be split into clear stages and each represents an increasing degree of maturity and confidence in the technology's ability to function effectively and become a fully commercialized product, deployed for real-world applications. By moving forward through the levels, the risks decreases while the performance, scalability and reliability are increased. The TRLs were proposed at NASA during the 1970s to estimate the maturity of technologies during the acquisition phase in space programs. The concept spread beyond this particular use and the European Commission since 2010 have adopted this scale for the definition of EU-funded research and innovation projects.

electrode's surface. The electrolyte transfers the ions produced in these reactions between the electrodes, resulting in hydrogen being generated at the cathode and oxygen at the anode (*Figure 4*). The specific reactions occurring at the electrodes differ based on the electrolyte and the chosen electrolysis technology.

The fundamental equation describing the process is:

$$H_2O \xrightarrow{Electricity+Heat} H_2 + O_2$$

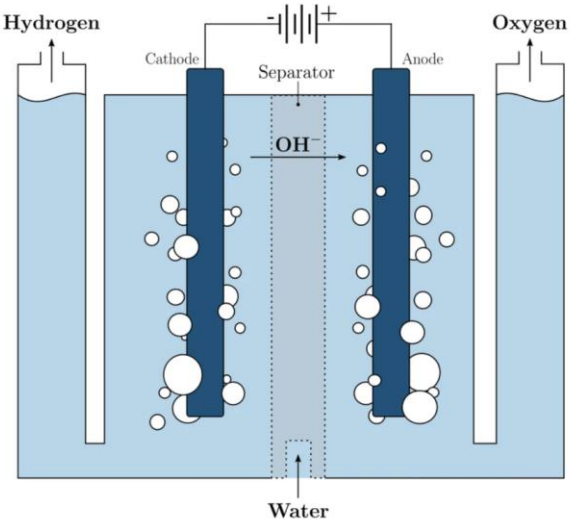

*Figure 4: The electrolysis of water (Stargate Hydrogen, Exploring the Basics of Hydrogen Electrolysis / Water Electrolysis, 2025)*

Water electrolysis still faces other several challenges: scalability, high production costs, low technology performance, lack of infrastructure and few policies and standards for its commercialization (Simões and Santos, 2024).

According to the International Energy Agency's (IEA) global energy review, the total global production in 2021 was 94 million tons (Mt) of $H_2$. Natural gas accounted for 62%, coal for 19%, and naphtha reforming at refineries for 18%. The associated emissions of $CO_2$ were more than 900 Mt. Low-carbon $H_2$ production was less than 1 Mt, with blue $H_2$ accounting for 0.7% of total $H_2$ production and only 0.04% (35 kt H2) for green $H_2$. However, recently, there has been significant research and development into water electrolysis technology, increasing efficiency and lowering overall costs.

The hydrogen sourcing and production stages are closely linked to each other, but also to storage and distribution, making their planning highly complex. Key decisions involve the type, number, location and size of production facilities, often modelled using Mixed Integer Linear Programming (MILP) or Geographic Information System (GIS) approaches to balance facility investment with resource availability and transport costs. Demand levels significantly influence optimal configurations: in early adoption phases, decentralized small-scale production is more convenient because of cost-effectiveness due to lower transport needs, whereas higher adoption favors centralized, large-scale plants benefiting from economies of scale. Factors such as grid electricity use, technology maturity, electrolyser lifetime and cost reductions also affect these decisions, alongside environment and safety.

### 1.5.2 Storage

Hydrogen storage serves two key functions in the supply chain, as stated by Tlili et al : providing seasonal capacity to cope with renewable energy variability and bridging mismatches between production and fluctuating demand for later use in applications. Planning decisions involve the type, number, capacity and location of storage facilities, often supported by MILP modelling, and are tightly linked to production and distribution processes. There are two forms of storage systems, fixed and mobile. The former consists in storing hydrogen at production or consumption sites, where energy generation are the main uses for stationary storage technologies (Maka, 2025). The latter plans to utilize $H_2$ in a moving vehicle or transport it to other locations to utilize or store.

Another classification ideated by Sebbagh et al, consists in the storage techniques, which can be of two types: physical-based and materials-based. Physical-based storage involves storing hydrogen as either a gas or a liquid. Gaseous hydrogen is compressed at high pressures of 350–700 bar in reliable containers for storage, reinforced with carbon fiber. Liquid hydrogen requires being stored in specific tanks that sustain cryogenic temperatures of -252.87°, due to $H_2$ extremely low boiling point. Materials-based storage consists in hydrogen being stored through absorption or adsorption inside or on the surface of solids, such as metal hydrides, nanostructures, porous carbons or chemical carriers that can reversibly release hydrogen. The choice of storage method and technique depends on transport requirements, demand and intended usage duration, with continuous research aimed at improving performance, efficiency and reducing costs.

### 1.5.3 Transportation

In the hydrogen economy, the transportation phase allows the distribution of clean $H_2$ from production sites to end-use locations or storage facilities. Planning decisions are focused on selecting the most efficient distribution infrastructure system, which depends on the amount of production, $H_2$ demand that has to be met, hydrogen's storage technique, and transport distance.

The three main transportation modes are road transportation, pipelines and shipping.

- Road transportation carries hydrogen conveyed mainly in its liquid form (but also as a gas), using specially designed trucks or trailers. This method offers extra flexibility and it is preferred for short distances, while less efficiency is performed for large volumes over long distances. Furthermore, it relies on cryogenic technology to maintain extremely low temperatures.
- Pipelines networks, high-pressure gas cylinders or tube trailers, are dedicated usually to transport hydrogen as a gas, mainly used when volumes are large and distances are long. They offer a fast and reliable delivery with low maintenance costs, though requiring significant upfront investment. Otherwise, already existing natural gas pipelines can be repurposed and converted for the transport of hydrogen.
- Maritime shipping is used for international transport, often by converting hydrogen into ammonia ($NH_3$) or another carrier for easier handling, with reconversion once destination is reached. The transport mean are special ships, provided with larger storage tanks used to safely deliver orders overseas (Maka et al, 2025).

Storage and transportation face several challenges. Firstly, due to hydrogen's low energy density compared to natural gas, larger storage facilities and more reliable and stronger containers are required. Then, processes of compressing or liquefying hydrogen consume a significant amount of energy, with consequent increase of cost and complexity.

IEA's Global Hydrogen Review 2024 reports approximately 5000 km of hydrogen pipelines which are already in operation worldwide, whereas the total length of natural gas pipelines is currently 1 million km (with about 70 000 km under construction and about 160 000 km under consideration). While existing natural gas pipelines can be used for hydrogen transport, blending is typically limited to about 10% by volume, with possible increases to 15–20% or even 50% if investments are made (Sebbagh et al, 2024).

Hydrogen storage and transportation remain major bottlenecks due to limited infrastructure, high costs, safety risks and technical challenges. Current pipelines and storage facilities are scarce and poorly connected, and sometimes not suitable to manage $H_2$ properties, such as its tendency to leak through materials, high flammability and low energy density, all which make handling and storage difficult. Safety concerns demand specialized equipment as well as frequent inspections and carefully designed refueling stations. There are now almost 1200 active stations globally, with only 280 in Europe. This lack of infrastructure creates a "chicken-and-egg" dilemma, as automakers hesitate to expand hydrogen vehicle production without fueling stations and suppliers are reluctant to build stations without demand. Compared to fossil fuels, hydrogen's underdeveloped network limits its market growth, particularly for green hydrogen, highlighting the urgent need for investment in R&D and improvement in aspects like safety and efficiency.

## 1.6 Cost Structure Analysis

Green hydrogen's large-scale infrastructures and production are associated with extremely high costs. Gray hydrogen ($1.50–$2.50/kg) nowadays remains the most cost-effective today but is increasingly constrained by carbon pricing; blue hydrogen ($2.00–$3.50/kg) offers a transitional pathway but depends on CCS costs, natural gas price volatility and regulatory support; green hydrogen ($3.50– $6.00/kg) currently carries a higher price tag, primarily due to the high cost of renewable electricity and electrolyzers, which constitutes a significant share of its production expenditures (Curcio, 2025).

Although cost remains one of the major barriers to large-scale deployment, there is anticipation that the production cost will decline in the future as renewable electricity prices will decrease, mostly driven by surpluses in RESs (Sebbagh et al, 2024), improvements in electrolyzer efficiency and the introduction of policy incentives. For instance, the Inflation Reduction Act (IRA), a law passed in the United States in 2022, provides tax credits of up to $3.00/kg, while other policies aim to lower green hydrogen costs to $1.00/kg by 2031.

We will focus on hydrogen cost analysis based on the findings of Curcio (2025) in *Techno-economic analysis of hydrogen production: Costs, policies, and scalability in the transition to net-zero*. The analysis is based on data from 2015 to 2023 and upon regions of EU, US and Asia Pacific.

### 1.6.1 Production Costs: CAPEX, OPEX and Feedstock

Capital expenditure (CAPEX) refers to significant, long-term investments in tangible assets (like buildings and equipment) that are depreciated over time. In hydrogen production facilities CAPEX comprehend electrolyzers or steam methane reforming (SMR) units, ancillary equipment, site preparation and the grid or pipeline connections. It's no doubt that electrolyzers make up the largest share of such costs, due to the relatively low readiness level (TRL) of such innovative technologies.

As reported in the IEA's Global Hydrogen Report 2024, installed water electrolyser capacity reached 1.4 GW at the end of 2023, almost double the installed capacity at the end of 2022. Alkaline electrolyzers remain the most popular electrolyser type, accounting for more than 60% of the installed electrolyser capacity in 2023, followed by proton exchange membrane (PEM) with 22%. Aalkaline and proton exchange membrane (PEM) electrolyzers currently dominate the market. Alkaline technology offers reliability, cost-effectiveness and are widely used for industrial-scale hydrogen production; PEM on the other hand provide higher efficiency and operational flexibility in intermittent renewable energy contexts, albeit at a higher cost.

In contrast, blue and gray hydrogen projects based on SMR have lower CAPEX, with blue hydrogen requiring the integration of carbon capture and storage (CCS) systems, which makes it fairly more costly than gray. For the main purpose of this thesis, we will focus only on green hydrogen, and the relative costs of electrolysis machinery.

The CAPEX for green hydrogen includes more specifically the cost of electrolyzer stacks, which represent about 50% of the uninstalled system, with the rest being the balance of plant (BoP) components, such as power supply unit (including the rectifier), cooling systems, water purification, oxygen separator tank, hydrogen compression, circulation pumps, piping and integration of renewable energy sources. Finally, installation costs amount to half of the final installed cost as represented in *Figure 5*.

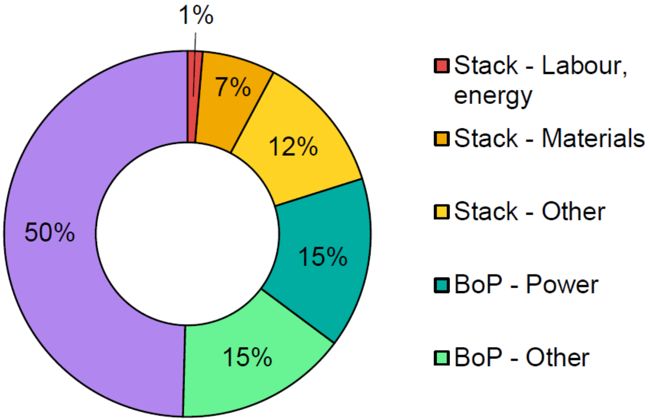

*Figure 5: CAPEX of a PEM electrolyser by component (Global Hydrogen Report 2023, IEA)*

The CAPEX value ranges from \$1500 to \$2500/kW for small-scale (1 MW) plants and \$800 to \$1500/kW for large-scale (100 MW) plants, reflecting significant economies of scale. Electrolyzers cost can range between \$800-\$1700/kW, depending on scale, efficiency and technology maturity.

Operational expenditure (OPEX) covers recurring, day-to-day costs which are expensed in the year they're incurred. It includes raw materials, routine maintenance, labor, energy consumption or rent. Green hydrogen generally has lower maintenance costs due to the simplicity of electrolyzer systems, but electricity costs dominate its OPEX, often resulting in 50–70% of total operating expenses. The cost of electricity varies widely depending on the availability and price of renewable energy. These expenses are calculated per unit of hydrogen produced; estimates range from \$0.04 to \$0.09/kg $H_2$ for 1 MW systems and \$0.02 to \$0.06/kg $H_2$ for 100 MW systems. Again, economies of scale are reached for larger volumes produced.

Feedstock costs represent the largest portion of the overall expenses in hydrogen production. For green hydrogen, the primary feedstock is electricity, and its cost structure is highly dependent on the availability of low-cost renewable power, which can come from wind, hydro, solar or geothermal sources. Green $H_2$ costs generally stay between \$1.50-\$3.00/kg $H_2$, depending on renewable energy prices.

Across all the value chain, production costs constitute approximately 90% of the total hydrogen costs, with transportation and storage being less than 10% and 5%, respectively. This distribution underscores the central role of production efficiency aiming at reducing costs, particularly in high-capacity facilities where economies of scale can be fully achieved.

The overall price of electricity generated from solar PV (Photovoltaics System) and wind sources has indeed decreased in the last decade, which led to significantly lower the cost of $H_2$ produced from electrolysis. However, to compete with conventional methods, its price must continue decreasing (Simões and Santos, 2024).

Another point of reflection is the learning rate. The learning rate shows how a technology's cost drops as we produce more of it. Essentially, the more we make, the better and more efficient we get at producing it, thanks to an increased expertise, often called learning-by-doing, along with economies of scale each subsequent unit cheaper to produce. In this context, the rate plays a crucial role in determining the cost trajectory of green hydrogen production. A higher learning rate accelerates cost reductions, while a lower rate slows progress. Sensitivity analyses conducted by Simões & Santos show that the learning rate has the strongest impact on PV-based hydrogen due to its limited annual operating hours. For example, raising the learning rate to 24% lowers PV hydrogen costs by up to 8.4%.

Advancing R&D and industrialization of green hydrogen technologies is therefore essential not only to improve economic feasibility, support carbon neutrality goals and enable large-scale deployment, but also effectively reduce costs related to production.

### 1.6.2 Transportation Costs

Hydrogen transportation costs vary depending on the mode and scale of delivery and on hydrogen storage state. Transport via hydrogen pipelines, as seen in the previous paragraph, is generally the most efficient for large volumes and long distances distribution. However, we need to distinguish between dedicated hydrogen pipeline and natural gas pipeline. The former is in fact, significantly more expensive than the latter, due to hydrogen's high diffusivity that leads to risks of steel embrittlement. To prevent leakages and degradation from happening, specialized alloys or internal coatings are needed.

It is possible to repurpose existing natural gas pipelines, that can indeed reduce capital costs by 50–70%, compared to building new ones; however, technical feasibility depends heavily on material compatibility and embrittlement still remains a central concern. A comparative analysis about pipelines cost has been conducted based on available case studies as shown in *Table 1*.

*Table 1: Pipeline transportation costs ($/Kg) (Curcio et al, 2025)*

| Pipeline Type | CAPEX ($/km) | OPEX ($/kg $H_2$) | Maximum Capacity (tons/ day) | Estimated Energy Loss (%) |
|---|---|---|---|---|
| New hydrogen pipeline | 1.0 M – 2.0 M | 0.10–0.15 | 100–500 | 0.5–1 |
| Repurposed gas pipeline | 0.3 M – 0.6 M | 0.07–0.10 | 50–300 | 1–2 |

Furthermore, it has been noticed that the cost-effectiveness of pipelines improves substantially when utilization rates are high, especially in regions with concentrated industrial demand, whereas in low-demand regions alternative methods must be considered.

For international and very long-distance transport, liquefied hydrogen ($LH_2$) shipping becomes a key consideration. Hydrogen must be cooled down to liquefy to extremely low temperatures, a process that consumes 30–40% of its energy content. Capital expenses (CAPEX) range from $300 million to $1 billion, while operational expenses (OPEX) include electricity and maintenance of cryogenic systems. Costs are further increased by boil-off losses of 0.2–0.4% per day, which makes this transport both capital and energy-intensive, as seen in *Table 2*. As a result, $LH_2$ transport with ships is generally recommended when distances are greater than 2000 km, where instead pipelines become impractical.

*Table 2: LHS transportation costs ($/Kg) (Curcio et al, 2025)*

| Transport Mode | Liquefaction Cost ($/kg $H_2$) | Shipping Cost ($/kg $H_2$ per 1000 km) | Boil-Off Losses (%) |
|---|---|---|---|
| LH2 (large-scale ship) | 1.5–2.0 | 0.50–1.20 | 0.2–0.4 |
| LH2 (small-scale barge) | 2.0–3.0 | 1.00–2.00 | 0.3–0.5 |

Compressed hydrogen trucking is primarily suited to local distribution networks and short distances between 200 and 500 km. The cost structure, presented in *Table 3* is influenced by storage pressure, trailer capacity and fueling infrastructure. Higher pressures can reduce cost per kg of hydrogen delivered but increase CAPEX for reinforced composite storage tanks. Beyond its optimal range, compressed trucking becomes less competitive than pipeline or $LH_2$ transport.

*Table 3: Compressed transportation costs ($/Kg) (Curcio et al, 2025)*

| Transport Mode | Compression Cost ($/kg $H_2$) | Trucking Cost ($/kg $H_2$ per 1000 km) | Storage Pressure (bar) |
|---|---|---|---|
| High-pressure tube trailer | 0.5–1.0 | 2.00–5.00 | 350–700 |
| Cryo-compressed truck | 1.0–1.5 | 1.50–3.50 | 250–400 |

An alternative to direct hydrogen transport is the use of material-based storage methods through chemical carriers such as ammonia ($NH_3$) or liquid organic hydrogen carriers (LOHCs). These allow a reduction of costs, since now hydrogen transported under ambient conditions, avoiding the need for high-pressure or cryogenic systems.

However, both options eventually require conversion and reconversion infrastructure, which add costs and results in efficiency losses. *Table 4* summarizes overall costs comparing ammonia with LOHCs.

*Table 4: Hydrogen carrier transportation costs ($/Kg) (Curcio et al, 2025)*

| Carrier Type | Synthesis Cost ($/kg $H_2$) | Transport Cost ($/kg $H_2$ per 1000 km) | Reconversion Cost ($/kg $H_2$) |
|---|---|---|---|
| Ammonia | 1.0–1.5 | 0.30–0.70 | 0.75–1.50 |
| LOHCs | 1.2–1.8 | 0.50–1.00 | 1.00–2.00 |

Despite these challenges, ammonia is emerging as a leading hydrogen carrier due to its established global shipping network and relatively straightforward storage conditions.

### 1.6.3 Storage Costs

Compressed hydrogen storage is the most used storage method for short-term and mobile applications, which include fuel cell vehicles, transport logistics and local industrial facilities. $H_2$ is typically stored at pressures of 350–700 bar to increase its energy density, therefore the need for specialized materials and energy-intensive compression processes makes this storage rather costly.

Liquefied hydrogen storage offers higher volumetric energy density than compressed storage by cooling hydrogen to –253 °C. This allows for larger quantities to be stored in a smaller footprint, but the liquefaction process consumes 30–40% of the hydrogen's total energy content and cryogenic storage facilities have high capital and operational costs. Maintaining such low temperatures also results in boil-off losses of 0.1–0.5% per day. Consequently, $LH_2$ storage is more appropriate for large-scale hydrogen hubs or as part of long-distance transport systems rather than small-scale applications.

Chemical storage options, including ammonia, LOHCs and metal hydrides, enable hydrogen to be stored at ambient pressure and temperature. These methods avoid the cost of high-pressure tanks and cryogenic systems but introduce additional synthesis and reconversion costs as well as significant energy losses, often between 25% and 50%. Ammonia synthesis costs range from \$1.20 to \$1.80/kg $H_2$, LOHCs from \$1.50 to \$2.20/kg $H_2$, and metal hydrides from \$2.20 to \$3.50/kg $H_2$, with reconversion costs adding up to several dollars more per kilogram.

Another potential form of storage, which has not been mentioned before, involves underground geological formations. Among others, salt caverns are the most frequent: they represent large-scale, seasonal and long-term storage solutions, which offer capital costs (around \$0.15–\$0.60/kg $H_2$) and high cycle efficiencies of 75–95%, making them ideally suitable for industrial storage. However, the eventuality of such formations depends on local geology and extensive assessment; moreover, regulatory approvals and long-term monitoring are required to manage leakage and contamination risks.

As shown in *Table 5,* CAPEX (capital investment in infrastructure), OPEX (operating expenditures) and energy losses are the three main key factors affecting the cost of hydrogen storage.

*Table 5: Cost and performance of hydrogen storage system (Curcio et al, 2025)*

| Storage Method | CAPEX (\$/kg $H_2$) | OPEX (\$/kg $H_2$/yr) | Energy Loss (%) | Ideal Use |
|---|---|---|---|---|
| Compressed gas (700 bar) | 1200–2700 | 9–18 | 10–15 | Short tem mobile applications |
| Liquid hydrogen | 1800–3800 | 45–85 | 25–30 | Long distance transport |
| Salt caverns | 0.15–0.60 | 0.02–0.07 | 5–10 | Seasonal/large scale storage |
| Ammonia | 1.0–1.8 | 0.35–0.80 | 25–40 | International trade |
| LOHCs | 1.2–1.8 | 0.55–1.10 | 30–45 | Medium term centralized storage |
| Metal hydrides | 2.2–3.5 | 0.90 1.80 | 35–50 | Niche applications |

Liquid hydrogen pays the highest amount of CAPEX because of the $H_2$'s cryogenic chilling to extremely low temperatures, which results in daily high boil-off losses. Compressed gas is a close second as it requires high-pressure tanks made of costly composite materials, in addition to compression procedures which translates in cost increases. The lowest cost is achieved by underground storage in salt caverns; however, downsides include limited applicability due to geological constraints.

### 1.6.4 Levelized Cost of Hydrogen (LCOH)

The hydrogen industry is growing, with a vast number of projects active worldwide, each with unique characteristics, objectives, scale and technology. The previous cost structure analysis has identified the following key financial components involved in producing hydrogen: CAPEX, OPEX, feedstock, distribution, storage. However, it is important to highlight that simply summing these costs to determine a project's economic competitiveness is both incorrect and misleading. Instead, we need a single and standardized metric that incorporates all these costs. This is where the levelized cost of hydrogen (LCOH) comes into act. LCOH is an essential indicator used to calculate the average cost of hydrogen production throughout its entire lifecycle (Li et al, 2025), but most importantly to evaluate a hydrogen project's long-term economic viability and compare it with others. It's not a simple sum of all expenses; rather, it represents the average cost per kilogram of hydrogen ($/kg) over the entire project's lifespan.

Overall, green hydrogen is currently the most expensive among other “color” type of options but could become more viable as technology and renewable prices improve. Blue hydrogen offers a lower-cost medium-term option dependent on CCS and carbon policies, while gray hydrogen is cheapest today but increasingly constrained by regulatory and environmental pressures.

An interesting insight come from the European Hydrogen Observatory, which provides the levelized cost of hydrogen production by technology in Europe in 2022 and 2023 (*Table 6*). Since our main focus is green hydrogen, we will compare costs sustained for only water electrolysis with a direct connection to a renewable energy source (renewable hydrogen).

*Table 6: Levelised cost of hydrogen production in Europe in 2022 and 2023 (European Hydrogen Observatory)*

| | **Year** | **Year** |
|---|---|---|
| | 2022 | 2023 |
| **Cost** | **Value (€/kg)** | **Value (€/kg)** |
| CAPEX | 66,00152666 | 109,8590616 |
| Electricity costs | 120,5834837 | 75,96434109 |
| Other OPEX | 18,77914526 | 4,389491533 |

CAPEX more than doubles, suggesting higher upfront investment per unit of hydrogen in 2023 compared to 2022. This increase could be due to factors such as simple infrastructure expansion, but may also be a result of inflation, supply chain issues or rising interest rates on capital. On the other hand, the electricity cost shows the largest improvement, going from 120.6 €/kg in 2022 to 76.0 €/kg in 2023. Since electricity is the dominant cost driver in electrolysis, there is a general cost reduction. This aligns with what discussed previously. Other OPEX represent another contributing factor, of course, because that also registered a substantial fall, from 18.8 €/kg to 4.4 €/kg, suggesting efficiency gains in operations or reduced ancillary costs.

## 1.7 Market Dynamics

### 1.7.1 Investment and Green Hydrogen Large-Scale Projects

Nowadays, there are still limited infrastructure, whose investment remains one of the most significant bottlenecks for large-scale green hydrogen projects. Although global investments in renewable energy reached $0.5 trillion in 2022 (Global Hydrogen Review 2024, IEA), this was not enough to match the annual levels required to stay on a 1.5 °C trajectory. The World Bank and Organisation for Economic Co-operation and Development (OECD) estimate that emerging markets and developing economies (excluding China) alone require $100 billion annually for hydrogen investments, with external financial support needs ranging between $10 and $40 billion per year until 2030.

High financing costs, combined with regulatory risks, discourage many investors from entering the sector, particularly in developing countries, where there is abundant but underutilized renewable energy potential due to limited access to capital. On the other hand, a major obstacle to scaling up green hydrogen lies in its relatively high production costs compared to grey hydrogen, with renewable electricity and electrolyser facilities being the primary cost drivers (IRENA, 2020). E. Curcio studies about cost assessment state that in regions where renewable resources are abundant, green hydrogen production could lower to $2.50–$3.50/kg by 2030, making it increasingly competitive.

In the last few years, there has been registered a substantial growth in hydrogen projects and production capacity, hence supply, highlighting once again the central role of this technology in achieving sustainability and carbon neutrality. Figure 6 reports a noticeable increase, especially from 2024 onwards, when considering both the yearly sum of the individual projects (black blocks) and the cumulative total (black line), mainly due to the technical advancements in hydrogen technologies such as RES-powered electrolysis (Evro et al, 2024).

It is extremely important, however, to distinguish between *supply* and *projects*, as they do not represent the same concept. Supply refers to the actual volume of green hydrogen currently being produced by operational facilities, whereas projects might be either operational or still in the planning, financing or permitting stage. Therefore, even though currently there are hundreds ongoing projects, which certainly indicate future potential, only operational projects must be considered for contributing to real supply today, which is much smaller.

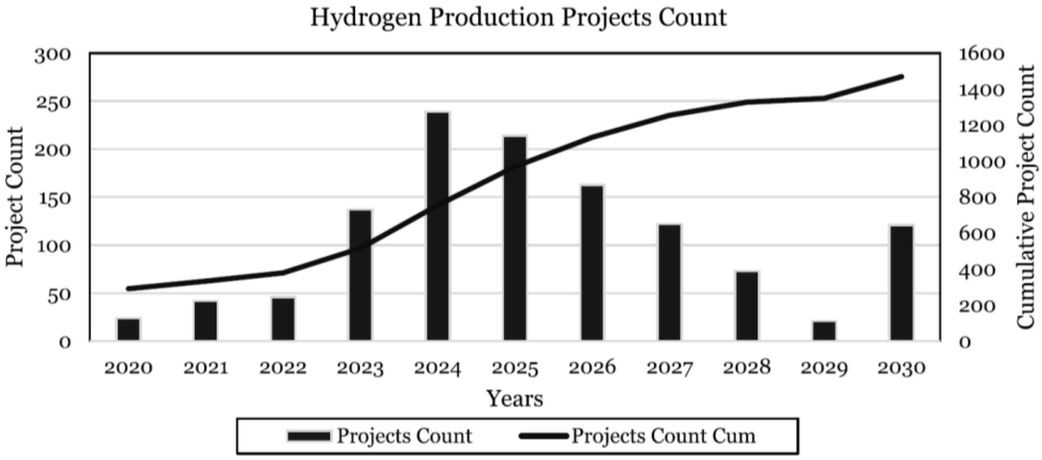

*Figure 6: Hydrogen production projects count as of January 2024 (Evro et al, 2024)*

Of course, such amount of large-scale hydrogen initiatives worldwide necessitates of parallel investment in infrastructures. For instance, in October 2022, over 680 large-scale hydrogen projects were worth $240 billion investment in hydrogen infrastructure (Evro et al, 2024), pointing out strategic efforts in integrating hydrogen across various industries, including transportation, industrial processes and as energy storage.

As of September 2024, the Hydrogen Council reported some quite promising data in their *Hydrogen Insights September 2024:* 1572 clean hydrogen projects have been announced globally, 1125 of which have a commercial operations date (COD) through 2030; $680 billion have been announced in direct investments in hydrogen value chains through 2030; $75 billion have been invested in projects that have passed final investment decision (FID) stage; 48 Mt p.a. of clean hydrogen supply through 2030 have been announced, of which 75% is renewable and 25% is low-carbon. As we can see from the map in *Figure 7*, there is a major concentration of projects in Europe, which in fact holds the greatest number of initiatives (617) as well as the highest total investments announced (USD 199 billion), however China leads in in terms of committed projects and could account for almost 70% of 2024 capacity (Global Hydrogen Review 2024, IEA).

*Figure 7: Global project overview worldwide (Hydrogen Insights September 2024, Hydrogen Council)*

Another visual representation is provided by the International Energy Agency through an interactive global map (*Figure 8*), which features operational and announced projects to produce low-emissions hydrogen, classified by technology route and status, from concept to operation (IEA, 2024). Among the 1485 project that IEA retrieved, we can see a high concentration of hydrogen production valleys and clusters in the European region, especially in the central area, coherently with the previous map.

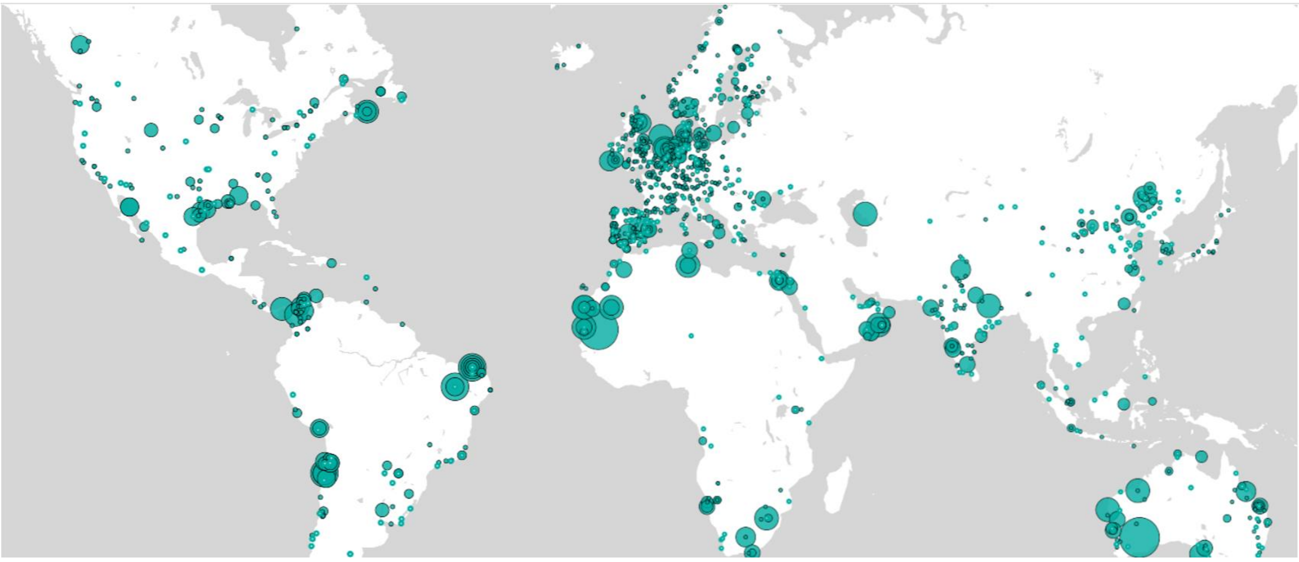

*Figure 8: Map of low-emissions hydrogen production worldwide (IEA, 2025)*

Nevertheless, balancing supply and demand is one of the most central challenges. As a matter of fact, "in Europe, there is a geographical and temporal mismatch between areas with a high potential for renewable energy generation and hydrogen demand hotspots"[15]. Indeed, numerous gaps exist between high supply regions with very limited demand.

Major organizations are actively addressing this issue. IRENA in its report *International Co-operation to Accelerate Green Hydrogen Development*, a brief from the IRENA Collaborative Framework on Green Hydrogen, offers some key insights about the current state of supply and demand.

On the supply side:

- The global green hydrogen project pipeline is still nascent, mainly concentrated in Europe and Asia, with China, Germany, Spain and Australia accounting for 50% of planned or installed capacity. The other half of the capacity still remains in the announcement phase, with only a small portion operational.
- High financing costs continue to represent a major barrier, especially in developing countries where there is easy access to renewable energy.
- Successful large-scale infrastructure deployment would require de-risking, risk-sharing, tailored financial mechanisms, community involvement and learning from best practices.

On the demand side:

- Progress in creating demand has been modest, and governments and companies must make efforts to generate more.
- Regulation and policy making should be maintained and strengthened in order to fully support green hydrogen deployment. In 2023 several bold regulatory and policy developments have been undertaken, such as the adoption of the Delegated Acts under the European Renewable Energy Directive, to stimulate demand.

Many are the efforts and incentives aiming at closing the gap between supply and demand (some of which are discussed in the following paragraphs) but even more effective actions must be pursued. Among them, regulatory transparency, investment support and international collaboration are essential for accelerating production and adoption.

### 1.7.2 The Inconsistencies of Supply and Demand

Supply of green hydrogen represents a small share of the overall hydrogen production; the big majority of produced $H_2$ indeed still mainly relies on fossil fuels and CUSS technologies. In 2020, hydrogen output reached 90 Mt, but only 0,03% came from water electrolysis (Wappler et al, 2022).

The following years, the situation remained the same. According to the yearly Global Hydrogen Reviews by IEA:

- In 2021, total global production was 94 million Mt $H_2$ with only 35 kt $H_2$ (0,04%) from electricity via water electrolysis, which increased by almost 20% compared to 2020;
- In 2022, total global production reached almost 95 Mt, but again $H_2$ produced from water electrolysis continued to be relatively small, with a 35% growth compared to the previous year (remaining still below 100 kt);
- And in 2023 total global hydrogen production accounted for 97 Mt, with green hydrogen reaching 100 kt.

Even though green $H_2$ volumes persist to be marginal compared to the total hydrogen production, growth is visible, with Europe and Asia leading the way especially through pilot projects and low-scale initiatives. However, most of them remain in the announcement phase and have not yet reached final investment decision. Moreover, supply growth is geographically uneven: while Europe, Asia and North America are advancing, many developing countries are still very behind facing high financing costs and risks despite abundant renewable energy potential. At the same time, electrolyser technologies

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[15] Hydrogen Europe, *Hydrogen Infrastructure Report – The recipe for a hydrogen grid action plan*, October 2024; https://hydrogeneurope.eu/wp-content/uploads/2024/10/2024.10_HE_.Hydrogen-Infrastructure-Report.pdf.

are still innovating and the benefits of cost reductions through economies of scale cannot yet be reached. With a more positive view, both Hydrogen Council and IEA stated that companies have announced 48-49 Mt p.a.[16] of clean hydrogen production capacity globally through 2030, of which about 9% of volume is in committed and 50% is in the planning stage. Overall, announced projects and future perspective highlight strong advancements. To continuing foster green hydrogen supply, other than policies and Government incentives, sufficient renewable energy and hydrogen production capacities, through electrolyzer installations, must be ensured. Looking forward, global green hydrogen deployment is projected to accelerate significantly after 2025 as projects reach final investment decision, incentive schemes take effect and infrastructure begins to scale. IRENA predicts a production in 2030 of 3 EJ (15 Mt $H_2$) reaching 19 EJ (95 Mt) in 2030[17].

On the demand side, progress has been quite modest. Current global hydrogen use (100 Mt in year 2024) is overwhelmingly fossil-based (Younus et al, 2025), and demand for green hydrogen in new sectors (steel, heavy transport, shipping, power) is minimal, showing how current demand is too little (below 1% of total demand) to keep pace with supply ambitions. Many regulatory initiatives have been promoted, such as the EU Renewable Energy Directive, Japan's hydrogen subsidies and U.S. Inflation Reduction Act, aimed at stimulating demand. Yet, stronger and more coordinated global efforts are required to ensure that demand growth aligns with supply expansion.

IRENA's Cooperative Framework on Green Hydrogen (CFGH) serves a global platform for dialogue and co-operation, where member countries are invited to share updates on recent green-hydrogen-related developments, which may include policies discussion, incentive schemes for demand and supply creations, challenges and ongoing projects. In this CFGH, IRENA reported, for instance, that Australia's ambition for green hydrogen is to achieve net-zero by 2050 and a 43% emissions reduction by 2030. China, considered the world's largest hydrogen producer, mainly from fossil fuels, aims to scale green hydrogen through the 2021–2035 Hydrogen Energy Plan[18]. United States focuses on decarbonizing hard-to-abate sectors, lowering hydrogen production costs, and more importantly creating regional hydrogen networks.

Regarding the European countries, practical advancements have been registered as well.

- Austria's 2022 national hydrogen strategy aims to decarbonize its economy and energy system by supporting hydrogen both across the entire value chain and its entering into industrial applications and mobility sectors. Austria plans to boost renewable hydrogen demand, build infrastructure, stimulate production investments and promote sustainable business models, with €3 billion available funds through 2030.
- The Netherlands is transitioning to a whole green hydrogen hub, building pipelines and shipping corridors, while promoting certification and new hydrogen carriers.
- Portugal aims to cut greenhouse gas emissions by 55% and accelerate green hydrogen adoption by 2030, while renewables will supply 80% of electricity by 2026.
- Sweden is sustaining green hydrogen and e-fuels advancements to decarbonize sectors like steel, mining, shipping and aviation, with supports coming from the government, the industry and EU. Sweden also leverages low-carbon electricity usage, low costs and a prepared workforce.

Furthermore, in the European Union, two delegated acts (CDR 2023/1184 and 2023/1185) under the Renewable Energy Directive set rules for renewable electricity use in hydrogen production, while ensuring temporal and geographical

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[16] Per Annum.

[17] Conversion from EJ to Mt made by Wappler et al., 2025.

[18] "China's medium- and long-term hydrogen plan targets 50,000 hydrogen fuel-cell vehicles and 100,000–200,000 tonnes/year of green hydrogen production by 2025, supported by the rollout of hydrogen refueling stations. The strategy promotes clean hydrogen use across transport, energy storage, power generation, and industry", International Energy Agency (2021), *Hydrogen Industry Development Plan (2021–2035)*; https://www.iea.org/policies/16977-hydrogen-industry-development-plan-2021-2035.

correlation and establishing criteria for GHG emission savings. These regulations apply to both domestic producers and international exporters to the EU. Another major contributor to the mission of increasing green $H_2$ demand is the European Hydrogen Bank (EHB), an important financing institution that complements these regulations by creating investment security and business opportunities for European and global renewable hydrogen production. Among its goals, the most relevant are creating a domestic EU market, facilitating imports, connecting renewable energy supply to EU demand, bridging the cost gap between renewable hydrogen and fossil fuels. One important event happened in November 2023, when the EHB launched its first bank auction for renewable hydrogen projects, awarding nearly €720 million to 7 renewable hydrogen projects across Europe[19]. If such projects succeed to start producing within 5 years, "they have the potential to produce 1.52 million tonnes of renewable hydrogen in their first 10 years of operation, avoiding more than 10 million tonnes of $CO_2$ emissions"[20].

In summary, this chapter is intended to reveal an overview of the enormous green hydrogen landscape, introducing the most relevant related concepts of sustainability, economy and technology. Ultimately, however, it noticeable how the development of green hydrogen is not only a matter of technology innovation, but also of international cooperation and governance, and the ability to build strong ecosystems across regions. From the European Hydrogen Bank to China's national strategy, recent initiatives show how governments, industries and institutions have come together to reach one common goal: connect supply and demand and set the bases for green hydrogen global market establishment. This broader perspective naturally leads into the next chapter, which will examine the business models and forms of collaboration that can support the growth of green hydrogen and its role in the energy transition.

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[19] European Commission (2024), *European Hydrogen Bank auction provides €720 million for renewable hydrogen production in Europe*; https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2333

[20] European Commission (2025), *European Hydrogen Bank;* https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/european-hydrogen-bank_en.

# 2 - LITERATURE REVIEW

This section is dedicated to the literature review, which provides a clear and concise overview of existing knowledge relevant to the thesis research topic.

## 2.1 Building Network Ecosystems: Supply Chains, Knowledge Sharing and Key Players

### 2.1.1 Advancing towards large-scale infrastructure establishing Hydrogen Hubs and Valleys

By the end of 2023, 99.9% of global hydrogen production still relied on fossil fuels, with green hydrogen representing only a negligible share (IEA, 2024). As discussed in the previous chapter, this technology holds significant potential as a renewable energy carrier for electricity generation and for decarbonizing hard-to-abate sectors, thereby contributing to the reduction of $CO_2$ emissions. In recent years, research activity in this field has grown considerably; however, only a limited number of technologies have reached a sufficiently high Technology Readiness Level (TRL) to enable effective commercialization. And while enthusiasm surrounding green hydrogen is spreading, no substantial growth has yet been achieved and key sectors are still very few: considering overall hydrogen production, the annual growth rate remains at only 1–2% (IEA, 2024), far below what is required to meet the 2030 sustainability targets. The trajectory of innovation is indeed rarely linear; rather, it is complex and often tortuous, shaped by a wide range of variables. What mostly affect the slow pace of progress are the high capital entry costs, lack of infrastructure, low efficiency, uncertain demand and strong dependence on renewable energy. As previously emphasized, scaling green hydrogen requires a comprehensive supply chain supported by effective governance, both of which are critical for successful implementation in the form of specific regional clusters or configurations. Of the 60 published national hydrogen roadmaps, 14 explicitly refer to the creation of co-located systems described with terms such as "hydrogen valleys," "hydrogen ecosystems," and "hydrogen hubs" (Karplus et al, 2025). A clear definition is provided by the Clean Hydrogen Partnership: "*Hydrogen Valleys are hydrogen ecosystems that cover a specific geography ranging from local or regional focus (e.g. industrial cluster, ports, airports, etc.) to specific national or international regions (e.g. cross border hydrogen corridors)190. Hydrogen Valleys showcase the versatility of hydrogen by supplying several sectors in their geography such as mobility, industry and energy end uses. They are ecosystems or clusters where various final applications share a common hydrogen supply infrastructure. Across their geographic scope, Hydrogen Valleys cover multiple steps in the hydrogen value chain, ranging from hydrogen production (and often even dedicated renewables production) to the subsequent storage of hydrogen and distribution to off-takers*"[21] (*Figure 9*). The great potential and singularity of hydrogen hubs have been recognized as early as 2019, as demonstrated by the International Energy Agency's groundbreaking publication "The Future of Hydrogen." A key goal that has already been set within this now-classic publication is to "make industrial clusters the nerve centers for scaling up the use of clean hydrogen." Indeed, according to this publication, a growing demand for hydrogen among major sectors holds tremendous promise for developing hubs aimed at reducing the costs of low-carbon hydrogen production options and unleashing new sources of demand among industries, as situating co-related clusters can create favorable conditions through often existing interconnections. Coastal industrial clusters, especially those that are also strategically related to a port, have also emerged as promising hubs due to an already present demand for hydrogen (IEA, 2019).

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[21] Clean Hydrogen Partnership. *Hydrogen Valleys*. Source: https://www.clean-hydrogen.europa.eu/get-involved/hydrogen-valleys_en

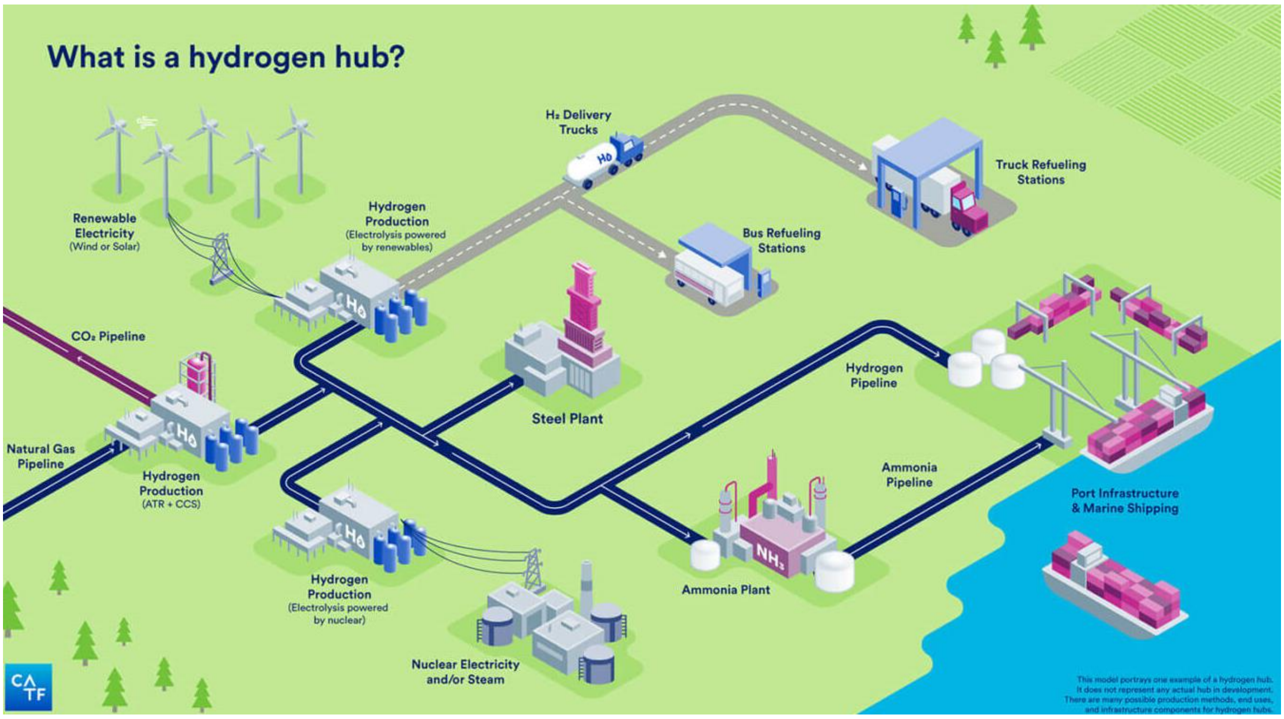

*Figure 9: The structure of a hydrogen hub (Clean Air Task Force, 2025)*

To effectively foster the development of green hydrogen, it is essential to move beyond small-scale pilot projects and adopt strategies that enable its large-scale penetration (Franco, 2025) and, at the same time, scaling hydrogen demand is required. For instance, producing one ton of steel entails approximately 70 kg of hydrogen, meaning large steel plants (over 1 million tons/year) need hydrogen production capacities of several gigawatts of renewable energy. Therefore, given the massive production facilities in these sectors and the high energy requirements, it is unrealistic to solely rely on renewable energy plants dedicated to individual industries. Instead, "the successful deployment of hydrogen in these industries will, therefore, require long-term planning, large-scale infrastructure investments, and relevant policy support" (Franco, 2025). Thus, the transition to a carbon-neutral EU energy system requires moving beyond local infrastructures toward integrated cross-border ecosystems, which strongly depends on the geographic balance between renewable generation and demand hubs. Upscaling infrastructure is not an easy path, but suggestions emphasize that a significant share of existing methane pipelines could be repurposed for hydrogen transport, limiting the need of investment and illustrating the value of collaborative strategies that cut across sectors and stakeholders (Arduin et al, 2022).

These insights reinforce the idea that hydrogen valleys and hubs, rather than isolated projects, represent a more effective pathway for scaling up hydrogen, as they combine infrastructure reuse, cross-sector coordination and systemic planning under a unified framework. It is also important to recognize that physical assets alone are not sufficient for hydrogen ecosystems functioning, but they must be surrounded by a broader framework, made up by standards, certification and robust governance mechanisms that can give certainty and trust to both investors and users. In this respect, the recent IRENA report *A Quality Infrastructure Roadmap for Green Hydrogen* (2024) highlights how a well-developed Quality Infrastructure (QI) is a prerequisite for moving from fragmented projects to integrated hydrogen hubs and valleys. QI is defined as the "system contributing to governmental policy objectives in areas including industrial development, trade competitiveness in global markets, efficient use of natural and human resources, food safety, health, the environment and climate change”[22]. Thus, it represents a catalyst for competitiveness and global market access, enhancing both quality improvement on a national scale and helping with demand stimulation. This leads to the invigoration of individual businesses and the economy as a whole, as well as free and safe participation in global trade and in value chains. Furthermore, current supply-demand mismatch and the current incapability of reaching net-zero targets suggest that hydrogen production must grow five-fold by 2050, but in order to achieve this growth, “regions with abundant renewable energy sources, due to lower production costs […] will deploy a substantial share of production facilities”. As a consequence, international trades, through corridors, are necessary. And hence infrastructure must be adequately expanded to facilitate cooperation and open dialogue. IRENA proposes a five-step roadmap to guide countries in aligning infrastructure development with QI services (*Figure 10****Error! Reference source not found.***). Their aim is to illustrate how a sharing a common strategy and vision can enhance cross-border trade through corridors between countries, system resilience and collaborative innovation across the hydrogen value chain.

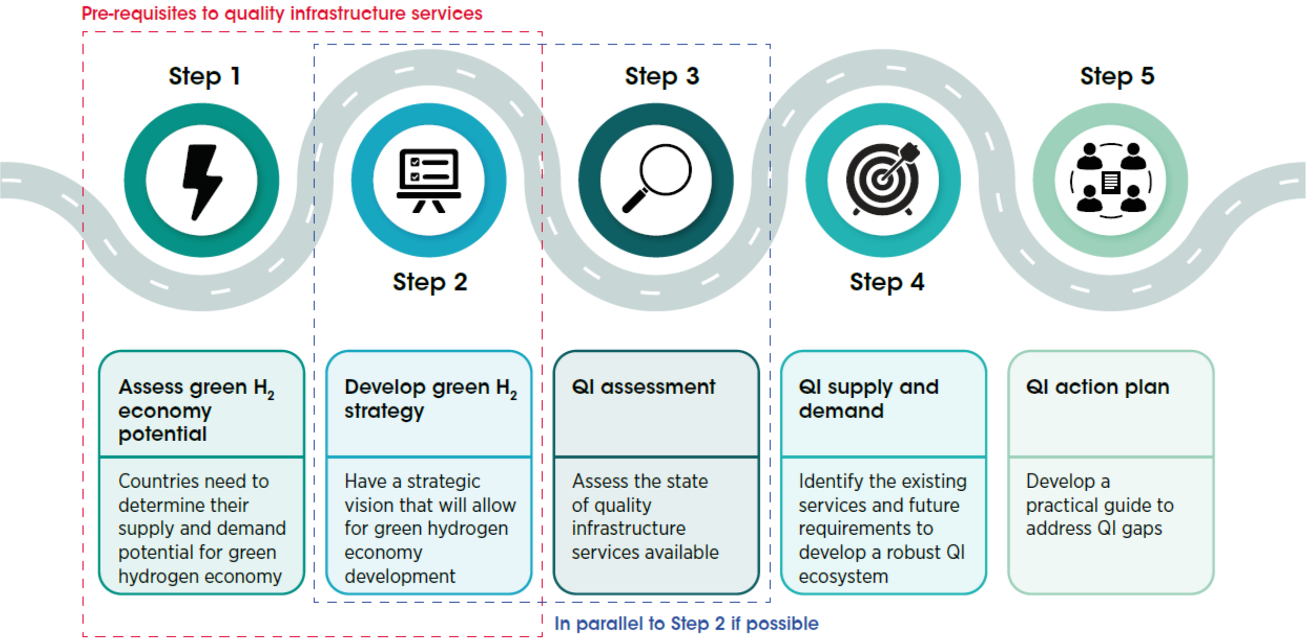

*Figure 10: Roadmap for a green hydrogen quality infrastructure (IRENA, 2024)*

The terms *ecosystem*, *hub*, *valley* and *corridor* will be used frequently throughout this thesis. It is important to keep in mind that, while all of them relate to the field of green hydrogen, each carries a distinct meaning. *Table 7* clarifies each term’s usual definition, from Cambridge Dictionary website, alongside a tailored definition, useful for a better understanding of this thesis.

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[22] UNIDO, *Quality Infrastructure: Building Trust for Trade*, United Nations Industrial Development Organization, 2016; https://www.unido.org/sites/default/files/2016-05/UNIDO_Quality_system_0.pdf.

*Table 7: Key concepts and their operational definitions in the context of the green hydrogen economy.*

| | Literal definition[23] | Definition in the context of this study[24] |
|---|---|---|
| Ecosystem | Any complicated system consisting of many different people, processes, activities, etc., especially relating to technology, and the way they affect each other. | The entire network of largely independent economic actors (companies, small and medium-sized enterprises, startups, researchers, policymakers, governments, etc.) engaged in the green hydrogen economy and interacting to foster innovation and deployment. |
| Hub | A place that is the center of a particular activity. | A central node where green hydrogen activities concentrate. It can be a city, a cluster or a facility that serves as a connector between supply and demand. |
| Valley | An area of low land between hills or mountains. | A "isolated" hub specialized in green hydrogen technology, where companies, startups, researchers and other organizations promote a strong environment for technological innovation. |
| Corridor | A passage with rooms on one or both sides. | A channel facilitating the flow of materials, knowledge, competences between hubs or valleys, across regions. |

### 2.1.2 Optimal supply chain design for green hydrogen

The optimal design of the hydrogen supply chain (HSC), consisting in production facilities, storage and distribution to other stakeholders through corridors, depends in each region on many local factors, such as location and type of major industries, political support and local funding, existing infrastructure and geographical conditions (Mendler et al, 2025). An optimal spatial structure can be impactful on the economic feasibility and success of hydrogen valleys. Although the ultimate goal of the hydrogen transition is large-scale deployment, small-scale and decentralized solutions remain still relevant in early market phases and in regions with limited infrastructure.

Jayachandran et al, analyze three different business models, focusing on the geographical and associating costs aspects of production and delivery. "Onsite production" is aimed at large-scale $H_2$ generation, powered by solar or wind energy. It places electrolyzers at the end-user site, eliminating associated transportation infrastructures and costs, but limited production capacity is a downside. "Offsite production" is meant for medium to long-term solutions, consisting in electrolyzers installed near renewable energy sources with hydrogen being stored and transported to end-users via pipelines or trucks, which allow economies of scale achievement and wider consumer distribution. Finally, "Decentralized generation and district distribution" is addressed as a short-term business model, which involves locating electrolyzers in proximity to end-user consumption points and directly connected to the local electrical grid, primarily powered by renewable energy. This hybrid model offers several advantages: it reduces production and transport costs, leverages economies of scale and shortens the development time.

Certainly, hydrogen supply modeling approaches must consider the quantity of demand coming from the different sectors, but also the integration with its feedstock systems and adopt computable general equilibrium (CGE) models to monitor economic data and behavior of firms (Riera et al, 2023). Stöckl et al. agree that the optimal hydrogen supply chain depends on the level of hydrogen demand and share of renewables, in particular for lower shares of RESs and low hydrogen demand, small-scale on-site electrolysis is the most beneficial, while for higher shares of RESs and higher demand, large-scale hydrogen infrastructures are the better choice.

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[23] Source: https://dictionary.cambridge.org/

[24] Source: Author's own elaboration

The choice of hydrogen carrier is also a relevant variable for such matter. Findings on comparing different methods (Spatolisano et al, 2023), such as ammonia, liquefied hydrogen ($LH_2$) and liquid organic hydrogen carriers (LOHCs), across industrial hydrogen valley and mobility applications, report that for industrial use, ammonia and LOHCs are the most cost-effective alternatives for transporting and storing hydrogen, while for a distance of 5000 km, ammonia prevails. For mobility applications, before end users' $H_2$ final consumption, reconversion into its initial gaseous form is required, either at the unloading terminal or directly at each end user. For $LH_2$, decentralization is preferred because it involved pumping the liquid before regasification, reducing compression work downstream and costs for fueling stations. On the contrary, centralized reconversion is better for ammonia, because large-scale cracking units at unloading points achieve economies of scale, making the process more efficient and cost-effective than multiple small, decentralized units. He et al. suggested that PEM electrolysis + pipeline mode is the optimum green hydrogen supply chain for its study case of the Inner Mongolia-to-Beijing corridor, achieving the lowest LCOH. Similar conclusion from Zhao et al, whose studies discovered that pipelines lead to economies of scale and that surprisingly $LH_2$ trucks beat tube trailers over long distances. Analyses to find the optimal hydrogen supply chain reveal that its structure is highly dependent on a matrix of local factors, therefore many are the possibilities, offering varying cost-effectiveness and logistical advantages tailored to specific applications like industry or mobility. This range of options includes the choice between onsite, offsite and decentralized production, as well as the selection of the optimal hydrogen carrier and transportation mode.

### 2.1.3 Business Models and Market Strategies in Hydrogen Hubs

The successful deployment of green hydrogen also depends on the choice of business and market models that administrate how value is created and distributed across the ecosystem. At the moment, the literature has not yet been able to provide a comprehensive framework that incorporates all the relevant business models in a single scientific contribution. Therefore, this paper is based on different sources, each focusing on different aspects, and attempts to create a more comparative picture of the emerging green hydrogen business.

One frequently discussed configuration is the concept of trading $H_2$ as a commodity, in which hydrogen is produced in large, cost-effective volumes and traded globally to consumers, mainly in the form of derivatives. It involves building infrastructure across the entire value chain, from power generation and electricity storage, to electrolysis, and all the way to transport (through pipelines and ships), hydrogen storage, and conversion plants (IRENA, 2025), creating a vertically integrated structure where the company controls each stage of the chain. Production hubs are placed where energy is cheapest while robust physical logistics networks for storage, transport and conversion are essential for international trade routes. This strategy reduces costs, increase efficiency and strengthen industrial competitiveness; however, it involves high initial investments (IRENA, 2025). The strategy of commodity market is mainly used for oil, gas or copper, while green hydrogen's actual trade today is limited and often project-specific, but experts predict that trading will be established between 2030 and 2035 (Steinbach and Bunk, 2024).

A different set of models shifts the focus from selling molecules to delivering services. Energy-as-a-Service (EaaS) or Energy Storage-as-aService (ESaaS) are the two different business models but complementary. Both foresee the producer entering into a service agreement with the users, who benefit from a service; in particular, the provider offers and delivers energy solutions built on hydrogen (power, heat, mobility) as a service. Under EssS, provider also invests in and operates the required end-use infrastructure, like fuel cell power plants, hydrogen boilers or refueling stations, while customers subscribe to the service and pay for the actual energy consumed, outsourcing the technological complexity of reconversion. ESaaS, on the other hand, treats storage itself as a service. The operator invests in centralized storage system, offering end-users the ability to lease storage capacity or participate in flexible energy trading by charging a service fee. These models lead to scalability and energy efficiency, while main challenges consist in data accessibility and conflicting needs among multiple stakeholders (Qiu et al, 2023).

Infrastructure leasing, an asset-oriented approach, consist in the company owning physical hydrogen infrastructure (electrolysers, storage tanks, fuel cells, refueling stations, pipelines etc.), which are rented to the costumer. No hydrogen or energy service is directly sold; instead, the costumer pays a fixed fee to access the equipment without investing capital. This model is considered "green" because it supports the circular economy that allows product recirculation both through multiple uses and through rebuilding, refurbishing or recycling (I. Ionașcu and M. Ionașcum, 2018). Advantages for the customers are lower upfront costs, especially when they are new entrants with limited capital, because it enables faster deployment of hydrogen technology and allows the provider to monetize assets while retaining ownership and control over the infrastructure.

Power-to-X (P2X) business models frame hydrogen, from a system-integration perspective, not as the final product but rather as an energy carrier acting as the focal link between multiple sectors. In this set-up, surplus renewable electricity is converted into hydrogen by electrolysis and stored for later use. Subsequently, hydrogen can be converted back into electricity, fed into the gas grid, supplied for heat, or even further processed into synthetic fuels and chemicals. Due to the flexibility of sector coupling, P2X has been under increasing attention in recent years as a means of integrating high shares of variable renewables into energy systems (Sorrenti et al, 2022). It allows for long-duration and seasonal storage, enhancing overall system flexibility, thus supporting the integration of various energy vectors-electricity, gas, and heatwithin one resilient and better interconnected energy system (Kountouris et al, 2022).

Yang et al offer a proposal of three alternative configurations of the business model based on the use of hydrogen credits. This is a relevant topic, as green hydrogen industry development necessitates financial incentives, such as subsidies and tax credits, to overcome current high production costs. In the investment-for-emission-reduction model, revenues are generated through the sale of hydrogen and the associated emission reductions. The substitution of fossil fuels by hydrogen also allows end users to save on carbon credit markets. Both hydrogen sales and HC portfolios are generating revenues using the investment-for-HC model. This is where the entity invests in $H_2$ projects, operates and monitors them, and applies for HC accreditation based on life-cycle emission data of the supplied hydrogen. In the benefit-sharing model, the ownership of HC is allocated along the value chain of hydrogen-production, transportation, and utilization-according to the contribution of each stakeholder to net $CO_2$-equivalent emission reductions. Although the entity is still receiving revenue from hydrogen sales, revenues from HC trading in carbon markets are shared across producers, distributors, and users.

Common to all these different structures is the requirement for a formal agreement between two or more parties, which will be fundamental to a successful hydrogen valley development, in addition to a sophisticated, co-optimized supply chain modeling approach to assure technological maturity.

### 2.1.4 Ecosystem theory and benefits through knowledge sharing within innovation networks

Previous paragraph's findings highlight the crucial role of both scaling-up and networking in fostering innovation and hence accelerate green hydrogen deployment in the world economy. The concept of network refers to an interconnected ecosystem where information, technology and human interactions converge to generate value across nodes (da Silva et al, 2025). In the recent years, digital transformation has significantly helped with expanding networks and facilitating exchanges, enabling more dynamic collaboration and interaction among network participants (da Silva et al, 2025).

When considered by themselves, individual actors, such as startups or small and medium-sized enterprises (SMEs), possess distinct resources, capabilities, assets and characteristics, yet these are typically limited in scope. Innovation, however, is an inherently complex phenomenon that often entails a technological shift of the current paradigm, whether of evolutionary or revolutionary nature, that no single entity can achieve alone. To reach high-level maturities of innovations, firms must acquire and integrate external knowledge and resources with their internal ones. For example, it is very common for a company to orchestrate collaborations, partnerships or acquisitions, all of which allow organizations to quickly gain complementary competencies, asset or knowledge they lack, rather than developing them internally. This is the main reason why creating networks between participating actors emerges as an essential prerequisite for effective innovation ecosystem.

Numerous studies have been conducted upon ecosystem theory and its associated benefits for open innovation. Some emphasize that resource integration leads to value-creation, where value is intended as the usefulness of a product or a service that individual costumers perceive (in this case, them being the end users of green hydrogen). The core concept is that the more resource-intensive the network is, the better value will generate, meaning that cooperation though resource sharing positively affects not only innovation velocity but also the quality of the technology provided (Prabowo et al., 2023). Risk sharing and risk mitigation are additional perks of networking, as collaboration allows firms to distribute uncertainties and reduce individual exposure. In particular, according to the DART model (Dialogue, Access, Risk mitigation, Transparency), reducing and distributing risks are fundamental mechanisms for ensuring the long-term survival and development of firms. Furthermore, network creation lowers transaction costs and limits opportunistic behavior, thereby fostering mutual trust and resilience (Yin and Zhao, 2024).

Some researchers suggests that collaboration and competitiveness must coexist to achieve successful outcomes. This concept, known as “co-opetition”, has gradually emerged as a key strategy for technological innovation, referring to a strategic interplay in which companies collaborate and compete simultaneously to achieve benefits that would be unattainable individually. Findings explain that co-opetition networks stimulate creation of knowledge (da Silva et al., 2025), identified as critical resource for sustaining competitiveness. Exchange of knowledge enables cross-pollination of ideas, blending diverse expertise and insights that can induce to innovative solutions. Employees with different background, though cooperation, are more effective in identifying gaps, improving operational efficiencies and proposing novel approaches that align with the firm’s strategic goals (Yuen et al., 2024). Therefore, knowledge sharing does foster a collaborative environment that nurtures a culture of continuous learning and adaptability, essential for rapidly responding to market changes and technological advancements.

### 2.1.5 Mapping and engaging the green hydrogen power players

Across the globe, international efforts to promote green hydrogen are intensifying, given the pressure of an urgent solution for sustainable and low-carbon energy. Since 2019, an increasing number of countries and regions have published hydrogen strategies, roadmaps and policies to facilitate technology and market development and to integrate hydrogen into the system (Flath and Quittkat, 2025). Before understanding the strategies and the collaboration between the actors involved in this mission, a clear mapping of such stakeholders is required, perceived as the power players that possess the authority, resources and influence to accelerate the deployment of the technology, joining forces to make it a reality (*Table 8*). In the European context, shaped by a mix of public and business interests, dominance is reinforced by strong political support from both EU and Member States. Environmental and climate organizations are the primary supporter of green hydrogen economy, while industrial stakeholders and incumbents in the gas and heating sectors advocate both a green and non-green hydrogen economy with more diverse application. Civil society actors, along with other sectors of the economy, were found to be peripheral.

Industry and Energy companies

Companies, ranging from energy giants to innovative start-ups, drive technological advances and have a direct influence on green hydrogen value chain, mainly through their investment decisions (Jesse et al, 2024).

- *Hydrogen producers*. Companies that produce green hydrogen through electrolysis at their facilities and subsequently store and distribute it. Examples include Air Liquide (FR), Linde Gas (DE) and Air Products (US). Among the start-ups: Heliogen (US), Everfuel (DK) and Fusion Fuel (PT).
- *Energy giants*. Multinational utilities and oil & gas companies such as Iberdrola (ES), Shell (NL/UK), BP (UK), TotalEnergies (FR), and Enel (IT), which invest in large-scale green hydrogen plants and integrate them into their energy portfolios.
- *Equipment and technology providers*. Firms supplying electrolysers, storage solutions and fuel cells, which are crucial enablers of production scale-up. Examples include Siemens Energy (DE), Cummins Inc. (US), ENGIE (FR), Nel Hydrogen (NO) and Plug Power (US). Among the start-ups: Hystar (NO) and Hydrogenious LOHC (DE).

National Governments and Policymakers

Recent geopolitical events, like the U.S.-China trade tensions and the Russia-Ukraine war, demonstrated how political factors can shape multinational firms' supply chain decisions and resilience, while studies show that only on firms' activities are inadequate for addressing operational resilience in today's complex environments (Hong et al, 2025). Opposites to companies, governments and policymakers hold a more indirect but active influence upon green hydrogen value chain and deployment. Their impact can be substantial through various measures: incentive policies, such as subsidies or $CO_2$ taxes, to influence cost-competitiveness, mandates to regulate demand, provide investments to encourage the use of new renewables or subsidies on hydrogen electrolyzers to reduce their costs (Jesse et al, 2024). Experts highlighted differing views: some emphasize governments' role as vital for innovation and competitiveness, as it provides overall security and growth, through regulatory frameworks, certifications and standardizations; others instead warn against strict overregulation, believing it could lead to possible bottlenecks and hence hinder scale-up (Jesse et al, 2024). Nevertheless, the most remarkable and impactful actor belonging in this category is of course the European Union, the forefront of the whole green hydrogen implementation. Through its many efforts, such as Hydrogen Strategy and IPCEI[25] projects to name a few, EU incentivizes the use of renewable hydrogen while giving financial support to large-scale projects across member states. To make it easier for projects to navigate through the various available funding programs, the EU created the Hydrogen Public Funding Compass[26]. Such programs and EU's policy instruments are designed to de-risk investments and build confidence among private stakeholders, thereby positioning Europe as a global leader in the hydrogen economy. *Figure 11* illustrates that the majority of stakeholders is based in EU Member States, accounting for 410 total (87.79 %) (Flath and Quittkat, 2025).

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[25] Important Projects of Common European Interest: this initiative, funded by the European Union, aims at facilitating large-scale cross-border projects that significantly benefit the EU. They combine their public and private knowledge, resources, expertise and economic actors from across Europe. IPCEIs may represent a significant contribution to economic growth, jobs, the green and digital transition and competitiveness for the Union industry and economy. Source: https://competition-policy.ec.europa.eu/state-aid/ipcei_en

[26] An online guide to public funding instruments supporting renewable and low-carbon hydrogen projects. Current instruments are the Connecting Europe Facility, Horizon Europe, Innovation Fund, InvestEU, Just Transition Fund, LIFE, Modernization Fund, Recovery and Resilience Facility, Net-Zero Industry Act, REPowerEUImportant Project of Common European Interest, Hy2Tech, Hy2Use, European Hydrogen Bank and Temporary Crisis and Transition Framework.

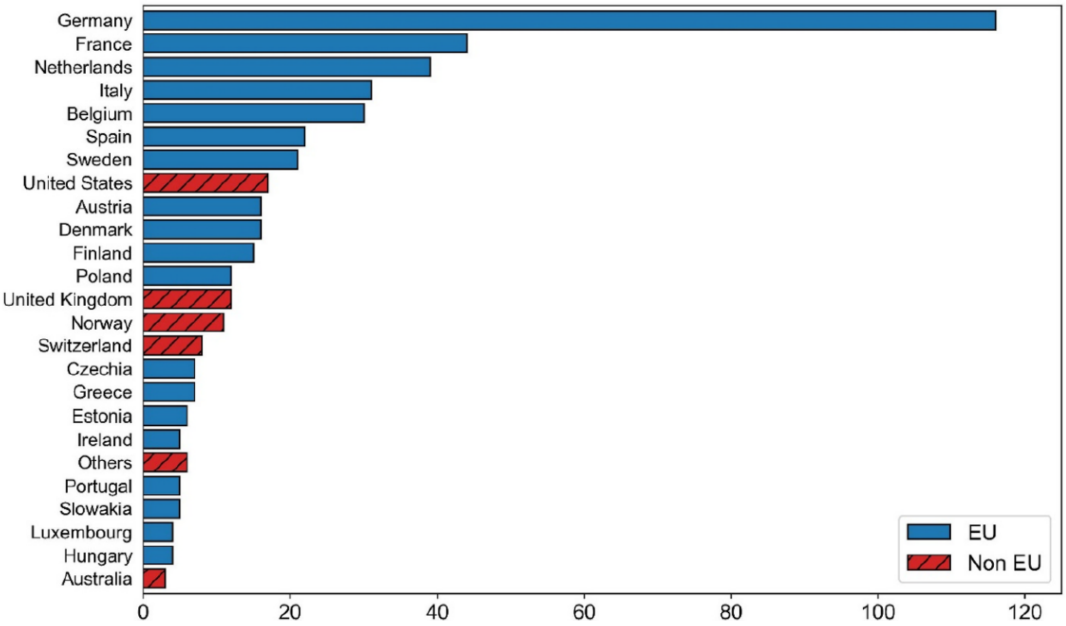

*Figure 11: Geographical distribution of hydrogen stakeholders (Flath and Quittkat, 2025)*

Germany positions itself as the country with most stakeholders (166 actors, being almost 25% of the total), because of its energy-intensive industries and their abundant electricity availability. Considering instead five of the six founding members of the EU Member States, collectively account for more than half of the national actors (Flath and Quittkat, 2025).

Anyway, other jurisdictions around the world, mainly from industrialized countries, are also actively supporting the economy of green hydrogen, even though using different approaches. The United States, one of the main economic leaders in the world, pursue a broader mix of carbon-free technologies, including SMR with CCS and nuclear, primarily through legislative measure like the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA), which provide substantial financial incentives, tax credits and fundings to stimulate investment in hydrogen production, infrastructure and related technologies. While these incentives accelerate deployment, they are often time-limited and primarily focus on supply-side support, with less emphasis on creating long-term demand in sectors like aviation and shipping. Japan is also committing to the mission, setting substantial initial investments in R&D and projects, which contribute to its establishment as a leader in patent filings (Graczyk et al, 2025). China is promoting large-scale hydrogen production and infrastructure development for industrial growth.

International organizations and Alliances

There is a countless number of existing stakeholders' partnership around the globe. In this paragraph there are listed the most relevant, especially in the European geographical context.

During this thesis, reports from intergovernmental organizations like International Energy Agency (IEA), International Renewable Energy Agency (IRENA) were frequently used as key references to provide data, analysis and policy insights on the hydrogen economy. Such bodies foster cross-border cooperation while setting common goals and standards.

Another type of international partnership is Hydrogen Council, which brings together leading companies facilitating knowledge sharing, policy guidance and coordinated global action in the hydrogen sector.

The European Clean Hydrogen Alliance (ECH2A) is part of EU's Hydrogen Strategy. Its members come from industry, public authorities, civil society, financial institutions and other stakeholders, which aim is to support clean hydrogen large-scale deployment and stimulate its production and use by 2030.

At the same level, Hydrogen Europe, made up by companies and research organizations in hydrogen and fuel sector, has been recognized as highly influential actor. Among the other organizations, it has indeed the most contact with the European Commission. Its primary focus lies in lobbying and policy shaping at the EU level, particularly in connection with the Clean Hydrogen Joint Undertaking[27]. The latter, better known as the Clean Hydrogen Partnership is a public–private partnership that brings together the European Commission and industry through Hydrogen Europe, with the research community represented by Hydrogen Europe Research. Generally, it will have the task of financing research and innovation activities along the hydrogen value chain to accelerate the development and deployment of clean hydrogen technologies, strengthening Europe's technological leadership while supporting the objectives of the European Green Deal. Finally, the Hydrogen Observatory is a European Commission knowledge platform that complements ECH2A and Hydrogen Europe, as it collects and provides data, forecasts, market analysis and statistics and other type of insights on hydrogen production, demand and policies in Europe.

### Research & Developments and Academia

As confirmed by Safronova and Barisa from Riga Technical University's Institute of Energy Systems and Environment, the introduction of hydrogen technologies requires specific funding programs and R&D networks establishment. Dedicated and coordinated investments, whether public or private, are crucial to bind academia with market applications while R&D influences competitiveness through patents, technological breakthroughs and responses to regulatory pressures. As the sector grows, R&D investments are expected to increasingly shape both sustainability outcomes and industrial profitability.

### Civil society and NGOs

Civil society organizations and NGOs constitute only a small fraction of the actors involved in EU hydrogen policy compared to business stakeholders, mainly due to structural and resource-related barriers rather than deliberate exclusion. The debate has been dominated by political, industrial and scientific actors, while the technical complexity of hydrogen and the lack of dedicated energy-focused NGOs further limit participation. Only large environmental NGOs such as WWF, Greenpeace or Climate Action Network have engaged so far making meaningful impacts on green hydrogen. As such markets and infrastructure continue to expand, NGO involvement is expected to grow (Flath and Quittkat, 2025).

*Table 8: Overview of stakeholders and their main contributions to the green hydrogen sector*

| Stakeholder Category | Main Takeaways |
|---|---|
| Industry & Energy Companies | - Central actors across the hydrogen value chain with direct influence through investment decisions.<br>- Include hydrogen producers, large utilities and oil and gas majors and technology providers.<br>- Drive technological innovation, industrial scale-up and cost reductions in infrastructure.<br>- Start-ups play an important role in developing niche applications and emerging technologies. |
| National Governments & Policymakers | - Indirect but decisive influence through regulation, funding and risk-reduction mechanisms.<br>- Public policy is crucial for making green hydrogen cost-competitive (subsidies, carbon pricing, standards). |

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[27] The *Clean Hydrogen Joint Undertaking* or *Clean Hydrogen Partnership* is a unique public-private partnership supporting research and innovation (R&I) activities in hydrogen technologies in Europe. It builds upon the success of its predecessor, the Fuel Cells and Hydrogen Joint Undertaking. Source: https://european-union.europa.eu/institutions-law-budget/institutions-and-bodies/search-all-eu-institutions-and-bodies/clean-hydrogen-joint-undertaking_en

| | |
|---|---|
| International Organizations & Alliances | - Promote international cooperation, shared standards and knowledge exchange.<br>- Provide data, scenarios and policy guidance that shape national and regional strategies.<br>- Help coordinate private-sector action and align expectations. |
| R&D and Academia | - Key drivers of technological breakthroughs, patents and scientific progress.<br>- Bridge the gap between research and market applications through dedicated funding and partnerships.<br>- Strengthen long-term industrial competitiveness and sustainability performance.<br>- Collaborative research networks are essential for accelerating innovation and commercialization. |
| Civil Society & NGOs | - Limited role compared to industrial stakeholders.<br>- Engagement mainly comes from large environmental NGOs. |

## 2.2 Encouraging Green Hydrogen Ecosystems and Hubs Formation through Effective Governance and Stakeholders' Collaborations

A solid and well-structured governance is the cornerstone of a functioning entity or ecosystem. Governance models can vary in their level of centralization. Some are highly centralized around national governments playing a leading role in planning and financing green hydrogen production and infrastructure, others are more decentralized, allowing regional authorities or local projects to take the initiative, developing strategies tailored to local needs and resources.

Either way, a growing consensus has emerged in the literature that no single actor, whether public or private, can alone overcome the current barriers impeding the deployment of green hydrogen; instead, targeted collective efforts are required by different stakeholders to build ecosystems that invest in R&D activities, integrate knowledge and share resources. As already mentioned, issues include lack of long-term demand, few available infrastructure, high CAPEX and OPEX. In response to these complexities, the following section is intended to deepen into a set of innovative and collaborative strategies and coordinated governance mechanisms that the literature increasingly recognized as effective solutions to enhance hydrogen deployment.

Organizations mainly tend to look inside themselves when dealing with innovative research. However, successful innovations, especially digital ones, are typically sourced from outside the firm, often through collaboration with technology providers who develop and introduce new technologies to customers or external stakeholders (Randhawa et al, 2024). The processes of *open innovation* (OI) "enable firms to source technologies externally, or commercialize internally developed technologies externally, thus leveraging external stakeholders to co-innovate beyond their boundaries" (Randhawa et al, 2024). Classic OI theory therefore emphasizes three main modes: outside-in, inside-out and coupled innovation. Nevertheless, recent literature suggests that this firm-centric view does not fully capture the dynamics of innovation. Applied to hydrogen ecosystems, *open innovation ecosystem* has emerged as an extension of OI, incorporating the outside-out innovation mode, which recognized the role of external stakeholders (companies, governments, research institutions, users and NGOs) interact independently with each other, actively sharing competencies and data across organizational borders. These interactions, although taking place beyond the direct control of technological providers, still affect innovation and thereby accelerate technological development and reducing duplication of efforts. From this context, green innovation concept is introduced, intended as innovations in products, processes and business models whose mission is to enhance cleaner, energy-efficient technology (Cambra-Fierro et al, 2024).

This logic directly translates into the green hydrogen sector. One of the most prominent regional initiatives is indeed the establishment of *hydrogen valleys* or simply *hubs*: regional ecosystems where production, storage, distribution and end-use applications are developed simultaneously and within a geographically concentrated area. By clustering demand and supply, valleys act as laboratories for innovation commercialization, reducing risks for investors and fostering cross-sector synergies. They also serve as replicable business models, offering a scalable blueprint that can be adapted across different regions and markets. Local hubs or small-scale projects or startups, active in off-grid renewable energy, can be strengthened through partnerships with multinationals as well as with external sources of finance, expertise and knowledge from both business and (non-)governmental organizations. The more these initiatives are integrated into multinational networks, the greater the potential for technology transfer, deployment and sustainable business opportunities (Kolk, 2015). This contribution is significant because it shifts the focus from states to firms as central actors in international technology transfer, highlighting how corporate strategies, foreign investments, and global networks influence the diffusion of environmental technologies.

### 2.2.1 Public-private partnership (PPP)

The public-private partnership is a collaborative governance, understood as a form of cooperation among governments (public) and profit-oriented (or non-profit) companies aiming at financing, building and operating projects to provide better public services (Dall-Orsoletta et al, 2022). PPPs allow large-scale government projects to be completed sooner with funding mainly coming from the private part but payments from the public sectors and/or users are required over the project lifetime. This particular collaboration appears to be an effective way to foster green transition in the energy sector, because risks, such as high investments and responsibilities can be shared between the parties. Furthermore, it promotes knowledge transfer and accelerated development.

In 2022, the United Nations Economic Commission for Europe (UNECE) issued *Introduction to Public-Private Partnerships in Support of the United Nations Sustainable Development Goals*, a document that provides a foundational explanation of how public-private partnerships (PPPs) can help achieve the UN Sustainable Development Goals (SDGs) across various sectors, including energy. Newborn companies must overcome upfront costs and PPP mechanism can be the key, because it brings “private investment, as well as new technology, innovation, and improved efficiency, to [companies’] energy capacity and systems”[28]. That is one of the reasons why government investing in R&D in hydrogen technologies has quadrupled in the past 5 years, as illustrated in *Figure 12*, highlighting a strong policy commitment to funding. This growth aims to ensure that communication and knowledge-sharing from low-emission hydrogen RD&D projects remain effective, transparent and widely accessible.

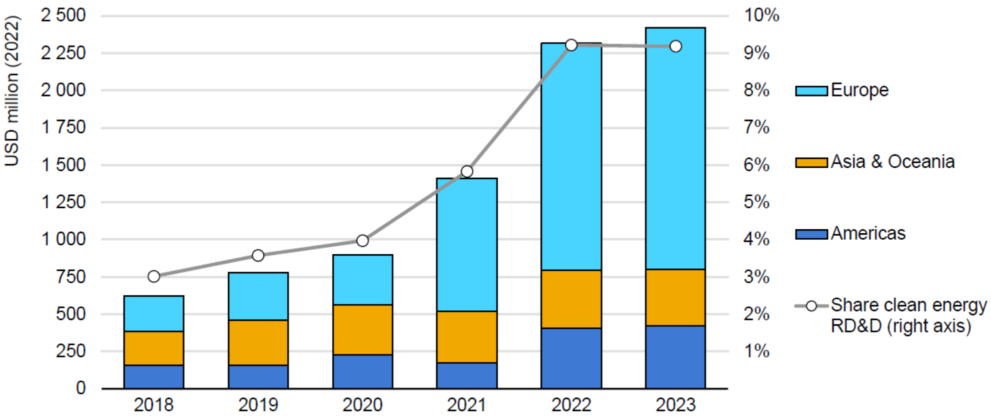

*Figure 12: Government R&D spending on hydrogen technologies by region, 2018-2023 (IEA Global Hydrogen Review 2024)*

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[28] United Nations Economic Commission for Europe (UNECE). (2022). *Introduction to Public-Private Partnerships in support of the United Nations Sustainable Development Goals* (ECE/CECI/WP/PPP/2022/6), https://unece.org/sites/default/files/2022-10/ECE_CECI_WP_PPP_2022_06-en.pdf

A practical initiative is represented by the Public-Private Action Statement signed by the International Hydrogen Trade Forum (IHTF) and the Hydrogen Council at COP28, which aims at enforcing the implementation of cross-border trade corridors in hydrogen and its derivatives internationally and analyze any other emerging ones, involving periodic reviews of priorities for collective action between the public and private sector.

### 2.2.2 Other types of alliances

Beyond PPPs, energy companies have also engaged in partnerships with other private entities. Co-development, for instance, often occurs when a company co-finance a supplier for developing R&D activities for some highly specific competences that the company does not wish to build in-house. It is important the concept of investments sharing, rather than revenue sharing, so that both parties equally bear market or technological risks, which can form the basis for a fair and balanced agreement. A notable example is the partnership between ENGIE and Schneider Electric, which developed solutions among various sectors, including in electricity. A joint venture is not defined merely by a contractual agreement but rather as an equity-based alliance built on a deeper institutional linkage between the participating entities. The partners may exchange shareholdings directly or establish a newly incorporated legal entity specific to the alliance. While this structure reduces ambiguity, it also entails significant transaction costs. As mentioned in the previous paragraph, universities and academic entities can also participate in R&D initiatives, with either private companies or the public sector, forming respectively industry-university partnerships, characterized by low-risk and symbiotic nature, and academia-public sector partnerships (Dall-Orsoletta et al, 2022). Cooperation with universities can be an attractive scheme for corporations because of the high level of their competences. Independent research groups from universities may create spin-offs or startups, which can be further acquired by companies or continue growing independently.

Vertical integration is a special type of business model where only one actor controls multiple stages of the value chain, from production to distribution and end-use. A high degree of vertical integration gives firm tighter control on both technological and business perspective, as well as greater efficiency, cost control and autonomy. However, high upfront investments are required so it is indeed suggested to those companies who do own a great base of funding. Many large-scale companies have indeed adopted this governance model; however, it can sometimes limit flexibility and expose firms to higher risks if market conditions or technologies shift rapidly. Iberdrola provides a relevant example of how vertically integrated energy companies are adapting their business models in the evolving renewable landscape. Traditionally, Iberdrola has operated along the entire value chain, from renewable generation to grid infrastructure and distribution, reflecting a strong vertical integration strategy. However, in recent years the company has increasingly turned to partnership with corporate and industrial clients through the so-called Power Purchase Agreements (PPAs), which is an "agreement between an energy buyer and a renewable energy producer. The producer commits to supply a certain amount of renewable energy over the long term […] at a set price. The buyer can be a company, organization, or government seeking to increase its clean energy production or meet sustainability goals"[29]. This shift, shown in *Figure 13* illustrates how even vertically integrated players leverage long-term contractual arrangements to secure stable demand.

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[29] Source: https://www.iberdrola.it/grandi-aziende/ppa

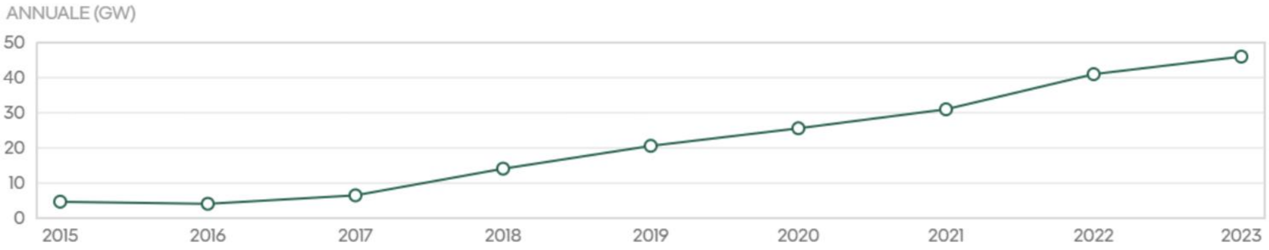

*Figure 13: Global volume of PPA contracts signed over the past ten years (Iberdola)*

## 2.3 Market incentives, financing instruments and supporting policies

Demand for hydrogen is highly price sensitive, particularly in the case of green hydrogen. Studies show that demand, and hence deployment, of such technology depends on several variables, with pricing representing the most influential one; price explains the need for policymakers to elaborate market incentives. Fiscal and financing instruments like tax credits, subsidies and grants can significantly lower entry barriers and reduce cost gap between fossil-based fuels and renewable hydrogen. Findings from Asghari et al. further emphasized the importance of implementing flexible policy frameworks, where governments not only provide tax discounts to producers but also actively monitor the hydrogen market landscape. Such measures ensure fair competition and stability, prevent monopolies and help manage price fluctuations, thereby creating a more reliable environment for scaling up green hydrogen.

Three important initiatives built to support hydrogen valleys in EU are the Hydrogen Strategy, IPCEI and Hydrogen Bank. Regarding policies, EU employs multidimensional framework, ranging from market-based trading scheme (ETS II[30]) (*Figure 14*), mandates (RED III), targeted taxation (Energy Taxation Directive) and infrastructure frameworks to establish an efficient, demand-pull mechanism (Graczyk et al, 2025).

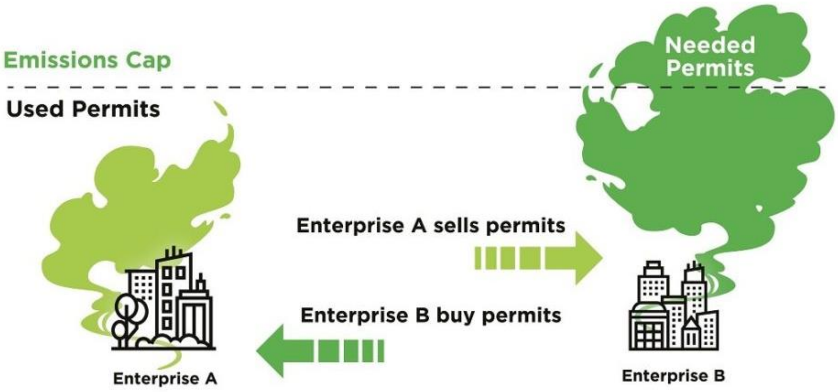

*Figure 14: The cap-and-trade system.*

Within the context of innovation, standardization does not directly create demand, but it plays a crucial role in enabling market functioning, growth and integration. By establishing shared rules and definitions, standards foster broader

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[30] ETS II is a new and separate emissions trading system revised from the original 2023 EU ETS. While ETS I cover large industrial installations, power plants and aviation, ETS II expands carbon pricing to previously unregulated sectors: buildings, road transport and small industries. ETS II still operates on a "cap and trade" principle, but all emission allowances from now on will be auctioned. Member States will be required to use ETS2 revenues for climate action and social measures, and they will report on how this money is spent. Source: https://climate.ec.europa.eu/eu-action/carbon-markets/ets2-buildings-road-transport-and-additional-sectors_en

networks among actors: the more organizations adopt them, the greater the connectivity, collaboration and overall economic value is generated. Standardization also ensures alignment on what qualifies as "green hydrogen," thereby building trust among stakeholders and reducing the risk of greenwashing. It also provides technical guidelines for infrastructure development ensuring compatibility across regions and companies. In doing so, it prevents market fragmentation and supports the convergence of national projects toward a common global objective. Nowadays, there are several international standards and norms for green hydrogen; however, no official globally accepted standard has been recognized. Progress have been registered in the transport sector within the ISO Technical Committee 197 (ISO/TC 197) (I.G. Sahebi et al., 2025), while others have been revealed at the COP28, known as ISO/TS 19870, presented as key tools to support climate action, facilitate global cooperation and provide a standardized, credible framework for achieving net-zero goals and promoting a just energy transition.

## 2.4 Global perspective

### 2.4.1 Geographical Parternships (EU vs USA vs Asia)

EU can build partnerships beyond its geographical borders, especially considering the increasing involvement of non-European powers, such as China, United States or Japan. China, in particular forecasts green hydrogen accounting for 82% of the total application hydrogen potential for 2050, with transportation sector being the major contributor to China's hydrogen growth (Pingkuo and Junqing, 2024). Unites States's most relevant directive is the IRA, already mentioned as a set of multiple tax incentives, that allocates USD 369 billion over ten years to clean energy, with generous tax credits for green hydrogen. In parallel, the Department of Energy launched the Regional Clean Hydrogen Hubs (H2Hubs) program, allocating USD 7 billion (plus USD 1 billion for demand-side support) to build a nationwide hydrogen network. Japan's Basic Hydrogen Strategy (2023) aims to expand both domestic and overseas markets, supported by a new Contracts for Difference (CfD) subsidy scheme starting in 2024. The program, covering both domestic and imported hydrogen, will bridge the cost gap with fossil fuels, offering up to 15 years of support. Eligibility requires meeting an emissions threshold of 3.4 kg $CO_2e$ per kg of hydrogen.

Marchionna discusses the future dynamics of trans- and Euro-Mediterranean energy relations, arguing that EU should consider the strategy of co-opetition, especially "with the UAE, balancing competition in areas where Europe maintains comparative advantages with cooperation in areas of mutual interest, particularly in developing green hydrogen corridors between Africa and Europe", to maintain influence. As MENA region is ideally positioned to become a leader in this industry, mainly thanks to its abundant renewable resources, the author insists that green hydrogen could be an opportunity to consolidate North-South Mediterranean relations and reshape them into a more balanced, integrated economic model where Mediterranean countries actively contribute to the value chain rather than merely exporting raw resources. To avoid creating a new form of one-sided dependency, Europe must carefully manage this transition by diversifying its suppliers beyond North Africa, integrating imports from regions such as Latin America or Australia.

### 2.4.2 Recent policy dialogue and stakeholder engagement

RITIFI Webinar on Clean Hydrogen (March 14, 2025)

On March 2025, the RITIFI Webinar on Clean Hydrogen revealed important insights. The online event invited experts to explore and discuss how Research and Technology Infrastructure (RIs and TIs) can drive innovation and accelerate hydrogen research and development. One of the key organizers, Nikolaj Zangenberg, Director at the Danish Technological Institute, presented best practices and barriers identified through two specific TI and RI case studies. He summarized several key points: the need to improve awareness of RI/TI capabilities through the *"proximity effect"*, where geographical closeness to companies facilitates logistics, collaboration, and resource sharing; the importance of enhancing service efficiency; and the necessity of covering the entire spectrum of TRL stages. He emphasized that RIs and TIs are complementary, and that stronger collaboration is required to bridge the full value chain from resource development to market deployment. Additional insights included challenges faced by SMEs and startups, particularly regarding funding, regulatory compliance and access to specialized infrastructures; safety and standardization requirements for testing and demonstration; and the potential for cross-border integration of RIs and TIs to maximize efficiency and knowledge sharing.

Conference on Shaping the Future of Hydrogen in Europe in Athens (April 29, 2025)
One of the most recent high-level international conferences on hydrogen and sustainable energy took place in Athens under the title *"*Shaping Europe's Sustainable Energy Future through Hydrogen*"*. The event, which marked the highlight of a three-day European workshop series on sustainable energy, green innovation and cross-border collaboration, gathered leading scientists, policymakers and representatives of the private sectors. Discussions concentrated on the role of clean hydrogen as a driver of decarbonization, labelled as the "final link" needed to achieve full carbon neutrality. Participants examined the barriers that still exist, the current state of research, development and innovation and how these can be further strengthened to accelerate deployment. The conference underlined the need for multilevel cooperation and evidence-based policy, while also calling for continuous research in key areas such as energy, climate adaptation, shipping, sustainable finance and innovation. In particular, the "importance of a multidisciplinary approach was emphasized, using energy system modeling tools, social impact analysis and ESG applications to support green policy"[31].

## 2.5 Current conditions for ecosystem effectiveness

The literature highlights that the effectiveness of a nascent green hydrogen ecosystem can be summarized with a few crucial variables: quality and large-scale cross-border infrastructure to connect RESs sourcing facilities, production sites and demand centers; solid partnerships among international stakeholders for shared risk and knowledge; integration of innovative projects in the bigger strategic picture through governance and long-term policy frameworks; substantial funding from Governments and institutional public financing.

Key success factors include standardization of technologies and regulations, sustained long-term investments to overcome high initial costs and eventually reaching economies of scale, development of specialized local competencies (skills and supply chains) while engaging in deep international collaboration. However, the ecosystem faces important challenges, such as the currently high costs of green $H_2$ production compared to its fossil fuel equivalents, infrastructure gap in transport and storage, persistent regulatory uncertainty. These limitations are intensified by the lack of market demand, potential technological lock-ins to less-green solutions and geographical imbalances in resource availability and infrastructure deployment.

In the next section, the thesis presents a comparative multiple-case study to examine different hydrogen-related projects, which vary in key dimensions, but commonly designed to establish hydrogen ecosystems. The purpose of the analysis is to identify the best possible business and governance models that effectively contribute to the deployment green hydrogen across multiple sectors.

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[31] Press Release: High-Level Conference on Sustainable Energy Future through Hydrogen; Source: [https://ae4ria.org/press-release-high-level-conference-on-sustainable-energy-future-through-hydrogen/](https://ae4ria.org/press-release-high-level-conference-on-sustainable-energy-future-through-hydrogen/)

# 3 – METHODOLOGY

This chapter follows the step-by-step process used to construct the database of green hydrogen case studies that represents the empirical core of this research. The methodological approach was intended to filter a broad and heterogeneous body of global information into a targeted and balanced portfolio of projects. The aim was to assemble a sufficiently large (20-25) and diverse set of hydrogen valleys and hubs to enable a multiple-case comparative analysis, assessing which business models and governance structures most effectively support the development of green hydrogen in an industrial context. To achieve this objective, the careful selection of cases is crucial, ensuring sufficient diversity across key analytical dimensions, including industrial applications, geographical contexts, public–private interaction models, technological configurations and market incentive frameworks.

Several methodological approaches were tested to select the most comprehensive database, with the third proving to be the most suitable for the objectives of the study.

## 3.1 Data Sourcing

As a preliminary step, Internet consultations were conducted to identify green hydrogen adoption projects worldwide that appeared, based on an initial screening, to meet the requirements of the analysis. This initial exploration through online resources and scientific articles provided a broad overview of ongoing initiatives; however, the large volume and heterogeneity of available information made it necessary to rely on more focused sources.

To guarantee the highest level of reliability and technical accuracy, data was retrieved from the primary international and European institutions leading the hydrogen transition, already introduced in the previous chapter of this thesis. Such institutional agencies offer structured, validated and comparable information on green hydrogen's most relevant initiatives and their relative deployment frameworks. This approach enabled the construction of a consistent and robust initial data panel, forming the basis for the subsequent selection phases.

The research integrated three major databases:

- **International Energy Agency (IEA)**: the institution is "at the heart of global dialogue on energy, providing authoritative analysis, data, policy recommendations, and real-world solutions to help countries provide secure and sustainable energy for all"[32]. For each project, IEA's database provides both qualitative and quantitative data on hydrogen production, consumption, technology details and electricity and end applications, allowing for cross comparisons and trend analysis.
- **European Hydrogen Observatory (EHO):** platform that monitors European hydrogen projects, market developments and policy initiatives across member states. It supports a detailed mapping of current green hydrogen projects and provides structured data on key characteristics, such as production capacity, consumption capacity and end-use applications.
- **Clean Hydrogen Partnership (CHP):** a public–private partnership between the European Union and industry and research stakeholders, whose aim is to accelerate the development and deployment of clean hydrogen technologies to enhance EU competitiveness and decarbonization, while supporting research, innovation and demonstration projects across the entire hydrogen value chain. This institution gathers a repository of EU-funded hydrogen research and innovation hubs, for which the following data are included: technical specifications about consumption, main developing stakeholder identity, funding information, value chain coverage and end use applications.

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[32] International Energy Agency. *Mission*. Source: https://www.iea.org/about/mission

### 3.2. Initial Filtering Criteria

Given the high volume of entries across the selected platforms, a multi-stage filtering process was implemented to isolate the most relevant and reliable cases. The screening criteria included project implementation status and data completeness, while keeping consistency with the definition of green hydrogen. In particular, projects were retained only when the hydrogen production pathway was explicitly based on renewable electricity and powered through water electrolysis, thereby excluding grey or blue hydrogen alternatives.

The IEA Hydrogen projects database, last updated in 18/09/25, contained the largest set of hydrogen production projects and the most comprehensive information for each entry. For this reason, it was subjected to a rigorous set of technical filtering criteria to ensure that the resulting sample accurately reflected the current state of the green hydrogen transition. The following parameters were applied:

- Date Online: only projects that became operational in the timeframe between 2020 and 2025 were considered, in order to capture the most recent technological advancements.
- Project Status: the search was restricted exclusively to "Operational" projects. By excluding "FID/Construction" or "DEMO" stages, the research ensures that the analysis is based on commissioned infrastructure and verified performance data.
- Technology: to maintain a focus on water electrolysis as green hydrogen production method, the sample was limited to Proton Exchange Membrane (PEM), Alkaline (ALK), Anion Exchange Membrane (AEM), Solid Oxide Electrolyzer Cell (SOEC).
- Energy Source (Technology Electricity): to ensure the low-carbon nature of the hydrogen produced, only projects powered by Dedicated Renewables, Grid + Renewables or Nuclear energy were included. This effectively filtered out projects relying solely on fossil fuels.
- End Product: the filter was set to "H2" to isolate pure hydrogen production from other chemical derivatives or carbon-heavy industrial outputs.

In our second database, European Hydrogen Observatory data, last updated in May 2025, was aligned with the IEA criteria to maintain consistency across sources. The same logic was applied to the Clean Hydrogen Partnership database. However, CHP is inherently dedicated to the development of the renewable hydrogen economy; therefore, the selection focused exclusively on the maturity of the initiatives.

### 3.3 Sample Selection Solution 1: Database Intersection

A significant challenge in the methodology was the selection of a restricted sample of case studies. One solution was to the application of an overlap between databases and consider only the ones they have in common, considered the most relevant projects among all. Many leading projects indeed are reported across multiple platforms but often feature slight variations in nomenclature, spelling or technical specifications. To resolve these discrepancies and create a cohesive dataset, a multi-step data-cleaning process was established.

1. Text Normalization

To facilitate accurate cross-referencing between the IEA, EHO and CHP database, the project names underwent a normalization process to eliminate "noise" that would prevent software-based matching:

- Case normalization: all project names were converted to lowercase (decapitalized) to ensure the matching algorithm was not case-sensitive.
- Punctuation removal: all punctuation marks and special characters were stripped from the strings.
- First-word tokenization: due to the inconsistent naming conventions across agencies (e.g., one database might list "Green H2 Valley" while another lists "Green Hydrogen Valley Project"), the selection logic was narrowed to the first word of the project name. This heuristic approach served as the primary key for identifying potential matches across different sources. The choice of using first word is based on the fact that projects are almost always named after their specific geographic location or brand name, which usually appears first.

2. Cross-Referencing with the IEA "Master" Database

The IEA Hydrogen Projects Database was selected as the reference database, seen as the most complete among the others. This decision was based on the IEA's superior data cleanliness, as well as a higher level of granular detail and comprehensive technical information compared to other sources.
Using the MATCH functions on Excel (and confirmed via MySQL queries), the following logic was applied:

- The cleaned "First-word" tokens from the EHO and CHP sets were compared against the IEA master list.
- Where matches were found, the entries appeared into a different column of the same Excel sheet.

3. Final Sample Overview

The application of this rigorous filtering process resulted in a final selection of approximately 20 projects. However, at this stage, there was no certainty that each project could be classified as a hub or valley, defined as a multi-stakeholder partnership. Further verification through targeted internet searches was conducted to confirm these assumptions. Based on this validation, an alternative methodological approach was adopted to ensure the accuracy and relevance of the final case selection.

### 3.4 Sample Selection Solution 2: Identifying Valleys and Hubs through a Keyword-based Research

The methodology shifted from quantitative filtering to a specific qualitative and semantic selection. The objective of this research is not merely to analyze individual electrolysis plants, but to investigate integrated hydrogen ecosystems.
To ensure the selected cases represented true "Hubs" and "Valleys", a keyword-based search was executed within the three consolidated database. Such keywords are illustrated in *Table 9*.

*Table 9: Keywords used for the qualitative and semantic selection of hydrogen hubs and valleys within the consolidated database*

| **Keywords** | | | |
|---|---|---|---|
| Valley | Vallée | Hub | Corridor |
| Ecosystem | Cluster | Group | Region |
| Network | Park | Alliance | Partnership |
| Consortium | | Framework | |

Projects were retained only if their official titles or descriptions explicitly included these terms. This criterion was fundamental to guarantee that the sample effectively consisted of hubs intended as a cross-sector and/or cross-regional collaboration between different stakeholders.

By applying these criteria, the research moved beyond simple production facilities to focus on systemic hubs that act as catalysts for the decarbonization of entire industrial clusters. Once the final sample of approximately 23 operational projects was defined, a comparative analysis was conducted to identify best practices, operational bottlenecks and strategic opportunities for optimizing green hydrogen adoption.

However, inconsistencies in data availability were observed across the different databases, making it difficult to compare projects with varying types of information. Moreover, some initiatives initially included in the sample still did not qualify as hubs or valleys, highlighting the importance of careful verification and methodological rigor in the selection process.

### 3.5 Sample Selection Solution 3: Clean Hydrogen Partnership

In this final solution, only the Clean Hydrogen Partnership (CHP) database was considered, as it provided certainty that the initiatives included are indeed hydrogen valleys and hubs. Initially, only projects classified as fully operational were selected, certifying that the analysis relied on initiatives with proven performance and reliable data.

However, once the analysis was limited to a single database, comparative consistency constraints were reduced. In order to expand the sample and capture a broader yet still mature set of projects, the selection was subsequently extended to include initiatives classified as Post-FID (Post–Final Investment Decision) and Under Construction. This approach allowed the inclusion of projects with secured financial and regulatory commitments, while continuing to exclude early-stage concepts or proposals still undergoing feasibility assessments. Specifically:

- Operational: projects that provide proven data and real-world performance metrics.
- Under construction: initiatives representing committed infrastructure already in the physical implementation phase.
- Post-FID: projects that have secured formal financial backing and regulatory approvals.

By applying these expanded status-based filters, the dataset now focuses on initiatives that have progressed beyond superficial planning and that are actively contributing to the industry's growth.

The final selection comprises 25 hydrogen hubs, representing a variety of geographical contexts and technological approaches. The chosen case studies provide a comprehensive overview of the green hydrogen landscape. Firstly, in terms of collaborative governance models, multiple stakeholders, both public and private, cooperate in various numbers and across different regions to establish a fully functioning hydrogen ecosystem. Second, regarding the value chain and multi-sectoral integration, the initiatives connect hydrogen production with multiple stages of the value chain and, where distribution is included, link end-users such as heavy industry and mobility. Finally, projects' infrastructure varies in complexity, each incorporating dedicated storage and transport solutions, like repurposed pipelines or trucking logistics, rather than simple production setups. This aspect particularly reflects the development of mature and operational supply chains. Collectively, these criteria ensure that the sample focuses on advanced, operational initiatives which actively contribute to the growth of the green hydrogen development.

To summarize, the transition from Solution 1 - Database Intersection and Solution 2 - Keyword-based research to the final selection via the Clean Hydrogen Partnership (CHP) database was a necessity, aimed at providing high reliability levels. Moreover, the research results from the initial solutions indicated high levels of 'noise' due to differences in the technical specification of projects within the IEA and EHO databases. However, by using the CHP sample, the research ensures that only recognized 'valleys' and 'hubs' that integrate production and consumption in close proximity are utilized.

### 3.6 Definition of KPIs

In order to carry out a standardized and rigorous comparison, the projects were evaluated using a streamlined set of Key Performance Indicators (KPIs). Most of these indicators were already provided in the database, while additional KPIs were introduced to offer a broader and more comprehensive understanding of the cases. Financial metrics, useful to evaluate the project's profitability over time, like IRR and NPV, are rarely disclosed in public project reports or early-stage feasibility studies. The research indeed evaluates the hydrogen hubs according to strategic, economic and operational parameters. The indicators were organized into four thematic pillars. Further details and descriptions are reported in *Table 10*.

**I. Technical and Financial**

1. **(Expected) Annual green hydrogen production (t $H_2$/year):** estimated amount of green hydrogen the project is expected to produce annually, in tons.
2. **(Expected) Normalized capacity (MWel):** installed or planned total electrical capacity required by the hydrogen production facility, including electrolyzers and auxiliary systems.
3. **Investment volume (M€):** total capital invested in the project, expressed in million euros. Includes private, public and co-financing sources.
4. **Founding sources:** origin of the project's financing, such as public funds, private investments, European funds, venture capital.

**II. Organizational Information: Project Stakeholders**

5. **Lead developer**: the main organization responsible for leading and developing the project.
6. **Lead developer entity type**: legal or organizational type of the lead developer.
7. **Total number of partners (n)**: total number of organizations participating in the project consortium or partnership.

**III. Supply Chain & Operations**

8. **Value chain coverage**: segments of the hydrogen value chain covered by the project.
9. **% Value chain covered**: percentage of the entire hydrogen value chain covered by the project.
10. **Type of renewable**: specific type of renewable energy used.
11. **H2 Production**: technologies used for hydrogen production.
12. **H2 Storage**: methods of hydrogen storage.
13. **H2 Transport**: means of transporting produced hydrogen.
14. **H2 Distribution**: channels and infrastructure used to supply hydrogen to end-users.

**IV. Target Market & Applications**

15. **End-user sector**: industry sectors or final markets served by the project.
16. **Application in mobility**: types of hydrogen use in transportation.
17. **Application in energy**: use of hydrogen in energy production or storage.
18. **Application in industrial use**: use of hydrogen in industrial processes.

This comparative framework enables the identification of which business model best performs and demonstrates stronger long-term prospects and a higher potential for green hydrogen deployment. Information has been retrieved from the Clean Hydrogen Partnership database and supplemented with publicly available sources on the Internet, notably each project's official website and its dedicated CHP project overview.

*Table 10: Summary and description of KPI*

| Cluster | KPI |
|---|---|
| **I. Technical and Financial** | **1. (Expected) Annual green hydrogen production (t $H_2$/year)** |
| | **2. (Expected) Normalized capacity (MWel)** |
| | **3. Investment volume (M€)** |
| | **4. Funding sources** |
| **II. Organizational Information: Project Stakeholders** | **5. Lead developer** |
| | **6. Lead developer entity type** |
| | **7. Total number of partners (n)** |
| **III. Supply Chain & Operations** | **8. Value chain coverage** |
| | **9. % Value chain covered** |
| | **10. Type of renewable** |
| | **11. $H_2$ Production** |
| | **12. $H_2$ Storage** |
| | **13. $H_2$ Transport** |
| | **14. $H_2$ Distribution** |
| **IV. Target Market & Applications** | **15. End-user sector** |
| | **16. Application in mobility** |
| | **17. Application in energy** |
| | **18. Application in industrial use** |

In the following chapter, a qualitative analysis is conducted to provide a general overview of each of the selected case studies, with the aim of identifying which organizational configurations and partnership structures are most conducive to supporting the large-scale deployment of green hydrogen.

# 4 – CASE STUDIES

The following chapter provides a detailed analysis of each individual hub resulting from the filtering process of the Clean Hydrogen Partnership database. Each case study is analyzed along three main dimensions: project objectives, business models and governance characteristics. The analysis of project objectives focuses on the strategic goals pursued by each initiative, such as decarbonization targets, industrial competitiveness, energy system integration and regional economic development, providing context for the subsequent assessment. The business model analysis examines how each hub creates, delivers and captures value. In parallel, governance structures are assessed to understand decision-making processes, describing the stakeholders' roles within the partnership and organizational frameworks.

## 4.1 Database Overview

The resulting database of green hydrogen valleys is composed by 25 case studies.

*Table 11: All 25 green hydrogen case studies*

| Id | Name | Main location | Continent | Start year | Status |
|---|---|---|---|---|---|
| 1 | Agder Hydrogen Hub | Norway | Europe | 2023 | Under construction |
| 2 | BalticSeaH2 | Finland | Europe | 2023 | Under construction |
| 3 | Basque Hydrogen Corridor BH2C | Spain | Europe | 2021 | post-FID (financing, tendering, etc.) |
| 4 | CRETE-AEGEAN H2 VALLEY (CRAVE-H2) | Greece | Europe | 2023 | Under construction |
| 5 | eFarm | Germany | Europe | 2020 | Fully operational |
| 6 | FLHyPorts: Flemish hydrogen ports valley | Belgium | Europe | 2023 | Under construction |
| 7 | Green Hysland | Spain | Europe | 2021 | Fully operational |
| 8 | H2iseO hydrogen valley | Italy | Europe | 2021 | Under construction |
| 9 | HY.City.Bremerhaven | Germany | Europe | 2022 | post-FID (financing, tendering, etc.) |
| 10 | hy.klettwitz | Germany | Europe | 2022 | post-FID (financing, tendering, etc.) |
| 11 | HY.Waiblingen | Germany | Europe | 2021 | post-FID (financing, tendering, etc.) |
| 12 | HyBalance | Denmark | Europe | 2018 | Fully operational |
| 13 | HyBayern | Germany | Europe | 2023 | Fully operational |
| 14 | Hydro3D | Romania | Europe | 2023 | Under construction |
| 15 | Hydrogen Valley Emsland | Germany | Europe | 2022 | Under construction |
| 16 | HyWays for Future | Germany | Europe | 2020 | Under construction |
| 17 | Mid Sweden Hydrogen Valley | Sweden | Europe | 2022 | Under construction |
| 18 | NEOM GREEN HYDROGEN | Saudi Arabia | Asia | 2021 | Under construction |
| 19 | Norddeutsches Reallabor (NRL) - Northern German Living Lab | Germany | Europe | 2021 | Under construction |
| 20 | Phi Suea House Project | Thailand | Asia | 2015 | Fully operational |
| 21 | SoHyCal | United States | North America | 2023 | Fully operational |
| 22 | Transylvania Hydrogen Valley | Romania | Europe | 2023 | post-FID (financing, tendering, etc.) |
| 23 | WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas | Austria | Europe | 2018 | Fully operational |
| 24 | WIVA P&G HyWest | Austria | Europe | 2021 | Under construction |
| 25 | ZEV - Zero Emission Valley | France | Europe | 2020 | Fully operational |

As shown in *Figure 15*, almost 90% of the case studies in the dataset is European. This is explained by the fact that the Clean Hydrogen Partnership (CHP) is mainly designed to contribute to European policy and European sustainable objectives. This concentration is therefore not incidental, but reflects the continent's coordinated efforts and policy commitment to green hydrogen as a new renewable energy vector. Over the past decade, as already mentioned in Chapter 1, several actions have been undertaken by European leading countries and actors, such as the European Green Deal in 2020 followed by hydrogen strategies at both EU and national levels, resulting in the affirmation of a comprehensive regulatory, financial and institutional system supporting in fact hydrogen development. At the same time, dedicated funding instruments, national recovery plans and regional innovation programs have actively promoted collaborative, large-scale, integrated initiatives rather than isolated production facilities.

Among all European countries, there is one that particularly stands outs in terms of number of ongoing green hydrogen hubs. *Figure 16* illustrates that Germany hosts 36,4% of the case studies (which corresponds to 9 case studies over a total of 25). If all Northern Europe is considered, then the percentage rises at almost 60%, with hubs located in 6 Northen countries, while the remaining 40% is distributed in 5 Southern countries. Such phenomenon can be explained by a stronger combination of industrial infrastructure availability, energy system characteristics and policy leadership in North Europe. In Germany, in particular, green hydrogen is driven by local demand, supported by EU and national policies and subsidies, local surplus of renewable electricity and technology development (Walker and Klagge, 2024). Furthermore, Germany, has been among the earliest adopters of national hydrogen strategies, supported by substantial public funding and strong coordination between federal, regional and industrial actors. Germany's *National Hydrogen Strategy*, adopted in 2020 and updated in 2023, is supported by the Federal Government and sets out ambitious goals "to promote hydrogen generation, build infrastructure and enable its use"[33] while strengthening industrial competitiveness.

Another important aspect to highlight is the fact that the majority of the selected projects are either still under construction or in post–final investment decision (post-FID) phases (*Figure 17*). This reflects the highly capital-intensive nature of green hydrogen technologies, indeed large-scale hydrogen ecosystems require significant development of multiple infrastructure components, including renewable energy to power electrolysis, electrolysis capacity, storage, transport and end-use applications, which significantly extends planning and implementation timelines.

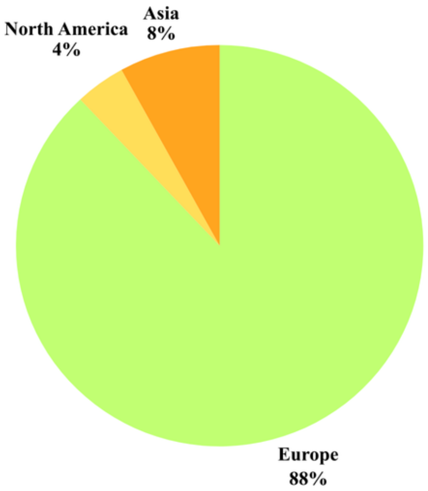

*Figure 15: Continental distribution of the 25 green hydrogen case studies in the sample.*

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[33] Federal Ministry for Economic Affairs and Climate Action. "*The National Hydrogen Strategy*." *Bundesministerium für Wirtschaft und Klimaschutz*, https://www.bundeswirtschaftsministerium.de/Redaktion/EN/Hydrogen/Dossiers/national-hydrogen-strategy.html

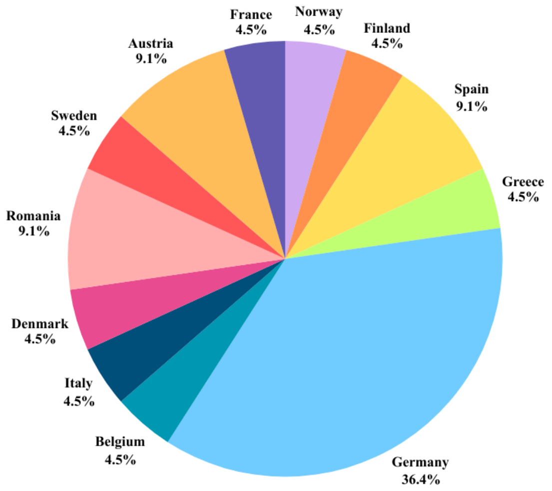


*Figure 16: European concentration of the 25 green hydrogen case studies in the sample.*

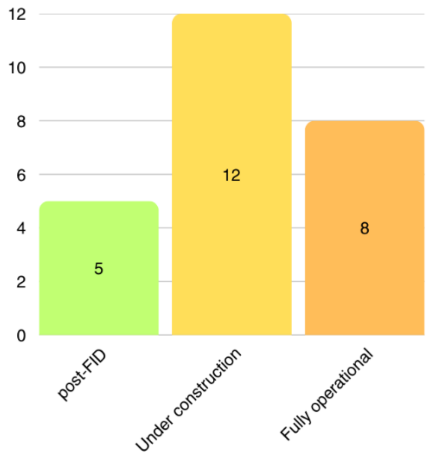


*Figure 17: Status of the 25 green hydrogen projects in the sample.*

## 4.2 Case Studies Description

1. Agder Hydrogen Hub (Norway)

- **Objectives**: to develop large-scale production of green hydrogen to support the decarbonization of hard-to-abate sectors, with a particular focus on maritime transport and heavy land mobility. The project uses hydropower and other renewables to provide low-carbon fuel and strengthen Norway's hydrogen economy.
- **Business Model**: centers on commercial green hydrogen production and sale, using renewable electricity and water electrolysis to generate green hydrogen for customers such as shipping companies, heavy-duty transport operators and potentially industrial users. Revenues will be generated through long-term hydrogen supply contracts and distribution via truck and ship from the strategic port locations. The model also relies on public funding, long-term site leases and collaboration with equipment and engineering partners to optimize production costs and ensure reliable delivery to early adopters in the market.
- **Governance Characteristics**: shaped by its project company structure, with Greenstat owning it 100 % through its subsidiary Greenstat Hydrogen AS, backed financially by major shareholder La Française de l'Énergie (FDE). The

project is supported by a network of stakeholders, including public agencies like Enova, which supports the project with significant grants, local authorities, port and industrial partners and engineering and equipment suppliers.

2. BalticSeaH2 (Finland)

- **Objectives**: to establish the first large-scale, cross-border hydrogen valley in Europe by building an integrated hydrogen economy around the Baltic Sea region, with a main corridor between southern Finland and Estonia. The project's goals are to connect production, storage, transport and use of hydrogen across borders, demonstrate hydrogen applications in industry, mobility and energy and show how hydrogen can reduce carbon emissions while improving energy self-sufficiency, providing a model for replication in other regions.
- **Business Model**: revolves around collaborative development and demonstration of a transnational hydrogen value chain, funded primarily through the EU's Horizon Europe program. Rather than a single producer selling hydrogen, the initiative brings together multiple partners to pilot and showcase hydrogen production, transport, storage and end-use cases across different sectors, attracting broader private and public investment.
- **Governance Characteristics**: consortium-based and collaborative, coordinated by CLIC Innovation Oy and Gasgrid Finland with funding from the EU Clean Hydrogen Partnership under Horizon Europe. The project brings together around 40 partners from nine Baltic Sea countries, including universities, research institutes, ports, technology developers, public authorities and private firms, each contributing expertise to different parts of the hydrogen value chain.

3. Basque Hydrogen Corridor (BH2C) (Spain)

- **Objectives**: to create a comprehensive hydrogen ecosystem in the Basque Country that accelerates decarbonization across key sectors such as energy, industrial processes, residential use and mobility, developing infrastructure and implementing diverse projects across the hydrogen value chain.
- **Business Model**: based on a collaborative network of over 70 organizations, working together on dozens of projects that span production, transport, storage, distribution and end uses of hydrogen. Funding comes from a mix of private investment and regional, national and EU support, deployed across specific infrastructure and application projects. By coordinating these efforts, BH2C aims to stimulate market demand, attract further investment while establishing a commercially viable hydrogen ecosystem that drives technological development and industrial deployment.
- **Governance Characteristics**: public-private association led by Petronor (part of the Repsol Group) with strong participation from government institutions, energy companies, industrial firms, technology centers, research institutes and public authorities across the Basque Country.

4. Crete-Aegean H2 Valley (CRAVE-H2) (Grece)

- **Objectives:** intended to establish a full hydrogen ecosystem on the island of Crete, covering the entire value chain. It seeks to decarbonize road transport and grid services via fuel cells, with potential future applications in marine fuel and industry. The project also prioritizes safe large-scale hydrogen use and positive socio-economic impact for the local community.
- **Business Model:** pilot and demonstration approach, funded largely through the EU's Horizon and Clean Hydrogen Partnership. The business model integrates hydrogen production, compression, storage, refueling infrastructure and end-use applications, resulting in attracting further investment and paving the way for scalable regional hydrogen markets by showcasing sustainable solutions in mobility and energy storage.

- **Governance Characteristics:** consortium-based, led by EUNICE and involving partners such as De Nora, Politecnico di Torino, CERTH, Ballard Europe, HEDNO and the Region of Crete, with EU political sponsorship. This multistakeholder structure aligns public authorities, research organizations, technology providers and local industry.

5. eFarm (Germany)

- **Objectives:** Germany's largest green hydrogen mobility project, targeting to build a complete regional hydrogen value chain in North Frisia, from production using wind and solar power to distribution and use in fuel cell vehicles. It seeks to secure a local supply of 100 % green hydrogen, emission-free mobility for buses, trucks and cars, stimulate regional value creation and finally serve as a blueprint for hydrogen ecosystems elsewhere.
- **Business Model:** focuses on producing green hydrogen via PEM electrolysis powered by onshore renewables, storing and transporting it by truck in mobile containers and supplying it at public hydrogen refueling stations for mobility applications. Supported by public funding and private investment, it develops infrastructure, generate local demand and integrate renewable energy into transport and heat uses.
- **Governance Characteristics:** regional joint project, initiated and operated by GP JOULE and the project company eFarming GmbH & Co. KG, with around 20 local partners including citizen-owned wind and solar farms and public authorities.

6. FLHyPorts: Flemish Hydrogen Ports Valley (Belgium)

- **Objectives:** to develop a hydrogen ecosystem across the Flemish ports area (Antwerp-Bruges, North Sea Port and Ostend) to decarbonize logistics, shipping, industry and mobility. The project focuses on building the full hydrogen value chain, from renewable hydrogen production to distribution, storage and local end use.
- **Business Model:** based on cross-sector cooperation and scaling real-life hydrogen applications in a major industrial and port region. It links renewable electricity (solar, onshore/offshore wind) to electrolysis, transport and use of hydrogen via trucks and ships, with hydrogen refueling stations and industrial customers driving demand. Public funding and strategic partnerships with energy, industry and service providers support such implementation.
- **Governance Characteristics:** consortium-based and collaborative, coordinated by WaterstofNet through the Waterstof Industry Cluster, with key partners including Hyoffwind (Virya/Messer), Fluxys, port operators, mobility and industry stakeholders and political actors like the Flemish government.

7. Green Hysland (Spain)

- **Objectives:** to build a fully cohesive green hydrogen ecosystem on the island of Mallorca, Spain, turning it into Southern Europe's first hydrogen hub. The project aims at using solar energy to produce green hydrogen for mobility, heat and power and to inject it into the local gas grid, enhancing decarbonization and increasing renewable energy penetration across tourism, transport, industry and energy sectors.
- **Business Model:** consists on deploying and demonstrating a complete hydrogen value chain, from production via electrolysis linked to PV plants, distribution infrastructure (pipeline, trailers, and refueling stations) to commercial end uses, primarily funded by the EU Clean Hydrogen Program and public sponsors. It also focuses on de-risking technologies and creating scalable, replicable solutions that attract further private and public investment.

- **Governance Characteristics:** coordinated by Enagás Renovable SA within a large consortium of partners (including energy companies, research institutes, public authorities and technology providers) under EU Horizon/Clean Hydrogen funding.

8. H2iseO Hydrogen Valley (Italy)

- **Objectives:** aims to create an industrial renewable hydrogen value chain in Val Camonica, Italy, focused on decarbonizing regional mobility by replacing diesel trains and buses with hydrogen-powered vehicles, in order to support the local energy transition towards sustainability. It will deploy hydrogen trains on the non-electrified Brescia–Iseo–Edolo line and build production, storage and refueling infrastructure to reduce transport emissions, and in parallel to expand its use beyond the regional level.
- **Business Model:** combination of public and private funding to invest in hydrogen production, storage, distribution and end-use for mobility, especially through regional funds, national recovery plans and corporate investment. Hydrogen production technologies include renewable electrolysis, supplying the regional mobility sector.
- **Governance Characteristics:** consortium led by FNM Group, with partners including Ferrovienord and Trenord, while supported politically and financially by Regione Lombardia and national agencies. This structure aligns public authorities, transport operators and industry partners to share decisions, coordinate infrastructure deployment and drive hydrogen mobility across the region.

9. HY.City.Bremerhaven (Germany)

- **Objectives:** to build a regional green hydrogen ecosystem in Bremerhaven, Germany, covering hydrogen production, distribution and use for sustainable mobility. It produces green hydrogen and supplies it to transport modes through a public refueling station, advancing low-carbon transport and regional climate goals.
- **Business Model:** focuses on local green hydrogen production and supply for mobility, funded through public programs and investments from partner companies. Hydrogen is produced on-site from local wind power and delivered to a public station next to the BremerhavenBus depot, where it fuels buses, trucks, private vehicles and commercial fleets, aiming at both creating demand and demonstrating scalable infrastructure.
- **Governance Characteristics:** consortium-based, coordinated by HY.City.Bremerhaven GmbH & Co. KG, with lead developer GP JOULE Hydrogen GmbH. This multistakeholder structure combines private companies, transport operators and public support to align strategy and implement the hydrogen value chain in the region.

10. HY.Klettwitz (Germany)

- **Objectives:** create a regional green hydrogen value chain in the Lusatia (Lausitz) region of Germany, covering hydrogen production, logistics, distribution and use for mobility (cars, buses, trucks) for regional decarbonization. It focuses on using water electrolysis powered by local renewable energy to supply hydrogen at local refueling stations and support emission-free transport in the former lignite mining area.
- **Business Model:** connects renewable electricity generation (solar and wind) with hydrogen production via PEM electrolysis, compressed storage, trucking logistics and distribution to refueling stations for mobility use. It is designed to scale production as demand grows and is funded through a mix of EU, national, regional and private contributions, aiming to demonstrate an integrated hydrogen value chain that supports local fleets and stimulates regional hydrogen markets.

- **Governance Characteristics:** consortium led by GP JOULE Hydrogen GmbH through Energiepark Lausitz Wasserstoff GmbH & Co. KG, with support from public funding programs and regional partners.

11. HY.Waiblingen (Germany)

- **Objectives:** to build a regional green hydrogen ecosystem in Waiblingen, Germany, producing hydrogen from local renewable electricity and supplying it through a refueling station for buses, trucks and cars. The project supports decarbonization of mobility in the Rems-Murr district, particularly enabling emission-free public transport from mid-2025 onward.
- **Business Model:** local production and supply of green hydrogen for transportation, funded through public programs alongside investment from partner companies. Hydrogen is produced on-site, compressed and sold via a hydrogen station to regional operators, creating regional demand and demonstrating scalable infrastructure.
- **Governance Characteristics:** regional consortium, led by Stadtwerke Waiblingen GmbH and GP JOULE Hydrogen GmbH, with participation from local authorities and transport partners.

12. HyBalance (Denmark)

- **Objectives:** designed to demonstrate large-scale power-to-hydrogen (PtH2) production from renewable electricity in Denmark, storing surplus wind energy as green hydrogen for use in grid balancing, industry and clean transport. It aimed to validate PEM electrolysis technology under real industrial conditions and show hydrogen's role in reducing emissions and integrating renewables into the energy system.
- **Business Model:** demonstration of hydrogen technologies rather than full commercial operations, funded through EU and Danish EUDP grants. Hydrogen produced by the electrolyser is sold to industrial customers and hydrogen refueling networks, helping assess revenue streams from multi-sector hydrogen use.
- **Governance Characteristics:** governed by a multi-partner consortium led by Air Liquide with key contributors including Cummins (Hydrogenics), Centrica, LBST and Hydrogen Valley, supported politically by EU and Danish public programs. This structure brought together technology providers, energy traders and research partners to share knowledge, align project decisions and integrate hydrogen production with end-use applications across sectors.

13. HyBayern (Germany)

- **Objectives:** located in Bavaria, Germany, aims at creating a closed cycle of hydrogen production, distribution and use to decarbonize regional mobility (especially buses) and support wider energy transition efforts. The project focuses on building an electrolyser in Pfeffenhausen and delivering green hydrogen to refueling stations serving buses and other vehicles, helping reduce $CO_2$ emissions in public transport and regional fleets.
- **Business Model:** revolves around regional green hydrogen production and supply via the operating company Hy2B Wasserstoff GmbH, supported by federal and regional funding. Hydrogen produced using local renewables is compressed, filled into trailers and transported to hydrogen stations for buses, trucks, and cars creating demand while demonstrating a viable hydrogen value chain.
- **Governance Characteristics:** governed through a multistakeholder structure led by Hy2B Wasserstoff GmbH, with shareholders including the districts of Landshut, Munich and Ebersberg, various (medium-sized) companies in the region, municipal utility companies, energy agencies, citizens' energy cooperatives, associations and universities, that coordinate production, distribution and use of green hydrogen across the region.

14. Hydro3D (Romania)

- **Objectives:** to develop a hydrogen gas sensor with a micro-heater using MEMS (micro-electromechanical systems) technology, aimed at being low-cost, reliable and efficient. It improves safety and detection for hydrogen infrastructure and applications such as vehicles and electrical equipment.
- **Business Model:** primarily an R&D demonstration, with a small investment under public and national funding. It intends to advance sensor technology by partnering research and technology organizations, aiming to create intellectual property and prototypes that can be commercialized or integrated into hydrogen systems to improve safety and monitoring, rather than direct hydrogen production or sales.
- **Governance Characteristics:** led by BEIA Consult International S.R.L. with partners such as ICPE-CA, National NANOFAB Center, MNTEK and Sogang University, supported by EU, national, regional and private funding.

15. Hydrogen Valley Emsland (Germany)

- **Objectives**: to develop a leading hydrogen economy in the Emsland region of Lower Saxony, Germany, covering the full value chain from production to transport and use in industry, mobility and energy applications. The initiative also emphasizes pipeline infrastructure and hydrogen utilization across sectors as part of the area's climate-neutral transformation.
- **Business Model:** based on regional networked development and scaling of hydrogen production, transport and demand, involving industrial partners deploying large electrolysers, development of transport pipelines and green hydrogen fueling stations that serve different users. The model is supported by public and private investment, often through EU, federal and regional programs, leveraging logistics infrastructure and cooperation between producers, industrial consumers and mobility operators.
- **Governance Characteristics:** network-based and collaborative, centered on the H2-Region Emsland network and its administrative office in Lingen, jointly supported by the County of Emsland and the City of Lingen. The network brings together regional companies, research institutions, government bodies and SMEs in thematic working groups to co-ordinate project implementation. In 2024, Emsland was recognised as "Hydrogen Valley of the Year," reflecting strong alignment and cooperation among these actors.

16. HyWays for Future (Germany)

- **Objectives:** located in the north-west Germany region, it aims to accelerate the market adoption of green hydrogen, especially in the transport sector (cars, buses, trucks) and industrial applications. It focuses on building hydrogen production capacity, fueling infrastructure while increasing demand for hydrogen mobility to help cut regional emissions and establish the Northwest as a leading hydrogen hub.
- **Business Model:** based on activating the hydrogen market by increasing electrolysis capacities (PEM and alkaline), building hydrogen refueling stations, with hydrogen transported by truck in compressed form. Supported by public funding and by a broad regional consortium, it links renewable hydrogen supply with mobility and industrial demand to stimulate both sides of the hydrogen economy.
- **Governance Characteristics:** consortium-based, led by EWE AG with partners coming from industry, energy, transport and public authorities collaborating across the Northwest metropolitan region.

17. Mid Sweden Hydrogen Valley (Sweden)

- **Objectives:** to develop an integrated hydrogen ecosystem in central Sweden that supports fossil-free industrial production, green transport and a resilient regional energy system. It brings together the steel industry, transport sector, academia and energy producers to use green hydrogen as a key enabler of climate-neutral growth and innovation, leveraging regional expertise and infrastructure to build a hydrogen-based value chain.
- **Business Model:** collaborative value chain development across production, storage, transport and end use, linking industrial partners, ports, logistics and renewable energy supply to create demand for hydrogen in both mobility and industrial applications. Rather than a single commercial producer, it functions as a network-driven platform that attracts investment, aligns pilot deployments and opens paths for future commercial hydrogen markets in the region.
- **Governance Characteristics:** multistakeholder and partnership-based, coordinated by actors like the Regional Chamber of Commerce, Region Gävleborg and Region Dalarna, with members from industry, logistics, academia, wind developers and transport stakeholders.

18. NEOM Green Hydrogen (Saudi Arabia)

- **Objectives:** to develop the world's largest green hydrogen production facility at Oxagon in NEOM, Saudi Arabia, powered entirely by renewable energy (solar and wind). It supports decarbonization of global transport and industrial sectors, while significantly reducing $CO_2$ emissions and enhancing sustainable development and local green job creation.
- **Business Model:** large-scale green hydrogen and ammonia production for export. Renewable power feeds electrolysers whose output is converted to green ammonia under a 30-year offtake agreement. Revenue is driven by long-term global contracts supplying clean fuel to industrial and transportation markets, positioning the facility as a cornerstone of the emerging global green hydrogen economy.
- **Governance Characteristics:** joint venture (NGHC) equally owned by NEOM, ACWA Power and Air Products, combining energy producers and industrial gas expertise.

19. Norddeutsches Reallabor (NRL) - Northern German Living Lab (Germany)

- **Objectives:** aims to test and demonstrate pathways to climate neutrality by decarbonizing high-energy-use sectors, such us industry, heat and mobility, across northern Germany. It deploys hydrogen via electrolyzers alongside other renewable and sector-coupling innovations to replace fossil fuels, reduce regional $CO_2$ emissions by up to ~75 % by 2035, and serve as a large-scale model for hydrogen-based energy transformation in Germany and Europe.
- **Business Model:** demonstration-driven and network-oriented, combining public funding (German federal ministries) with partner investments to implement subprojects across production, mobility, industrial use and heat coupling. Rather than a single commercial hydrogen seller, it facilitates deployment of multiple technologies and use cases at scale, creating evidence and pathways to attract future investment, stimulate market uptake and accelerate regional hydrogen markets.
- **Governance Characteristics:** multistakeholder and collaborative, led by an alliance of more than 50 partners from industry, science and government, coordinated through working groups and a Project Management Office (PMO) hosted by CC4E at Hamburg University of Applied Sciences.

20. Phi Suea House Project (Thailand)

- **Objectives:** located in Chiang Mai, Thailand, aims to be the world-first solar-hydrogen residential development whose goal is to demonstrate how renewable energy and hydrogen storage can power a multi-building residence off-grid 24/7. It combines solar photovoltaics with a hybrid hydrogen–battery system and fuel cells to maximize clean energy self-sufficiency, reduce carbon footprint and finally show practical hydrogen energy storage applications for sustainable living.
- **Business Model:** functions as a demonstration and technology showcase. Excess solar energy is stored as hydrogen (via electrolyzers) and then converted back to electricity when needed, helping validate hybrid storage systems and provide a proof of concept that can attract interest, replication and future investment in sustainable energy and hydrogen technologies.
- **Governance Characteristics:** led by the Phi Suea House team with technological input from Enapter and partners, functioning as a collaborative platform rather than a commercial corporation.

21. SoHyCal (USA)

- **Objectives:** aims to operate one of North America's largest green hydrogen production plants in Fresno County, California, producing renewable hydrogen to help decarbonize transport and other sectors.
- **Business Model:** based on renewable hydrogen production and supply for mobility markets, funded through private investment by H2B2 Electrolysis Technologies Inc. and supported by a grant from the California Energy Commission. Hydrogen is produced via PEM electrolysis powered by biogas initially and solar PV in later phases, then stored and transported to hydrogen refueling stations in the region, creating demand and supporting wider clean transport uptake.
- **Governance Characteristics:** led and operated by H2B2 Electrolysis Technologies Inc., with key support from the California Energy Commission and regional partners like the Fresno County Economic Development Corporation. This partnership aligns public clean-energy goals with private expertise in technology, financing and operations to implement and scale renewable hydrogen production in California.

22. Transylvania Hydrogen Valley (Romania)

- **Objectives:** to establish the first integrated green hydrogen ecosystem in Romania, centered around Cluj-Napoca. It will deploy a renewable-powered electrolyser to produce green hydrogen for public transport, district heating and future industrial use, while creating a regional clean-energy corridor with nearby cities to support decarbonization, energy independence and innovation across Transylvania.
- **Business Model:** building a hydrogen value chain that links renewable hydrogen production (via PEM electrolysis) with supply to transport and energy sectors. It attracts public funding and EU support and aims to stimulate regional demand, reduce emissions while demonstrating scalable hydrogen applications.
- **Governance Characteristics:** multistakeholder and locally anchored, led by the Municipality of Cluj-Napoca with partners such as Compania de Transport Public Cluj-Napoca and other regional municipalities, along with political sponsors including the Romanian Ministry of Energy and the EU Clean Hydrogen Partnership. This collaborative structure aligns public authorities, academia, transport operators and technical partners to coordinate implementation, decision-making and integration of the hydrogen ecosystem in the region.

23. WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas

- **Objectives:** aims to demonstrate the transformation of the Austrian economy toward a largely $CO_2$-neutral energy system by making green hydrogen and renewable gases a central component of energy, industry and mobility. It addresses production, storage, transport, conversion and utilization of renewable hydrogen across sectors to showcase a full hydrogen value chain and Austria as a hydrogen innovation leader.
- **Business Model:** research, demonstration and network-driven rather than a single commercial producer. It brings together over 30 completed and ongoing projects and ~25 subprojects that link production, storage, transport, infrastructure and applications of hydrogen and renewable gases across Austria. Public funding, especially from the Klima- und Energiefonds under the Vorzeigeregion Energie programs, is combined with partner contributions to de-risk technologies and lay foundations for broader market uptake in energy, industry and mobility.
- **Governance Characteristics**: multistakeholder and consortium-based, coordinated by the nonprofit Verein WIVA P&G with members from industry, research and public authorities. It aligns stakeholders through clusters and collaborative frameworks to plan, demonstrate and disseminate hydrogen solutions, share research insights and expand hydrogen technologies through regional and national initiatives.

24. WIVA P&G – HyWest

- **Objectives:** to create largely autonomous regional green hydrogen economy in Tyrol, western Austria, demonstrating cross-sector production, storage and application of green hydrogen. The project explores hydrogen use in mobility (hydrogen trucks and buses), industry (process heat), power-to-X systems and logistics to advance a regional clean energy transition and build a replicable model for Central Europe.
- **Business Model:** research and demonstration-driven, funded by the Austrian Klima- und Energiefonds under the Energy Model Region programs. It integrates complementary subprojects to test technical solutions and business cases for hydrogen production, distribution and utilization, creating local supply chains and validating cost-effective regional use of green hydrogen.
- **Governance Characteristics:** multistakeholder and consortium-based, coordinated by FEN Sustain Systems GmbH and involving partners like MPREIS, Zillertaler Verkehrsbetriebe, TIWAG-Tiroler Wasserkraft, TIGAS, the Energy Institute at JKU Linz, FEN Research, HyCentA and the WIVA P&G association.

25. ZEV - Zero Emission Valley

- **Objectives:** aims to establish one of Europe's most ambitious hydrogen mobility ecosystems in the Auvergne-Rhône-Alpes region of France, deploying a network of hydrogen refueling infrastructure and fuel cell vehicles to accelerate the uptake of zero-emission transport. The project plans to provide around 20 hydrogen refueling stations and over 1,000 hydrogen vehicles (light and heavy duty) and promote regional decarbonization of mobility, while anchoring hydrogen solutions in both public and private fleets.
- **Business Model:** regional deployment of hydrogen infrastructure and vehicle fleets supported by public grants (EU and national/regional funds) and private partnerships. Hydrogen is produced through PEM electrolysis powered by renewables, stored and transported to refueling stations across the region and eventually sold to fleets and operators under long-term offtake arrangements. This blended public-private funding and infrastructure deployment seeks to create a viable hydrogen mobility market and scale hydrogen demand in transport.
- **Governance Characteristics:** consortium coordinated by Hympulsion under the leadership of the Auvergne-Rhône-Alpes Regional Council, with strategic partners including ENGIE, Michelin, Crédit Agricole and Banque des Territoires, and political support from regional authorities and EU programs.

*Table 12: Summary of the 25 hydrogen hubs' main characteristics*

| Id | Project | Objective | Business Model | Governance | Target Market |
|---|---|---|---|---|---|
| 1 | Agder Hydrogen Hub | Decarbonize hard to abate sectors | Commercial production and sale; truck & ship distribution to customers | Private-public partnership | National |
| 2 | BalticSeaH2 | Demonstrate hydrogen applications across sectors and show how hydrogen can reduce carbon emissions while improving energy self sufficiency | Demonstration of a transnational value chain (production, transport, storage and end use across different sectors); Establishment of a main corridor between Finland and Estonia | Consortium | International |
| 3 | BH2C | Create a comprehensive hydrogen ecosystem in the Basque Country that accelerates decarbonization across key sectors and stimulate market demand | Collaborative multi-project model across the entire hydrogen value chain | Public-private partnership | Regional |
| 4 | CRAVE H2 | Establish a full hydrogen ecosystem to decarbonize road transport and grid services | Pilot and demonstration approach for sustainable solutions in mobility and energy storage | Consortium | Regional |
| 5 | eFarm | Secure a local supply of 100 % green hydrogen, emission free mobility | Supply green hydrogen at refueling stations for mobility applications | Regional joint project | Regional |
| 6 | FLHyPorts | Develop a hydrogen ecosystem across the Flemish ports area to decarbonize logistics, shipping, industry and mobility | Cross sector cooperation and scaling real life hydrogen applications in a major industrial and port region | Consortium | Regional |
| 7 | Green Hysland | Produce green hydrogen for mobility, heat and power to inject it into the local gas grid, enhancing decarbonization and increasing renewable energy penetration | Deployment and demonstration of a complete hydrogen value chain to de risk technologies and create scalable, replicable solutions | Consortium | Regional |
| 8 | H2iseO | Decarbonization of regional mobility by replacing diesel trains and buses with hydrogen powered vehicles, in order to support the local energy transition towards sustainability | Public-private funded value chain; Supply to customers through refueling stations | Consortium | Regional |
| 9 | HY.City.Bremerhaven | Production, distribution and use for sustainable mobility advancing low-carbon transport and regional climate goals | Local production and supply of hydrogen for mobility delivered customers at a public station | Consortium | Regional |
| 10 | HY.Klettwitz | Create an integrated value chain for regional mobility decarbonization | Production and sale to customers through refueling stations supporting local fleets and stimulating regional hydrogen markets | Consortium | Regional |
| 11 | HY.Waiblingen | Decarbonization of mobility in the Rems Murr district, enabling emission free public transport from mid-2025 onward | On-site production, storage and distribution via hydrogen stations to regionals operators, creating demand and demonstrating scalable infrastructure | Consortium | Regional |
| 12 | HyBalance | Large scale power to hydrogen (PtH2) production from renewable electricity, storing surplus wind energy as green hydrogen for use in grid balancing, industry and clean transport | Demonstration and technologies' de-risking; Sale to industrial customers and refueling networks | Consortium | National |
| 13 | HyBayern | Hydrogen production, distribution and use to decarbonize regional mobility (especially buses) and support wider energy transition efforts | Regional production and supply to refueling stations serving buses and other vehicles | Consortium | Regional |
| 14 | Hydro3D | Development of a hydrogen gas sensor with a micro heater aimed at improving safety and detection for hydrogen infrastructure and applications | R&D demonstration by partnering research and technology organizations, aiming to create intellectual property and prototypes that can be commercialized | Consortium | Regional |
| 15 | Hydrogen Valley Emsland | Integrate a regional hydrogen value chain to transport and use in industry, mobility and energy applications; Emphasizes pipeline infrastructure and hydrogen utilization across sectors | Networked production and supply; Development of transport pipelines and green hydrogen fueling stations to serve different mobility users | Open network and platform for collaboration | Regional |
| 16 | HyWays for Future | Accelerate the market adoption of green hydrogen, especially in the transport sector (cars, buses, trucks) and industrial applications to help cut regional emissions | Local hydrogen production with hydrogen transported by truck in compressed form to refueling stations | Consortium | Regional |
| 17 | Mid Sweden Hydrogen Valley | Develop an integrated hydrogen ecosystem in central Sweden that supports fossil free industrial production, green transport and a resilient regional energy system | Collaborative value chain development linking industrial partners, ports, logistics and renewable energy supply to create demand in both mobility and industrial applications | Consortium | Regional |
| 18 | NEOM Green Hydrogen | Decarbonization of global transport and industrial sectors, while significantly reducing $CO_2$ emissions and enhancing sustainable development and local green job creation | Large scale green hydrogen and ammonia production for export supplying clean fuel to industrial and transportation markets | Equally owned joint venture NGHC | International |
| 19 | NRL | Test and demonstrate pathways to climate neutrality by decarbonizing high energy use sectors, such us industry, heat and mobility | Test bed, demonstration and deployment of innovative technologies to commercialize globally | Consortium | International |
| 20 | Phi Suea House | Demonstrate how renewable energy and hydrogen storage can power a multi building residence off grid 24/7 | Demonstration and technology showcase to provide replication and future investment in sustainable energy and hydrogen technologies | Private-public partnership | Local |
| 21 | SoHyCal | Production of renewable hydrogen to help decarbonize transport and other sectors | Hydrogen production and supply for mobility markets; Stored and transported to hydrogen refueling stations in the region | Private-public partnership | Regional |
| 22 | Transylvania Hydrogen Valley | Produce green hydrogen for public transport, district heating and future industrial use, while creating a regional clean energy corridor with nearby cities to support decarbonization | Build a hydrogen value chain that links renewable hydrogen production with supply to transport and energy sectors | Consortium | Regional |
| 23 | WIVA P&G | Demonstrate the transformation of the Austrian economy toward a largely $CO_2$ neutral energy system by making green hydrogen and renewable gases a central component of energy, industry | Research, demonstration and network driven bringing together more than 50 projects and subprojects that link each stage of the value chain | Consortium | National |
| 24 | WIVA P&G HyWest | Technical solutions and business cases for hydrogen production, distribution and utilization for mobility and industry, supporting energy transition and build a replicable model for Central | Research and demonstration driven, integrating complementary subprojects to test technical solutions creating local supply chains and validating cost effective regional use | Consortium | Regional |
| 25 | ZEV | Deploying a network of hydrogen refueling infrastructure and fuel cell vehicles to accelerate the uptake of zero emission transport | Production, storage and transportation to refueling stations across the region and sale to fleets and operators under long term offtake arrangements | Public-private partnership | Regional |

# 5 – COMPARATIVE ANALYSIS

The purpose of this chapter is to provide and discuss the results of the analysis conducted for the aim of this thesis, taking into account the 18 KPIs, previously identified in Chapter 3, used to compare the 25 case studies selected. The data and technical information were obtained from specific database and the official websites of the projects, using only publicly available information. A comparison of the case studies is then made to determine which ones are the best-performing hydrogen hubs. Finally, this chapter investigates the factors that explain the success of the best-performing hydrogen hubs. Many hubs have decided not to disclose some information, making it difficult to provide the best comparison of all 25 case studies.

## 5.1 Technical and Financial Analysis

The chart represented in *Figure 18* shows the distribution of the annual green hydrogen production expressed in $tH_2$/year. There is a clear focus on small to medium-scale production. The most common category is 100-1,000 t/year of $H_2$, followed by projects with a capacity of 1,000-10,000 t/year. On the other hand, small-scale projects where annual production is below 100 t/year and large-scale projects, with an annual production above 10,000 t/year, are less common. This data indicates that most of the hydrogen hubs are currently in an intermediate stage of development, being still on demonstration and early commercial-scale stages. However, the presence of even few large-scale projects indicates a trend towards larger hydrogen hubs, which could play an essential role in future market scale-up.

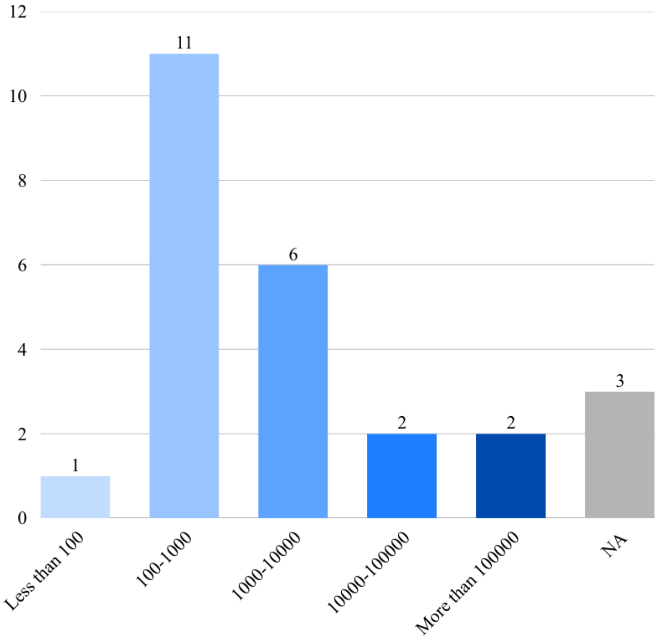


*Figure 18: (Expected) Annual green hydrogen production (t H2/year)*

*Table 13: Names of green hydrogen hubs by (expected) annual green hydrogen production (t H2/year)*

| Less than 100 | 100-1000 | 1000-10000 | 10000-100000 | More than 100000 | NA |
|---|---|---|---|---|---|
| Phi Suea House Project | CRAVE-H2<br>eFarm<br>Green Hysland<br>H2iseO hydrogen valley<br>HY.City.Bremerhaven<br>HY.Waiblingen<br>HyBalance<br>HyBayern<br>HyWays for Future<br>SoHyCal<br>Transylvania Hydrogen Valley | Agder Hydrogen Hub<br>FLHyPorts<br>hy.klettwitz<br>NRL<br>WIVA P&G<br>ZEV | BH2C<br>Hydrogen Valley Emsland | BalticSeaH2<br>NEOM Green Hydrogen | Hydro3D<br>Mid Sweden Hydrogen Valley<br>WIVA P&G HyWest |

A distinct concentration in the small- to medium-scale range can be also seen in the distribution of expected normalized plant capacity among the examined hydrogen hubs in *Figure 19*. Only a small number of hubs plan capacity beyond 100 MWel, while projects with less than 5 MWel are the most common group, closely followed by those in the 11–100 MWel range. A sizable portion of cases also state that no data is available, which is indicative of the projects' early stages of development or their lack of transparency.

This shows once again that the large majority of hydrogen hubs are currently being planned as pilot, demonstration or early commercial-scale facilities. Smaller capacities allow for lower costs and testing of technology and business models, aiming at a gradual increase of local demand. Large-scale plants, on the other hand, require high upfront investment, long-term contracts and more complex infrastructure for the transportation of hydrogen and the delivery of energy.

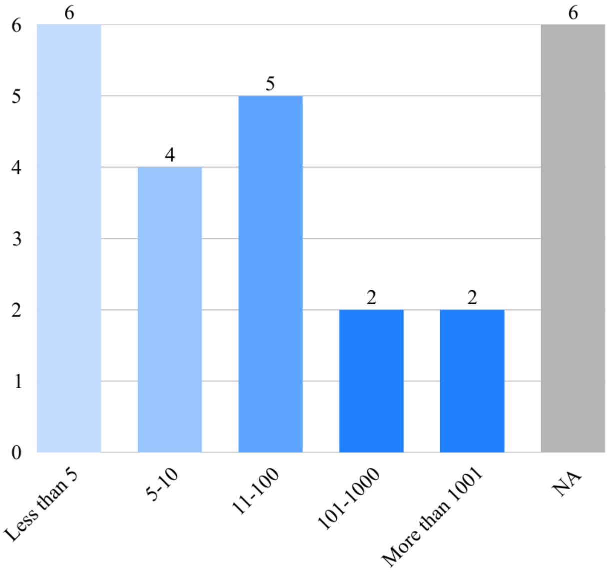


*Figure 19: (Expected) Normalized capacity (MWel)*

*Table 14: Names of green hydrogen hubs by (expected) normalized capacity (MWel)*

| Less than 5 | 5-10 | 11-100 | 101-1000 | More than 1001 | NA |
|---|---|---|---|---|---|
| eFarm | H2iseO hydrogen valley | Agder Hydrogen Hub | BH2C | BalticSeaH2 | CRAVE-H2 |
| Green Hysland | HyBayern | FLHyPorts | Hydrogen Valley Emsland | NEOM Green Hydrogen | Hydro3D |
| HY.City.Bremerhaven | SoHyCal | hy.klettwitz | | | Mid Sweden Hydrogen Valley |
| HY.Waiblingen | ZEV | NRL | | | Phi Suea House Project |
| HyBalance | | WIVA P&G | | | Transylvania Hydrogen Valley |
| HyWays for Future | | | | | WIVA P&G HyWest |

From what concerns the distribution of the investment amounts in the hubs under analysis (*Figure 20*), it is clear that the majority are concentrated in the lower ranges of capital expenditure. The most common ranges are investments under €20 million and the range between €20 million and €100 million, as these have the highest frequency in the multiple-case studies. Although these numbers may seem rather moderate in comparison to large-scale energy infrastructure investment, they still represent the capital-intensive nature of green hydrogen investment, particularly if one takes into account the fact that most of the hubs under investigation are still in the pilot or early commercial stage. There is a smaller number of investments in the ranges between €101 million and €500 million, as well as the range between €1 billion and €5 billion, while the investments above €5 billion are scarce, indicating that large-scale hubs are still limited.

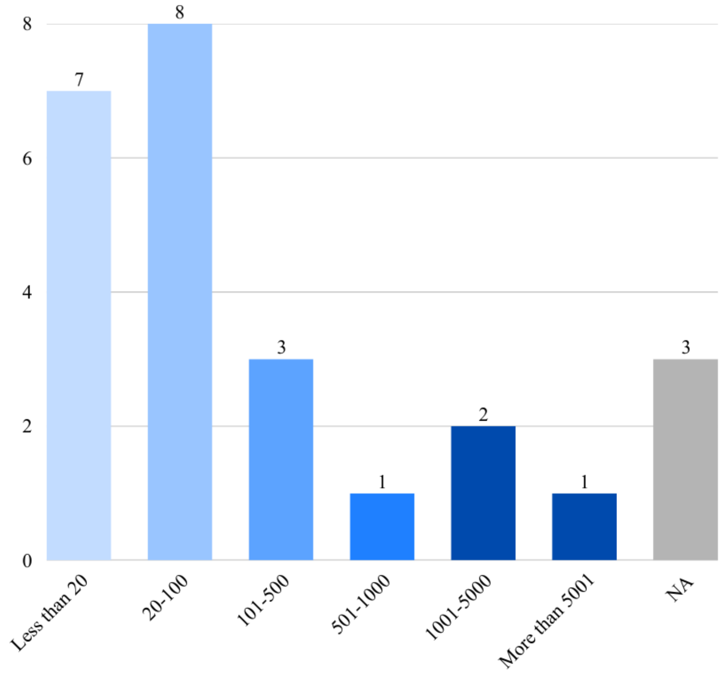


*Figure 20: Investment volume (M€)*

*Table 15: Names of green hydrogen hubs by investment volume (M€)*

| Less than 20 | 20-100 | 101-500 | 501-1000 | 1001-5000 | More than 5001 | NA |
|---|---|---|---|---|---|---|
| CRAVE-H2<br>eFarm<br>HY.City.Bremerhaven<br>HyBalance<br>Hydro3D<br>Phi Suea House Project<br>Transylvania Hydrogen Valley | Agder Hydrogen Hub<br>FLHyPorts<br>Green Hysland<br>HyBayern<br>HyWays for Future<br>SoHyCal<br>WIVA P&G HyWest<br>ZEV | H2iseO hydrogen valley<br>NRL<br>WIVA P&G | BH2C | BalticSeaH2<br>Hydrogen Valley Emsland | NEOM Green Hydrogen | hy.klettwitz<br>HY.Waiblingen<br>Mid Sweden Hydrogen Valley |

Shifting our attention to funding, the donut chart (*Figure 21)* shows the funding model of the analyzed hydrogen hubs, with a significant presence of mixed funding (private + public), which accounts for 71.4% of the analyzed cases. This confirms the significance of public funding as a means of de-risking investment, while simultaneously utilizing private sector engagement to ensure project development. The presence of 28.8% of hubs exclusively financed by public funding points to the importance of initiatives taken by governments or public authorities, especially for projects in early development stages or of strategic importance. On the other hand, hubs financed exclusively by private funding represent only 4.8% of the total. If we look more closely at the sources of funding, Figure 21*Figure 22* shows the number of green hydrogen hubs supported by different levels of funding. From this, we can see that national funding is the major form of support, with 17 case studies, followed closely by private funding, which appears in 16 of the case studies. Supranational funding, mainly in the form of EU funding, also plays a significant role in supporting green hydrogen development, found in 10 case studies. On the other hand, we see that public funding at the subnational level plays a much smaller role, as only 4 of the case studies report regional funding, while only 2 report local-level funding. National governments play a significant role in the development of green hydrogen hubs, due to their strategic importance to national industry policy and in parallel the strong presence of private funding signals growing market interest and confidence, particularly when projects are sufficiently de-risked through public backing. The comparatively limited involvement of regional and local authorities suggests that, despite the place-based nature of hubs, financial leadership remains concentrated at higher governance levels.

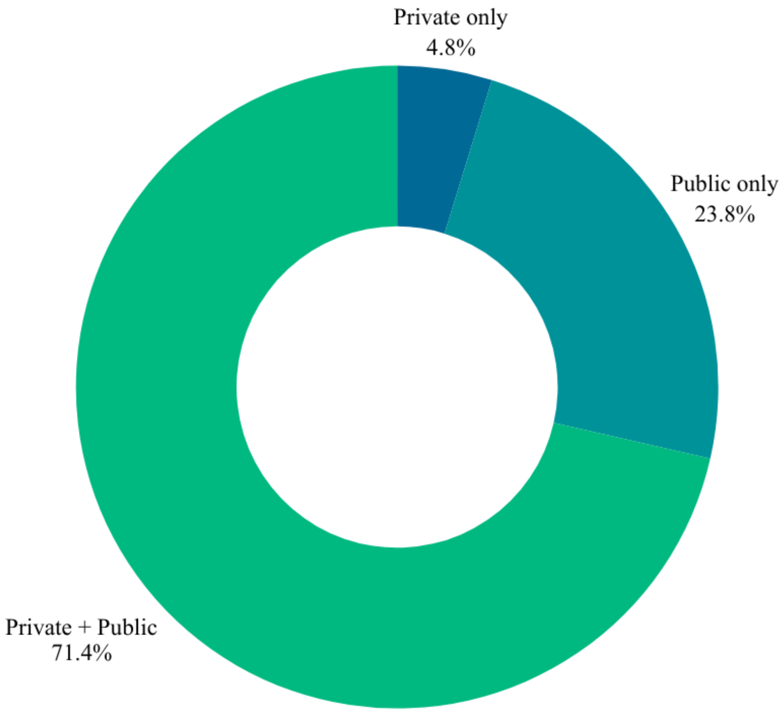


*Figure 21: Nature of funding sources*

Table 16: Names of green hydrogen hubs by nature of funding sources

| **Private only** | **Public only** | **Private + Public** | **NA** |
|---|---|---|---|
| Phi Suea House Project | Agder Hydrogen Hub | BalticSeaH2 | FLHyPorts |
| | hy.klettwitz | BH2C | HY.City.Bremerhaven |
| | Hydro3D | CRAVE-H2 | HY.Waiblingen |
| | Transylvania Hydrogen Valley | eFarm | Mid Sweden Hydrogen Valley |
| | WIVA P&G HyWest | Green Hysland | |
| | | H2iseO hydrogen valley | |
| | | HyBalance | |
| | | HyBayern | |
| | | Hydrogen Valley Emsland | |
| | | HyWays for Future | |
| | | NEOM Green Hydrogen | |
| | | SoHyCal | |
| | | NRL | |
| | | H2iseO hydrogen valley | |
| | | NRL | |
| | | WIVA P&G | |
| | | ZEV | |

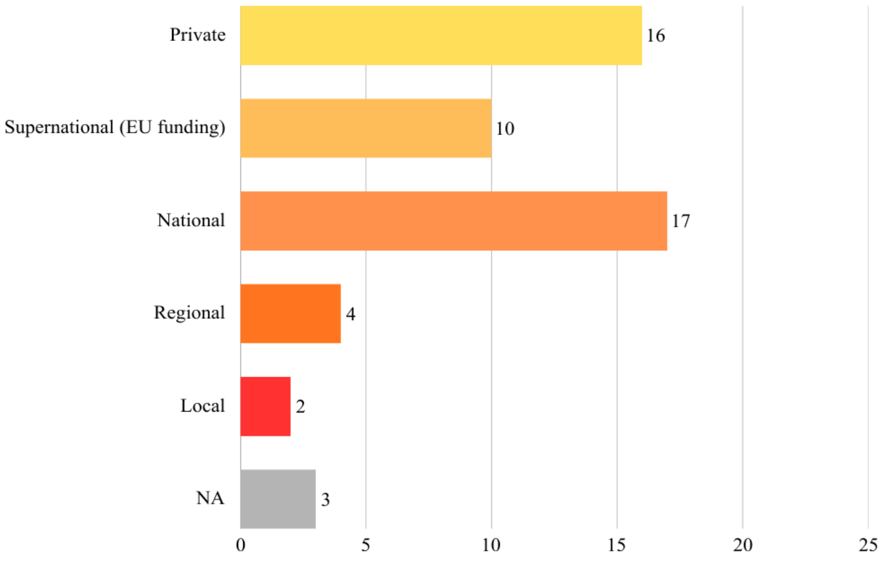


*Figure 22: Number of case studies by funding source*

### 5.2 Organizational Information: Project Stakeholders Analysis

The stakeholder composition of the analyzed hydrogen valleys highlights a fundamental point: multi-actor collaborations are a key driving force in the green hydrogen transition. As shown in *Figure 23*, 64% of the projects are led by private companies, followed by public authorities, research and academia, industrial associations and NPO/NGO. Because green hydrogen valleys are mainly market-oriented initiatives operating within an industrial context, companies tend to take the commercial and financial lead. In contrast, Governments and public institutions appear more often as facilitators or regional coordinators. Among private-sectors companies, names of big or already well-established players have been identified: Air Liquide (**HyBalance**), GP Joule (**eFarm**, **HY.City.Bremerhaven**), EWE (**HyWays for Future**), Repsol Group (**BH2C**), as well as gas grid firms and regional utilities companies such as Stadtwerke (**HY.Waiblingen**) or Enagás (**Green Hysland**). That explains that hydrogen valleys often do not start from scratch, instead they frequently build upon, or evolve as an extension of, existing energy, gas and industrial systems. These incumbents are already well positioned in the market scene and can more easily integrate hydrogen as part of their decarbonization and diversification strategies.

Only 4 cases present a public authority as lead developer, mainly represented as regional council (**ZEV**), municipality (**Transylvania Hydrogen Valley**) and district governments (**HyBayern** and **Hydrogen Valley Emsland**). While they may not embody the best way to lead the technical development of hydrogen hubs, they bring strong efforts in regional coordination and geographical planning (in relation to linking transport, industry and energy sectors) and, most importantly, in attracting and providing funding. Since hubs are placed-based, local and regional governments can help the hubs spreading territorially and supporting their broader diffusion. Fewer cases were identified in which research and academia act as the main developer, showing a modest leadership role, despite possessing scientific expertise and technical knowledge. Large-scale project leadership may be indeed more challenging for universities and research centers, as they often represent relatively new entrants in commercial and industrial project development. Industrial association further strengthen the institutional and relational infrastructure of hydrogen valleys, as they support coordination across sectors and value chains. Finally, NGOs and NPOs tend to play a different role: their involvement helps ensure that hydrogen valley initiatives are not only economically and technically viable, but also socially legitimate and environmentally credible.

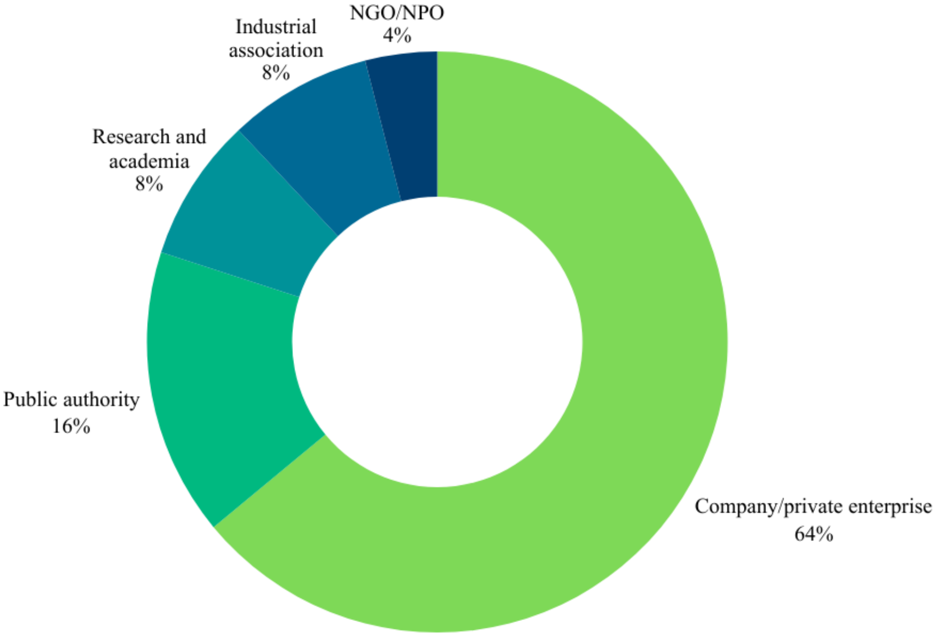


*Figure 23: Lead developer entity*

*Table 17: Names of green hydrogen hubs by lead developer entity*

| Company/private enterprise | Public authority | Research and academia | Industrial association | NGO/NPO |
|---|---|---|---|---|
| Agder Hydrogen Hub | HyBayern | NRL | WIVA P&G | FLHyPorts |
| BalticSeaH2 | Hydrogen Valley Emsland | WIVA P&G HyWest | Mid Sweden Hydrogen Valley | |
| BH2C | | | | |
| CRAVE-H2 | Transylvania Hydrogen Valley | | | |
| eFarm | ZEV | | | |
| Green Hysland | | | | |
| H2iseO hydrogen valley | | | | |
| HY.City.Bremerhaven | | | | |
| hy.klettwitz | | | | |
| HY.Waiblingen | | | | |
| HyBalance | | | | |
| Hydro3D | | | | |
| HyWays for Future | | | | |
| NEOM Green Hydrogen | | | | |
| Phi Suea House Project | | | | |
| SoHyCal | | | | |

Now we shift our attention to the number of partners that contribute to the development of each hub (*Figure 24*). Within the 21 projects for which partner data is available (with 4 projects offering no data), there is a notable variety in the size of the consortia, ranging from small-scale groups of 3-10 partners to very large-scale collaborations involving 30, 40, or even more than 70 partners (**Basque Hydrogen Corridor BH2C**). This diversity is not only a matter of administrative convenience but also reflects different degrees of personal ambition. Small-scale consortia are typically found in projects that are focused or pilot-scale in nature and aim to address a specific part of the hydrogen value chain, such as a particular production method or a specific end-use sector. Larger consortia, on the other hand, are generally found in hubs that are more comprehensive in nature and involve the entire hydrogen valley, including production, transportation, storage and various end-use sectors. Such projects naturally involve a wide range of stakeholders, including energy providers, infrastructure companies, industrial users, mobility stakeholders, research organizations and government bodies. In this sense, hydrogen valleys can be seen as innovation ecosystems, with the number of partners being a useful indicator of the level of sector coupling and system integration. Exceptions exist, such as in the case of **NEOM Hydrogen Valley**, a large-scale initiative presenting only few partners.

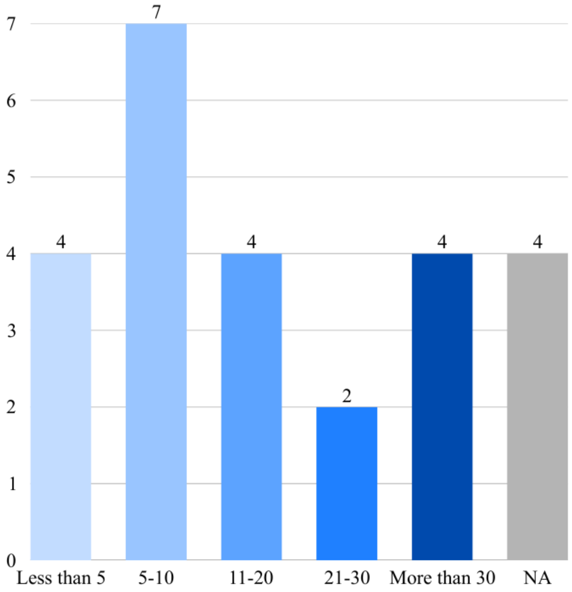


*Figure 24: Total numbers of partners (n)*

### 5.3 Supply chain and Operations Analysis

Moving on to the supply chain section, as can be seen in *Figure 25*, the distribution of the 25 case studies across different stages in the green hydrogen supply chain is as follows: the most included stage in the hubs' development is hydrogen production, which has been identified in 24 out of 25 case studies. Downstream infrastructure is also strongly represented, with 23 hubs including the stage of hydrogen transport, 22 including the stage of hydrogen distribution and 21 including the stage of hydrogen storage. In contrast, the least frequent stage in the hubs' supply chain is primary energy supply, which has been identified in 16 case studies. Overall, it can be concluded that most hydrogen hubs follow an integrated and value-chain approach, with a stronger emphasis on midstream and downstream infrastructure that is required for the transportation and delivery of hydrogen to consumers. The relatively lower importance given to the primary energy component may be due to the reliance on existing renewable resources or the scope of the project, which is more on hydrogen management than on power production. *Figure 26* shows a different perspective on the level of supply chain integration within the hydrogen hubs. The majority of hydrogen hubs demonstrate high levels of integration, with 12 out of 25 case studies (48%) covering the entire hydrogen supply chain (100%), while a further 9 cases (36%) cover approximately 80% of the hydrogen supply chain, mainly leaving out the primary energy stage own supply. Only a few hydrogen hubs show low levels of integration, with 2 cases covering approximately 60% and a further 2 cases covering 40% of the hydrogen supply chain. The high occurrence of near or fully integrated hydrogen supply chains shows a clear pattern that most hubs are designed to be all-rounded, strategically focusing on creating an efficient system that enclose primary energy, H2 production, H2 storage, H2 transport and H2 distribution.

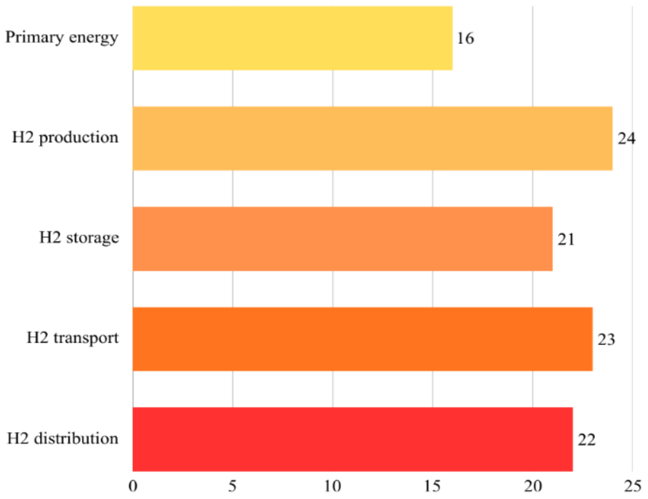


*Figure 25: Number of case studies covering a specific stage of the supply chain*

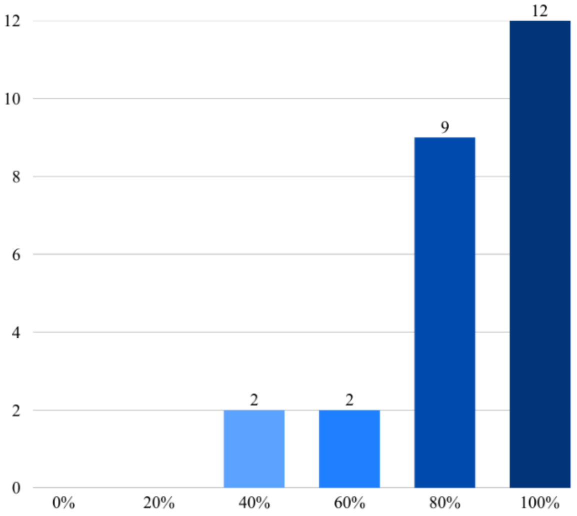


*Figure 26: Supply chain coverage*

*Table 18: Names of green hydrogen hubs by supply chain coverage*

| **40%** | **60%** | **80%** | **100%** |
|---|---|---|---|
| Hydro3D | HyBalance | BalticSeaH2 | Agder Hydrogen Hub |
| Mid Sweden Hydrogen Valley | NRL | H2iseO hydrogen valley | BH2C |
|  |  | HY.City.Bremerhaven | CRAVE-H2 |
|  |  | hy.klettwitz | eFarm |
|  |  | HY.Waiblingen | FLHyPorts |
|  |  | HyBayern | Green Hysland |
|  |  | Phi Suea House Project | Hydrogen Valley Emsland |
|  |  | SoHyCal | HyWays for Future |
|  |  | Transylvania Hydrogen Valley | NEOM Green Hydrogen |
|  |  |  | WIVA P&G |
|  |  |  | WIVA P&G HyWest |
|  |  |  | ZEV |

Among renewable energy sources, necessary to convert water into green hydrogen through electrolysis, most hubs present a combination of 2 or more energy sources. There is a clear dominance of solar and wind (*Figure 27*) and frequently appear in combination, with 9 out of 25 case studies explicitly adopting an only the solar-wind hybrid configuration. Beyond these leading technologies, several hubs draw on other renewable resources where local conditions are favorable, such as hydropower in water-rich regions (**Agder Hydrogen Hub**, **Mid Sweden Hydrogen Valley**).

Overall, the statistics suggest a strong trend towards hybrid and diversified systems of energy supply, sometimes in combination with grid connection, in order to achieve a more consistent level of hydrogen production. This move towards multi-source systems may aim at maximize utilization of production facilities and minimize the Levelized Cost of Hydrogen (LCOH).

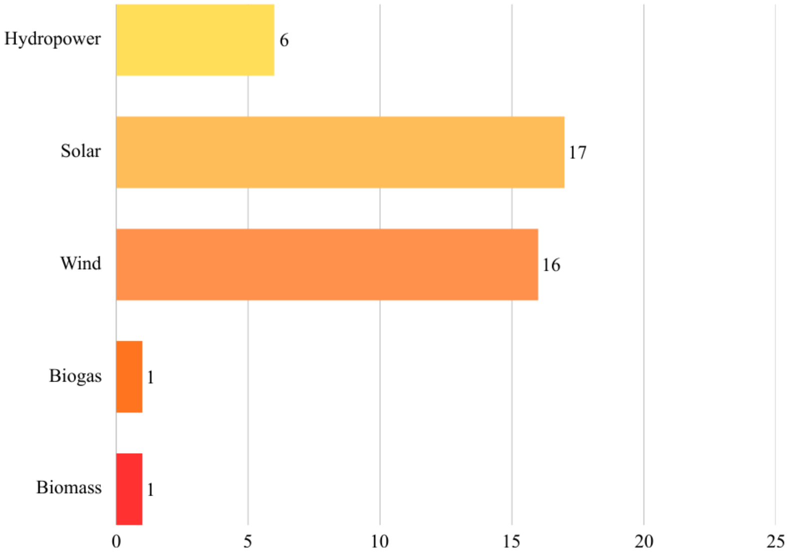


*Figure 27: Primary energy sources*

## 5.4 Target Market and Applications

A distinct trend in the targeted end-use market applications is shown in *Figure 28*, *Figure 29* and *Figure 30*. The mobility sector is included in 100% of the case studies, making it the dominating demand segment across all hubs. This demonstrates the importance of decarbonizing transportation as well as the increasing awareness of green hydrogen as a solution to electrify modes like shipping, long-distance trucking or cars. The energy sector appears in 56% of the case studies, making it the second most common end-use sector. This includes a range of end-applications such as stationary fuel cells for distributed production, hydrogen injection into the gas grid and hydrogen utilization in gas-fired power plants. Lastly, 44% of the hubs receive demand by the industrial sector as a supplier for the steel, chemical or refinery industries. While hard-to-abate industry is a widely recognized sector with relation to long-term demand for hydrogen, this lower percentage may indicate higher entry barriers, longer investment cycles or greater infrastructure.

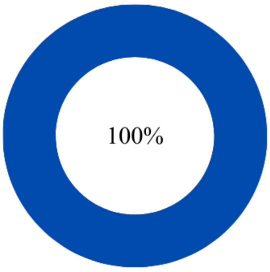


*Figure 28: Share of case studies including MOBILITY application*

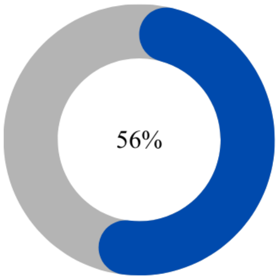


*Figure 29: Share of case studies including ENERGY application*

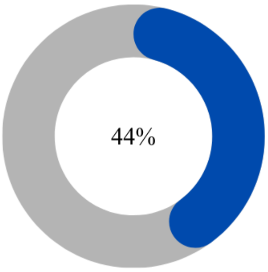


*Figure 30: Share of case studies including INDUSTRIAL USE AS FEEDSTOCK application*

## 5.5 Results and KPI Comparison and Takeaways

The comparative analysis of the 25 green hydrogen hubs reveals that successful projects are not defined by a single technical or financial parameter, but rather by the coherent alignment of scale, stakeholder structure, supply chain integration and demand configuration.

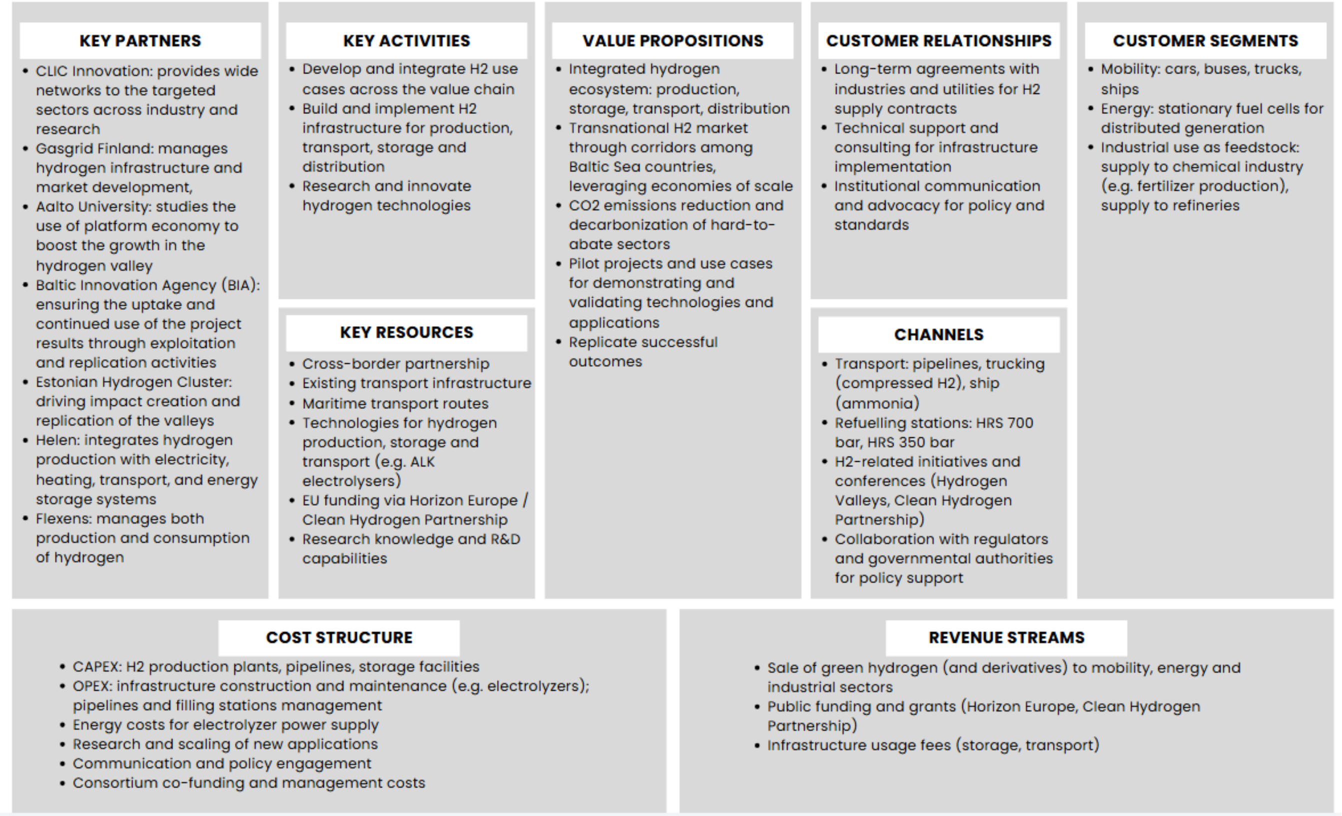
From a technical and financial point of view, the majority of hubs continue to be focused on relatively moderate investment levels and small- to medium-scale output, suggesting that the industry is mostly in a demonstration and early-commercial stage, when learning-by-doing, research, innovation and risk containment are more important than full industrial size. Green hydrogen hubs now rely on public support to de-risk private investments, especially for reason such as uncertain demand, changing regulations and expensive upfront costs, as seen by their heavy reliance on mixed funding approaches. Organizationally, the dominance of private-sector-led projects mixed with massive multi-actor consortia emphasizes that hydrogen hubs function as innovation ecosystems rather than single projects. The presence of established industrial and energy organizations as main developers means that hydrogen deployment is often involved in existing industrial and infrastructure systems, but at the same time, coordination and finance aspects are supported by the participation of associations, research institutions and public bodies. Because it allows the distribution of risks, expertise and investment along the value chain, this multi-actor structure seems to be a crucial enabling condition for hub development. The supply chain analysis reinforces this perspective. The majority of hubs have a high level of vertical integration, including all stages from green energy feedstock to distribution. The usage of hybrid renewable energy sources also suggests high emphasis on cost optimization and higher electrolyzer utilization rates, indicating a growing focus on long-term economic sustainability. On the demand side, the prevalence of mobility applications and the relatively lower involvement of industrial users indicate that in their early stages, hydrogen hubs typically give priority to more accessible and scalable demand segments. Although it is widely acknowledged that full-scale integration of green hydrogen into hard-to-abate industries like steel is necessary to achieve deep decarbonization, several challenges are still to be faced. Such industries, despite being technically ready to integrate green hydrogen, have to overcome important policy barriers and infrastructure challenges, as it requires physical connectivity and financial incentives, and often present lack of access to hydrogen pipelines or renewable electricity in many industrial zones, which necessitate the development of hydrogen corridors (Usman et al, 2026).

## 5.6 Focus on Three Main Case Studies

Building on the comparative analysis carried out in the previous sections, it is interesting to look more closely and digress at certain hubs that can act as global standards for the hydrogen economy. While the majority of the cases studied are still in early commercial or demonstration stages, three of them seem to emerge as “better performers”: BalticSeaH2, Hydrogen Valley Emsland and NEOM Green Hydrogen. These three projects not only exceed the average KPIs for production capacity and investment volume but also embody highly integrated business models capable of addressing the most complex technological and market challenges. To better visualize each hub’s core values and elements, the Business Model Canvas framework is provided (*Figure 31*, *Figure 33*, *Figure 35*).

### 5.6.1 BalticSeaH2 (Finland)

BalticSeaH2 represents an ambitious large-scale green hydrogen hub, whose main objective is the establishment of the first truly cross-border hydrogen valley in Europe to enable self-sufficiency of energy and minimize carbon emissions from different industries. The corridor is strategically centered between southern Finland and Estonia and expanding



**KEY PARTNERS**

- CLIC Innovation: provides wide networks to the targeted sectors across industry and research
- Gasgrid Finland: manages hydrogen infrastructure and market development,
- Aalto University: studies the use of platform economy to boost the growth in the hydrogen valley
- Baltic Innovation Agency (BIA): ensuring the uptake and continued use of the project results through exploitation and replication activities
- Estonian Hydrogen Cluster: driving impact creation and replication of the valleys
- Helen: integrates hydrogen production with electricity, heating, transport, and energy storage systems
- Flexens: manages both production and consumption of hydrogen

**KEY ACTIVITIES**

- Develop and integrate H2 use cases across the value chain
- Build and implement H2 infrastructure for production, transport, storage and distribution
- Research and innovate hydrogen technologies

**KEY RESOURCES**

- Cross-border partnership
- Existing transport infrastructure
- Maritime transport routes
- Technologies for hydrogen production, storage and transport (e.g. ALK electrolysers)
- EU funding via Horizon Europe / Clean Hydrogen Partnership
- Research knowledge and R&D capabilities

**VALUE PROPOSITIONS**

- Integrated hydrogen ecosystem: production, storage, transport, distribution
- Transnational H2 market through corridors among Baltic Sea countries, leveraging economies of scale
- CO2 emissions reduction and decarbonization of hard-to-abate sectors
- Pilot projects and use cases for demonstrating and validating technologies and applications
- Replicate successful outcomes

**CUSTOMER RELATIONSHIPS**

- Long-term agreements with industries and utilities for H2 supply contracts
- Technical support and consulting for infrastructure implementation
- Institutional communication and advocacy for policy and standards

**CHANNELS**

- Transport: pipelines, trucking (compressed H2), ship (ammonia)
- Refuelling stations: HRS 700 bar, HRS 350 bar
- H2-related initiatives and conferences (Hydrogen Valleys, Clean Hydrogen Partnership)
- Collaboration with regulators and governmental authorities for policy support

**CUSTOMER SEGMENTS**

- Mobility: cars, buses, trucks, ships
- Energy: stationary fuel cells for distributed generation
- Industrial use as feedstock: supply to chemical industry (e.g. fertilizer production), supply to refineries

**COST STRUCTURE**

- CAPEX: H2 production plants, pipelines, storage facilities
- OPEX: infrastructure construction and maintenance (e.g. electrolyzers); pipelines and filling stations management
- Energy costs for electrolyzer power supply
- Research and scaling of new applications
- Communication and policy engagement
- Consortium co-funding and management costs

**REVENUE STREAMS**

- Sale of green hydrogen (and derivatives) to mobility, energy and industrial sectors
- Public funding and grants (Horizon Europe, Clean Hydrogen Partnership)
- Infrastructure usage fees (storage, transport)

*Figure 31: BalticSeaH2 - Business Model Canvas*

across the wider Baltic Sea region. By coordinating production, storage, transportation, derivative manufacturing and end-use through more than 20 concrete use cases and more than 10 investment cases, which will showcase the diverse applications of hydrogen across multiple sectors, the Finnish hub reveals approximately €3 billion in industrial-scale investments. Its business model is based on collaborative development and demonstration of an integrated hydrogen value chain (excluding primary energy feedstock stage) at transnational scale. This aggregation of supply and demand across borders reduces market risk, especially in relation to a shared use of existing and planned infrastructure, such as gas pipelines, electricity grids, port logistics and emerging hydrogen corridors. Such corridors, like the Nordic-Baltic Hydrogen Corridor, Baltic Sea Hydrogen Collector and Nordic Hydrogen Route, enable the creation of the conditions for a functioning regional hydrogen market. The initiative links hydrogen to actual, bankable offtake in maritime fuels, low-carbon fertilizers and sustainable chemicals and plastics, guaranteeing commercial pull rather than technological push.

Its governance structure, which unites infrastructure operators, industry, ports, technology providers and research actors under a common framework, also supports the hub's success in developing green hydrogen. The consortium consists of 40 partners from nine countries (Finland, Estonia, Latvia, Lithuania, Poland, Germany, Denmark, Norway and Sweden). Coordinated infrastructure design, regulatory alignment and cooperative technology testing in an actual economic setting are made possible by this multilayer, cross-border governance, which enables interfaces throughout the hydrogen value chain to be evaluated and optimized prior to scale-up. Furthermore, significant funds have been registered that brought great support, such as €25 million in EU funding through the Clean Hydrogen Partnership. BalticSeaH2 establishes a self-reinforcing hydrogen ecosystem that speeds up deployment, supports energy self-sufficiency, reduces emissions in hard-to-abate sectors like shipping and heavy industry and serves as a replicable model for how green hydrogen valleys can drive a wider European industrial transition by combining public de-risking, industrial commitment, existing strategic infrastructure in the Gulf of Finland and coordinated development of supply, transport and demand.

### 5.6.2 Hydrogen Valley Emsland (Germany)

The Hydrogen Valley Emsland, located in northwest Germany, is a prime example of a regional hydrogen ecosystem that integrates large-scale production, infrastructure development, including pipelines, and stakeholder engagement to support the adoption of green hydrogen across sectors as part of the area's climate-neutral transformation. This region is designated as the 'Hydrogen Valley of the Year 2024' under the EU's Clean Hydrogen Partnership, with existing large-scale production of green hydrogen with a current installed electrolyser capacity of 22 MW across various locations (*Figure 32*), expanding from a 6 MW plant that started operations in 2011 to become a large-scale industrial hub with a potential installed capacity of 414 MW by 2027 through significant investment plans from RWE and BP. The governance structure of the valley is based on a strong network organization, named H2 Region Emsland, made up by almost 20 actors including local industries, SMEs, research institutions, municipalities and regional authorities to jointly develop projects along the entire hydrogen value chain, from supply from renewable energy generation to industrial distribution to application in industry and mobility. The leading stakeholder belongs to the public sector and not a private one, making it easier for a regional strategy to be developed connecting large-scale production with transport infrastructure and end-users.

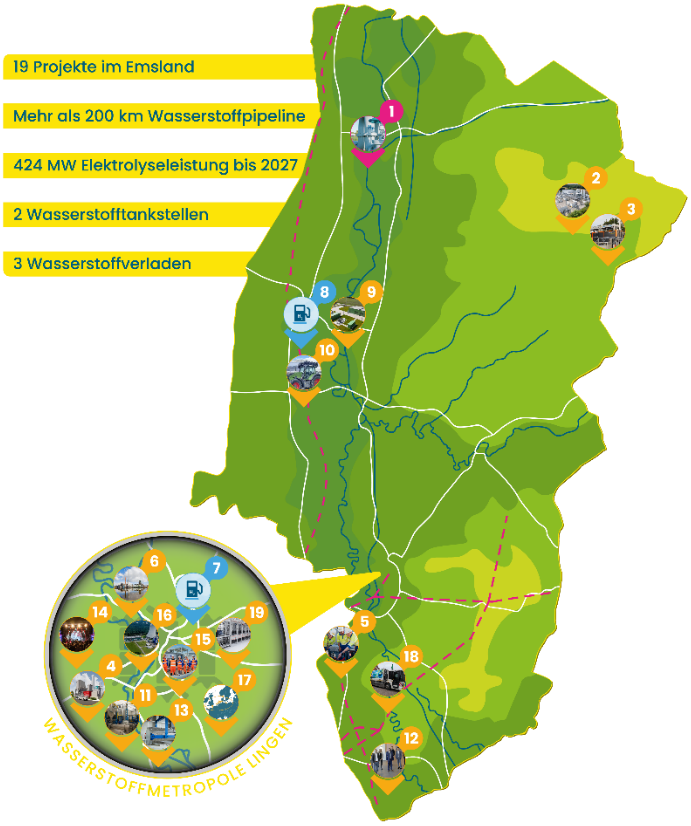
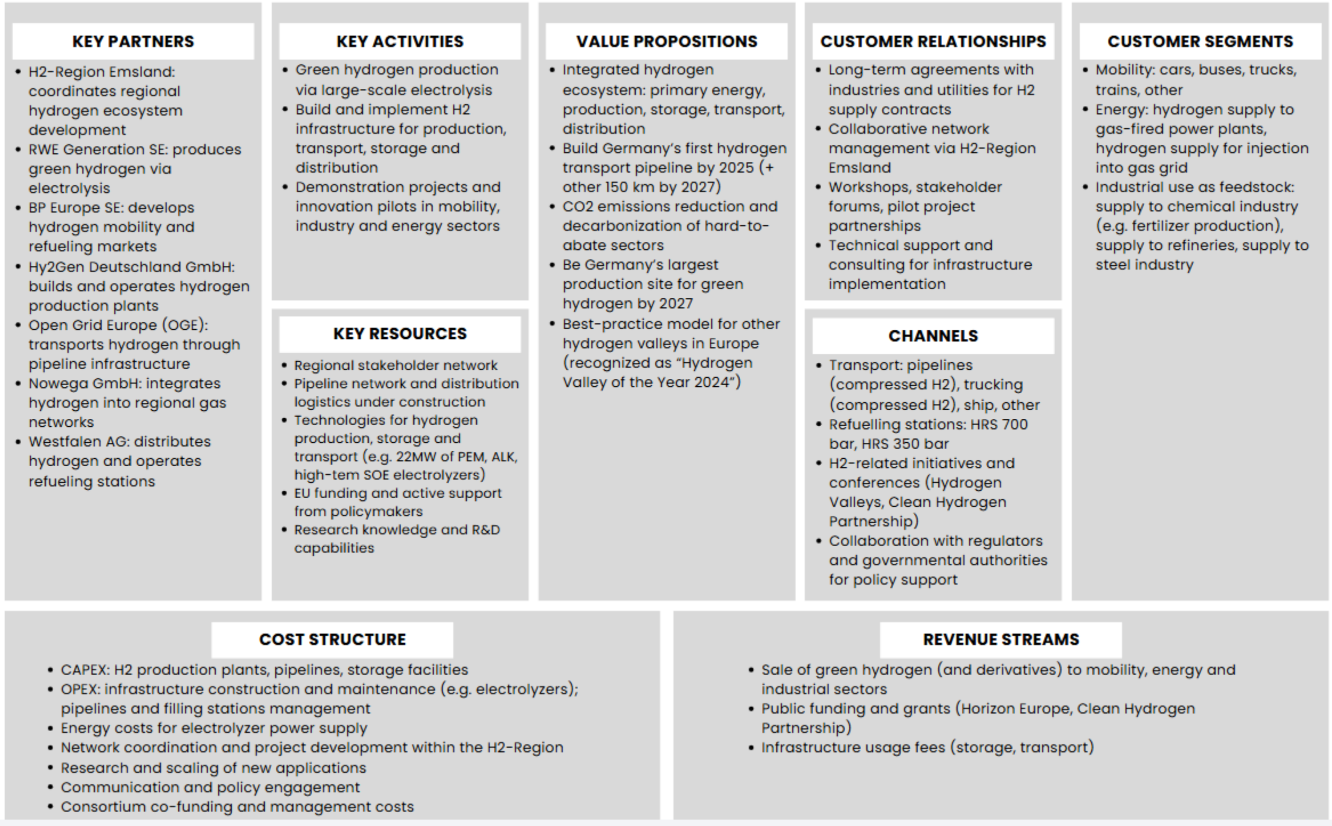


*Figure 32: Supply chain of Hydrogen Valley Emsland*

This concept of developing hydrogen projects in terms of expanding infrastructure, cooperating stakeholders and scaling up production and transport has allowed the region to successfully attract investment, develop projects and demonstrate commercially relevant hydrogen solutions, making it a leading region in Germany and a role model for hydrogen valleys in Europe. On the basis of the analysis of the project data and the comparative tables, the success of the Hydrogen Valley Emsland in the deployment of hydrogen can be attributed to its distinctiveness in terms of the combination of industrial scalability and governance. Unlike most other projects that are of a smaller scale, such hub has been able to successfully scale up to an industrial level, placing itself in the topmost bracket in terms of production (above 10,000 t $H_2$/year) as well as electrolyzer capacity. Additionally, by raising an enormous number of investments (in excess of 1 billion euros) through this diversified mode of finance, it has been possible to de-risk the high capital costs of this project.



**KEY PARTNERS**

- H2-Region Emsland: coordinates regional hydrogen ecosystem development
- RWE Generation SE: produces green hydrogen via electrolysis
- BP Europe SE: develops hydrogen mobility and refueling markets
- Hy2Gen Deutschland GmbH: builds and operates hydrogen production plants
- Open Grid Europe (OGE): transports hydrogen through pipeline infrastructure
- Nowega GmbH: integrates hydrogen into regional gas networks
- Westfalen AG: distributes hydrogen and operates refueling stations

**KEY ACTIVITIES**

- Green hydrogen production via large-scale electrolysis
- Build and implement H2 infrastructure for production, transport, storage and distribution
- Demonstration projects and innovation pilots in mobility, industry and energy sectors

**KEY RESOURCES**

- Regional stakeholder network
- Pipeline network and distribution logistics under construction
- Technologies for hydrogen production, storage and transport (e.g. 22MW of PEM, ALK, high-tem SOE electrolyzers)
- EU funding and active support from policymakers
- Research knowledge and R&D capabilities

**VALUE PROPOSITIONS**

- Integrated hydrogen ecosystem: primary energy, production, storage, transport, distribution
- Build Germany's first hydrogen transport pipeline by 2025 (+ other 150 km by 2027)
- CO2 emissions reduction and decarbonization of hard-to-abate sectors
- Be Germany's largest production site for green hydrogen by 2027
- Best-practice model for other hydrogen valleys in Europe (recognized as "Hydrogen Valley of the Year 2024")

**CUSTOMER RELATIONSHIPS**

- Long-term agreements with industries and utilities for H2 supply contracts
- Collaborative network management via H2-Region Emsland
- Workshops, stakeholder forums, pilot project partnerships
- Technical support and consulting for infrastructure implementation

**CHANNELS**

- Transport: pipelines (compressed H2), trucking (compressed H2), ship, other
- Refuelling stations: HRS 700 bar, HRS 350 bar
- H2-related initiatives and conferences (Hydrogen Valleys, Clean Hydrogen Partnership)
- Collaboration with regulators and governmental authorities for policy support

**CUSTOMER SEGMENTS**

- Mobility: cars, buses, trucks, trains, other
- Energy: hydrogen supply to gas-fired power plants, hydrogen supply for injection into gas grid
- Industrial use as feedstock: supply to chemical industry (e.g. fertilizer production), supply to refineries, supply to steel industry

**COST STRUCTURE**

- CAPEX: H2 production plants, pipelines, storage facilities
- OPEX: infrastructure construction and maintenance (e.g. electrolyzers); pipelines and filling stations management
- Energy costs for electrolyzer power supply
- Network coordination and project development within the H2-Region
- Research and scaling of new applications
- Communication and policy engagement
- Consortium co-funding and management costs

**REVENUE STREAMS**

- Sale of green hydrogen (and derivatives) to mobility, energy and industrial sectors
- Public funding and grants (Horizon Europe, Clean Hydrogen Partnership)
- Infrastructure usage fees (storage, transport)

*Figure 33: Hydrogen Valley Emsland - Business Model Canvas*

### 5.6.3 NEOM Hydrogen Valley (Saudi Arabia)

The NEOM Green Hydrogen valley, operating company based in Oxagon, NEOM, northwest Saudi Arabia, is a historic joint venture between ACWA Power, Air Products and NEOM to develop and operate the world's largest green hydrogen production facility. The NEOM Green Hydrogen Company is developing a massive clean energy project that leverages up to 4 GW of dedicated solar and wind power to support the electrolysis process, enabling the production of up to 600 tons of green hydrogen each day, which is then used for the production of green ammonia for export and has the potential to support the decarbonization of industries such as heavy industries and transport, while saving up to 5 million tons of $CO_2$ each year (*Figure 34*). The success of this giant ecosystem as a hydrogen development and deployment model is based on the large-scale level, the strategic nature of the governance structure which provide its commercial certainty: as a joint venture of leaders in the field, with Air Products serving both as the Engineering, Procurement and Construction partner and offtake buyer. Financially, it has been reached a cost of USD 8.4 billion, with 23 local, regional and international financial institutions providing backing for the project, as well as an exclusive offtake agreement for 30 years of all of the project's production.

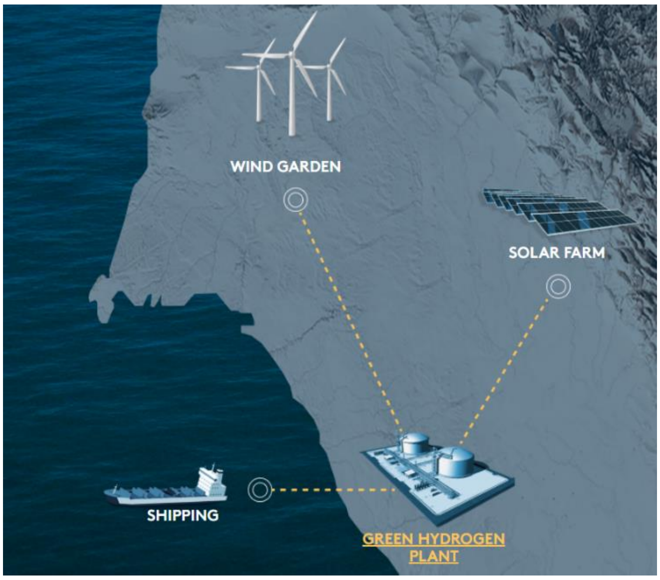
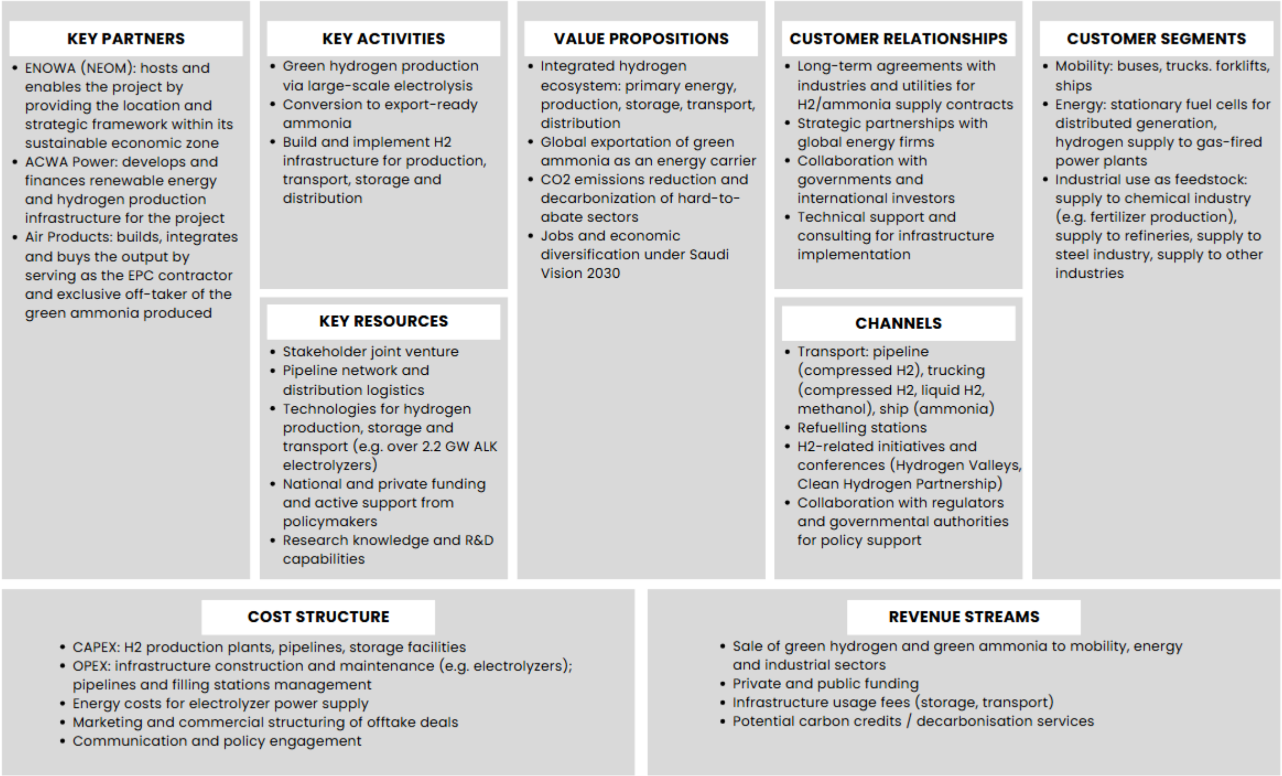


*Figure 34: Supply chain of NEOM Hydrogen Valley*

A strong competitive advantage can be found within the NEOM location, considered a future sustainable industrial ecosystem with modern infrastructure, port connectivity and access to renewable resources, as it provides efficient logistics and export opportunities that are essential for the success of a large-scale hydrogen market. With all these factors in place, the NEOM Hydrogen Valley is a prototype of a globally significant hydrogen hub that will help facilitate the transition to a low-carbon energy future.



**KEY PARTNERS**

- ENOWA (NEOM): hosts and enables the project by providing the location and strategic framework within its sustainable economic zone
- ACWA Power: develops and finances renewable energy and hydrogen production infrastructure for the project
- Air Products: builds, integrates and buys the output by serving as the EPC contractor and exclusive off-taker of the green ammonia produced

**KEY ACTIVITIES**

- Green hydrogen production via large-scale electrolysis
- Conversion to export-ready ammonia
- Build and implement H2 infrastructure for production, transport, storage and distribution

**KEY RESOURCES**

- Stakeholder joint venture
- Pipeline network and distribution logistics
- Technologies for hydrogen production, storage and transport (e.g. over 2.2 GW ALK electrolyzers)
- National and private funding and active support from policymakers
- Research knowledge and R&D capabilities

**VALUE PROPOSITIONS**

- Integrated hydrogen ecosystem: primary energy, production, storage, transport, distribution
- Global exportation of green ammonia as an energy carrier
- CO2 emissions reduction and decarbonization of hard-to-abate sectors
- Jobs and economic diversification under Saudi Vision 2030

**CUSTOMER RELATIONSHIPS**

- Long-term agreements with industries and utilities for H2/ammonia supply contracts
- Strategic partnerships with global energy firms
- Collaboration with governments and international investors
- Technical support and consulting for infrastructure implementation

**CHANNELS**

- Transport: pipeline (compressed H2), trucking (compressed H2, liquid H2, methanol), ship (ammonia)
- Refuelling stations
- H2-related initiatives and conferences (Hydrogen Valleys, Clean Hydrogen Partnership)
- Collaboration with regulators and governmental authorities for policy support

**CUSTOMER SEGMENTS**

- Mobility: buses, trucks. forklifts, ships
- Energy: stationary fuel cells for distributed generation, hydrogen supply to gas-fired power plants
- Industrial use as feedstock: supply to chemical industry (e.g. fertilizer production), supply to refineries, supply to steel industry, supply to other industries

**COST STRUCTURE**

- CAPEX: H2 production plants, pipelines, storage facilities
- OPEX: infrastructure construction and maintenance (e.g. electrolyzers); pipelines and filling stations management
- Energy costs for electrolyzer power supply
- Marketing and commercial structuring of offtake deals
- Communication and policy engagement

**REVENUE STREAMS**

- Sale of green hydrogen and green ammonia to mobility, energy and industrial sectors
- Private and public funding
- Infrastructure usage fees (storage, transport)
- Potential carbon credits / decarbonisation services

*Figure 35: NEOM Hydrogen Valley - Business Model Canvas*

# 6 – DISCUSSION

## 6.1 Business Model

Analyzing our three top green hydrogen hubs, it's clear they take pretty different routes to deal with the same issue: reducing $CO_2$ emissions by providing a low-carbon alternative in the form of green hydrogen. The development of this strategic energy carrier is enabled through distinct business model configurations, governance arrangements and market formation strategies (*Table 19*).

BalticSeaH2 goes for a system-integration approach. That means it's about piecing together cross-border demand, multiple layers of governance and a blend of public and private funds to actively build the market. What makes it efficient is how it mitigates risks: by aggregating demand from different sectors and countries and making use of already existing infrastructure and corridors. Furthermore, the hub reduces dependency on a single off-taker or technology pathway while accelerating learning across the value chain.

Hydrogen Valley Emsland shows another way: the locally focused cluster model. By keeping production and end use close together, it keeps transport and infrastructure costs down. Strong local public oversight means industrial policy, land use and investment are all on the same page. Tech here ramps up gradually and its mix of funding helps avoid huge upfront costs and risks. This setup works really well for decarbonizing industry locally, because co-locating hydrogen production with existing industrial demand can not only lower costs and but also improve decarbonization outcomes as shared infrastructure and proximity enhance efficiency and reduce logistical barriers (Rattle, 2024).

NEOM represents a third different efficiency logic, which is practically the opposite: it intends to expand globally, exporting green hydrogen in the market as ammonia derivative. Important aspects to achieve such ambition are leveraging economies of scale and ensuring contracts certainty. Its centralized joint venture sets the tone, deploying technology on a massive scale and locking in long-term sales, so the financial side looks predictable. Risk is kept low through full vertical integration and export deals, but building a local market or connecting with the broader system isn't a top priority.

From an efficiency perspective, no single model is universally superior, in fact each is optimized for different structural conditions. The NEOM model is likely the most financially efficient in terms of speed of deployment and capital mobilization per unit of hydrogen produced, due to economies of scale and contractual risk elimination. Emsland might be the best fit for regions aiming to green their industries without duplicating infrastructure, since it inserts hydrogen right into what's already there. BalticSeaH2, while potentially slower and more complex to coordinate, in the long run, it might create the most flexible and resilient hydrogen market, especially across borders.

A recurring issue that was determined in the Background section was the consistency in supply-demand balance. As seen within the business models described in this particular sample of research, there are attempts to 'de-risk' the gap by utilizing different strategies. As seen in the NEOM Hydrogen Valley, there is a 30-year offtake contract signing to secure the supply before production begins, while in more regional hub, like Hydrogen Valley Emsland, the focus is on creating proximal demand to lower the cost gap initially determined during the early stages of developing the hydrogen economy.

*Table 19: Summary of business structure and strategies*

| | BalticSeaH2 | Hydrogen Valley Emsland | NEOM Hydrogen Valley |
|---|---|---|---|
| **Business logic** | Integration of supply and demand on a regional and transnational scale | Regional industrial ecosystem based on physical proximity between production and end use | Commodity-export on global scale leveraging economies of scale and contractual certainty |
| **Governance structure** | Multi-level, cross-border network | Regional public governance | Centralized corporate joint venture |
| **Demand structure** | Diversified, cross-sector demand (maritime fuels, fertilizers, chemicals, industry) aggregated across multiple countries | Primarily regional industrial and mobility demand linked to already existing energy-intensive industries | Single large-scale, export-oriented demand secured through long-term offtake agreement (green ammonia) |
| **Technology approach** | Demonstration and integration of multiple technologies across the value chain in real market conditions | Gradual scaling of proven electrolysis technologies integrated into existing industrial systems | Deployment of mature large-scale electrolysis and ammonia synthesis technologies optimized for giga-scale production |
| **Funding and de-risking model** | Blended finance with strong EU public funding support combined with distributed industrial investments | Mixed public–private funding with strong role of regional institutions to attract and de-risk private capital | Large-scale international project financed by equity partners and long-term offtake contract ensuring revenue certainty |

## 6.2 Consortium-based Governance Structure

Multiple-stakeholders' partnerships in hydrogen valley projects aren't just helpful, but it's the key for green hydrogen development. Unlike single energy projects where one utility or developer runs the show, hydrogen hubs only work if the whole value chain moves together, from producing hydrogen and building out infrastructure to delivering it to end users. Usually, these partnerships tie together industrial companies that bring in both technological capabilities, steady demand, infrastructure operators that enable system integration through grids, pipelines and ports, and public bodies that make sure projects match up with local growth plans and regulations. Research centers and industry groups further contribute by supporting knowledge diffusion, keeping innovation moving and making it easier for different sectors to work together. Such multi-actor collaborations are risk-reducing not only from a financial but also from an institutional perspective, as joint decision-making enables long-term commitment and collective learning. Conversely, the structure of partnerships indicates varying strategic emphases: whereas partnerships with a strong focus on the industrial core emphasize speed of commercialization and scale, partnerships with a broader focus on public and research involvement emphasize experimentation, system integration and policy alignment. In this regard, partnerships are more than just enabling structures: they are, in fact, integral to the business model itself. Asghari et al, in a recent study, found that the cooperative strategy has emerged as the most effective approach for sustainable growth, registering the highest share of green hydrogen production.

In all three hubs, there is a significant role played by both the private and public sectors, who gather to form strategic public-private partnerships (PPP). This is particularly important in the hydrogen sector, which faces significant costs, changing regulations and uncertain demand, and therefore cannot rely solely on market forces for development in the initial phase. This involvement of the public sector in hydrogen development helps in de-risking and aligning it with the broader decarbonization and regional development agendas, while the involvement of the private sector ensures that the projects are economically viable and operationally effective. The balance between public and private leadership varies across the three hubs: Emsland sees regional public authorities owning a strong role in terms of leadership; a well-balanced level of public and private actors characterizes the multi-level transnational governance in BalticSeaH2; finally, NEOM is represented by a more private and corporate-led model, with however significant support from political sponsor. Hydrogen valleys require a hybrid governance model: PPP address cost barriers by incentivizing industrial-scale deployment while reducing long-term financial risks for governments and ensures policy stability (Singh et al, 2025). While these consortia effectively manage stakeholder alignment, long-term success is highly dependent on the ability to integrate a robust infrastructure. As was identified in the Literature Review, it is the physical assets that need to be underpinned by international standards and certification mechanisms in order to nurture trust among investors and cross-border partners. For hubs like BalticSeaH2, operating transnationally will require the adoption of the 2024 IRENA Quality Infrastructure Roadmap, thereby providing the framework for harmonizing technical safety and carbon-intensity certifications across Finland and Estonia and turning what was initially a fragmented regional project into a truly integrated international corridor.

### 6.3 Environmental and Social Aspects

In addition to supporting higher level social/environmental objectives, such as implementing Environment, Social, and Governance principles, the three successful green hydrogen hubs aim at creating environmental and social value. All three hubs include a common focus on decarbonizing hard-to-abate industries, including mobility, energy industries and heavy industries. The development of these green hydrogen hubs leads to job creation and skills development opportunities. The European Commission has estimated that every $1 billion invested in green hydrogen could generate 20,000 jobs throughout the entire green hydrogen value chain (direct, indirect and induced) per billion dollars invested. In the EU region alone, these multiplier impacts could generate up to 1 million jobs by 2030 and up to 5.4 million jobs upstream from creating the jobs by 2050 (IRENA, 2024). BalticSeaH2 contributes to cross-border emissions reductions by integrating multiple sectors across Finland, Estonia and the wider Baltic region, while simultaneously encouraging regional job creation through its diversified use cases and industrial-scale investments. Hydrogen Valley Emsland emphasizes regional industrial transformation, supporting local employment and skills development while decarbonizing existing manufacturing and energy-intensive processes in northwest Germany. NEOM Hydrogen Valley, with its large-scale export-oriented production, delivers global environmental impact by producing green ammonia to displace fossil-based fuels internationally and simultaneously promotes social objectives by developing a sustainable industrial ecosystem with modern infrastructure and high-skill employment opportunities in Saudi Arabia.

### 6.4 Takeaways

The comparison of the business strategies of BalticSeaH2, Hydrogen Valley Emsland and NEOM Hydrogen Valley shows that a single perfect business model does not exist for the development of green hydrogen markets. Instead, success seems to be driven by the alignment of business strategies with structural and regional conditions. In comparison with the diverse business strategies for the development of green hydrogen markets, some important implications for the global energy sector can be derived:

- Necessity of hybrid governance: the hydrogen markets need to be developed as they suffer from high costs and uncertain demand. Thus, the markets cannot be left to the forces of the market. Strategic PPPs are needed for de-risking the markets and aligning them with the energy transition agendas.

- Scalability vs. resilience: although the centralized model of NEOM has the highest level of financial efficiency and speed of deployment through economies of scale, the cross-border model of BalticSeaH2 may provide more resilience in the long term.
- Infrastructure optimization: in the case of established industrial regions, the most efficient path to decarbonization is the direct integration of hydrogen production into existing industrial demand to avoid duplication and minimize logistical hurdles.
- Strategic collaboration: either in the form of consortium or joint venture, in order to realize the development of the sector, the entire value chain must adopt the collaborative governance structure. Collaboration is not just additive, it is a core component of the business model, allowing mutual learning and long-term engagement.
- Socio-economic value creation: in addition to the obvious environmental contribution, these valleys are also drivers of social growth. For instance, the sector also has significant potential in the creation of high-skilled employment.

In conclusion, the development of the hydrogen economy will likely be characterized by the coexistence of these models, where the choice between the global export model and local industrial integration is dependent upon geographical advantages and specific policy regulations and agendas.

# 7 – CONCLUSION

This thesis intends to lay out the role of green hydrogen as a key strategy for industrial decarbonization, with a particular emphasis on how hydrogen hubs and valleys coordinate business models, governance and ecosystems dynamics to shape the green hydrogen market and encourage its development globally. Green hydrogen has gained increasing attention not only as a unique energy carrier, but also as enabling solution, which can address some of the most pressing challenges across hard-to-abate sectors such as steel, chemicals, heavy transportation and energy-intensive industries.

The research highlighted that the transition to a hydrogen-based economy is not only conditional on the readiness of technology to support such transition but is limited by the complexity of simultaneously managing infrastructure, investment, policy and demand creation. In such scenario, hydrogen hubs and valleys allow the clustering of production, storage, distribution, research and applications within a defined geography. Most importantly, such configurations facilitate a collaborative environment in which all the risks and the associated costs can be mitigated by all the users. Another important finding has to do with the value chain planning, which reveals hubs dealing with more than one segment of the entire value chain, ranging from energy production to final application, as being considerably more resilient. However, some challenges still need to be faced, such as high upfront investments (CAPEX) for the installation of electrolyzers, storage facilities and logistics infrastructure. Uncertainty of demand also contribute to delay the large-scale deployment of green hydrogen. Fortunately, learning curves, economies of scale and a supportive policy mechanism are expected to reduce costs in the future.

The outcome of the comparative analysis of the selected case studies indicates that there is no dominant or standardized business model for hydrogen hubs; however, common to the majority of the initiative was the consortium-based structures, which proved to be a fundamental for the development of hydrogen hubs, especially during early stages where high innovation level and investments are required. By bringing together public institutions and private sectors stakeholders, such hybrid governance systems facilitate innovation, risk-sharing between all actors and achievements of operational efficiency.

A deeper focus on the three "best performing" hydrogen hubs, BalticSeaH2 (Finland), Hydrogen Valley Emsland (Germany) and NEOM Hydrogen Valley (Saudi Arabia) let us observe three distinct yet complementary approaches to ecosystem development. BalticSeaH2 portrays a highly integrated model; it facilitates the availability of renewable energy and cooperation between countries in the context of the Nordic-Baltic region linking industries while scaling up using public financing schemes and EU policy support. Hydrogen Valley Emsland utilizes a consortium approach, connecting local industrial players, the public sector and technology developers to green existing industries. In this scenario, hydrogen is integrated into an established and highly developed industrial environment. In contrast, NEOM Hydrogen Valley embodies a large-scale, export-focused concept leveraging centralized renewable power generation, as well as an international market strategy. It highlights how hydrogen hub concepts can be leveraged as geopolitical economy tools through a structural reliance on robust state-backed investment and partnership strategies. Zooming out to the whole dataset, some recurring dynamics are highlighted: as already stated, there is the emergence of consortium-based governance structures as a key enabler for risk-sharing and stability of long-term investment. Second, fully integrated business models covering several stages of the hydrogen value chain, from production to final application, have higher potential economic resilience. Third, the majority of the hydrogen hubs are conceptualized as demonstration and technology showcase to provide replication mechanisms. They act as innovation test beds in which regulatory frameworks, financing models and cross-sector collaborations are being experimented with and fine-tuned. Their contribution to the acceleration of industrial decarbonization goes, hence, beyond emissions reduction: they contribute to regional economic development, technological leadership and energy system resilience.

The given study has several limitations. Firstly, hydrogen technologies and policies are rapidly evolving. This aspect implies a frequent change in cost data, regulatory frameworks and project status. Furthermore, not all projects choose to disclose their data, which hindered the comprehensiveness of the dataset and KPI analysis. Future research could include a broader set of hydrogen hubs, in terms of geography and business structures diversity, to investigate the long-term operational performance of existing hubs in greater detail, or explore demand-side dynamics, particularly those relating to industrial off-takers and hydrogen derivatives such as ammonia and e-fuels.

In conclusion, green hydrogen might have huge potential to support the global decarbonization pathway, and its successfulness not only depends on technological progress, but it also needs coordinated ecosystems and sustained collaboration between stakeholders, especially public and private actors. Hydrogen hubs and valleys represent a practical and strategic response to this challenge, offering a replicable framework through which the hydrogen economy can make the step from ambition to implementation.

# APPENDIX A – KPI Comparison of the 25 Case Studies

| | I. Technical and Financial | | | |
|---|---|---|---|---|
| | (Expected) Annual green hydrogen production (t $H_2$/year) | (Expected) normalized capacity | Investment volume (M€) | Funding sources |
| Agder Hydrogen Hub | 7200 | 60 | 41.70 | Public: National |
| BalticSeaH2 | 150000 | 1049.4 | 3950.00 | Private, Public: Supernational (EU funding), National |
| Basque Hydrogen Corridor BH2C | 21000 | 132.5 | 900.00 | Private, Public: Supranational (EU funding), National, Regional |
| CRETE-AEGEAN H2 VALLEY (CRAVE-H2) | 500 | N.A. | 12.50 | Private, Public: Supranational (EU funding) |
| eFarm | 126 | 1.125 | 17.60 | Private, Public: National, Local |
| FLHyPorts: Flemish hydrogen ports valley | 1887 | 25 | 92.00 | N.A. |
| Green Hysland | 300 | 2.5 | 50.00 | Private, Public: Supranational (EU funding) |
| H2iseO hydrogen valley | 800 | 5 | 392.40 | Private, Public: Supranational (EU funding), National, Regional |
| HY.City.Bremerhaven | 270 | 2 | 10.00 | N.A. |
| hy.klettwitz | 2027 | 80 | N.A. | Public: National |
| HY.Waiblingen | 260 | 2 | N.A. | N.A. |
| HyBalance | 200 | 1.5 | 15.00 | Private, Public: Supranational (EU funding), National |
| HyBayern | 700 | 5 | 45.00 | Private, Public: National |
| Hydro3D | N.A. | N.A. | 0.50 | Public: National |
| Hydrogen Valley Emsland | 75000 | 400 | 4000.00 | Private, Public: Supranational (EU funding), National |
| HyWays for Future | 200 | 2 | 90.00 | Private, Public: National |
| Mid Sweden Hydrogen Valley | N.A. | N.A. | N.A. | N.A. |
| NEOM GREEN HYDROGEN | 1000000 | 2200 | 40000.00 | Private, Public: National |
| Norddeutsches Reallabor (NRL) – Northern German | 4300 | 48.7 | 398.00 | Private, Public: National |
| Phi Suea House Project | 5 | N.A. | 5.00 | Private |
| SoHyCal | 584 | 7.5 | 63.50 | Private, Public: Regional |
| Transylvania Hydrogen Valley | 153 | N.A. | 20.00 | Public: Supranational (EU funding), National, Local |
| WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas | 2027 | 21.1 | 258.00 | Private, Public: Supranational (EU funding), National |
| WIVA P&G HyWest | N.A. | N.A. | 23.00 | Public: National |
| ZEV - Zero Emission Valley | 1700 | 10 | 36.00 | Private, Public: Supranational (EU funding), National, Regional |

|  | .II Organizational Information: Project Stakeholders |  |  |
|---|---|---|---|
|  | **Lead developer** | **Lead developer entity type** | **Total number of partners (n)** |
| Agder Hydrogen Hub | FDE & Greenstat | Company/private enterprise | ~11 |
| BalticSeaH2 | CLIC Innovation Oy, Gasgrid Vetyverkot Oy | Company/private enterprise | 40 |
| Basque Hydrogen Corridor BH2C | Petronor (Repsol Group) | Company/private enterprise | 75 |
| CRETE-AEGEAN H2 VALLEY (CRAVE-H2) | EUNICE | Company/private enterprise | 8 |
| eFarm | GP JOULE Hydrogen GmbH | Company/private enterprise | ~20 |
| FLHyPorts : Flemish hydrogen ports valley | WaterstofNet | NGO/NPO | ~8 |
| Green Hysland | Enagás | Company/private enterprise | 30 |
| H2iseO hydrogen valley | FNM S.p.a. | Company/private enterprise | 3 |
| HY.City.Bremerhaven | GP JOULE Hydrogen GmbH | Company/private enterprise | N.A. |
| hy.klettwitz | GP JOULE Hydrogen GmbH | Company/private enterprise | ~3 |
| HY.Waiblingen | Stadtwerke Waiblingen GmbH, GP JOULE Hydrogen | Company/private enterprise | ~3 |
| HyBalance | Air Liquide | Company/private enterprise | 9 |
| HyBayern | District Office (Landratsamt) Landshut | Public authority | N.A. |
| Hydro3D | BEIA CONSULT INTERNATIONAL S.R.L. | Company/private enterprise | 5 |
| Hydrogen Valley Emsland | H2-Region Emsland | Public authority | ~18 |
| HyWays for Future | EWE AG | Company/private enterprise | 10 |
| Mid Sweden Hydrogen Valley | a, Chamber of commerce, Mid Sweden, b, Region | Industrial association | 35 |
| NEOM GREEN HYDROGEN | ENOWA - HYDROGEN AND GREEN FUELS | Company/private enterprise | ~8 |
| Norddeutsches Reallabor (NRL) - Northern German Living Lab | CC4E/HAW Hamburg | Research and academia | 59 |
| Phi Suea House Project | Phi Suea House / Enapter | Company/private enterprise | N.A. |
| SoHyCal | H2B2 Electrolysis Technologies Inc | Company/private enterprise | ~4 |
| Transylvania Hydrogen Valley | Municipality of Cluj-Napoca | Public authority | 11 |
| WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas | Association WIVA P&G | Industrial association | 30 |
| WIVA P&G HyWest | FEN Sustain Systems GmbH representing the Green | Research and academia | 9 |
| ZEV - Zero Emission Valley | Auvergne-Rhône-Alpes Regional Council | Public authority | N.A. |

| | III. Supply Chain & Operations | |
|---|---|---|
| | **Value chain coverage** | **% Value chain covered** |
| Agder Hydrogen Hub | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| BalticSeaH2 | H2 Production, H2 Storage, H2 Transport, H2 Distribution | 80% |
| Basque Hydrogen Corridor BH2C | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| CRETE-AEGEAN H2 VALLEY (CRAVE-H2) | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| eFarm | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| FLHyPorts : Flemish hydrogen ports valley | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| Green Hysland | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| H2iseO hydrogen valley | H2 Production, H2 Storage, H2 Transport, H2 Distribution | 80% |
| HY.City.Bremerhaven | H2 Production, H2 Storage, H2 Transport, H2 Distribution | 80% |
| hy.klettwitz | H2 Production, H2 Storage, H2 Transport, H2 Distribution | 80% |
| HY.Waiblingen | H2 Production, H2 Storage, H2 Transport, H2 Distribution | 80% |
| HyBalance | H2 Production, H2 Storage, H2 Transport | 60% |
| HyBayern | Primary energy, H2 Production, H2 Transport, H2 Distribution | 80% |
| Hydro3D | H2 Storage, H2 Transport | 40% |
| Hydrogen Valley Emsland | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| HyWays for Future | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| Mid Sweden Hydrogen Valley | Primary energy, H2 Production | 40% |
| NEOM GREEN HYDROGEN | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| Norddeutsches Reallabor (NRL) - Northern German Living Lab | H2 Production, H2 Transport, H2 Distribution | 60% |
| Phi Suea House Project | Primary energy, H2 Production, H2 Storage, H2 Distribution | 80% |
| SoHyCal | Primary energy, H2 Production, H2 Transport, H2 Distribution | 80% |
| Transylvania Hydrogen Valley | H2 Production, H2 Storage, H2 Transport, H2 Distribution | 80% |
| WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| WIVA P&G HyWest | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |
| ZEV - Zero Emission Valley | Primary energy, H2 Production, H2 Storage, H2 Transport, H2 Distribution | 100% |

|  | III.  Supply Chain & Operations |  |  |  |
|---|---|---|---|---|
|  | **H2 Production** | **H2 Storage** | **H2 Transport** | **H2 Distribution** |
| Agder Hydrogen Hub | Water electrolysis with PEM electrolyser | Cylinder | Trucking, Ship |  |
| BalticSeaH2 | Water electrolysis with ALK electrolyser | Cylinder | Pipeline, Trucking, Ship | HRS 700 bar, HRS 350 bar |
| Basque Hydrogen Corridor BH2C | Water electrolysis with PEM electrolyser, Water electrolysis with ALK electrolyser, Water electrolysis with high-temp SOE electrolyzer, Other | Cylinder, Cavern, Other | Pipeline, Trucking | HRS 700 bar, HRS 350 bar |
| CRETE-AEGEAN H2 VALLEY (CRAVE-H2) | Water electrolysis with ALK electrolyser | Cylinder | Trucking | HRS 350 bar |
| eFarm | Water electrolysis with PEM electrolyser | Cylinder | Trucking | HRS 700 bar, HRS 350 bar |
| FLHyPorts : Flemish hydrogen ports valley | Water electrolysis with ALK electrolyser | Other | Trucking, Ship | HRS 700 bar, HRS 350 bar |
| Green Hysland | Water electrolysis with PEM electrolyser | Cylinder | Pipeline, Trucking | HRS 700 bar, HRS 350 bar |
| H2iseO hydrogen valley | Water electrolysis with PEM electrolyser, SMR with CC(U)S, External sourcing from outside the H2 valley | Cylinder | Trucking | HRS 350 bar |
| HY.City.Bremerhaven | Water electrolysis with PEM electrolyser | Cylinder | Trucking | HRS 700 bar, HRS 350 bar |
| hy.klettwitz | Water electrolysis with PEM electrolyser | Cylinder | Trucking | HRS 700 bar, HRS 350 bar |
| HY.Waiblingen | Water electrolysis with PEM electrolyser | Cylinder | Trucking | HRS 700 bar, HRS 350 bar |
| HyBalance | Water electrolysis with PEM electrolyser | Cylinder | Pipeline, Trucking |  |
| HyBayern | Water electrolysis with ALK electrolyser |  | Trucking | HRS 350 bar |
| Hydro3D |  |  |  |  |
| Hydrogen Valley Emsland | Water electrolysis with PEM electrolyser, Water electrolysis with ALK electrolyser, Water electrolysis with high-temp SOE electrolyzer | Other | Pipeline, Trucking, Ship, Other | HRS 700 bar, HRS 350 bar |
| HyWays for Future | Water electrolysis with PEM electrolyser, Water electrolysis with ALK electrolyser | Cylinder | Trucking | HRS 700 bar, HRS 350 bar |
| Mid Sweden Hydrogen Valley |  |  |  |  |
| NEOM GREEN HYDROGEN | Water electrolysis with ALK electrolyser |  | Pipeline, Trucking, Ship |  |
| Norddeutsches Reallabor (NRL) - Northern German Living Lab | Water electrolysis with PEM electrolyser |  | Pipeline, Trucking | HRS 700 bar, HRS 350 bar |
| Phi Suea House Project | Water electrolysis with PEM electrolyser, Water electrolysis with ALK electrolyser, Other | Cylinder |  | HRS 350 bar |
| SoHyCal | Water electrolysis with PEM electrolyser |  | Trucking |  |
| Transylvania Hydrogen Valley | Water electrolysis with PEM electrolyser |  |  |  |
| WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas | Water electrolysis with PEM electrolyser, Water electrolysis with high-temp SOE electrolyzer | Cylinder, Other | Pipeline, Trucking | HRS 700 bar, HRS 350 bar |
| WIVA P&G HyWest | Water electrolysis with ALK electrolyser | Cylinder | Trucking |  |
| ZEV - Zero Emission Valley | Water electrolysis with PEM electrolyser | Cylinder | Trucking | HRS 700 bar, HRS 350 bar |

|  | IV. Target Market & Applications |  |  |  |
|---|---|---|---|---|
|  | **End-user sectors** | **Application in mobility** | **Application in energy** | **Application in industrial use** |
| Agder Hydrogen Hub | Mobility | Trucks, Ships, Other |  |  |
| BalticSeaH2 | Mobility, Energy, Industrial use as feedstock | Cars, Buses, Trucks, Ships | Stationary fuel cells for distributed generation | Supply to chemical industry (e.g. fertilizer production), Supply to refine |
| Basque Hydrogen Corridor BH2C | Mobility, Energy, Industrial use as feedstock | Cars, Buses, Trucks, Forklifts, Ships | Hydrogen supply for injection into gas grid | Supply to refineries, Supply to steel industry, Supply to other industries |
| CRETE-AEGEAN H2 VALLEY (CRAVE-H2) | Mobility, Energy | Buses | Stationary fuel cells for distributed generation |  |
| eFarm | Mobility, Energy | Cars, Buses, Trucks, Other | Other |  |
| FLHyPorts : Flemish hydrogen ports valley | Mobility, Energy, Industrial use as feedstock |  |  |  |
| Green Hysland | Mobility, Energy | Cars, Buses | Stationary fuel cells for distributed generation, Hydrogen supply to gas-fired power plants |  |
| H2iseO hydrogen valley | Mobility | Buses, Trains |  |  |
| HY.City.Bremerhaven | Mobility | Cars, Buses, Trucks, Other |  |  |
| hy.klettwitz | Mobility | Cars, Buses, Trucks |  |  |
| HY.Waiblingen | Mobility | Cars, Buses, Trucks |  |  |
| HyBalance | Mobility, Industrial use as feedstock |  |  | Supply to other industries |
| HyBayern | Mobility | Cars, Buses |  |  |
| Hydro3D | Mobility, Energy |  |  |  |
| Hydrogen Valley Emsland | Mobility, Energy, Industrial use as feedstock | Cars, Buses, Trucks, Trains, Other | Hydrogen supply to gas-fired power plants, Hydrogen supply for injection into gas grid | Supply to chemical industry (e.g. fertilizer production), Supply to refineries, Supply to steel industry |
| HyWays for Future | Mobility, Energy, Industrial use as feedstock | Cars, Buses, Trucks, Other | Other | Supply to steel industry |
| Mid Sweden Hydrogen Valley | Mobility, Industrial use as feedstock | Cars, Buses, Trucks |  | Supply to steel industry |
| NEOM GREEN HYDROGEN | Mobility, Energy, Industrial use as feedstock | Buses, Trucks, Forklifts, Ships | Stationary fuel cells for distributed generation, Hydrogen supply to gas-fired power plants | Supply to chemical industry (e.g. fertilizer production), Supply to refineries, Supply to steel industry, Supply to other industries |
| Norddeutsches Reallabor (NRL) - Northern German Living Lab | Mobility, Industrial use as feedstock | Cars, Buses, Other |  | Supply to chemical industry (e.g. fertilizer production), Supply to refineries, Supply to other industries |
| Phi Suea House Project | Mobility, Energy | Other | Stationary fuel cells for distributed generation |  |
| SoHyCal | Mobility | Cars, Buses, Trucks |  |  |
| Transylvania Hydrogen Valley | Mobility, Energy | Cars, Buses, Trucks | Hydrogen supply for injection into gas grid |  |
| WIVA P&G - Wasserstoffinitiative Vorzeigeregion Austria Power & Gas | Mobility, Energy, Industrial use as feedstock | Cars, Buses, Trucks | Stationary fuel cells for distributed generation, Hydrogen supply to gas-fired power plants, Hydrogen supply for injection into gas grid | Supply to refineries, Supply to steel industry |
| WIVA P&G HyWest | Mobility, Energy, Industrial use as feedstock | Trucks |  | Supply to other industries |
| ZEV - Zero Emission Valley | Mobility | Cars |  |  |

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