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Governing the Hydrogen Transition: Hydrogen Valley case in the Northern Netherlands

Master Thesis

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Executive Summary

As the global energy transition accelerates, hydrogen valleys have emerged as critical governance models for developing integrated hydrogen economies. However, the complex governance structures in a hydrogen valley present significant challenges for effective implementation, requiring coordinated public and private stakeholders across different scales. The thesis examines the governance of the hydrogen transition through the Hydrogen Valley in the Northern Netherlands, and the main research question is "How is the hydrogen transition governed in the Hydrogen Valley of the Northern Netherlands, and what insights about the governance of the Hydrogen Valley can be drawn for facilitating regime shifts towards the hydrogen economy in other contexts?".

The HEAVENN project, the first and only hydrogen valley initiative in the Northern Netherlands, is selected as the case study for this research to address the research questions. The study employs a qualitative research design, incorporating seven semi-structured interviews with key stakeholders and an analysis of relevant documents to facilitate a comprehensive investigation. Later, the study applies a mixed theoretical approach that combines the Multi-Level Perspective (MLP) framework to analyze socio-technical hydrogen transition dynamics. The research further utilizes the Governance Assessment Tool (GAT) to evaluate the governance effectiveness across five dimensions (Levels and Scales, Actors and Networks, Problem Perspectives and Goal Ambitions, Strategies and Instruments, and Responsibilities and Resources) and four quality criteria (Extent, Coherence, Flexibility, and Intensity).

In the MLP analysis, green hydrogen production is represented as a niche innovation in the developmental phase, fostering experimentation in the Hydrogen Valley and regional network in the Northern Netherlands. However, the interactions between niche and regime reveal tensions for several reasons. Resistance from established regime, such as an immature market and insufficient financial incentives, impedes the niche growth. The GAT evaluation demonstrates strong governance extent through broad stakeholder involvement, but moderate intensity and coherence because of the conflict between national and regional support. A weakness exists in flexibility due to a fixed timeline and a limited project budget.

Drawing from interviews and document analysis, the key barriers in this case include the persistent "chicken-and-egg" problem of simultaneous supply and demand development, infrastructure dependency, and policy alignment challenges. These issues reflect the research questions on governance challenges, indicating a need for coordinated strategies to bridge niche-regime-landscape interactions.

Recommendations for other regions aiming to develop similar hydrogen initiatives include flexible governance, versatile infrastructure, and a balanced hydrogen value chain to address political and economic challenges. The findings provide a governance blueprint for the hydrogen transition by offering actionable strategies and underscore the necessity for adaptive governance frameworks to bridge the gap between long-term transition goals and short-term implementation challenges. While acknowledging limitations in sample size and regional specificity, this study offers valuable insights for global scaling of hydrogen economies and suggests future comparative research across different hydrogen valley contexts.

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List of Acronyms

IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
EU	European Union
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
TES	Total Energy Supply
GHG	Greenhouse Gas
MLP	Multi-Level Perspective
GAT	Governance Assessment Tool
MS	Member States
SMEs	Small and Medium Enterprises
FID	Final Investment Decision

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1. Introduction

1.1. Background

The energy transition represents a fundamental transformation in energy systems, shifting from fossil fuel dependence toward renewable energy sources (RES), including solar, wind, hydropower, and geothermal technologies (United Nations Development Programme, 2025). International Energy Agency data from 2024 indicates global carbon dioxide emissions from fossil fuels increased by 1.3%, exceeding pre-pandemic levels, with fossil fuels constituting 81% of the total energy supply globally. Recent geopolitical events, particularly the Russia-Ukraine conflict, have demonstrated the economic vulnerability of fossil fuel dependence through unprecedented price volatility. Meanwhile, human-caused climate change impacts intensify worldwide, with the Intergovernmental Panel on Climate Change (IPCC) indicating that between 3.3 and 3.6 billion individuals reside in regions highly susceptible to climate change effects. Consequently, accelerating the energy transition is imperative for ensuring long-term energy security, price stability, and national resilience (IRENA, 2022).

Hydrogen has emerged as a critical element within this transition, enabling decarbonization across multiple sectors, including energy, transportation, industry, and power generation (Kaheel et al., 2023; Bampaou & Panopoulos, 2025). Research demonstrates hydrogen's efficacy in reducing greenhouse gas emissions, particularly for green hydrogen produced using renewable energy, although this varies with production methods like grey or blue hydrogen. And its synergistic integration with renewable energy sources to facilitate energy system transformation (Hassan et al., 2023). Furthermore, hydrogen provides valuable energy storage capacity for intermittent renewable energy sources (Egeland-Eriksen et al., 2021). Despite these advantages of positioning hydrogen as instrumental in energy transition strategies, significant challenges persist regarding production methodologies, infrastructure development, and technological limitations (Ishaq et al., 2022). The hydrogen valley concept has consequently emerged as both a risk mitigation approach for hydrogen technology implementation and a foundation for broader hydrogen economy development (Bampaou & Panopoulos, 2025).

1.2. Problem Statement

Hydrogen Valleys represent an emerging governance model for fostering hydrogen-based energy systems, yet their development faces significant challenges in governance coordination, regulatory frameworks, and stakeholder alignment. While Hydrogen Valleys integrate public and private sector actors across multiple governance levels, existing regulatory frameworks often lack clarity on hydrogen integration (Bampaou & Panopoulos, 2025), leading to uncertainty for investors and project developers. Furthermore, fragmented governance structures and inconsistent policy incentives hinder the effective deployment of Hydrogen Valleys as scalable energy solutions (Vezzoni, 2024).

Additionally, knowledge management and workforce training gaps pose barriers to implementation, as hydrogen technologies require specialized expertise that is not yet widely available (Henry et al., 2022). Public awareness and acceptance also remain critical concerns, as hydrogen is often perceived as unsafe due to misconceptions about its storage and transport risks (Ricci et al., 2008). Public resistance may slow adoption without proper communication and demonstration projects (Emodi et al., 2021).

Given these challenges, there is a need to examine how governance structures, policy instruments, and stakeholder collaboration can affect the effectiveness of Hydrogen Valleys as drivers of the hydrogen transition. This study addresses this gap by analyzing the governance and organization of the Hydrogen Valley in the Northern Netherlands, identifying key success factors, barriers, and policy recommendations to inform similar initiatives in other regions.

1.3. Research Objective

The Netherlands is well-positioned to play a key role in Europe's low-carbon hydrogen market. It is a major European energy hub with a strong chemical industry. Its location along the North Sea, with significant offshore wind potential and an extensive gas and oil infrastructure, provides a strong foundation for hydrogen development (Stam et al., 2024).

The Hydrogen Valley in the Northern Netherlands is a leading initiative in the shift toward a low-carbon economy (Ter Berke et al., 2024). This region benefits from its existing energy infrastructure, strategic location, and supportive policy environment. These factors make it a crucial testbed for advancing hydrogen as a key energy carrier. The study aims to provide insights that support broader shifts toward a hydrogen-based economy by analyzing a real case in the Northern Netherlands.

This research examines how the hydrogen transition is governed in the Hydrogen Valley. The study aims to:

- Analyze the governance structures, stakeholder involvement, and policy instruments that shape the Hydrogen Valley's development.

- Identify key drivers and barriers in hydrogen development, focusing on policy frameworks, infrastructure development, and market dynamics.
- Evaluate the effectiveness of governance mechanisms using the Multi-Level Perspective (MLP) and Governance Assessment Tool (GAT) to assess coordination among different governance levels and actors.
- Policy recommendations to improve hydrogen governance, strengthen stakeholder collaboration, and address regulatory and market challenges in the other regions.

1.4. Research Questions

How is the hydrogen transition governed in the Hydrogen Valley of the Northern Netherlands, and what insights about the governance of the Hydrogen Valley can be drawn for facilitating regime shifts towards the hydrogen economy in other contexts?

Sub-questions:

- How is the Hydrogen Valley organized and developed? What are the key principles and factors that contribute to its establishment?
- What barriers are observed in the niche-regime interactions in the Hydrogen Valley case, and in which ways do they affect the hydrogen transition?
- How are different governance levels, elements, and qualities aligned in the Hydrogen Valley, and what governance challenges arise based on the Governance Assessment Tool (GAT) framework?
- What policy and other relevant recommendations can be made for different regions based on the Hydrogen Valley case analysis results?

2. Literature Review

2.1. Hydrogen Development

2.1.1. Hydrogen Innovation and Transition

Hydrogen is an energy carrier that can be produced and used in various ways (McDowall, 2012). The concept of hydrogen as an energy vector dates to the 1970s energy crisis when it was explored as an alternative fuel; however, due to the challenges of production and transportation, the interest in hydrogen declined (Franco, 2025).

Transitioning to a hydrogen-based economy is a versatile process involving technological innovation, policy development, and infrastructure expansion. Due to climate change, hydrogen is increasingly recognized as a key player in reducing greenhouse gas emissions and achieving carbon neutrality. Hydrogen production, storage, and application innovations across various sectors drive this transition. The integration of hydrogen with renewable energy sources, such as wind and solar, is crucial for ensuring a reliable energy supply and grid stability. For the hydrogen production and storage, innovation methods include water electrolysis and advanced techniques for extracting hydrogen from fossil fuels with minimal environmental impact; underground storage solutions, such as salt caverns and depleted gas fields, offer high storage efficiency and safety (Kuterbekov et al., 2024).

Germany and South Korea are recognized as global frontrunners in hydrogen technology adoption, focusing on quality infrastructure and social acceptance to facilitate transition (Ashari et al., 2024). Germany's 'H2 Mobility' program, initiated in 2009, aims to roll out hydrogen fuel cell vehicles through a cross-sectoral approach, highlighting the importance of government involvement in hydrogen innovation (Hacking & Eames, 2011). Despite the promising potential of hydrogen technologies, the challenges, such as high production costs, a lack of infrastructure, and safety concerns, remain significant barriers to widespread adoption (Zemite et al., 2023). Addressing these issues will be essential for realizing the full benefits of hydrogen in the transition to a sustainable energy future.

2.1.2. Hydrogen Valley

Hydrogen valleys constitute integrated geographical ecosystems encompassing the complete hydrogen value chain from production through utilization, serving as critical components in facilitating the transition toward a hydrogen-based economy. These valleys are regions where hydrogen production, storage, distribution, and consumption systems operate as interconnected networks. Figure 1 shows an overview of the hydrogen valley concept. Renewable energy sources such as solar, wind, and hydropower are powering electrolyzers for hydrogen production. Hydrogen can be stored as compressed gas or liquid or converted into derivatives like methanol or ammonia. After storage, it is transported to end-use locations via pipelines, trucks, or ships and used in power, mobility, and industrial sectors, both locally and externally (Bampaou & Panopoulos, 2025).

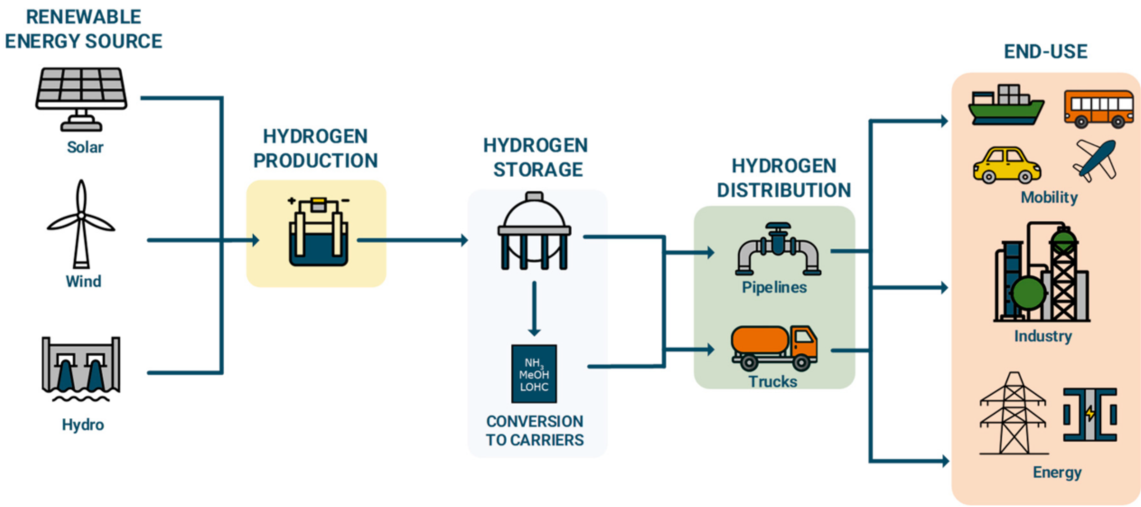

Figure 1. Overview of involved technologies and scope of this work (Bampaou & Panopoulos, 2024)

The development of hydrogen valleys involves the integration of various technologies across the hydrogen value chain, including production, storage, distribution, and end-use applications. The concept of hydrogen valley optimizes the hydrogen value chain through efficient resource utilization, economies of scale, and stakeholder collaboration. A key aspect of hydrogen valleys is the coupling of RES with electrolyzers to produce green hydrogen, essential for reducing carbon emissions (Bampaou & Panopoulos, 2024).

Economic and policy factors play a crucial role in shaping hydrogen valleys. The European Union's REPowerEU Plan aims to accelerate renewable hydrogen production, setting a target of 10 million tonnes by 2030. This initiative highlights the strategic importance of hydrogen valleys in meeting these goals (Bonafé et al., 2023). However, financial support remains critical. The high initial costs of renewable hydrogen production make it less competitive than fossil-based alternatives. As technology matures, costs are expected to decline, making green hydrogen more viable. In 2020, the cost of renewable hydrogen was $6.00 (€5.09) per kilogram. By 2030, under average European wind energy productivity, it is projected to drop to $2.50 (€2.12) per kilogram. Additionally, the recent decline in renewable energy costs opens new opportunities for large-scale hydrogen deployment (Kakoulaki et al., 2021).

Beyond energy transition benefits, hydrogen valleys also contribute to economic growth. They create manufacturing, installation, and maintenance jobs while attracting investment and fostering innovation (Majka et al., 2023). However, despite their potential, hydrogen valleys face several challenges that must be addressed to ensure their successful implementation.

2.2. Theoretical Frameworks

This section introduces two theoretical frameworks: the Multi-Level Perspective (MLP) and the Governance Assessment Tool (GAT), to analyze the niche-regime interaction from a governance perspective. The primary research question focuses on how the hydrogen transition is governed in the Northern Netherlands. The transition process involves the formation and protection of niches, as well as the potential restriction from the existing regime and pressure from the landscape level; thus, the insights from the MLP framework would be valuable. Given that this research concentrates on governance, applying the GAT is essential for examining the current governance context and identifying the weaknesses through its five dimensions and four quality criteria. The MLP framework enhances and complements the GAT by clarifying the barriers and enablers in this transition process. Simultaneously, the GAT framework provides an opportunity to evaluate the development of this hydrogen valley through a governance perspective (Jain et al., 2017). The complementarity of two frameworks can help deeply investigate the current dilemma within the project and emphasize the potential difficulties in implementing and further scaling the hydrogen valley.

2.2.1. Multi-Level Perspective (MLP)

The Multi-Level Perspective (MLP) framework distinguishes between three analytical levels: niche-innovations, socio-technical regimes, and the socio-technical landscape (Rip & Kemp, 1998; Geels, 2002). These levels are not direct representations of reality but rather heuristic tools to analyze the complex dynamics of technological and societal change. MLP is a middle-range theory that conceptualizes patterns of socio-technical transitions (Geels, 2011). It draws from multiple theoretical perspectives from evolutionary economics (e.g., trajectories, regimes, niches, speciation, path dependence, routines), science and technology studies (e.g., innovation as a social process shaped by broader societal contexts), structuration theory, and neo-institutional theory (e.g., rules and institutions as deep structures that both shape and result from human actions).

Transitions in MLP occur through non-linear interactions between three levels:

(1) Niches – spaces for radical innovations that challenge existing systems.
(2) Socio-technical regimes – dominant structures, rules, and practices that maintain stability in existing systems.
(3) Socio-technical landscape – external pressures and macro-level trends that shape long-term development (Rip and Kemp, 1998; Geels, 2002; Geels, 2005a).

Each level consists of heterogeneous elements, with higher levels being more structurally stable than lower ones. The alignment or misalignment of these elements influences the pace and direction of transitions.

Niches represent distinct spaces where radical innovations can emerge and thrive (Geels, 2002). These specialized spaces often challenge and disrupt existing systems, providing a room to protect new technologies and ideas from the pressures and expectations of the mainstream market. For these niches to successfully cultivate innovation, they need protection, support, and chances to learn, especially when they align with shifts in the broader socio-technical landscape and established regime (Geels & Schot, 2007).

Regimes refer to the dominant system encompassing a network of technologies, policies, and practices frameworks that shape the status quo. Regimes often aim to maintain stability and may actively resist changes that threaten their established order (Geels, 2014). However, they can also adapt gradually when niches begin to gain attention and when external pressures from the landscape become significant enough for reconsidering existing practices.

Landscape consists of overarching trends and external factors that shape and influence the socio-technical environment. These factors are economic growth, wars, broad political coalitions, social and cultural values, and environmental issues (Geels, 2002). When the landscape evolves, it can provide niches for chances to penetrate and eventually alter the rigid structures of the regime (Geels, 2014). In this way, the dynamic interplay between niches, regimes, and landscapes is vital for fostering transformative change and enabling new technologies to flourish in what may have been previously inhospitable conditions.

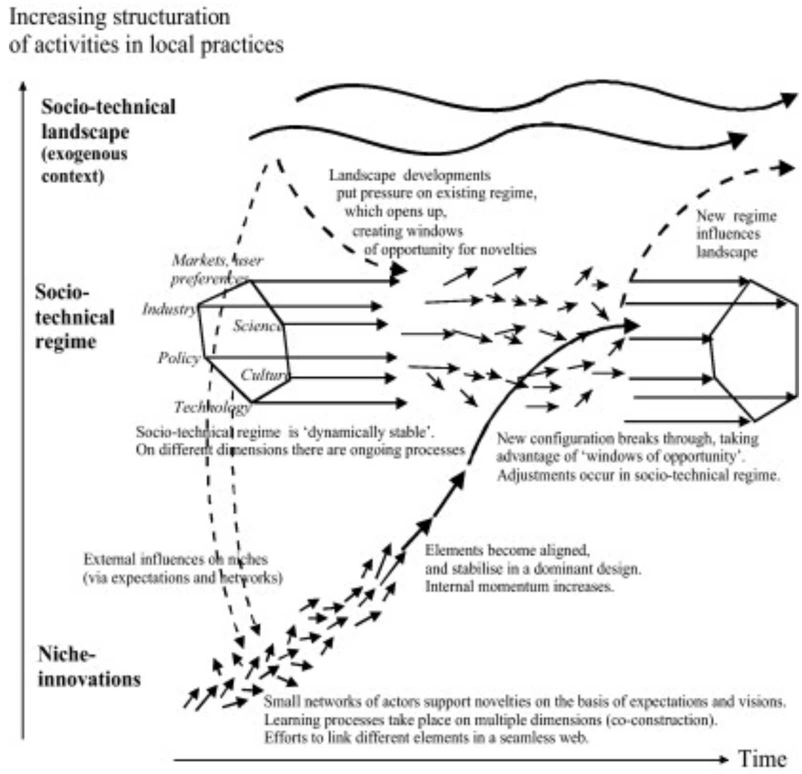

Figure 2. Multi-Level Perspective on transitions (Geels, 2002).

2.2.2. Governance Assessment Tool (GAT)

The Governance Assessment Tool (GAT) was developed to systematically evaluate governance structures across various sectors (Bressers et al., 2015). The tool is based on insights into governance. It is grounded in Contextual Interaction Theory (Boer and Bressers, 2011), which views implementation as a multi-actor process influenced by both top-down and bottom-up interactions (Jain et al., 2020). It helps identify strengths, weaknesses, and areas for governance improvement, allowing organizations and governments to make strategic decisions. By applying GAT, policymakers and scientists can assess how governance processes influence the effectiveness of policy implementation.

GAT evaluates governance through five key dimensions:

(1) Levels and Scales – How governance is distributed across different administrative levels.
(2) Actors and Networks – The involvement of stakeholders and their interactions.
(3) Problem Perspectives and Goal Ambitions – How the issue is framed and what objectives are set.

(4) Strategies and Instruments – The policies, rules, and mechanisms to address the problem.
(5) Responsibilities and Resources – The allocation of authority and financial or human resources.

Each dimension includes descriptive questions that help outline key governance elements. Additionally, assessments are conducted based on four quality criteria:

- Extent – The degree to which governance elements are present.
- Coherence – The alignment and consistency between governance elements.
- Flexibility – The ability to adapt to new challenges.
- Intensity – The strength of governance efforts in driving change.

The GAT has been effectively used in sustainability case studies. Jain et al. (2017) applied the GAT to assess the adoption of net zero-energy buildings (NZEB) within the governance framework in New Delhi. In another study, Jain et al. (2020) explored the governance of sectoral innovation and niche formation of green and low-energy buildings in Singapore and Delhi. Additionally, the DROP project (Bressers et al., 2015) utilized the GAT to assess drought adaptation governance in six Northwest European regions: Twente and Salland in the Netherlands, Eifel-Rur in Germany, Brittany in France, Somerset in the United Kingdom, and Flanders in Belgium, focusing on water management for nature, agriculture, and freshwater. This study provided insights into the governance context, identifying region-specific recommendations to enhance drought resilience. These studies highlight the GAT's capability to evaluate governance aspects of sustainable projects, with each of the five dimensions including a time-related question to help identify trends as countries face project deadlines (Bressers et al., 2016).

Governance dimension	Quality of the governance regime			
	Extent	Coherence	Flexibility	Intensity
Levels and Scales	How many levels are involved and dealing with an issue? Are there any important gaps or missing levels?	Do these levels work together and do they trust each other between levels? To what degree is the mutual dependence among levels recognized?	Is it possible to move up and down levels (upscaling and downscaling) given the issue at stake?	Is there a strong impact from a certain level towards behavioural change or management reform?

Actors and Networks	Are all relevant stakeholders involved? Are there any stakeholders not involved or even excluded?	What is the strength of interactions between stakeholders? In what ways are these interactions institutionalized in stable structures? Do the stakeholders have experience in working together? Do they trust and respect each other?	Is it possible that new actors are included or even that the lead shifts from one actor to another when there are pragmatic reasons for this? Do the actors share in 'social capital' allowing them to support each other's tasks?	Is there a strong pressure from an actor or actor coalition towards behavioural change or management reform?
Problem Perspectives and Goal Ambitions	To what extent are the various problem perspectives taken into account?	To what extent do the various perspectives and goals support each other, or are they in competition or conflict?	Are there opportunities to reassess goals? Can multiple goals be optimized in package deals?	How different are the goal ambitions from the status quo or business as usual?
Strategies and Instruments	What types of instruments are included in the policy strategy? Are there any excluded types? Are monitoring and enforcement instruments included?	To what extent is the incentive system based on synergy? Are trade-offs in cost benefits and distributional effects considered? Are there any overlaps or conflicts of incentives created by the included policy instruments?	Are there opportunities to combine or make use of different types of instruments? Is there a choice?	What is the implied behavioural deviation from current practice and how strongly do the instruments require and enforce this?

Responsibilities and Resources	Are all responsibilities clearly assigned and facilitated with resources?	To what extent do the assigned responsibilities create competence struggles or cooperation within or across institutions? Are they considered legitimate by the main stakeholders?	To what extent is it possible to pool the assigned responsibilities and resources as long as accountability and transparency are not compromised?	Is the amount of allocated resources sufficient to implement the measures needed for the intended change?

Table 1. The GAT matrix with its main evaluation questions (Adapted from: the Governance Assessment Guide, 2015)

3. Research Design and Methodology

3.1. Research Design

This research employs a qualitative case study research design to address the research question and its corresponding subquestions regarding the evolution of the Hydrogen Valley in the Northern Netherlands. Qualitative research methods have gained increasing prominence in energy research for their ability to access and interpret narratives associated with everyday energy use and the complex evolution of energy-related social practices (Bickerstaff et al., 2015).

The HEAVENN project, the only hydrogen valley initiative in the Northern Netherlands, is selected as the sole case study for this research. Data was collected through document analysis and semi-structured interviews with key stakeholders. The findings are examined using the MLP and GAT frameworks. The MLP framework explores the complex interactions among niche, regime, and landscape during the transition to a hydrogen economy. Meanwhile, the GAT framework focuses on governance mechanisms related to niche protection, identifying challenges faced during the project implementation.

3.2. Case Selection

The Northern Netherlands was the first region to receive subsidy support for developing a Hydrogen Valley. It has a well-established energy infrastructure, including gas pipelines and storage facilities, which can be repurposed for hydrogen transport and storage (Government of the Netherlands, 2022; Stam et al., 2024). The Fuel Cells and Hydrogen

2 Joint Undertaking (now the Clean Hydrogen Partnership) approved the region's subsidy application. This funding supports the HEAVENN program (Hydrogen Energy Applications in Valley Environments for Northern Netherlands), a six-year initiative launched in 2020 to develop a fully functional green hydrogen value chain.

The HEAVENN project, based in the Northern Netherlands, produces hydrogen primarily through electrolysis powered by renewable energy sources, such as offshore wind energy. The region leverages its abundant wind energy potential and existing energy infrastructure, including gas pipelines and storage facilities, to support green hydrogen production. The large-scale pilot project involves production, distribution, storage, and local hydrogen end-use, turning into an integrated and well-functioning “H2 valley” (H2V). The concept is across six locations in the Northern Netherlands: Eemshaven, Delfzijl, Zuidwending, Emmen, Hoogeveen, and Groningen, where existing and planned project clusters are.

The main goal is to utilize green hydrogen throughout the entire value chain, while developing replicable business models for widespread commercial deployment across the regional energy system.

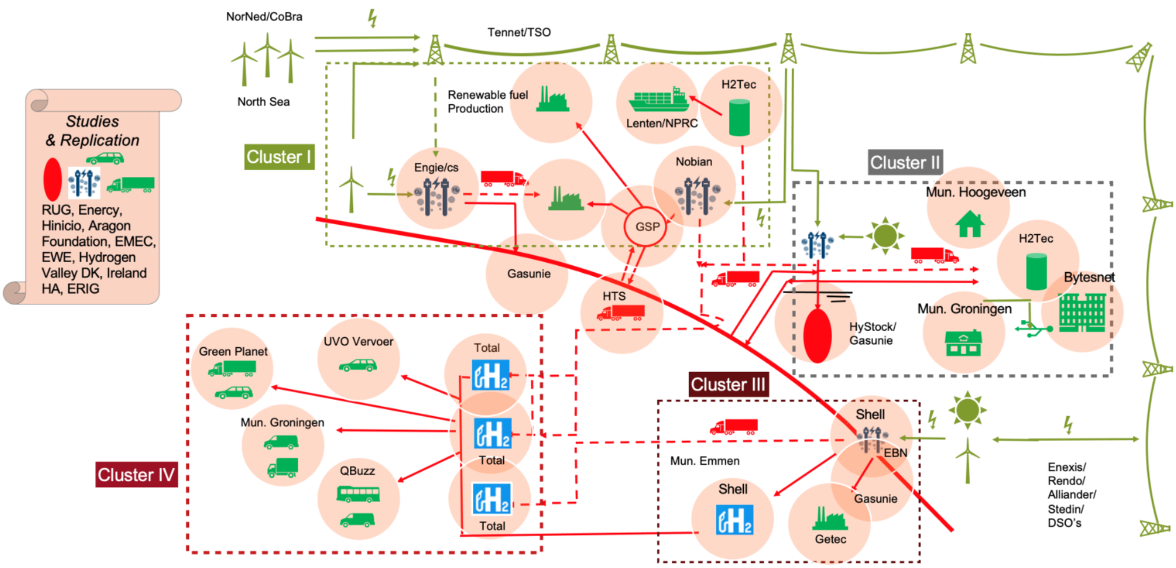

Figure 3. The scheme of the HEAVENN project (Adapted from the HEAVENN official website[1])

In addition to HEAVENN, several large-scale hydrogen projects are emerging near the North Sea. One key initiative is NorthH2, a partnership between Equinor, ENECO,

[1] https://heavenn.org/about/

Gasunie, Groningen Seaports, RWE, and Shell Nederland. These projects aim to integrate offshore wind energy with hydrogen production, strengthening the region's role in the hydrogen transition.

Another reason for selecting the Northern Netherlands is its abundant natural resources and strong wind energy potential, which is a vital incentive for governmental investment. And it presents an exceptional opportunity to study the governance challenges of integrating renewable energy into a Hydrogen Valley. The region is well-suited for producing green hydrogen through electrolysis powered by renewable energy (Government of the Netherlands, 2015; Stam et al., 2024). The Dutch government and key stakeholders formalized their commitment to this transition by signing the North Sea Agreement in 2020. This agreement aligns with EU legislation and the National Climate Agreement (Government of the Netherlands, 2019). Among its five core tasks, the agreement prioritizes energy transition, driven by the rapid expansion of offshore wind farms and related activities. This transformation supports CO_2 emission reductions and the development of a new energy system in the North Sea (Government of the Netherlands, 2022).

Figure 4. Indicative View of the Planned Hydrogen Ecosystem towards 2030 (Province of Groningen, 2020).

3.3. Data Collection

The data collection of this research comprises two components: policy and relevant documents analysis, and semi-structured interviews.

The first component involves a systematic analysis of governmental and industrial reports and documents related to hydrogen energy development in the Netherlands, focusing on the northern region. This analysis will include data on hydrogen production capabilities, infrastructure development, and cluster formation in the Northern Netherlands Hydrogen Valley.

The second component comprises semi-structured interviews with key stakeholders. This approach has demonstrated reliability in analyzing stakeholders' perceptions of hydrogen technology and energy transition processes (Parente et al., 2024). Semi-structured interviews offer a significant advantage by providing focus and flexibility, allowing the investigator to maintain research direction while exploring relevant emerging ideas during the interview process (Adeoye-Olatunde & Olenik, 2021).

The semi-structured interview (SSI) utilizes a mix of closed- and open-ended questions, often enhanced by follow-up inquiries such as “why” or “how”. Approximately one hour is generally considered the maximum for SSIs, aiming to reduce fatigue for the interviewer and the respondent (Adams, 2015). Several distinct groups were identified to categorize potential interviewees: policymakers, academic and research stakeholders, and private sector representatives. The interview questions were designed based on the two theoretical frameworks and are attached in Appendix 1. The initial interviewees were selected based on the stakeholders list within the HEAVENN project, as shown on their website[2]. From this list, sixteen stakeholders were identified as relevant to the research field due to their direct involvement in key aspects of the project. These stakeholders were chosen to ensure a comprehensive representation of hydrogen value chain, covering public, private, and public-private perspectives. Upon reaching out to all of them, seven responded positively and expressed their willingness to participate in interviews. Ultimately, seven interviews were conducted, as detailed in Table 2.

Table 2. List of interviewees

Num.	Stakeholder	Sector	Role
1	Provincial Government	Public sector	Former Official
2	Provincial Government	Public sector	Policy Officer

[2] https://heavenn.org/partners/

3	Network Consortium	Public/Private	Project Manager
4	Hydrogen Consultancy	Public/Private	CEO
5	Hydrogen Transport and Storage	Private	Business Developer
6	Hydrogen Production	Private	Product Development Manager
7	Hydrogen Infrastructure	Private	Business Developer

Integrating document analysis with stakeholder interviews will facilitate a comprehensive study, providing detailed insights into the governance and development of the Hydrogen Valley in the Northern Netherlands.

3.4. Data Treatment Analysis

An abductive coding and data analysis approach was adopted. Abductive coding represents a methodologically sophisticated approach to qualitative data analysis that combines elements of both inductive and deductive coding strategies. This analytical method starts with existing theoretical frameworks while remaining open to emergent patterns and unexpected findings in the data (Timmermans & Tavory, 2012).

To conduct abductive coding for the North Netherlands Hydrogen Valley stakeholder interviews, there is a designed iterative process inspired by Vila-Henninger et al. (2024). First, create a preliminary list of codes based on the GAT and MLP frameworks and relevant literature. Next, similar codes are grouped into themes by referencing governance theories to form hypotheses about patterns like centralized decision-making or stakeholder misalignment. Then revisit the data to verify and refine these themes, ensuring they align with the interviews and theoretical insights. Finally, the themes are mapped to the cross-cutting findings of the GAT and MLP to analyze the hydrogen valley's governance structure.

This study applies the GAT as the main analytical framework, evaluating the governance structures, stakeholder coordination, and policy frameworks shaping the Hydrogen Valley in the Northern Netherlands. The analysis of the MLP focuses on the interactions between the landscape, regime, and niche levels to assess how the Hydrogen Valley aligns with the broader hydrogen transition in complement to GAT analysis.

3.5. Research ethical, validity, and reliability

To ensure an ethically responsible research, the ethical assessment was approved by the Ethical Committee of the Faculty of Behavioral, Management, and Social Sciences (BMS) at the University of Twente prior to data collection. This research involved semi-structured interviews, and all participants received informed consent forms outlining the study's purpose, voluntary participation, and data usage. Interviews were recorded for accurate transcripts, and personal information will remain anonymous in compliance with GDPR. The interview data and recordings are securely stored on the University of Twente's OneDrive account, accessible only to the researcher.

To ensure validity and reliability, the study employed the MLP and GAT as theoretical frameworks to analyze governance dynamics. Document analysis and semi-structured interviews were also used to enhance credibility. A semi-structured interview was conducted with open-ended questions to elicit in-depth responses from participants. For the data analysis, a codebook based on the MLP and GAT guided the coding process and was consistently applied to the interviews and documents. The document was selected based on relevance to the study, such as Hydrogen Valley and hydrogen economy, to ensure replicability. While the small sample size limits generalizability, the depth of qualitative data and triangulation with documents enhanced reliability. Future studies could increase sample size to strengthen robustness.

4. Results

The chapter presents the results of the case study on the Hydrogen Valley in the Northern Netherlands. The findings are structured by two analytical frameworks: the MLP and the GAT. First, the MLP analysis examines the interaction among niche innovations, the fossil-based energy regime, and the landscape pressures. Second, the GAT analysis evaluates governance structure with five dimensions and four quality criteria. Eventually, a synthesis integrates MLP and GAT findings to understand the HEAVENN project comprehensively.

4.1. Multi-Level Perspective (MLP) Analysis

This section presents the results of the MLP analysis, which reveals the complex dynamics of hydrogen transition governance and the multi-level challenges facing the HEAVENN project, a large-scale demonstration initiative to develop a fully integrated green hydrogen value chain in the Northern Netherlands.

The main goal of this project is to utilize abundant renewable energy sources to produce green hydrogen, fostering a sustainable business model in deployment. The New Energy Coalition is leading the project, coordinating thirty-one public and private partners from six European countries.

The hydrogen transition in the Northern Netherlands is shaped by the interplay of niche innovations, such as green hydrogen technology, with the socio-technical regime of fossil-based energy systems, influenced by external pressures from the socio-technical landscape. The interactions among the three levels reveal ongoing tensions and (mis-)alignment. While green hydrogen technology demonstrates technical feasibility and is progressing as a niche solution, economic challenges and an immature market continue to present obstacles within the regime. Furthermore, pressure from the landscape level, such as EU directives concerning hydrogen targets, intensifies the transition experienced by EU Member States (MS). The following analysis details these interactions, as summarized in Table 3.

Niche Innovations

The Northern Netherlands drives its hydrogen transition at the niche level through innovative green hydrogen technologies (Stam et al., 2023). Green hydrogen production via electrolysis is a niche innovation in the Hydrogen Valley. It uses renewable energy, especially offshore wind (Stam et al., 2024). The region repurposes existing gas infrastructure for hydrogen production, storage, and distribution. This approach reduces costs and leverages local expertise. Also, the HEAVENN project fosters strong collaborations through public-private partnerships. It brings over 30 different partners across six EU countries working together for a sustainable future. Private companies aim for profits, while public entities focus on decarbonization and economic growth.

Niches need shielding, nurturing, and learning. Several protective measures are in place to protect this project. EU subsidies, such as the Clean Hydrogen Partnership, are crucial in reducing financial difficulties. Additionally, regional funding initiatives support this venture. Nurturing involves coordination and reskilling initiatives from the municipalities to support growth. For example, Groningen has set up training programs to prepare drivers for hydrogen trucks, helping fill the existing skill gaps in the workforce. Learning occurs through pilot projects like HEAVENN, providing valuable data and lessons of reference.

There are bold plans to scale the hydrogen economy (Alam et al., 2024). The Aragon Hydrogen Association (FHA) will conduct a replication study of HEAVENN with several organizations. The regions involved are Denmark, Aragon, Orkney, Northwest Germany, and Ireland. This project positions HEAVENN as a pioneering model for international hydrogen valleys. It sets the foundation for a major shift in energy use and sustainability on a global scale.

Socio-Technical Regime

In the Netherlands, the fossil fuel-based energy regime dominates (Brummelhuis et al., 2024). It relies on natural gas infrastructure and established markets. A noticeable shift towards sustainability is taking place. This change is driven by cultural beliefs that emphasize environmental responsibility. The Northern Netherlands is embracing sustainability as a core cultural belief as well. Green hydrogen emerges as a safe, promising solution, supporting the transition to a more sustainable energy landscape. Significant advances are being made in science and technology, including improvements in pipeline adaptations and the efficiency of electrolyzers. These innovations challenge traditional energy technologies, especially fossil fuels.

Despite the promise of hydrogen as an energy source in this case, the market is still unprepared. Demand for hydrogen remains low, which complicates its adoption. This situation in the HEAVENN project is known as the "chicken-and-egg" problem. High production costs make hydrogen unappealing to potential buyers. Meanwhile, those buyers hesitate to invest without a reliable supply. The industry structure includes diverse actors, although this project has a strong consortium, the lack of large-scale producers remains a significant gap. On the regulatory side, strict and diluted national policies pose further barriers. These regulations limit the flexibility needed for new initiatives. These challenges create tensions between the regime and niche levels and the (mis-)alignment with the landscape level, which will be explained more in the next chapter.

Socio-Technical Landscape

External pressures from the socio-technical landscape include several factors. Regarding EU climate policies, the RED III and REPowerEU Directive drive hydrogen adoption with clear targets in place. Meanwhile, the major geopolitical events have influenced hydrogen development. The Paris Agreement 2015 has propelled long-term energy transitions, while the Russia-Ukraine war since 2022 has disrupted energy markets. Notably, advancements in renewable energy technologies have been observed, including hydrogen (Kakoulaki et al., 2021). These factors have created opportunities for niches to break through. As for the shift in cultural intention, cultivating public trust in hydrogen production pathway and management of pipelines is essential for the transition (Gordon et al., 2024). In the HEAVENN project, for instance, the municipality of Hoogeveen successfully advocated the use of hydrogen for house heating, aided by well-informed information from the government.

Table 3. Results of the MLP Analysis

MLP level	Description	Interactions with Other Levels	Barriers/Enablers
Niche Innovations	Green hydrogen projects and technologies (e.g., electrolysis, storage, end-use applications).	- Niches leverage the regime's existing gas pipelines and infrastructure for hydrogen transport. - Challenge the regime's fossil fuel dominance with green hydrogen as a decarbonization alternative. - Landscape pressures (e.g., EU targets) accelerate niche development by providing funding and policy support.	- Barriers: High production costs ($6/kg in 2020, Kakoulaki et al., 2021; all the interviewees). - Enablers: EU subsidies (Clean Hydrogen Partnership) and strong knowledge base from gas industry experience.
Socio-Technical Regime	Dominant energy systems based on fossil fuels and related infrastructure, policies, and practices.	- Niches integration is challenged by economic uncompetitiveness and regulatory uncertainty. - Regime's infrastructure facilitates niche scaling. - Landscape policies (e.g., RED III) push the regime to adapt green energy systems, but the goal often faces dilution.	- Barriers: high costs and regulatory rigidity maintain fossil fuel dominance. - Enablers: existing infrastructure repurposing and EU policy alignment support regime transition.
Socio-Technical Landscape	External environment includes EU policies,	- Landscape policies, such as RED III and REPowerEU Directive,	- Barriers: high energy prices and import competition.

	geopolitical events, climate pressures, and global markets.	create opportunities for niche innovations. - Pressures from climate urgency and geopolitical events challenge the regime's stability, opening windows for niche growth. - Landscape trends align with niche scaling efforts.	- Enablers: EU funding and climate goals accelerate landscape support.

Multi-Level Interactions and Transition Dynamics

Niche-Regime Tensions

The analysis reveals significant tensions between niche innovations and regime structures. While hydrogen technologies demonstrate technical feasibility, regime-level economic structure maintains competitive disadvantages. The chicken-and-egg problem, which is identified by multiple interviewees, exemplifies this tension: "A partner in our project wants to build hydrogen refueling stations, but they need enough offtakers, like hydrogen cars and trucks. On the other hand, the company won't buy hydrogen trucks if there aren't enough refueling stations" (Interviewee 3). Besides, the financing mechanisms show misalignment between niche needs and regime capabilities. Long-term hydrogen projects require at least eight years, such as the HEAVENN project, which was designed in 2019 and is estimated to be finished in 2027. Still, the interviewee pointed out that the government funding cycles operate on 1 to 3 years, creating systematic under-investment in niche development.

Landscape-Regime (Mis-)Alignment

EU policy ambitions at the landscape level face systematic dilution at the regime level. The EU's RED III regulation sets targets, at least 42 percent of the hydrogen used in industry must come from renewable fuels of non-biological origin (RFNBOs), but EU MS implement them differently (Council of the EU, 2023). The Netherlands initially set ambitious targets, requiring companies to prove 42% green hydrogen use, but diluted this to 4% (Hydrogen Insight, 2025). An interviewee mentioned that neighboring MS, such as Germany, does not mandate individual company targets. Germany subsidizes select projects, like steelmakers using 100% green hydrogen, to meet national goals (Doucet et al., 2024). This approach is more pragmatic but less equitable than the Netherlands' attempt to distribute responsibility evenly. Companies in Germany face less obligations, making it more attractive for business, though the Dutch system aims for fairness. However, the reduction from 42% to 4% green hydrogen requirements demonstrates how landscape pressures are mediated and often weakened by regime-level political and economic considerations. Additionally, geopolitical events create both alignment and misalignment pressures. While the Russia-Ukraine war increases energy security urgency, it also increases energy costs and reduces available capital for long-term investments.

4.2. Governance Assessment Tool (GAT) Analysis

This section presents a comprehensive governance assessment of the Hydrogen Valley in the Northern Netherlands by applying the Governance Assessment Tool (GAT) framework. This analysis evaluates governance effectiveness across five dimensions (i.e., Levels and Scales, Actors and Networks, Problem Perspectives and Goal Ambitions, Strategies and Instruments, and Responsibilities and Resources) and four quality criteria (i.e., Extent, Coherence, Flexibility, and Intensity).

4.2.1. Governance Dimensions

4.2.1.1. Levels and Scales

Governance in the Hydrogen Valley spans regional, national, and EU levels. The EU sets overarching climate targets (e.g., in the directives RED III and REPowerEU) and provides funding. The national government influences legislation and prioritizes large-scale projects like the hydrogen national backbone in the Randstad region over regional initiatives like HEAVENN (Interviewee 2, 3). Regional government offers subsidies and permits, such as the Nationaal Programma Groningen (NPG), for infrastructure at the regional level.

EU Level

The EU provides the overarching policy framework through directives like RED III and funding mechanisms such as the Clean Hydrogen Partnership. “The EU has the most influence, providing subsidies and key policies like the Renewable Energy Directive” (Interviewee 5).

National Level

The role of the Dutch government shows significant variation across stakeholders' perceptions. “The national government has the most influence, as it translates EU directives into policy and regulation" (Interviewee 1). However, other interviewees criticized national-level support: "The Dutch government prioritizes large hydrogen projects, like national backbone, over regional initiatives like HEAVENN" (Interviewee 2).

Regional Level

Regional governments play a crucial role in providing environmental permits and subsidies and facilitating stakeholder coordination, even though they have limited legislative power compared to national and EU levels. "Locally, the province and municipality strongly support hydrogen, recognizing its economic benefits and leveraging existing gas infrastructure and knowledge" (Interviewee 3).

4.2.1.2. Actors and Networks

According to the interviewee, the HEAVENN project involves 34 partners across six countries, strengthening networks through annual meetings and cluster coordination. Collaboration is generally positive, but tensions arise from competitor sensitivities and differing priorities between large, and small and medium enterprises (SMEs). Interviewee 3 also mentioned, "The large producers are currently missing out within the project; it would be better if the projects could include universities to enhance research, but it is not critical." For instance, Hanze University of Applied Sciences often collaborates with the HEAVENN project for presentations and delegations, though they're not formal partners.

While the number of stakeholders within the project is comprehensive, the network faces coordination challenges. Multiple interviewees emphasized the importance of SMEs: "SMEs are more motivated and benefit more from funding," and are "critical for innovation and energy." However, the complexity creates management difficulties, and too many stakeholders and interdependencies among parties are regarded as significant challenges from the governmental side. What's more, with the HEAVENN project ending in 2027, new parties are unlikely to join at this time.

Pubic Sector Actors

The project includes EU institutions, the Dutch national government, the Provincial Government, and the Municipalities of Groningen, Hoogeveen, and Emmen. The New Energy Coalition is the central coordinator of the HEAVENN project operation and progress track, which entails facilitating collaboration among diverse stakeholders, ensuring alignment of tasks and timelines, and monitoring the technical and financial progress.

Private Sector Actors

As for the private sector, the stakeholders range from large multinational corporations (e.g., Shell and Gasunie) to SMEs. A critical finding is the different levels of engagement: "For a small company, like a taxi service using hydrogen cars, this project is their core business. For a large corporation like Shell or Gasunie, HEAVENN is one of their many projects" (Interviewee 3). Meanwhile, the large corporations often have difficulties in sharing detailed cost information, but both sides reached a compromise by limiting data sharing to the consortium.

4.2.1.3. Problem Perspectives and Goal Ambitions

Most stakeholders share a common goal of decarbonization through green hydrogen, but the perspectives vary. Economic concerns dominate with high hydrogen prices and the chicken-and-egg problem as key barriers. The high cost and the immature market limit the ambition of the regional hydrogen economy.

Goal Alignment

The stakeholders have different motivations but share the goal of sustainability. While visions align on advancing hydrogen, individual priorities vary based on company benefits. Companies focus on delivering products or services and their profitability, while regional governments aim for regional prosperity to maintain jobs. On the other hand, knowledge institutes prioritize training people for a sustainable economy. Their paths differ, but the end goal aligns.

Shared Problem Definition

All stakeholders recognize the need for decarbonization and energy transition. Nevertheless, the stakeholders face common challenges, such as high hydrogen prices and the chicken-and-egg problem. These challenges delay the goals for both the public and private sectors.

4.2.1.4. Strategies and Instruments

EU subsidies, regional funds (e.g., Nationaal Programma Groningen), and other company investments support the development of the HEAVENN project. Nevertheless, the complex subsidy processes and inflexible application processes reduce coherence; moreover, the state aid laws prohibit excessive government support to ensure fair market competition, yet slow the project progress and complicate cooperation (Interviewees 2, 3, 5, 7).

Financial Instruments

The project contains several EU subsidies (Clean Hydrogen Partnership) and regional funding from the Province of Drenthe and the Province of Groningen. It concerns a subsidy of 20 million euros with a public-private co-funding of 70-80 million euros (HEAVENN website). As for the national subsidies for the industrial side, the application complexity creates a barrier: “For every million euros of subsidy you want to earn, you must invest at least 100,000 euros in man-hours to get it” (Interviewee 7). Additionally, as an existing project, HEAVENN faces challenges applying for new funding like REPowerEU, which typically supports new project proposals (Interviewee 3).

Regulatory Instruments

The national hydrogen policy faces significant implementation challenges. The interviewee from the industry highlighted the policy dilution. “The Netherlands initially set ambitious targets, requiring companies to prove 42% green hydrogen use, but diluted this to 4% now” (Interviewee 6). State aid laws also increase complexity, described as “complex and often outdated” (Interviewee 2).

4.2.1.5. Responsibilities and Resources

Responsibilities are clearly assigned to sectors, with each partner having dedicated staff for stakeholders' activities. In general, human resources are sufficient. For example, the municipality of Groningen trained drivers for hydrogen trucks, addressing skill gaps through targeted training. Yet, securing the offtakers in the hydrogen value chain remains challenging.

Responsibility Distribution

The interviewees agree with the clear sectoral division with appropriate role allocation. However, the details are unclear to some degree. For example, the stakeholders know they must provide feedback on their tasks, but the required level of detail is not specified (Interviewee 5).

Financial Resources

The financial resources present a significant gap despite substantial investments. With the interviewees mentioned, the world and global energy system have changed a lot from the starting year of the project to the present. This project needs more funding and subsidies to secure the long-term offtake in the hydrogen value chain (Interviewee 4, 5). Additionally, the government can strive to subsidize the amount of hydrogen produced from electrolyzers or imported from other countries (Interviewee 7).

Human Resources

The HEAVENN project benefits from previous path dependence with the original expertise in natural gas, which shares similarities with hydrogen, allowing the reskilling of workers. One subsidy scheme developed by the Province of Groningen focuses on reskilling and fostering knowledge through school projects and collaboration with institutions like the Hydrogen Valley Campus Europe.

Technical Resources

The infrastructure resources show mixed availability. While existing gas infrastructure can be repurposed, offshore wind connection faces a delay due to grid congestion, impacting the green hydrogen production (Interviewee 1, 2).

4.2.2. Governance Qualities

4.2.2.1. Extent

- Levels and Scales: High–All relevant governance levels are involved, from EU to local. Multiple interviewees confirmed that policies and funding are present across all levels, with EU and regional contributions notable.
- Actors and Networks: Moderate to High–The HEAVENN project includes nearly the entire value chain with 34 partners across six countries, but large producers and new entrants are underrepresented (Interviewees 2, 5).
- Problem Perspectives and Goal Ambitions: High–Shared decarbonization goals are evident, though economic and logistical concerns vary.
- Strategies and Instruments: Moderate to High–Diverse instruments (subsidies, permits) are in place, yet gaps exist in long-term financing and regulatory clarity.
- Responsibilities and Resources: Moderate–Clear role distribution, but resource gaps like funding and green energy infrastructure persist.

4.2.2.2. Coherence

- Levels and Scales: Moderate–While EU and regional alignment are strong, national-level support shows inconsistencies. Northern regions require lobbying to align with national priorities and EU goals.

- Actors and Networks: Moderate–Strong level of cooperation between actors exists, but organizational tensions emerge from competitor sensitivities and different priorities between SMEs and large firms. Multiple stakeholders mentioned transparency challenges with competitor sensitivities and priority differences.
- Problem Perspectives and Goal Ambitions: Moderate–Strong level of consensus on climate decarbonization goals exists, but the chicken-and-egg problem for lacking offtakers and high hydrogen production costs conflicts create tension.
- Strategies and Instruments: Low–Policy dilution demonstrates inconsistency between EU ambitions and national-level policy implementation. Also, subsidies and infrastructure plans lack coherence due to state aid constraints and delays.
- Responsibilities and Resources: Moderate–Sectoral responsibilities are assigned equally, but funding disparities and transparency issues limit coherence.

4.2.2.3. Flexibility

- Levels and Scales: Low–Though stability is considered more important than flexibility for investor confidence (Interviewee 2), rigid national policies, inflexible subsidy schemes, and fixed timelines interfere with adaptation to new challenges (e.g., the Russia-Ukraine war).
- Actors and Networks: Low to Moderate – Even if the network could incorporate new actors, new partnerships might not want to join due to restrictive funding and the fixed timeline of the project.
- Problem Perspectives and Goal Ambitions: Low to Moderate–The pilot nature allows for some goal reassessment, but market immaturity constrains flexibility. The HEAVENN project was designed in 2019 when the hydrogen market was relatively small; now it has to adapt to the current landscape.
- Strategies and Instruments: Low–Regulatory hurdles and subsidy complexity reduce adaptability. "Currently, many policymakers lack this experience, working from behind desks, and policy changes take too long—over a year and a half—while companies need to act quickly" (Interviewee 1).
- Responsibilities and Resources: Low–Resource pooling is possible, but budget allocations are fixed, and state aid constraints compromise adaptability. Most of the budget within HEAVENN was set in 2019 and is not future-proof, making additional funding necessary (Interviewee 5).

4.2.2.4. Intensity

- Levels and Scales: High–Strong. EU commitment through major funding programs and policy frameworks. Regional level shows particularly high intensity through substantial subsidy schemes and active coordination.
- Actors and Networks: Moderate to High–Pressure for the coalition exists; nowadays, only small logistics projects of filling stations have been realized. However, other projects are still in the Final Investment Decision (FID) phase, on the edge of being realized (Interviewee 7).

- Problem Perspectives and Goal Ambitions: Moderate–Decarbonization goals deviate from business-as-usual, aiming to complete by 2027. Some projects are finished, but others face challenges and may not be ready until late 2025 or early 2026. As a subsidy project, data collection needs two years, ideally starting by the end of 2025. However, not all projects will meet this timeline (Interviewee 3).
- Strategies and Instruments: Low–EU and regional subsidies encourage change, but enforcement and market readiness are weak. With the complicated application process and restrictive conditions for national subsidies, there is a misalignment between the requirements and the project implementation.
- Responsibilities and Resources: Moderate–In general, allocated resources are sufficient to support the project development. Nevertheless, funding and technical gaps hinder effectiveness.

Table 4. Results of the GAT Analysis

Governance dimension	Extent	Coherence	Flexibility	Intensity
Levels and Scales	High	Moderate	Low	High
Actors and Networks	Moderate to High	Moderate	Low to Moderate	Moderate to High
Problem Perspectives and Goal Ambitions	High	Moderate	Low to Moderate	Moderate
Strategies and Instruments	Moderate to High	Low	Low	Low
Responsibilities and Resources	Moderate	Moderate	Low	Moderate

4.3. Synthesis of the Findings

This section synthesizes insights from both the MLP and GAT analyses to provide a holistic understanding of hydrogen valley governance in the Northern Netherlands. By integrating the interactions between niche innovations, socio-technical regimes, and the socio-technical landscape (MLP) with the structured evaluation of governance dimensions and qualities (GAT), the synthesis of findings highlights key patterns, challenges, and opportunities that influence the hydrogen transition. Additionally, this synthesis presents cross-cutting themes that emerged from the abductive coding process, highlighting critical governance challenges and opportunities that transcend individual analytical frameworks.

4.3.1. The overview of MLP and GAT

The MLP analysis reveals a dynamic interplay where niche innovations, such as green hydrogen production via electrolysis (Interviewees 6, 7) and storage solutions (Interviewee 5), challenge the reliance of the socio-technical regime on fossil fuels, particularly natural gas, which has historically dominated the Northern Netherlands. The existing infrastructure on the regime level, such as repurposed gas pipelines, serves as a critical enabler for niche scaling. At the same time, the socio-technical landscape (e.g., EU climate policies and geopolitical pressures like the Russia-Ukraine war) creates external momentum for change. However, barriers such as high production costs ($6/kg in 2020, projected to $2.50/kg by 2030, Kakoulaki et al., 2021) and grid congestion delay the niche growth, aligning with the resistance of the regime due to economic incentives for cheaper energy resources.

In the GAT analysis, the high extent of governance elements reflects a robust foundation (Government of the Netherlands, 2022). However, moderate coherence due to national-regional misalignment and low flexibility from rigid policies mirrors the identified tensions between regime stability and niche adaptability in the MLP analysis. Intensity varies, with strong EU-driven coordination but weak operational enforcement, aligning with landscape pressures pushing for transition yet facing regime inertia.

Synthesis of the results of MLP and GAT analyses reveals complex multi-level governance dynamics where transition pressures interact with governance structures in enabling and constraining ways. The MLP analysis identifies EU climate policies as the dominant landscape-level driver. In contrast, the GAT analysis confirmed the extent and intensity of the EU's substantial governance through funding mechanisms and policy frameworks. However, both analyses revealed a critical implementation gap at the national level due to a lack of sufficient support from the Dutch government.

Policy dilution emerges as a critical finding in both analyses. The MLP analysis identified this as a challenge for breaking through regime stability, while the GAT analysis revealed it as a coherence problem in the governance instruments.

Another critical synthesis finding is the systematic misalignment between transition timelines and resource allocation mechanisms. The MLP analysis identified this as a temporal mismatch between niche development needs (8-year projects) and regime-level funding cycles (1-3 years). The GAT analysis confirmed this as a resources and responsibilities dimension problem, with low flexibility and moderate intensity scores reflecting the inability to adapt resource allocation to changing transition needs.

Also, both analyses reveal fundamental tensions between innovation requirements and implementation constraints. The MLP analysis showed this through the chicken-and-egg problem, where niche innovations cannot scale without regime-level market development. The GAT analysis identified this through moderate coherence scores in problem perspectives and goal ambitions, where the reality conflicts to establish a whole hydrogen economy.

Together, MLP and GAT highlight a governance system where landscape opportunities and regime assets nurture niche innovations; nevertheless, the progress is constrained by governance challenges: policy dilution, resource limitations, and foundational tensions.

4.3.2. Cross-Cutting and Emerging Themes

The abductive coding process, combining interview data with MLP and GAT theoretical frameworks, revealed the emergence of several cross-cutting themes that provide additional insights into hydrogen valley governance dynamics. These themes, presented in Table 5, reflect recurring patterns and new insights critical to the development of Hydrogen Valley.

Table 5. Cross-Cutting and Emerging Abductive Coding Themes

Theme	MLP relevance	GAT relevance
Economic Viability Challenges Description: High costs and pricing disparities delay hydrogen adoption.	Landscape pressures (e.g., price volatility) and niche barriers (e.g., high cost) impact regime transition.	Strategies and Instruments; Problem Perspectives

Infrastructure Challenges Description: Barriers related to hydrogen production, storage, transport, grid congestion, pipeline delays, and offshore wind connection issues (Interviewee 1, 2).	Regime-level infrastructure lock-in and path dependencies limit niche scaling opportunities.	Responsibilities and Resources
Policy Alignment Challenges Description: Gaps between policy ambitions and implementation, including target dilution, regulatory complexity (Interviewee 6, 7)	Landscape policies push niches, but regime resistance and governance misalignment slow progress.	Affects Coherence and Intensity across dimensions.
Governance Innovation Description: New governance models are needed to manage complexity, uncertainty, and multi-level coordination challenges in energy transition contexts.	Institutional innovation at the regime level to support niche development and respond to landscape pressures.	Levels and Scales, Actors and Networks

5. Discussion

This section reflects on the findings from the MLP and GAT analyses, addressing the research questions to evaluate the governance of Hydrogen Valley in the Northern Netherlands and derive lessons for facilitating regime shifts toward a hydrogen-based economy in other contexts. The discussion explores the current state and challenges, situates the findings within academic debates, and reflects on policy and practice implications.

5.1. The status quo and current problems of the Hydrogen Valley

The Hydrogen Valley in the Northern Netherlands represents a pioneering effort to transition toward a low-carbon economy, leveraging its existing gas infrastructure, offshore wind potential, and regional subsidies (Government of the Netherlands, 2022;

Stam et al., 2024). The MLP analysis highlights niche innovation, such as green hydrogen production via electrolysis, that challenges the fossil dominance in the socio-technical regime, supported by landscape pressures like EU climate policies and geopolitical events. However, the GAT analysis reveals governance weaknesses: a high extent of involvement across levels and actors is undermined by moderate coherence due to national-regional misalignment, low flexibility from rigid policies, and variable intensity due to weak enforcement. This case study, HEAVENN, is a pilot initiative advancing green hydrogen production as a niche innovation challenging the current regime, driven by EU and regional infrastructure advantages. However, the governance is restrained by moderate coherence and low flexibility.

Current problems include the high costs of green hydrogen (Münster et al., 2024), exacerbating the chicken-and-egg problem where production and offtake lag (all interviewees). Infrastructure dependency is a bottleneck, with wind farm delays pushing production timelines (Interviewee 2). The report North Sea programme 2022–2027 also mentioned a roll-out plan for the hydrogen infrastructure, which would be conducted by the Ministry of Economic Affairs and Climate Policy and Gasunie. However, in December 2024, Hynetwork Services, the subsidiary of Gasunie, reported that the cost estimate for the hydrogen network had risen to €3.8 billion due to the new pipeline installation, higher material, and labor costs (Hynetwork Services, 2025). Also, policy alignment challenges, such as unclear implementation regulations and state aid constraints (Interviewee 3), further slow the progress. These issues reflect the research questions on governance challenges, indicating a need for coordinated strategies to bridge niche-regime-landscape interactions.

5.2. Use of MLP and GAT in analyzing a regional case study

The study uses MLP and GAT to analyze the Hydrogen Valley case study. The frameworks complement each other. MLP examines socio-technical transition. It covers niche, regime, and landscape interactions. GAT assesses governance structures. It focuses on five dimensions and four quality criteria. MLP can be utilized to examine the interactions among systemic factors that contribute to regime change, as well as the influence of niche innovation in this transition, while GAT can be applied to investigate the elements that shape the governance of a sectoral domain, regardless of whether it is in transition. For instance, MLP highlights the chicken-and-egg problem in niche-regime tensions. GAT categorizes this into dimensions of problem perspectives and goal ambitions and links them to the assessment of coherence criteria. Drawing from this study, only using MLP might miss governance details; GAT alone may lack the hydrogen transition context. Also, MLP lacks depth in the dimension of governance and institutions, which is why a complementary framework that effectively addresses these aspects is necessary. Both frameworks are needed to provide a complete picture of this study. For future studies that analyze regional sustainable transition cases, combining these two frameworks can ensure a robust analysis of transitions.

5.3. Academic merit and relevant academic debates

The findings contribute to academic debates on socio-technical transitions and governance frameworks. The MLP analysis aligns with Geels' studies. It supports the theory's non-linear transition model by demonstrating the complex and iterative interactions among niche innovations, regime resistance, and landscape pressures. Meanwhile, the GAT analysis builds on Bressers et al. (2015), offering empirical evidence that governance extent and intensity can be high, yet coherence and flexibility are low for various reasons.

Emodi et al. (2021) found that over 50% of hydrogen-related technology studies were based in Europe, and the Netherlands was in third place in study location. This shows that the Netherlands has a strong commitment to hydrogen research. The HEAVENN project, the first hydrogen valley in Europe, highlights this effort in the hydrogen economy. In this study, cost remains a key barrier to adopting hydrogen technology, and many participants are aware of hydrogen use for transport in the Netherlands, as seen in the HEAVENN project. However, Majka et al. (2023) mentioned that the weakness of HEAVENN is the need to reconcile many local government strategies, which did not emerge in this study. The lack of trained and specialized personnel, brought up by Bampaou & Panopoulos (2025), does not seem to be the case within this study because of the reskilling adaptability. And Hasankhani et al. (2023) warned that centralized hydrogen production could face logistical challenges. Distribution inefficiencies could affect a regional system like HEAVENN. The project should address the challenges of future development.

In contrast, this study contributes to Stam et al. (2024), who pointed out that the Netherlands is prepared to be the driving force to shape the European low-carbon hydrogen economy with many announced hydrogen projects. However, some adjustments in policy instruments need to be taken to attract more pre-FID projects into the FID phase. This is also demonstrated in the HEAVENN project, which is consistent with the interviewees in this study. As for the infrastructure issues mentioned in the study, aligning with the report conducted by the Government of the Netherlands (2022), which indicated that combined tenders for offshore wind energy and onshore electrolysis will be developed to support the roll-out. Yet, offshore electrolysis will not be able to be substantial until after 2030 due to the immature technology and the high costs; the national government will assist in setting up more pilot projects to complete the hydrogen infrastructure.

6. Conclusion and Recommendations

6.1. Answering Research Questions

The main research question is: How is the hydrogen transition governed in the Hydrogen Valley of the Northern Netherlands, and what insights about the governance of the Hydrogen Valley can be drawn for facilitating regime shifts towards the hydrogen economy in other contexts? This question is addressed through the following sub-questions:

- How is the Hydrogen Valley organized and developed? What are the key principles and factors that contribute to its establishment?

  The Hydrogen Valley is organized as a multi-level governance model, with the EU providing strategic direction and funding, the national government setting the legal framework, and the regional government driving implementation via subsidies and infrastructure. Key principles include stakeholder collaboration and governmental support, with factors like systematic funding and offtake guarantee contributing to establishment.

- What barriers are observed in the niche-regime interactions in the Hydrogen Valley case, and in which ways do they affect the hydrogen transition?

  Barriers include high production costs, grid congestion, and the chicken-and-egg problem, which delays niche growth. Regime resistance, such as regulatory inertia, slows adoption. These barriers impede the scaling of the hydrogen transition and reinforce fossil fuel dominance, suggesting other regions need cost-reduction strategies and flexible policies to overcome similar dynamics.

- How are different governance levels, elements, and qualities aligned in the Hydrogen Valley, and what governance challenges arise based on the Governance Assessment Tool (GAT) framework?

  Governance levels show a high extent but moderate coherence due to the national focus on Randstad, with low flexibility from rigid policies and variable intensity. Challenges include policy misalignment, stakeholder gaps, and resource shortages. Therefore, aligning incentives and enhancing flexibility are critical to improve governance quality in this context.

- What policy and other relevant recommendations can be made for different regions based on the Hydrogen Valley case analysis results?

  Recommendations include prioritizing versatile infrastructure and a structured roadmap to tackle economic and logistical barriers. A diverse, flexible consortium and simplified dependencies enhance stakeholder collaboration, while value chain inclusion and SME focus boost innovation. Daily alignment with supportive policies ensures sustained progress. A localized approach complements these by mitigating dependency risks, addressing the chicken-and-egg problem, and addressing infrastructure gaps. These insights, drawn from the experience of the Northern Netherlands, offer a blueprint for regions to navigate multi-level governance and niche-regime tensions

6.2. Limitations and Future Research Suggestions

This study has several limitations that need consideration. Considering the relevance mentioned in 3.3 Data Collection and the number of responses, the analysis relied on seven interviews, which may not fully represent all perspectives of the hydrogen valley stakeholder ecosystem. Some stakeholders, such as large hydrogen producers or academic institutions, were underrepresented.

Also, the concentration on the Northern Netherlands limits generalizability, as regional factors like its existing gas infrastructure and wind energy potential are unique. These conditions may not exist elsewhere. Moreover, the perspective of the national government in this case is solely derived from the Dutch context, offering a narrow viewpoint that could be enriched by comparative analysis with other countries and highlight variation in governance approaches. In addition, the qualitative nature of the study lacks quantitative metrics to validate governance effectiveness. Metrics could be validated objectively. For example, a techno-economic modeling approach, as applied by Rosén et al. (2024), could simulate the total energy system cost in hydrogen pipelines within a hydrogen valley to validate the argument of governmental investment in a mathematical way, which could complement the qualitative data.

Furthermore, the sequential application of MLP and GAT in this study raises the potential for confirmation bias, as the initial use of MLP as a sensitizing framework may have influenced the subsequent categorization of findings with GAT. To address this, both frameworks developed a preliminary code list. The themes were iteratively refined by revisiting raw data to ensure application with MLP and GAT independently, rather than forcing GAT findings to conform to MLP-derived categories. These two frameworks are conducted in parallel to minimize the bias and enhance complementarity.

Future research should compare with more case studies, such as the hydrogen valleys in other countries, and test the transferability of these findings. Also, future studies about the Northern Netherlands could track infrastructure (e.g., wind farm and grid construction) and subsidy efficacy to assess long-term impacts. Exploring technological advancements, such as next-generation electrolyzers, and their governance implications by 2030, aligning with the EU and North Sea programme goal of installed electrolysis capacity, could further refine recommendations.

6.3. Recommendations to the Hydrogen Valley

Followed by the last research sub-question and based on the Hydrogen Valley case analysis in the Northern Netherlands, the following recommendations are proposed for regions aiming to develop similar hydrogen initiatives, drawing on (synthesis of) insights from interviewed key stakeholders:

- Prioritize infrastructure development with versatile applications

  Start with robust infrastructure, such as pipelines and storage, designed not only for hydrogen as a burning fuel but also as a molecule for creating value-added products like basic plastic molecules. This approach aligns hydrogen pricing with industrial applications, making it more competitive than a direct natural gas replacement, and supports a diversified hydrogen economy.

- Build a diverse and flexible consortium with intense lobbying

  Form a strong consortium of motivated partners, including a mix of large and small companies, to leverage diverse expertise and resources. Effective lobbying is critical to secure governmental support, while building flexibility into project designs ensures adaptability to rapid global changes, a lesson from the evolving hydrogen landscape since 2019.

- Establish a structured roadmap with government support and education

  Pursue Hydrogen Valleys through a clear roadmap that aligns stakeholder tasks, skills, and timelines. This includes government support for training and education, ensuring universities prepare engineers by key milestones. A dedicated project organization is essential, as governments are not suited to lead directly, highlighting the need for specialized coordination.

- Develop localized initiatives with balanced demand and production

Focus on localized, small-scale projects that minimize dependencies on large infrastructure like backbones or storage, which have faced delays (e.g., water electrolyzers) with high-demand offtakers, such as refineries that can absorb variable output and supplement with grey hydrogen. This balance reduces risks and leverages existing demand, offering a practical starting point until broader infrastructure develops.

- Simplify dependencies and set incremental goals

  Avoid excessive complexity and interdependencies among parties, limiting key dependencies to 2 or 3 actors. Regions should take small, realistic steps with short-, medium-, and long-term goals to maintain progress, reducing the risk of stalling due to cost or complexity, as observed in the HEAVENN project.

- Involve the entire value chain with a focus on SMEs and storage

  Emphasize the importance of involving the entire hydrogen value chain, including diverse end-users, and prioritizing storage for operational flexibility. Small and medium enterprises (SMEs) should not be overlooked, as they drive innovation and show greater motivation than large, slower-moving companies, enhancing regional dynamism.

- Maintain focus and align daily actions with supportive policies

  Maintain a clear focus on hydrogen development, create supportive policy instruments, and align actions daily to achieve goals. This consistent effort, supported by flexible and responsive governance, is crucial to overcoming economic and market barriers, as seen in the Northern Netherlands' experience.

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Appendix 1. Interview Questions

Section 1: Background and Role

1. Can you briefly describe your role and organization/company in the Northern Netherlands Hydrogen Valley? What is your primary focus (e.g., policy, industry, research)?

Section 2: Organization and Development

2. From your perspective, what are the key factors (e.g., infrastructure, policy, funding) driving the Hydrogen Valley's establishment, and how is it organized (e.g., projects like HEAVENN)?

Section 3: Governance Levels and Scales (GAT Dimension 1)

3. How is decision-making distributed across local (e.g., Groningen), national, and international (e.g., EU) levels? Which level is most influential, and are there barriers to their cooperation?
4. How flexible is the governance structure in adapting across levels to new challenges (e.g., policy changes)? Provide an example.

Section 4: Actors and Networks (GAT Dimension 2)

5. Which stakeholders (e.g., government, companies, residents) are involved in the Hydrogen Valley, and are any key groups excluded?
6. How is collaboration conducted among you and other stakeholders, and what factors promote or hinder it?

Section 5: Problem Perspectives and Goal Ambitions (GAT Dimension 3)

7. What are the core challenges and primary goals of the Hydrogen Valley (e.g., decarbonization, economic growth) in your view?
8. Do stakeholders share a common vision for the Hydrogen Valley, or are there divergences? If so, where?

Section 6: Strategies and Instruments (GAT Dimension 4)

9. Which policies or subsidies support the Hydrogen Valley, and how effective are they? Are any measures missing or conflicting?
10. Can these policies adapt to changes or combination (e.g., technological advancements, funding issues)? Can you provide an example?

Section 7: Responsibilities and Resources (GAT Dimension 5)

11. Are responsibilities for implementation (e.g., infrastructure) clearly assigned, and are they supported by sufficient resources (e.g., funding, expertise)? If not, what is lacking?
12. How legitimate is the allocation of responsibilities, and are there concerns about accountability or transparency? If so, how to solve them?

Section 8: Niche-Regime Interactions (MLP Framework)

13. What barriers prevent niche innovations (e.g., green hydrogen) from scaling up against the existing energy regime (e.g., fossil fuel systems)?
14. How do broader trends and policies, such as EU climate targets, global energy price changes, or advancements in renewable energy technologies, shape the development of the Northern Netherlands Hydrogen Valley? For example, do they drive funding, policy support, or technology adoption?

Section 9: Closing and Recommendations

15. What do you believe are the key success factors of the Hydrogen Valley, and what governance practices or lessons could other regions adopt? Is there anything else you would like to add about its governance, development, or future?
16. If follow-up questions come up, would you be open to being contacted again? If not, is there someone else we could speak to?

Appendix 2. The Coding List

1. Multi-Level Perspective (MLP) Codes
1.1. Niche Innovations

A. Code: Green Hydrogen Technology
B. Network formation
C. Visioning and setting expectations
D. Learning
E. Shielding
F. Nurturing
G. Scaling

1.2. Socio-Technical Regime

A. Cultural Beliefs and Symbols
B. Science and Technology
C. Market Demand and User Practices
D. Industry Structure and Production
E. Policy and Regulations
F. Infrastructure and Technology

1.3. Socio-Technical Landscape

A. Code: EU Climate Policies
B. Code: Global Energy Prices
C. Code: Climate Change Urgency
D. Major geopolitical events
E. Major technological change
F. Major shift in cultural intention

2. Governance Assessment Tool (GAT) Codes
2.1. Levels and Scales

A. Extent
B. Coherence
C. Flexibility
D. Intensity

2.2. Actors and Networks

A. Extent
B. Coherence
C. Flexibility
D. Intensity

2.3. Problem Perspectives and Goal Ambitions

A. Extent
B. Coherence
C. Flexibility
D. Intensity

2.4. Strategies and Instruments

A. Extent
B. Coherence
C. Flexibility
D. Intensity

2.5. Responsibilities and Resources

A. Extent
B. Coherence
C. Flexibility
D. Intensity

3. Cross-Cutting Themes
3.1. Economic Viability Challenges
3.2. Infrastructure Challenges
3.3. Policy Alignment Challenges
3.4. Governance Innovation