ABM of Institutional Design for Hydrogen Storage in 'Cluster 6'

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By

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Preface

Writing this thesis has been a challenging yet deeply rewarding journey, and I would like to take this opportunity to express my sincere gratitude to the people who supported me throughout the process.

First and foremost, I would like to thank my supervisors, Zofia, Amineh, and Renske, for their invaluable guidance, constructive feedback, and constant encouragement. Their expertise and thoughtful insights greatly shaped the direction and quality of this work. I am grateful for the freedom I was given throughout the graduation project, which allowed me to explore the subject on my own terms, with both depth and creativity.

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I am also incredibly grateful to my family for their unwavering support and belief in me. Their love, understanding, and encouragement have been the driving force behind my academic pursuits. Thank you for giving me the freedom to follow my interests and the strength to persevere.

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— Aleksander Władysław Pęszko
[August, 2025]

Summary

As the Netherlands accelerates its energy transition, green hydrogen is expected to play a central role in decarbonizing industrial heat processes in hard-to-abate sectors. While five main industrial clusters have been prioritized for infrastructure development, 'Cluster 6', which includes smaller, dispersed industrial companies, faces challenges in adhering to the EU and National Strategies. The main issues include limited access to infrastructure, constrained financial capacity, and a lack of clarity regarding who should provide and operate hydrogen storage facilities. Storage infrastructure is crucial to ensure supply security and flexibility, particularly when hydrogen is produced from intermittent renewable sources. However, due to uncertainties in demand and unclear regulatory frameworks, industrial companies remain hesitant to invest, and public institutions have yet to formalize a nationwide framework. This research addresses the institutional considerations of storage by investigating which ownership model is most likely to promote hydrogen adoption among industrial firms in decentralized clusters.

To investigate this, the study draws on insights from literature on institutional economics, behavioral science, and energy transition studies. The research is guided by the main research question, "*Which hydrogen storage ownership model is most likely to enhance the adoption of hydrogen by 'Cluster 6' companies?*" It aims to examine the currently underdeveloped institutional structure and aims to bridge the knowledge gap that hinders hydrogen uptake. The answer will help understand how different institutional frameworks may influence the emerging hydrogen system and which is most suitable under current conditions. The core method involves developing an agent-based model (ABM) that captures how companies react to stimuli and how their decisions affect hydrogen adoption. The model incorporates technical, economic, and behavioral aspects embedded within the institutional environment of the diverse and decentralized nature of Cluster 6. Behavioral rules are based on behavioral theories from the literature, and technical and economic parameters such as storage efficiencies, capital and operational costs, energy prices, taxes, and subsidies are sourced from reports and literature.

Three institutional models are explored, namely centralized public governance, private market-led operation, and cooperative ownership by industrial firms. Rather than analyzing technical feasibility alone, the simulation evaluates how different ownership models influence system behavior, adoption timing, investment patterns, and overall equity among firms. Results demonstrate that structure significantly shapes the trajectory of the hydrogen transition. Storage ownership and access rules determine how investment risk is distributed, which in turn influences firms' willingness and ability to participate in the transition. Institutional models that reduce upfront costs and enable predictable access are more likely to support timely and inclusive adoption, while uncoordinated institutions can delay investment and widen disparities between firms.

The findings offer important implications for policymakers and stakeholders of the hydrogen value chain. The design of hydrogen storage governance is not just a technical matter but a strategic decision that can accelerate or hinder system-wide decarbonization. By examining these dynamics through a behavioral simulation lens, the study provides a structured basis for identifying effective, equitable, and scalable solutions for hydrogen infrastructure in decentralized industrial regions.

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Abbreviations

Abbreviation	Definition
ABM	Agent-Based Modeling
CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CES	Cluster Energy Strategy
CO_2	Carbon Dioxide
DSO	Distribution System Operator
ETS	Emissions Trading System
H_2	Hydrogen
KPIs	Key Performance Indicators
LCoS	Levelized Cost of Storage
MLP	Multi-Level Perspective
NPV	Net Present Value
OPEX	Operational Expenditure
P2G	Power-to-Gas
RES	Renewable Energy Sources
ROI	Return on Investment
SMEs	Small and Medium-sized Enterprises
SNM	Strategic Niche Management
TPA	Third-Party Access

1 Introduction

Hydrogen has long been recognized as a promising energy carrier, frequently highlighted in decarbonization strategies over the past decades. However, its role in the energy transition has been a topic of ongoing debates and setbacks—primarily due to the technical and economic challenges of storing hydrogen and scaling its use for widespread adoption. This chapter introduces the reader to the evolving role of hydrogen in the Dutch energy transition and outlines the specific problem this research seeks to address. It also provides an overview of the report's structure, clarifies the scope and focus of the study, identifies key knowledge gaps in the existing literature, formulates the guiding research questions, and introduces the methodological approach adopted to investigate the topic.

1.1 Background

The Netherlands has committed to achieving climate neutrality by 2050 and reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (Government of the Netherlands, 2023). Meeting these targets requires deep decarbonization of hard-to-abate sectors, particularly heavy industry, which relies on natural gas for heat generation. To support this, green hydrogen[1] has become a key part of the energy transition strategy because it can act as both an energy carrier and a feedstock (CE Delft, 2022).

While green hydrogen is regarded as a cornerstone of the Dutch energy transition, the path toward large-scale deployment is hindered. A core issue arises from the nature of hydrogen production via electrolysis, as it depends on renewable electricity from wind and solar power, which are inherently variable and weather-dependent (Mallapragada et al., 2020). This intermittency of supply introduces reliability concerns, especially for industrial applications that require stable and continuous input flows.

To mitigate this, storage becomes a crucial part of the hydrogen value chain, enabling buffering between fluctuating production and relatively inflexible demand profiles (TNO, 2023). The literature identifies several hydrogen storage technologies, each suited to specific applications (Moran et al., 2023). One widely discussed option involves underground storage in salt caverns or depleted gas fields. These facilities offer extremely large capacities and are particularly well-suited for seasonal storage, as they require infrequent injection and withdrawal cycles. However, their development is time-intensive and geographically constrained (Crown, 2023). An alternative is above-ground storage in pressurized gas tanks or cryogenic liquid tanks. This method offers modularity and ease of deployment, making it more flexible in spatial planning. Nevertheless, it incurs significantly higher costs per unit of stored hydrogen and is better suited for short-term storage needs, such as weekly buffering. Due to limited capacity, these systems may require frequent refilling, potentially up to 120 times per year (Crown, 2023).

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[1] Green hydrogen refers to hydrogen produced via electrolysis powered by renewable electricity sources, resulting in zero direct greenhouse gas emissions during production

The Dutch government laid out its hydrogen ambitions in the 2020 Government Hydrogen Strategy, which estimates a need for both underground and above-ground storage, totaling up to 1-3 TWh of capacity by 2030, with a long-term goal of 14-29 TWh by 2050 (Government of the Netherlands, 2020; TNO, 2023). This strategy is executed through the National Hydrogen Programme (NWP), which sets a timeline for scaling up the capacity, creating demand in industry and mobility, and establishing a robust infrastructure for transport and storage (Nationaal Waterstof Programma, 2023).

Because the Dutch industry is concentrated in clusters, with five main clusters accounting for a significant part of CO_2 emissions, the approach focuses on a "cluster strategy," targeting large-scale industrial hubs to maximize the impact (PBL, 2022). As part of the strategy, a national hydrogen backbone is being developed, led by the state-owned gas infrastructure operator Gasunie, via its subsidiary Hynetwork Services (Gasunie, 2022). This backbone will connect five major industrial clusters through approximately 1,200 km of repurposed and new pipelines. The scheme is illustrated in Figure 1. This core infrastructure is designed to enable national and cross-border hydrogen transportation, ensure supply security, and lower the cost of hydrogen through scale effects. The backbone is expected to be operational in phases from 2025 onward.

Figure 1: National Hydrogen Backbone (Gasunie, 2022)

However, not all industries are situated in these five clusters; some fall outside the scope of the backbone and are the last to be connected to the pipeline (WaterEnergySolutions, 2022; FuelCellsWorks, 2025). These decentralized industries spread across the country are together considered **'Cluster 6'**. They primarily specialize in chemical, petrochemical, and metal production, as well as food processing. Together, they represent 10–15% of total industrial CO_2 emissions (Berenschot, 2022) with the chemical sector, active in polymer production, fine chemicals, and plastic recycling, being responsible for approximately 44% of these emissions, followed by refineries (21%), the metal industry (15%), and food processing companies (10%) (OECD, 2021).

1.2   Problem Statement

Implementing hydrogen into the energy mix of industrial companies is challenging, especially in decentralized clusters. The dispersity from the backbone not only limits access to pipeline-based supply but also constrains opportunities to participate in national-scale economies that reduce costs through shared infrastructure (Stam et al., 2024). Companies in Cluster 6 typically lack the spatial concentration and sufficient demand required to justify investments in underground or salt cavern storage. If these regions aim to decarbonize without waiting for future backbone connections, they must rely on localized green hydrogen production or external supply (e.g., through tube trailers). In such a context, storage becomes essential, not only to mitigate the intermittency of renewable energy sources but also to ensure supply continuity and reduce dependence on frequent external deliveries. Consequently, modular above-ground storage solutions, such as pressurized tanks, emerge as a critical enabler for energy security in decentralized industrial clusters, despite their higher per-unit cost and operational complexity (Moran et al., 2023).

However, the main challenge of integrating storage into the hydrogen value chain lies in the institutional and regulatory framework (TNO, n.d.). Current Dutch hydrogen policy focuses on scaling storage capacity and transmission infrastructure, but does not clearly define governance arrangements. There is no clear guidance on the level of unbundling required for hydrogen storage, as the Dutch Gas Act is designed for natural gas and has yet to be updated to include hydrogen (HyLaw, 2019; CIEP, 2022). As a result, no established framework exists to specify roles, responsibilities, or ownership models for hydrogen storage facilities. This lack of clarity creates significant investment risk and leads to fragmented decision-making among local stakeholders, as all decisions related to hydrogen are hindered by uncertainty. Empirical studies show that stakeholders score incomplete infrastructure as a major barrier, with 87.88% of respondents, and inadequate regulatory standards, with 81.82% of respondents (Hasankhani et al., 2024).

Consequently, industrial companies face a double bind: on one hand, they are under pressure to decarbonize in line with national and EU targets; on the other, they lack the infrastructure, scale, and institutional support to make that transition feasible. Without targeted governance strategies and inclusive planning, 'Cluster 6' risks being left behind in the hydrogen economy, exacerbating spatial inequality in the Dutch energy transition.

1.3   Scope

The study focuses on rules and regulations regarding access, governance, and ownership structure of hydrogen storage. These aspects present core uncertainties that currently hinder investments in hydrogen storage infrastructure. Until the property rights of storage are clarified in legal documents such as the Dutch Gas Act (in Dutch "Gaswet"), stakeholders will be hesitant to invest in the storage facilities. This exemplifies a typical "chicken-egg" problem, where one side waits for the other. Without a legal framework and market formation, users will not adopt, whereas without sufficient demand, the market will not develop, and no investments will be made. For companies with high energy demand, the lack of a stable and secure hydrogen supply presents a major obstacle to decarbonization. This urges having a local storage facility within the cluster area, as it enhances energy security and ensures a more stable hydrogen supply. Eslamizadeh et al. (2023) argue that developing local industrial energy systems is critical in these contexts, as they reduce dependence on national infrastructure during

periods of external supply scarcity and highlight the role of institutional coordination in facilitating regional energy transitions.

Therefore, to support hydrogen adoption, this research examines the optimal configuration of rules and roles for operating local hydrogen storage facilities at the industrial sites. It explores various organizational models for hydrogen storage among industrial energy users, examining how different governance arrangements shape adoption dynamics and investment decisions. By situating the analysis in an industrial 'Cluster 6', this study provides a grounded exploration of how institutional design can accelerate hydrogen integration in practice. These decentralized industrial clusters contribute largely to CO_2 emissions in the Netherlands and are part of the Cluster Energy Strategy (CES) framework, aligning with national decarbonization objectives (RVO, 2023b).

The key stakeholders involved hydrogen socio-technical system include:
- Industrial companies: energy users seeking a reliable and sustainable hydrogen supply.
- System Operator (SO): responsible for managing the energy infrastructure and facilitating the integration of hydrogen into the energy system.
- Energy and hydrogen producers: involved in green hydrogen and renewable energy generation, and supplying green hydrogen to the industrial cluster.
- Regulatory body: legislative authority responsible for imposing rules and regulations regarding infrastructure access, subsidies for building facilities, or market formation.

By examining the interactions of these stakeholders, the study aims to identify effective governance frameworks that can support the integration of hydrogen storage into decentralized industrial clusters.

1.4   Knowledge Gap and Research Questions

Government-imposed regulations determine the rules that govern stakeholders' behaviors within the hydrogen system (Enserink et al., 2022; Walters & Wiseman, 2025). These formal regulations often serve as a framework within which stakeholders develop informal norms and practices to ensure compliance and promote industry growth. The challenge of designing a comprehensive regulatory framework lies in creating a set of rules that various stakeholders can easily interpret and adhere to. Collaborative action among stakeholders has been seen to mitigate economic and logistical challenges. Karlsson et al. (2008) emphasize the potential of industrial and regional collaboration to optimize resource utilization, particularly for heat-intensive industries with limited alternatives to natural gas. Yet, the current governance structure is not tailored for hydrogen storage, creating a need for designing integrated governance approaches, especially for the companies in Cluster 6, which exhibit difficulties in accessing financial support from the government.

Governance and network theories have stressed that many actors that are involved in decision-making not only possess vital resources to realize policy goals and outcomes but also have different perceptions of the problem definition and have different information and ideas on solutions (Edelenbos & Klijn, 2005). Therefore, allowing the stakeholders to participate in the decision-making may accelerate technology adoption. One way to accomplish that is by promoting shared storage ownership to incentivize end-user investments. This strategy encourages smaller industrial users to participate in hydrogen storage projects by granting them ownership stakes if they are willing to invest their capital. This increased sense of ownership is expected to enhance commitment to the energy transition, making industrial users more inclined to invest in and adopt hydrogen-based solutions.

Although extensive research has examined the techno-economic dimensions of hydrogen deployment, substantial gaps remain in understanding the interplay between regulation and stakeholder dynamics. Existing studies have largely emphasized cost-optimization for infrastructure, often overlooking the complex interactions between formal regulations, informal norms, and sector-specific requirements (Schlund et al., 2022). Likewise, the influence of governance mechanisms and regulatory frameworks on hydrogen integration has received limited attention (Hasankhani et al., 2024). Closing these gaps calls for a holistic approach that embeds stakeholder perspectives into both regulatory design and infrastructure planning, fostering a balanced and inclusive hydrogen system across industries of varying scales and regions.

This research seeks to explore how targeted interventions in the regulatory framework could facilitate the integration of decentralized industries within Cluster 6 into the national hydrogen strategy. Therefore, the research question is the following:

"Which hydrogen storage ownership model is most likely to enhance the adoption of hydrogen by 'Cluster 6' companies?"

To be able to answer the main research question, the following sub-questions are formulated to guide the research process:

1. *What formal regulations and policies govern hydrogen (storage) in the Netherlands?*
2. *Who are the actors involved, and what are their interactions and responsibilities in the emerging hydrogen system in a decentralized industrial cluster?*
3. *Which agents, institutional rules, and technical structures regarding hydrogen storage should be incorporated into the Agent-Based Model (ABM)?*
4. *What are the possible storage governance models?*
5. *Which key performance indicators (KPIs) should be used to assess hydrogen adoption?*

1.5   Research Approach

This research incorporates a modelling approach informed by qualitative data. It begins with desk research to examine institutional structures and the emerging hydrogen economy, drawing on academic literature and policy documents. Additional context-specific insights are obtained through a case study of 'Cluster 6', which includes specialized reports on decentralized industrial clusters and insights from stakeholders involved in Dutch energy operations. The case study enables a focused exploration of the institutional, spatial, and behavioral dimensions of hydrogen storage governance. To support this, relevant national and regional policies, academic sources, and industry reports on storage technologies and regulatory frameworks are mapped. These inputs feed into the development of a simulation model that analyzes hydrogen storage adoption and governance dynamics within the cluster.

The core of the research approach is built around Agent-Based Modeling (ABM). This method is selected for its strength in simulating the interactions of autonomous agents within a defined institutional and physical environment. The model is conceptualized using the MAIA framework, which structures the model into agents, institutions, physical structures, and rules, drawing from Ostrom's Institutional Analysis and Development (IAD) framework (Ghorbani et al., 2013). Stakeholder behavior in the model is informed by behavioral theories such as the Unified Theory of Acceptance and Use of Technology (UTAUT) or the Diffusion of Innovation Theory, capturing the heterogeneity in decision-making and

adoption behavior (Morchid et al., 2025). The model evaluates different storage ownership models, each with different implications for system emergence, based on key performance indicators (KPIs). The integrated approach allows for both qualitative understanding and quantitative analysis of complex socio-technical systems.

1.6   Societal Relevance

The societal relevance of this research lies in its potential to accelerate decarbonization through the integration of renewable hydrogen. It addresses the demand side of the energy value chain, focusing on industrial end-users. By fostering a supportive institutional environment with targeted policies and regulations, economies of scale in hydrogen production can be achieved—driving down costs and enhancing the competitiveness of green hydrogen relative to fossil fuels such as natural gas (Høyland et al., 2023; Schlund et al., 2021). Greater affordability, in turn, can spur adoption in high-emission sectors, including heavy industry and transportation. Expanding the use of green hydrogen would substantially cut GHG emissions, contributing to the fight against global warming. Evidence shows that well-designed institutional frameworks can lower both production and transaction costs while boosting adoption rates (IRENA, 2020; Osman et al., 2021). Achieving these outcomes will require aligning stakeholders through clear regulations and effective governance mechanisms.

1.7   Link with MSc Program

The relevance of this study to the CoSEM program lies in its multi-level, multi-actor approach, integrating technical innovation, institutional governance, and societal impact within socio-technical systems. Through this comprehensive lens, the research seeks to identify key challenges in adopting the renewable hydrogen value chain. It employs stakeholder analysis and agent-based modeling to explore the interplay between formal regulations, informal norms, and economic incentives—directly aligning with CoSEM's mission to address complex systemic challenges. Beyond advancing theoretical understanding, the study offers practical guidance for designing institutional policies that balance technical feasibility with social acceptance, thereby contributing to Sustainable Development Goals such as Affordable and Clean Energy and Climate Action (United Nations, 2015).

1.8   Structure of the Report

This thesis is structured into nine chapters. Chapter 2 presents the literature review of relevant academic and policy-oriented work on technical, institutional, and social aspects of the hydrogen storage system. Chapter 3 outlines the research methodology, detailing the rationale for using Agent-Based Modeling (ABM), the stakeholder mapping process, and the integration of institutional and behavioral frameworks. Chapter 4 describes the model conceptualization, including the definition of the agents, their attributes and roles, the institutional rules, and the technical and physical structures relevant to the hydrogen storage system. Chapter 5 shows the results of the baseline simulation, followed by uncertainty analysis in Chapter 6. The simulation results of the three proposed storage ownership models are described in Chapter 7. Chapter 8 provides a discussion of the findings concerning the broader institutional, technical, and policy context. Finally, Chapter 9 concludes the thesis by summarizing the main findings, including answering research questions, and presents the limitations and future directions of this work.

2 Literature Review

This chapter provides a comprehensive review of the scientific literature and Dutch policy documents related to hydrogen storage. As a vital part of the hydrogen value chain, storage is integral to a complex socio-technical system that encompasses technical, institutional, and social factors. Moreover, institutional framework and behavioral theories relevant to this socio-technical system will be introduced the help guide the ABM.

2.1 Decentralized Green Hydrogen System

With ongoing technological progress and rapid deployment of renewable energy infrastructure across multiple decentralized locations, the design of modern energy systems is shifting toward greater sustainability and flexibility (Fu et al., 2020). This change requires transitioning from the centralized natural gas infrastructure to a decentralized green hydrogen system. While the traditional natural gas network operates with unidirectional flow, from extraction sites to end-users, the hydrogen system functions through a network of distributed electrolyzers powered by renewable sources such as wind, solar, and biofuels. This production method, known as power-to-gas (P2G), is considered carbon-neutral and has been included in the Netherlands Hydrogen Strategy as the preferred approach, aiming to fully replace steam methane reforming (SMR) (Gbangbola, 2022).

2.1.1 Multi-Energy System

Integrating green hydrogen production with other energy systems adds significant complexity due to the variability of renewable electricity and the need for dynamic coordination among production, storage, and consumption. In response to these challenges, several studies have proposed models for multi-energy integration (Di Micco et al., 2023; Fu et al., 2020; Lei et al., 2024; Li et al., 2020; Liu et al., 2023; Xia et al., 2024). Xia et al. (2024) introduce the concept of an Electricity-Hydrogen Multi-Energy System (EHMES), which localizes the production and use of renewable electricity and hydrogen to improve industrial flexibility. As shown in Figure 2, the system includes co-located renewable generation (wind and PV), battery storage, electrolyzers, and hydrogen storage, all connected to the upstream grid. Liu et al. (2023) expand this model further by adding heating and cooling networks, creating a fully integrated multi-energy framework suitable for industrial parks (see Figure 3).

This decentralized approach decreases dependence on the central grid but raises the need for advanced coordination mechanisms, especially in balancing supply and demand, because of the intermittent nature of renewable energy sources. To tackle these issues, the green hydrogen value chain is integrated with SMART electrical grids. By linking hydrogen production with SMART grids, it becomes feasible to optimize electrolyzer operations based on real-time electricity availability and demand, improving the overall system flexibility and resilience (Han et al., 2022; Koirala et al., 2015; Meegahapola, 2023).
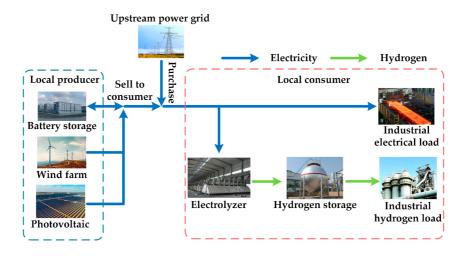
Figure 2: Decentralized electricity-hydrogen multi-energy system (EHMES) (Xia et al., 2024)
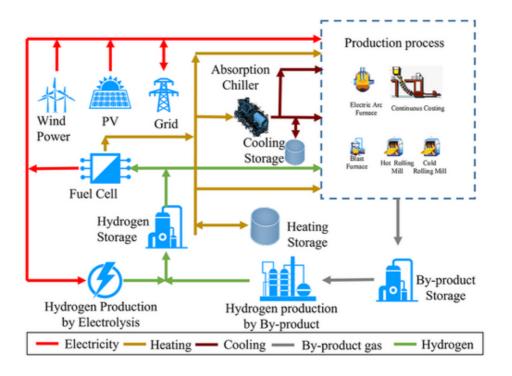
Figure 3: The multi-energy system of an industrial park (Liu et al., 2023)

Liu et al. (2023) highlight the importance of coordination optimization in hydrogen-based multi-energy systems with various storage options for industrial parks. Their research emphasizes the need for integrated planning and operational strategies to improve energy efficiency and lower system costs. By considering the interactions among different energy carriers and storage systems, such approaches can greatly enhance the performance and sustainability of industrial energy systems.

The green hydrogen value chain comprises several critical components (Eicke & De Blasio, 2022):

- **Production**: Electrolyzers convert water into hydrogen using electricity from renewable sources. The Netherlands has initiated several projects, such as the NortH2 initiative, aiming to produce green hydrogen using offshore wind energy (RVO, 2022).
- **Transportation**: Hydrogen can be transported via repurposed natural gas pipelines or newly constructed hydrogen-specific infrastructure. Gasunie is developing a national hydrogen network to connect industrial clusters (Gasunie, 2022).
- **Storage**: Given the variability of renewable energy production, storage solutions are essential to ensure a stable hydrogen supply.
- **End-use**: Hydrogen serves as a feedstock to generate heat for industrial use, a fuel for transportation, and a means for electricity generation, contributing to decarbonization across sectors.

2.1.2 Hydrogen Storage Technologies

Considering the transition to a green hydrogen system, exploring different hydrogen storage technologies is crucial. In the Netherlands, two primary storage methods are under active consideration, each suited to different spatial and demand contexts:

- **Underground Hydrogen Storage (UHS):** UHS utilizes geological formations, such as depleted gas fields and salt caverns, to store hydrogen on a large scale. This method is well-suited for seasonal storage (from summer to winter), long-term storage, and bulk storage, providing high energy density and favorable economics. The levelized cost of storage (LCoS) is significantly lower in UHS systems, around 0.25 £/kg (Crown, 2023), thanks to economies of scale and less frequent needs for compression or reinforcement infrastructure, making it competitive with fossil-based options (Moran et al., 2023). However, this storage method has a limitation in the number of injection and withdrawal cycles, between 2 and 9 times per year, depending on the technology. Salt caverns typically support 9 cycles, while depleted gas fields support two cycles. Due to the intermittent nature of renewable sources, more frequent injections and withdrawals are necessary, which UHS cannot accommodate. Therefore, it cannot serve as the sole storage method and must be complemented by more accessible options, such as above-ground storage. The Dutch subsurface conditions are generally favorable for this type of storage, and ongoing studies are assessing its safety, technical feasibility, and regulatory implications (EBN-TNO, 2024).

- **Above-Ground Storage (AGS):** AGS involves storing hydrogen in either gaseous, liquid, or metal hydride form in pressurized tanks or cryogenic containers, in smaller quantities, in locations that are not spatially constrained. These technologies are useful for short-term (daily or weekly) storage, addressing reduced production output due to lower sun or wind activity, rather than seasonal low production times. For industrial clusters that are farther from the national hydrogen backbone, AGS technologies are more feasible and accessible. These options enable proximity-based access near local production and consumption sites, thereby minimizing transportation needs and enhancing accessibility. However, AGS typically involves higher capital costs and lower storage capacities, leading to a higher LCoS compared to underground storage. Both compressed and liquid AGS cost around £1.4 per kg, and the injection/withdrawal cycles are 120 and 52 times per year, respectively (Crown, 2023). Lowering the LCoS of AGS is crucial but challenging, as storage is an essential part of the green hydrogen value (Moran et al., 2023). Only by achieving economic competitiveness will green hydrogen become the leading energy source in industrial use.

2.2　Institutional Framework for Hydrogen Storage

The transition to a decentralized green hydrogen system necessitates a re-evaluation of existing institutional structures. Incorporating hydrogen storage near production sites and end-users introduces additional complexities in governance, regulation, and operational responsibilities. This section examines current legal frameworks, national strategies, and comparative analyses to clarify the institutional environment affecting hydrogen adoption in the Netherlands.

2.2.1　Regulatory Framework

European Level

The two most important EU documents guiding hydrogen policy are the EU Hydrogen Strategy (2020), which provides a long-term roadmap for scaling up renewable hydrogen from 2020 to 2050, and the Renewable Energy Directive (RED), which establishes legally binding targets for the share of renewable hydrogen in final energy consumption. The EU's Hydrogen Infrastructure Report emphasizes the urgency of expanding hydrogen storage capacity to support REPowerEU goals (Hydrogen Europe, 2024). To reach the 2030 targets, approximately 45 TWh of hydrogen storage is needed across the European Union, but only 9 TWh are currently planned, indicating a significant gap. The long lead times for new UHS projects (typically between 5 and 11 years) and the lack of a dedicated market for hydrogen discourage investments and create serious implementation challenges (Hydrogen Europe, 2024). Until these issues are properly addressed through binding legal instruments, widespread adoption of hydrogen is unlikely to meet the 2030 targets. Achieving these goals depends on Member States' commitment to fully implement the steps outlined in the EU Hydrogen Strategy and to incorporate the Renewable Energy Directive (RED) into their national laws to fulfill their respective obligations.

National Level

At the national level, the legal framework for hydrogen is still being developed, and current regulations are based on those for natural gas. On December 10, 2024, the Dutch Senate (Eerste Kamer) officially approved the Energy Act (Energiewet), which will replace and consolidate the Gas and Electricity Acts in the near future (QG&M Law, 2024). This new law modernizes the Dutch energy system and explicitly includes renewable energy sources like hydrogen within its scope. Before, hydrogen was not recognized as a regulated gas, so the infrastructure, including storage, was not covered by the law's definitions and responsibilities (CMS Law, 2023). This means that if companies consider adopting hydrogen, they must purchase and organize their own storage only after they obtain all necessary safety and special permits, resulting in high transaction costs and lengthy processing times.

The Energy Act updates the rules for the technical operation and market access of energy infrastructure, with a focus on the changing role of system operators. It recognizes the growing complexity of decentralized, multi-actor energy systems and creates a more adaptable institutional framework to support local and modular energy solutions. Specifically, the Act redefines the responsibilities of Transmission System Operators (TSOs) and Distribution System Operators (DSOs) regarding energy transport, including the "handling of special transport conditions and the development of an investment prioritization framework" (NedZero, 2024). Under this framework, the operation of storage facilities falls under system operators' responsibilities.

Nevertheless, decentralized industrial clusters that implement green hydrogen systems, usually with storage located alongside production and end-use facilities, need more specific regulatory guidance. This raises important governance questions about who should oversee hydrogen storage based on its location and capacity, and how to ensure a reliable supply for users within these clusters.

Subsidies and Incentive Schemes

To mitigate the financial risks associated with regulatory uncertainty, both the European Union and the Dutch government have implemented various subsidy programs aimed at supporting the development of hydrogen infrastructure. These subsidies are accessible to stakeholders throughout the hydrogen value chain, empowering them to actively contribute toward meeting both EU and national hydrogen goals. The subsidies include:

- **SDE++** (Stimulering Duurzame Energieproductie en Klimaattransitie): The main subsidy scheme for sustainable energy, which includes green hydrogen production from electrolysis using renewable power. It compensates for the difference between the market price and the cost price (RVO, 2023a).
- **IPCEI-Hy2Use** and **Hy2Tech**: These Important Projects of Common European Interest enable Member States to inject public funding into hydrogen infrastructure, including electrolyzers, transport, and storage, without breaching EU state aid rules (European Commission, 2023a).
- **OWE** (Opschaling Waterstofproductie Electrolyse): A Dutch national scheme specifically targeting the scaling up of electrolysis capacity (RVO, 2023a).
- **DEI+** (Demonstration Energy and Climate Innovation): This program supports pilot projects and demonstrators in hydrogen-based industrial systems.

Most subsidies available are directed toward scaling up production capacity, leaving hydrogen storage significantly under-incentivized. Without targeted financial support, storage capacity risks lagging behind production growth, leading to system imbalances. To prevent this, regulators need to assign a market value to storage in the same way they do with production. Only then will it attract investments and enable parties to participate in downstream activities.

2.2.2   Hydrogen Storage Institutions

In contrast to a well-developed natural gas framework, hydrogen storage lacks clear institutional guidance. While both above-ground tanks and underground salt caverns are being considered, there is no formal licensing framework for hydrogen storage operators outlined in the Energy Act, and the rules-in-use are being developed. The Authority for Consumers and Markets (ACM) published a document, "Guidelines on Hydrogen Terminals," that clarifies the access rules for hydrogen storage (ACM, 2024). It states that hydrogen storage will follow the same Third-Party Access (TPA) model as natural gas storage under ACM's supervision. This means that hydrogen terminal operators must offer access to their terminals' capacity to users, and it is up to them to negotiate agreements regarding the conditions and tariffs for access. However, there is no information available on whether hydrogen users can invest in storage capacity themselves or arrange for another party to build storage. Since no rule exists on this, actors are unsure if they are permitted to invest in infrastructure (CMS Law, 2023).

Ownership Structure

The question of ownership in hydrogen storage infrastructure needs further exploration, as it plays a central role in shaping the institutional design of the hydrogen value chain. Existing literature on

institutional economics and market design outlines several potential governance models (Jaag & Trinkner, 2011; Williamson, 2000). If hydrogen institutions were designed as natural gas, storage facilities would likely be owned by public TSO Gasunie, with access potentially granted to third parties to ensure market openness (Gasunie, 2022).

However, since hydrogen storage in above-ground tanks is likely to be co-located with industrial sites, its operation would be delegated to a designated entity such as the regional Distribution System Operator (DSO). This way, storage would be bundled with distribution infrastructure, resulting in a natural monopoly, where DSO is given the property rights. Another possibility is a higher degree of market opening and allowing private actors to develop and operate storage systems. Here, storage acts as a separate component in the value chain, promoting competitiveness on the free market. Finally, in cases where decision-making authority is retained by energy users themselves, collective ownership models, where industrial companies jointly invest in and manage storage, could offer a promising approach to enhance alignment with local needs and foster collaboration. The HyDelta 3.0 project examines the "rollout of (temporary) self-sufficient hydrogen regions" and how these regions can be managed under a differentiated ownership model (HyDelta, 2023). The findings indicate that "local clusters have demonstrated the potential to be self-sufficient hydrogen regions, where they produce and use hydrogen independently, reducing reliance on centralized infrastructure" (Sprenkeling & HyDelta, 2023).

2.3   Conceptual Framework & Behavioral Theories

To develop a model that captures the full complexity of actors, components, and interdependencies within the system, a guiding framework is essential. Such a framework informs the structure of the agent-based model (ABM), ensuring consistency across institutional, technical, and behavioral dimensions. Beyond the formal institutional and infrastructural elements, the system also entails a social dimension that requires examining actors' motivations, constraints, and decision-making processes (Geels, 2004; Markard, Raven, & Truffer, 2012). To address this, the study incorporates behavioral theories relevant to the adoption of emerging technologies. These theories provide a foundational rationale for modeling the cognitive and strategic behavior of agents in the simulation.

2.3.1   MAIA Framework

The Modeling Agent systems based on Institutional Analysis (MAIA) framework, developed by Ghorbani et al. (2013), provides a structured methodology for designing agent-based models in complex socio-technical settings. It extends the Institutional Analysis and Development (IAD) framework by Ostrom (2005), translating its core concepts into discrete modeling components that can be directly implemented in simulations.

MAIA distinguishes between five main building blocks: **actors**, **activities**, **artifacts**, **institutions**, and the **physical environment**. Each block defines a layer of the system: actors represent decision-making entities; activities reflect actions and processes; artifacts represent tangible or intangible resources; institutions define rules and norms; and the physical environment sets spatial and technical boundaries. This decomposition enables modelers to explicitly map how institutional settings influence the actions of agents, how these actions interact with infrastructure, and how system outcomes emerge from the interplay of these components.
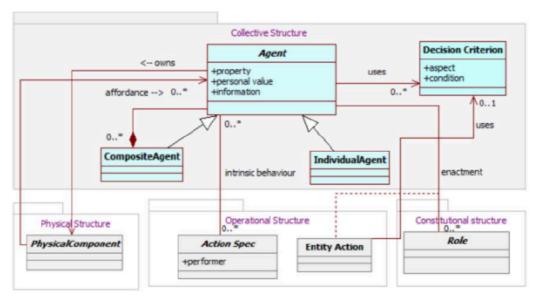
Figure 4: MAIA representation (Ghorbani et al. 2013)

Importantly, MAIA is not a mathematical or programming framework, but a conceptual tool. It ensures that the assumptions behind agent behavior and system design are made explicit and that the transition from conceptual to computational modeling is traceable and well-structured. This enhances model transparency and reproducibility, which are key attributes for scientific modeling in policy-relevant contexts.

The framework has been widely applied in domains characterized by institutional complexity and interdependent actor behavior, such as energy transitions (Ghorbani et al., 2013). In the context of hydrogen storage, MAIA provides a robust structure for capturing the multi-level governance arrangements, investment decisions, and technological constraints that define the dynamics of regional industrial clusters. By offering a systems-oriented view, it allows integration of policy, economics, and social science into a coherent simulation structure.

2.3.2   Behavioral Theories

To examine stakeholder decision-making in the hydrogen transition, several behavioral theories from the technology adoption literature provide helpful perspectives. These theories help uncover the behavioral patterns that influence how different actors engage with adopting new technologies such as hydrogen storage. They are outlined in the table below (from Morchid et al., 2025).

Table 1: Description of behavioral theories of technological innovation adoption

Theory	Author	Application
Innovation Diffusion Theory	Rogers, 2003	Categorizes adopters into innovators, early adopters, early majority, late majority, and laggards, based on their readiness to adopt new technologies
The Theory of Reasoned Action	Fishbein & Ajzen, 1975	Emphasize that individual behavior is driven by attitudes toward the behavior, subjective norms, and perceived behavioral control. These theories are relevant when assessing how stakeholders' social environments and internal norms influence their decision to invest in innovative technologies
Theory of Planned Behavior	Ajzen, 1991	

The Technology Acceptance Model (TAM)	Davis, 1989	Focuses on perceived usefulness and perceived ease of use as key predictors of adoption. People are potentially limiting perceived ease of use, due to complexity or uncertainty
Unified Theory of Acceptance and Use of Technology (UTAUT)	Venkatesh et al., 2003	Combines these theories and adds moderators such as performance expectancy, effort expectancy, social influence, and facilitating conditions. UTAUT is applicable in multi-actor energy systems, where contextual factors heavily influence adoption decisions

Together, these theories offer a comprehensive analytical framework for studying stakeholder behavior in storage adoption. They help distinguish the decision-making between the companies, indicating what factors influence these dynamics, and what interventions can accelerate their transition. These insights can inform scenario planning and aid in modeling the potential development of hydrogen systems. For instance, in governance settings where public system operators manage hydrogen storage, their actions are shaped by public service obligations. These entities prioritize policy compliance and alignment with national regulatory mandates, often favoring early infrastructure deployment to achieve societal objectives such as decarbonization and energy security (S&P Global Ratings, 2023; CMS Law, 2023). For industrial companies, this model can generate a sense of reliability and strategic assurance. The presence of a publicly governed storage provider signals a coordinated national transition toward hydrogen, allowing companies to adopt without assuming significant organizational responsibility. In such cases, perceived inclusiveness and long-term policy alignment may enhance social acceptance and reduce adoption resistance.

In contrast, a storage governance model led by a private investor operates on the basis of commercial incentives, where investment decisions are typically guided by profit expectations. While this model may offer faster and more decisive infrastructure roll-out, its market-driven nature can reduce trust among risk-averse firms, particularly smaller ones that lack economies of scale. However, companies may benefit from more flexible contractual arrangements, with greater autonomy in negotiating access terms (Blagrave & Furceri, 2021). The promise of operational efficiency and rapid scaling may appeal to firms seeking agility in energy transition strategies, even if the societal alignment is weaker.

When decision-making authority and ownership are allocated to the users themselves, behavioral dynamics become more complex. Participating firms must coordinate investments, synchronize timelines, and align governance rules. Here, behavioral traits such as peer influence, trust, and strategic foresight play a more prominent role. Companies that are innovation-oriented or sustainability-driven may emerge as leaders, while risk-averse actors may hesitate or opt for limited participation. Perceptions of hydrogen vary widely: some firms may see it as a compliance burden, others as a strategic opportunity for competitive differentiation. These decisions are influenced by internal factors like capital availability, exposure to energy market fluctuations, and confidence in long-term infrastructure viability (HyDelta, 2023; Venkatesh et al., 2003).

The above entails that in models where infrastructure is already provided by external operators, behavior may be more reactive; in collaborative models, it becomes more proactive and strategic. Recognizing these patterns is essential for policymakers: behavioral profiles shape system dynamics, and anticipating stakeholder responses enables the design of more inclusive and adaptive governance frameworks (Rogers, 2003; Venkatesh et al., 2003).

2.4   Knowledge Gap in the Literature and Contribution of this Research

Despite ambitious decarbonization goals set by the Dutch government, significant gaps remain in how national and cluster-level strategies include decentralized industrial companies. Although the five major industrial clusters are central to the National Hydrogen Strategy, Cluster 6 is still at the back of the line for transportation and UHS infrastructure access, despite facing the same regulatory obligations to decarbonize.

While the emerging hydrogen-based multi-energy systems described by Di Micco et al. (2023), Fu et al. (2020), Lei et al. (2024), Li et al. (2020), Liu et al. (2023), and Xia et al. (2024) focus on technical system design, the institutional framework needed to operationalize these systems has not been sufficiently examined. Although the Energy Act (Energiewet) aims to modernize legal structures to support renewable energy systems, it still does not fully address the complexities and implications of designing the hydrogen value chain. The biggest gap concerns the absence of clear rules and norms for hydrogen storage. Unlike the natural gas sector, where ownership and operation are centralized and highly regulated under the TSO Gasunie, the hydrogen domain lacks a similarly coherent framework. There is currently no established division of roles, responsibilities, or property rights regarding the ownership, operation, and financing of hydrogen storage infrastructure (QG&M Law, 2024; CMS Law, 2023). Given the decentralized configuration of hydrogen production and consumption, questions arise as to whether Distribution System Operators (DSOs) should manage storage assets, or whether storage should be fully unbundled and managed by private operators or the energy users themselves.

These institutional aspects are absent in the current literature, pointing to a substantial gap in regulatory and governance studies. This gap becomes even more problematic considering that hydrogen storage operates as a complex socio-technical system involving a diverse set of actors, each with distinct perceptions, capabilities, and motivations. Coordinating these actors in the absence of clear and comprehensive regulatory guidance creates inefficiencies and uncertainty across the system. Although studies by Høyland et al. (2023), Hasankhani et al. (2024), Schlund et al. (2022), and Sprenkeling & HyDelta (2023) have included stakeholder perspectives in hydrogen system planning, they do not address stakeholders' views on different storage ownership models. Little is known about how stakeholders in the hydrogen value chain perceive the risks, responsibilities, and benefits of having different operators of storage facilities. This lack of empirical data hampers policymakers in designing governance mechanisms that align with stakeholder incentives. Consequently, the lack of adoption by end-users could significantly hinder the pace of the hydrogen transition.

This research helps close these knowledge gaps by examining the institutional framework for hydrogen storage in Cluster 6. It combines qualitative analysis of stakeholder roles, needs, and regulatory conditions with an agent-based modeling approach that simulates agents' behavior under different storage ownership scenarios. The results aim to support the development of inclusive and effective regulations for hydrogen storage.

3 Methodology

This chapter outlines the research goal, case study selection, and methodological approach used to analyze the institutional dynamics of hydrogen storage in industrial clusters. It details the selected methods, data requirements, and implementation, and concludes with model verification and validation to ensure reliability.

3.1 Research Approach

The goal of this research is to explore how institutional design influences the development of hydrogen storage infrastructure and the adoption of hydrogen by industrial companies. To do so, the study integrates both empirical and theoretical data within a computational model. The methodology consists of three main steps: (1) desk research, (2) stakeholders' interviews, and (3) agent-based modeling (ABM).

Desk research involves a detailed review of academic literature, policy documents, and industry reports to identify the institutional environment and get all the necessary parameters to run ABM. It helps define the relevant actors, rules, and governance frameworks shaping the hydrogen value chain. Besides the structural information, during desk research, both technical and institutional data are gathered, which are the input parameters for the model.

The stakeholder interviews complement the knowledge obtained through desk research by providing qualitative insights from actors directly involved in the energy transition. These conversations offer practical perspectives on business strategy, infrastructure investment, and rules and norms of storage functioning. From that, the agents' attributes can be drawn that inform behavioral rules.

At the core of the methodology lies the agent-based model, which simulates system-level outcomes emerging from the interaction between industrial actors and their environment. The model incorporates data from desk research and interviews, enabling dynamic exploration of how varying institutional settings affect hydrogen adoption pathways over time.

3.2 Case Study

The study is grounded in a case-based context, using a theoretical yet representative industrial setting. This research examines a hypothetical decentralized industrial cluster that is part of 'Cluster 6', representing a real-world industrial park situated away from the national hydrogen backbone. The cluster comprises 13 industrial companies operating in various sectors, including (petro)chemicals, food processing, metalworking, and general manufacturing. These firms share similar energy profiles: high thermal and process energy demand currently supplied by natural gas, with increasing pressure to decarbonize their operations in accordance with national and EU climate goals.

The cluster receives hydrogen from a nearby 4 MW high-pressure electrolyzer that converts locally generated renewable electricity into green hydrogen. The energy mix includes electricity from wind farms, solar parks, and biomass facilities, ensuring some diversity and resilience in production. This

electrolyzer is the main source of green hydrogen for the cluster and demonstrates the localized production infrastructure likely to develop in areas without a backbone connection.

The hydrogen energy value chain in the case study includes the following stakeholder categories:
- **Hydrogen Producers**: Operate the electrolyzer and manage renewable energy input. Their role is to ensure consistent hydrogen output despite fluctuating renewable input.
- **Storage & Infrastructure Operators**: These may include public system operators or private infrastructure companies responsible for managing the hydrogen distribution lines and potential storage assets.
- **Industrial Users**: The 13 industrial companies are the end users of hydrogen.
- **Policy and Regulatory Actors**: National and regional authorities define access rules, ownership structures, and subsidy levels, all of which shape investment behavior.

3.3   Desk Research

The desk research phase served as a foundational step in building the model by collecting and synthesizing both technical and institutional data relevant to hydrogen storage governance. A comprehensive review of academic literature, national policy documents, industry reports, and regulatory codes was conducted to map the institutional environment, define possible storage ownership structures, and extract key input parameters for the agent-based model.

On the technical side, infrastructure specifications—including storage tanks capacities, investment costs, build times, and discharge efficiencies—were drawn from scientific publications and engineering reports. Technical studies from TNO, HyDelta, and HyChain were particularly valuable in providing realistic assumptions. These sources ensured that the model reflected credible technology profiles for above-ground storage design.

Institutional information was obtained through an analysis of Dutch and European regulatory frameworks. Key sources included the Dutch Gas Act, relevant gas codes, the "Guidelines on Hydrogen Terminals," and supporting legal commentaries. This enabled the identification of feasible governance scenarios based on public or private operation, including aspects such as Third Party Access (TPA) rules, profit regulation for operators, permitting requirements, and safety protocols. In addition, policy documents and regulatory forecasts from the EU and national sources provided input for the model's economic conditions, such as projected carbon tax levels (ETS) and hydrogen/natural gas price trajectories.

3.4   Stakeholders' Interviews

Less accessible information was collected from stakeholders engaged in the hydrogen value chain and market design of energy systems. To this end, an interview with a chemical company in a decentralized cluster involved in the energy transition was conducted[2]. This gave insights into the design criteria from the perspective of the end user of hydrogen storage. Moreover, the researcher engaged in discussions

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[2] Before the interview, informed consent was obtained from the participant. The interviewee received a briefing document explaining the purpose of the study, the voluntary nature of participation, and how her responses would be anonymized and used for academic purposes.

with experts in energy or market design. Experts were selected based on their knowledge of market design, storage development, hydrogen infrastructure, and its integration into industry production. These provided empirical insights into the energy market structure and institutions (contracts), helping to shape policy-relevant scenarios within the ABM. The insights were used to inform agent decision rules, scenario design, and model assumptions. Key topics of the conversations included:

- **Hydrogen Storage Projects** with:
    - The process of developing and executing public/private hydrogen underground storage projects (similar process institutionally to above-ground storage projects)
    - Implications of hydrogen storage facilities on a company's business strategy (long-term investment, cost savings, energy security)
    - Complexity of storage-distribution infrastructure
- **Institutional** and **Market Design** of **Storage**, including:
    - Degree of market opening (natural monopoly vs competition)
    - Vertical (un)bundling of the value chain
    - Capacity allocation and contracting mechanisms (tendering, cycling)
    - Access regimes (regulated vs negotiated third-party access)
    - Investment barriers due to regulatory uncertainty
    - Dependence on subsidies and lack of market-driven investment
    - Price and volume risks for short-term hydrogen storage
    - Institutional and contractual design (vertical integration, pattern of use)
- **Demand Side** of **Hydrogen System**, discussing:
    - Role of collaboration and competition in decentralized systems
    - Perspective and role of an industrial company in the hydrogen transition
    - Strategy and motivation to become energy sustainable while remaining profitable
    - Institutional and governance preferences regarding storage ownership and operation
    - Barriers to adoption (price, accessibility, affordability, acceptance)
    - Shared perspectives with other industrial companies in the cluster

3.5   Agent-Based Model (ABM)

Agent-Based Modeling (ABM) served as the primary analytical method in this research, enabling the translation of the socio-technical structure and key parameters into observable outcomes. By simulating hydrogen storage utilization under various institutional configurations, the model made it possible to identify emergent patterns and adoption dynamics. These insights provided a foundation for evaluating and comparing ownership models, ultimately supporting the identification of the most effective governance structure for hydrogen storage in Cluster 6.

3.5.1   What is ABM?

Agent-Based Modeling (ABM) is a bottom-up computational technique used to simulate the actions and interactions of autonomous entities, called agents, within a specified environment. These agents can represent individuals, organizations, or other decision-making units, each with unique characteristics and behavioral rules. Unlike traditional system dynamics or equation-based models that rely on aggregate assumptions, ABM is designed to capture heterogeneity, bounded rationality, and local interactions, making it especially useful for analyzing complex socio-technical systems (Bonabeau, 2002; Macal & North, 2010).

Agent-Based Modelling (ABM) is particularly effective for capturing the dynamics of complex socio-technical systems, where diverse stakeholders—each with unique goals, constraints, and behavioral patterns—interact within layered institutional and technical contexts (Macal & North, 2010; Ghorbani et al., 2013; Nikolic, 2009). Its strength lies in its ability to simulate emergent behavior, where global patterns and outcomes develop from simple rules at the micro level. These emergent outcomes often reveal non-intuitive system dynamics that are hard to capture through top-down analytical methods (Epstein & Axtell, 1996). For instance, agents can adapt their decisions over time based on internal preferences and external changes, enabling researchers to explore how dynamic systems evolve under different scenarios (Railsback & Grimm, 2019).

In practice, ABM consists of:
- **Agents**: Independent actors with defined behaviors and attributes,
- **Rules of interaction**: Logic dictating how agents behave and respond to environmental and other agent-based stimuli,
- **Environment**: A shared space or network structure where interactions occur,
- **Emergence**: System-level patterns generated through repeated micro-level interactions.

ABM has been widely adopted in fields such as energy systems (Zhang et al., 2021), public policy, economics, and environmental science. Its flexibility and realism make it an ideal tool for exploring the interdependencies among stakeholders, technologies, and institutional rules, especially in capturing patterns in socio-technical systems.

3.5.2 ABM in this Context

This study employs Agent-Based Modeling (ABM) to simulate how various stakeholders make decisions about hydrogen storage under different ownership models. The model aims to examine how system outcomes arise from the localized, autonomous actions of stakeholders.

The main purpose of using ABM in this context is to examine the effectiveness of different storage governance scenarios on the hydrogen adoption rate. Apart from the status quo, where companies arrange the storage themselves through storage tank manufacturers, the model considers three other scenarios. These scenarios were debated in Section 2.2.2 in the Literature Review and include:
- **DSO-owned** storage, where a public network operator builds and manages the storage infrastructure along with distribution to users,
- **Third-party** operated storage, where a private company invests in storage capacity, and allows access to energy users via usage fees,
- **Collective ownership**, where energy users jointly invest in and control the storage facility.

The structure of the model is based on the MAIA framework. Each agent is assigned a behavioral rule set that reflects its institutional role, operational objectives, and constraints, which is based on empirical data and theoretical insights from behavioral frameworks on technology and innovation adoption. These behaviors include decisions such as whether to invest in a shared storage facility, wait for public infrastructure, or adopt hydrogen. Agents interact with each other and their environment. The model monitors emergent system-wide outcomes, such as the level of adoption, the overall reliability of the hydrogen supply, and how investment burdens are distributed. Importantly, ABM allows these results to develop organically from agent interactions rather than being pre-set by equations or centralized control, which mimics real-world energy transition conditions. Chapter 4, "ABM Development," explains the content and rationale of the model in more detail.

3.5.3 Software Utilized

This research uses Python as the programming language to develop the ABM. Python is ideal for iterative modeling, data manipulation, and visualization. Additionally, its intuitive syntax enables quick prototyping and straightforward implementation of agent behaviors, while its compatibility with libraries like NumPy, Pandas, and Matplotlib, ensures efficient data management and analysis.

To implement the ABM, the study uses the Mesa library, an open-source ABM framework built in Python. Mesa is specifically designed to support the development of agent-based simulations in social and institutional settings. It provides modular components for defining agents, scheduling interactions, and collecting model outputs over time. Notably, Mesa also allows browser-based visualizations, enabling the researcher to observe the evolution of agent behaviors in real time. These features make it especially useful for exploring emergent dynamics among multiple interacting stakeholders.

3.5.4 Data Requirements

In order to run ABM effectively, it is essential to gather a comprehensive dataset. This includes quantitative variables such as energy demand, pricing forecasts, and storage costs, alongside institutional and behavioral parameters that shape stakeholders' perception towards hydrogen-based systems. The following section outlines the types of data required to simulate the transition to hydrogen via on-site storage, detailing both their purpose and application within the model.

Technical Data

The model requires data on each company's yearly energy demand to determine their hydrogen needs and assign the storage size appropriately. Estimates of natural gas dependency and switching potential help establish the baseline for measuring hydrogen adoption. For hydrogen storage, data on CAPEX, OPEX, modular construction time, scalability, and discharge efficiency of above-ground tanks are required. Subsidy trajectories, such as planned reductions over time, are incorporated into the cost calculations to evaluate investment attractiveness under changing policy support. Additionally, fuel prices (hydrogen versus natural gas) are dynamically integrated, allowing the model to simulate the economic and market involvement.

Institutional and Regulatory Data

Institutional inputs define the governance and policy environment within which companies operate. These include legal definitions of infrastructure ownership, rules for access and investment coordination, as well as the integration of storage operator's responsibilities within the system. The model also uses forward-looking policy signals, such as hydrogen backbone rollouts, evolving subsidy eligibility and taxation on the fossil fuels, to capture the influence of institutional timelines on adoption behavior. The knowledge of these rules is used to shape contract structures, investment thresholds, and eligibility for shared infrastructure in the model.

Behavioral and Socio-Institutional Data

Behavioral data is essential for capturing heterogeneity in company decision-making. Each agent is assigned parameters that determine their likelihood of adopting hydrogen. Some behavioral parameters are drawn from literature, while others are stylized to allow for sensitivity analyses. The model's behavioral structure enables the exploration of scenarios where adoption is driven by internal motivation, peer influence, or external cost signals—mimicking real-world organizational diversity.

3.5.5 Model Verification and Validation

The verification and validation of the ABM is done internally within the model to confirm that the parameter value selection and model logic are correct, so that agents behave coherently under the defined rules. It begins with testing the selected parameter values within the baseline model using uncertainty analysis, which helps verify that the model is properly calibrated and behaves as intended. Once the baseline is verified to yield consistent and meaningful results, the sensitivity analysis can be applied to modeled scenarios to confirm that institutional scenarios are implemented consistently, allowing meaningful comparisons of outcomes.

Uncertainty Analysis

Given the uncertainty of key parameters, such as behavioral traits, storage cost, and investment capacity, uncertainty analysis is used to assess whether the selected baseline values are appropriate. This is done through One-Factor-at-a-Time (OFAT) analysis, where each parameter is varied independently across a plausible range while all others remain fixed. This method, commonly used in ABM research (Czitrom, 1999; Ligmann-Zielinska et al., 2014), isolates the impact of each parameter on model outcomes and helps identify which variables have the greatest influence on adoption dynamics. The results indicate how sensitive the system is to each parameter and whether the chosen baseline values produce stable, interpretable outcomes. This helps validate the robustness of the model setup and avoid undue reliance on arbitrary or extreme values.

Sensitivity Analysis

Sensitivity analysis in this study is used to ensure that scenario outcomes are comparable and well-framed. This is achieved through a detailed evaluation of how scenario-specific modifications, such as changes to storage ownership, pricing mechanisms, and investment responsibility, alter model behavior. The goal is to confirm that these institutional changes influence the system within a reasonable and interpretable range, without distorting the underlying model logic or introducing unintended biases.

To ensure comparability:
- Scenarios were implemented modularly, affecting only institutional rules while keeping global parameters such as storage costs, hydrogen and natural gas pricing dynamics, and subsidy levels constant.
- Agent structural logic, such as adoption decisions and budget constraints, remained unchanged.
- Simulation output generation and KPI tracking are identical across all scenarios.

This ensures that observed differences across scenarios can be attributed to institutional configurations rather than to structural inconsistencies.

4 ABM Development

This chapter outlines the development of the agent-based model (ABM) used to simulate decision-making around hydrogen storage in the case study settings. The ABM is built upon the MAIA framework, which provides a structured representation of the socio-technical system. This is combined with behavioral insights derived from literature to reflect the heterogeneity and bounded rationality of agents involved in hydrogen storage decisions. The following sections guide the reader through each step in the model development process, including system overview, conceptual design, scenario implementation, parametrization, and definition of performance indicators.

4.1 System Overview

This section introduces the overall structure of the hydrogen value chain as modeled in ABM. It outlines the key technical components, stakeholder roles, and interactions relevant to the transition toward a hydrogen-based system.

4.1.1 Hydrogen Value Chain Decomposition

The hydrogen value chain consists of multiple interconnected components, spanning from hydrogen production to end-use applications (see Figure 5). This research narrows its focus specifically to the **storage** segment, which is a critical yet often underexplored part of the system. In this context, storage is treated not only as a technical asset but as a socio-technical node involving multiple stakeholder groups with diverse roles and responsibilities.
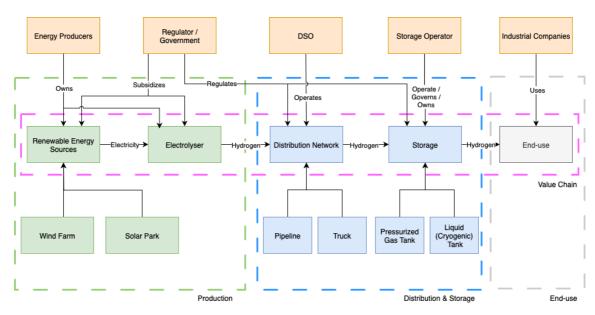
Figure 5: System diagram of decentralized green hydrogen value chain

The system comprises the following key actor groups involved in or influenced by hydrogen storage[3]:

- **DSOs**: Entities responsible for the distribution of hydrogen to end users.
- **Government agencies** and **regulators**: Institutions responsible for setting regulations and incentives to encourage hydrogen adoption.
- **Industrial companies**: Hydrogen end users that drive demand.
- **Storage operators**: Entities eligible to invest, build, and manage a storage facility for the industrial park under specific institutional conditions.

4.1.2 Transition to Hydrogen-Based Energy System

Achieving the transition from a fossil-based to a hydrogen-based energy system demands a series of coordinated interventions at both the macro level (e.g., policy, infrastructure, market design) and the micro level (e.g., organizational change, stakeholder behavior, local investments). The flowchart in Figure 6 helps illustrate the process by mapping the steps and factors influencing them.
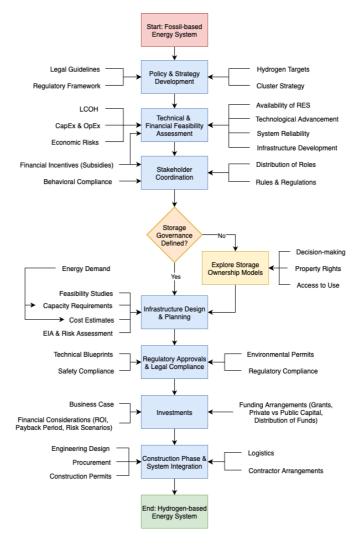
Figure 6: Transition to Hydrogen-Based System flowchart

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[3] *Note: Energy producers are excluded because they have no direct influence on storage.*

The process begins with the national government developing policy and strategy, guided by European and national climate targets. These policies reflect broader decarbonization goals and are shaped by legal guidelines, the availability of renewable energy sources (RES), system reliability, infrastructure readiness, and technological capabilities. Once the policy direction is established, a technical and financial feasibility assessment is performed. This involves analyzing the levelized cost of hydrogen storage (LCoS), which includes capital and operational costs (CapEx and OpEx), economic risks, and the structure of financial incentives such as subsidies. These factors help determine whether a hydrogen-based system is a technically feasible and economically viable alternative to fossil fuels.

The next step is to establish hydrogen storage governance, which is defined by market design and allocation of property rights. Under the current regulatory environment, there is no clear mandate or market structure governing the ownership of hydrogen storage facilities at the industrial cluster level. As a result, there is considerable uncertainty about who can legally develop and operate such infrastructure, under what conditions, and with what level of access and oversight. Without a designated operator or standardized access framework, companies wanting to adopt hydrogen must independently organize storage for their individual needs, which discourages them from participating in the transition.

Once governance is established, infrastructure design and planning can proceed, starting with determining the energy capacity needed to meet demand, conducting feasibility studies, assessing risks, and defining technical requirements. The design phase then shifts to securing regulatory approvals, ensuring legal compliance, and ultimately planning investments. Construction and integration follow, including managing logistics and contractor arrangements. The final outcome is a fully functional hydrogen energy system, with coordinated policies, technical infrastructure, and governance structures that support a reliable and sustainable energy transition.

4.2   ABM Conceptualization

The conceptual model serves as the foundational design phase in which the system's structure is defined in a way that can be translated into a modeling language. It outlines both the institutional structure and the behavioral decision-making logic of the actors involved, establishing the core elements and interactions to be represented in the agent-based simulation.

4.2.1   Institutional Structure of ABM

The institutional structure captures model functioning by mapping the relations between components, whether these are technical or social. To this end, the MAIA framework guides the process of identifying the key actors, institutional rules, physical infrastructure, artifacts, and activities that constitute the hydrogen storage system. These elements are integrated into a coherent conceptual structure. Each component is explicitly described in the following sections, concluding with a diagram that visualizes their interconnections.

Actors

Actors are autonomous decision-making entities, each characterized by specific goals, capabilities, and behavioral patterns. In this model, the system comprises two main actor groups: industrial companies and the storage operator. Their roles, objectives, and modeled behaviors are outlined in Table 2 below.

Table 2: Actors Modeled in Hydrogen Storage ABM

Actor	Role	Objectives	Behavior
Industrial Companies	End-users of hydrogen	• Ensure reliable, continuous, and affordable energy supply for their production processes; • Minimize costs and risks while aligning with sustainability and decarbonization goals	• Assess hydrogen adoption based on technical and economic feasibility • Decide whether to adopt not adopt hydrogen
Storage Operator	Operator of the storage facility	• Provide access to the storage facility • Comply with existing rules and regulations	• Build and operate the storage facility • Facilitate connections and access terms with users

Institutions (Rules & Norms)

Institutions refer to the formal rules and informal norms that guide and constrain the behavior of agents within the system. They define which actions are permitted, prohibited, or incentivized, and thereby play a central role in shaping the system's evolution. Formal rules are typically codified in laws, regulations, and policy directives issued by governmental and regulatory bodies. The relevant regulatory provisions that structure the hydrogen storage system are presented below.

Table 3: Formal Rules Guiding Hydrogen Storage

Rule	Description	Source
Storage Ownership Eligibility	Defines who may own and operate hydrogen storage.	Energy Act (2024); Gas Act (current version)
Access to Storage (Third-Party Access)	Storage owners must provide non-discriminatory access to users.	ACM's Guidelines on Hydrogen Terminals
Balancing Responsibility	Storage operator must ensure demand-supply balancing; imbalance penalties may apply.	Network Code Gas (in adaptation for hydrogen)
Investment Subsidy Eligibility	Hydrogen storage projects eligible for subsidies must meet project scale thresholds, green energy sourcing requirements, and technological readiness criteria.	OWE & SDE++ Scheme IPCEI-Hy2Use funding
Permit and Licensing Requirements	Building a hydrogen storage facility requires safety certification, spatial planning permits, and adherence to ATEX safety regulations.	Dutch Spatial Planning Act; PGS 35 Guidelines
Pricing Regulation	Storage operators are subject to ACM's pricing regulation on tariffs from the users.	Energy Act 2024; ACM Market Monitoring
Environmental Liability for Storage Operators	Storage operators are liable for hydrogen leaks, contamination, and environmental damage.	EU Environmental Liability Directive

Informal norms, by contrast, are unwritten but widely recognized behavioral expectations followed by stakeholders. These norms emerge organically through system interactions and are shaped by the lived experiences, habits, and collective behavior of actors within the system. Their influence depends heavily on how stakeholders interpret institutional rules and anticipate the behavior of others in the system. Table 4 outlines the key informal norms described in the model.

Table 4: Informal Norms of Stakeholders

Norm	Description
Risk Aversion among Industrial Users	Energy users are cautious about adopting technologies with uncertain supply, price volatility, or unclear long-term regulatory support.
Peer Adoption Influence	Companies are more likely to adopt hydrogen if competitors or neighboring firms move first (Innovation Diffusion Theory).
Trust in External Operators	The degree of users trusting external operators depends on the level of fair access and service reliability.
Collective Action Difficulty	Collaboration between companies often fails if trust between firms is low or if free-riding concerns dominate.
Perception of Subsidy Stability	Perceived uncertainty about the future of subsidy programs (e.g., OWE and SDE++ continuation) reduces investment willingness.
Long-Term Energy Security Mindset	Users focus on not just immediate costs, but on securing long-term stable energy access to avoid future dependency risks.
Innovation Reputation Advantage	Early hydrogen adopters anticipate reputational benefits (first-mover advantage), which may offset economic risks partially.

Physical System

The physical system represents the tangible infrastructure. In this model, the **hydrogen storage facility** is the sole physical element represented, which consists of modular, above-ground pressurized tanks strategically located between the hydrogen production site and the industrial users. These tanks function as short-term buffers, absorbing fluctuations in hydrogen supply caused by the variability of renewable energy sources and ensuring a steady flow to meet industrial demand. The modular design enables scalable expansion over time, allowing the storage capacity to grow in alignment with adoption rates and investment behavior.

Artifacts

Artifacts include the goods, services, and resources that are produced, exchanged, consumed, or invested in by agents within the system. These artifacts form the material and economic basis for interaction and decision-making. In this model, the key artifacts include:

1. **Hydrogen Gas** – The energy source used for industrial heat applications.
2. **Storage Capacity** – The available volume for storing hydrogen at the decentralized site.
3. **Investment Capital** – The financial resources available to agents for hydrogen investments.
4. **Financial (Dis)Incentives** – These include subsidies, grants, or tax credits provided by regulators to encourage hydrogen adoption. Conversely, disincentives include increasing carbon taxes on natural gas usage to discourage reliance on fossil fuels.

Activities

Activities represent the set of actions that agents can undertake to influence both the physical and institutional states of the system. Within the context of the study, the key modeled activities include:

1. **Invest in Hydrogen Storage** – Agents assess whether to allocate capital toward building or expanding hydrogen storage infrastructure.
2. **Access Hydrogen Storage** – Agents engage with the storage system by obtaining formal access to stored hydrogen.
3. **Adopt Hydrogen as an Energy Carrier** – Industrial companies decide whether to transition part or all of their energy supply from natural gas to hydrogen.
4. **Wait and Monitor System Evolution** – Agents may decide to delay investment or adoption, waiting for better conditions (e.g., lower hydrogen price, proven reliability, peer adoption).

Below is a visual representation of the institutional structure, which integrates previously discussed components into an interconnected diagram.
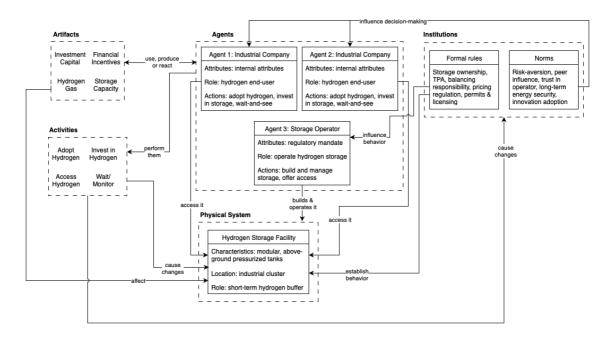
Figure 7: Visual Representation of ABM

4.2.2 Agent Behavioral Modeling

The process of modeling agent behavior captures how behavioral, social, and techno-economic factors influence stakeholder decision-making. Grounded in the behavioral theories discussed in the literature review, the model incorporates these insights to simulate how agents evaluate choices and make decisions.

Decision Rules

The model applies a deterministic, score-based approach to simulate hydrogen adoption. Each agent calculates an adoption score, representing its internal evaluation of whether hydrogen is a suitable alternative to natural gas. The **adoption score**—ranging from 0 to 1—reflects how favorably a company views hydrogen based on internal, social, and economic factors. A score closer to 1 indicates a high likelihood of adoption, while a score near 0 suggests resistance.

The adoption score function is structured as:

$$
\begin{aligned}
Adoption\ Score\ = W_1\ * \\
* \left(Willingness\ to\ Adopt\ * \left(\frac{Energy\ Security}{Importance\ of\ Energy\ Security} \right) * \left(\frac{Risk\ Tolerance}{Risk\ Associated} \right) \right. \\
* \left(Peer\ Influence\ * \frac{Peer\ Adoption\ Rate}{Peer\ Influence\ Sensitivity} \right) \\
\left. * \left(\frac{Regulatory\ Knowledge\ Needed}{Regulatory\ Awareness} \right) * \left(\frac{Subsidy\ Easiness}{Subsidy\ Responsiveness} \right) \right) + \\
+ W_2\ *\ Access\ To\ Infrastructure + W_3\ \times \Delta Cost
\end{aligned}
$$

where:
- $\Delta Cost$ is calculated as the normalized price difference between hydrogen and natural gas.
- The Peer Adoption Rate is the fraction of the other agents who currently want to adopt hydrogen.
- The Access to Infrastructure indicates the institutional ease for accessing storage.
- Energy Security, Risk Associated, Peer Influence, Regulatory Knowledge, and Subsidy Easiness are scenario-behavioral parameters that influence the adoption score.
- W_1, W_2, W_3 are weights controlling the influence of the behavioral, institutional, and economic components, respectively.

Adoption occurs once the computed adoption score exceeds a predefined threshold. This **adoption threshold** represents the minimum score needed for an agent to perceive hydrogen as an attractive option. A lower threshold means the agent is more receptive to adoption, while a higher threshold indicates greater reluctance or a need for stronger incentives. Once an agent expresses the intention to adopt hydrogen into his energy mix, he assesses the financial feasibility of investing in storage. The decision is constrained by capital availability, investment cost, and the expected advantage of using hydrogen over natural gas.

The investment is triggered if the following condition is met:

$$W_3 * (H_2\ Price\ incl.Levelized\ Storage\ Cost) + W_4 * (1 - Willingness\ to\ Invest) \leq Natural\ Gas\ Price$$

where $W_3\ and\ W_4$ are the weights controlling the investment decision.

If the condition is satisfied, the agent proceeds to invest in the maximum storage capacity affordable within its current capital constraints and initiates the construction process, subject to a predefined build delay.

Heterogeneity Among Agents

To distinguish differences in agent behavior regarding their possible adoption, agent attributes are initialized with varied values. These heterogeneities are built into the ABM to define each agent's behavior rules. The table below provides a description of the attribute, value range, and the effect it has on the decisions.

Table 5: Description of Agent's Attributes

Agent's Attribute	Variation	Affects
Hydrogen demand	Varies based on company size, industrial process, and energy intensity	Storage capacity and investment size
Capital availability	Varies based on company size and income	Ability to invest in storage
Motivation to Adopt (Willingness to Adopt)	High (1) vs. low (0)	Adoption decision

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Willingness to Invest	High (1) vs. low (0)	Investment decision
Perceived Importance of Energy Security	Important (1) vs. not important (0)	Adoption probability and interest in storage ownership
Access to Hydrogen Infrastructure	Easy access (1) vs. difficult access (0)	Facilitating conditions for adoption
Peer Influence Sensitivity	High (1) vs. low (0)	Impact of neighboring companies' decisions on own adoption
Risk tolerance	High (1) vs. low (0)	Willingness to adopt early or wait
Regulatory Awareness	High (1) vs. low (0)	Sensitivity to policy signals
Peer influence Sensitivity	Strong (1) vs. weak (0)	Sensitivity to others' decisions
Subsidy Responsiveness	High (1) vs. low (0)	Effectiveness of policy instruments

4.3   Scenario Design

This section presents the description and implementation of three alternative hydrogen storage governance configurations in the ABM. These include storage operated by: (A) a Distribution System Operator (DSO), (B) a private third-party investor, and (C) a collective of energy users. While the underlying physical system and agent roles remain consistent, each scenario applies distinct institutional logics in terms of investment behavior, access conditions, and pricing mechanisms.

4.3.1   Scenario A – DSO-Owned Storage

In the DSO ownership model, the **Distribution System Operator** assumes full responsibility for owning and operating the hydrogen storage facility as part of the broader distribution network. This enables centralized management and system-wide integration. Investment decisions are guided by the objective of maximizing net social benefit (NSB) through the use of Cost-Benefit Analysis (CBA).

The NSB is calculated as:

$$NSB = \sum Benefit - \sum Cost$$

On the benefit side, the analysis accounts for:
- Fuel-switch savings for industrial users,
- Access fee revenue generated by the DSO,
- Emission reductions that lead to lower CO_2 costs and increased public health benefits.

On the cost side, the model includes:
- Capital expenditures (CapEx) for building storage,
- Operational expenditures (OpEx) related to maintenance and system operation.

If the result of this analysis yields a positive NSB, the DSO proceeds with the investment and integrates storage capacity into the cluster. Industrial companies can request a certain share of hydrogen to include in their energy mix, and the DSO is responsible for supplying it through previously organized

storage and charges users a regulated access fee based on the Levelized Cost of Storage (LCoS), calculated as follows (Elestor, n.d.):

$$LCoS\left[\text{€}/MWh\right] = \frac{Total\ investment\ costs\ [\text{€}]}{Total\ delivered\ energy\ during\ storage\ lifecycle\ [MWh]} =$$

$$= \frac{CapEx[\text{€}] + OpEx[\text{€}]}{Capacity[MWh] * (Dis)charge\ efficiency[\%]}$$

Access to the storage facility is governed by fair, non-discriminatory principles, with tariffs set by the national regulatory authority, the Authority for Consumers and Markets (ACM). These fixed tariffs guarantee equal treatment for all users and eliminate the need for individual negotiations.

4.3.2 Scenario B – Third-Party-Owned Storage

In the third-party ownership model, a **private commercial operator** is responsible for developing, owning, and operating the hydrogen storage facility. Unlike the DSO model, access to storage is not guaranteed or regulated. Instead, it is market-based, meaning that industrial users must individually seek out storage providers. The operator identifies potential demand within an industrial cluster and, if the business case is favorable, decides to construct a storage facility in that location.

Once operational, the storage operator allocates the total capacity into discrete portions, allowing companies to reserve the amount—or "bundle"—they require. Access is granted through individual contracts between each company and the operator, specifying both the logistical and financial terms, including injection and withdrawal procedures. Users pay access fees for their reserved share, while the operator is obligated to deliver the contracted volume reliably. It is the operator's responsibility to coordinate energy flow within the cluster and ensure that no user experiences service interruptions.

Since the pricing regime is governed by market conditions, and in the absence of clearly defined regulatory rules, access fees are assumed to include a profit margin comparable to that observed in battery energy storage systems—typically between 15% and 25% (Better-tech, 2024). The fee structure can be expressed as:

$$Access\ fee\left[\text{€}/MWh\right] = (1 + Profit\ margin\ [\%]) * LCoS[\text{€}/MWh]$$

This market-based governance model brings private capital into hydrogen infrastructure and redirects the system's orientation toward efficiency. Compared to the DSO scenario, access fees in this model are generally higher due to the inclusion of a profit margin. However, the private operator's focus on cost-effectiveness, responsiveness to demand, and project delivery timelines often results in more efficient system deployment (Sheshinski, 2003).

4.3.3 Scenario C – Collective Ownership by Energy Users

In the collective ownership, **industrial companies** co-invest in and co-own the hydrogen storage facility. This model is grounded in shared governance, where responsibilities, costs, rights, and risks

are distributed among participants according to their financial contributions. Rather than purchasing access from an external operator, companies collectively determine the required storage capacity and contribute capital upfront to finance the facility. In return, each company receives access rights proportional to its investment, ensuring that higher contributors are entitled to a larger share of the storage capacity.

This arrangement shifts decision-making directly to energy users. Companies must evaluate whether the long-term strategic benefits—such as improved energy security, reliable hydrogen access, and operational autonomy—justify the upfront capital expenditure. While these benefits can be substantial, shared ownership also introduces coordination challenges. Participating firms must build trust, align on decision-making procedures, and establish clear governance mechanisms for jointly managing the infrastructure. The success of this model depends heavily on the ability of companies to act in the interest of the entire cluster.

Compared to previous governance models, this scenario promotes inclusive governance and empowers local stakeholders. Co-investment fosters a sense of ownership and accountability, encouraging earlier engagement with hydrogen technologies. Early adoption can offer competitive advantages, such as innovation leadership, cost savings, and improved positioning in a decarbonizing market. Moreover, the collective model is particularly attractive to firms that value autonomy and strategic control over their energy systems.

Table 6 below distinguishes the features of the governance models.

Table 6: Differences in Modeled Scenarios

Feature	Scenario A	Scenario B	Scenario C
Storage Owner	Public Distribution System Operator (DSO)	Private commercial operator	Group of industrial companies
Contracting	Users request access; regulated, non-discriminatory allocation; tariffs set by ACM	Individual contracts between operator and each user; commercial terms apply	No external contracts; internal agreement among participants based on proportional investment
Investment	DSO uses cost-benefit analysis to evaluate Net Social Benefit; builds if NSB is positive	Investor builds based on profit expectations and demand forecast	Investment only if a minimum number of firms contribute capital to meet cost threshold
Access Rules	Guaranteed access under Third-Party Access (TPA) regulation	Access based on negotiated bundles; not guaranteed	Access is proportional to capital contribution
Pricing	Fixed tariff for all users	Variable (market) fee depending on the contract arrangements	No formal pricing; internal cost-sharing based on investment shares
Risk Allocation	Low risk for users; moderate for DSO	Medium to high risk for users; moderate risk for investor	High coordination and capital risk
Peer Influence	Low	Medium	Very high

4.3.4 Investment Decision Flowchart

The investment decision process usually begins with industrial companies estimating their future hydrogen demand. This estimate is driven by factors such as each company's annual energy consumption, operational demand profile, and its strategic goal to shift toward hydrogen. The rate of utilizing hydrogen in the energy mix depends on several motivational factors, such as the desire to meet carbon neutrality targets, willingness to adopt new technologies, and the need to avoid higher CO_2 taxes. Below is the flowchart mapping the decisions for each governance model.
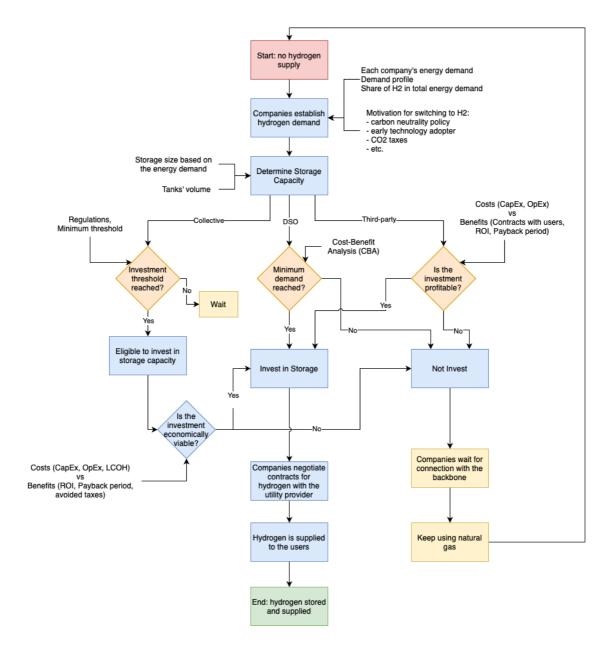

Figure 8: Decision flowchart for hydrogen storage investment for different ownership models

4.4   Parametrization

Parametrization involves assigning specific values to the parameters within the agent-based model. This includes defining the key technical, institutional, and behavioral characteristics of both the agents and the system.

Industrial Energy Demand

The model includes 13 industrial companies, collectively representing a synthetic cluster with a total annual energy demand of 10,050 MWh. Individual companies' demands range from 300 MWh/year to over 1,715 MWh/year, based on varying production sizes. Initially, 100% of energy demand is met using natural gas. Full demand values per company are listed in Table 12 (Appendix A).

Storage Infrastructure

Hydrogen is stored in modular above-ground pressurized tanks (types I–IV), suitable for short-term buffering with approximately 120 charging/discharging cycles per year. The tanks support incremental expansion, with each module representing a maximum of 1,100 m³ (Rheinmetall, n.d.). Key technical and economic parameters include:

Table 7: Storage Infrastructure Parameters

Parameter	Value / Assumption	Source
Energy density	1 kg H_2 = 33.33 kWh	Moran et al., 2023
CapEx	€1,073.43 per kg H_2 storage capacity	Moran et al., 2023;
OpEx	2% of CapEx annually → ~€0.41/kg H_2 per week	Steward, 2009
Efficiency	90% (dis)charging efficiency	Moran et al., 2023
Construction Time	2 years (including permitting)	Agastya Hydrogen, 2025;
Payback Period	7–10 years	Mensah et al., 2024

Subsidy Levels

Subsidies for hydrogen storage CapEx are included based on Dutch support programs such as OWE, SDE++, and DEI+ (RVO, 2023a). These subsidies are time-sensitive and decrease over time to simulate market maturity. Year-by-year values are shown in Table 14 (Appendix B).

Natural Gas Cost

The initial price of natural gas is set to €36.8/MWh, based on the Dutch TTF benchmark for 2025 (Trading Economics, n.d.). Each MWh of natural gas usage leads to approximately 486 kg CO_2e emissions (EIA, 2021). The model includes the EU Emission Trading System (ETS) tax, which increases over time. Full ETS projections used in the simulation are listed in Table 14 (Appendix B). The effective natural gas price is:

$$Effective\ Gas\ Price = Base\ Price + ETS\ Tax$$

Green Hydrogen Cost

As hydrogen markets are still developing, price estimates are derived from the levelized cost of hydrogen production via electrolysis (European Commission, 2023b). Key price milestones:

- €8/kg in 2025 (Colaluce, 2024) → ~€240/MWh
- €5/kg by 2030 (Collins, 2023)
- €3/kg by 2033 (market ramp-up, infrastructure backbone completed)
- €2/kg by 2050 (Mulder et al., 2019)

These values are interpolated annually in the model. Full pricing trajectory is available in Table 14 (Appendix B).

$$H_2\ Price_{€/MWh} = \frac{€/kg}{0.03333\ MWh/kg}$$

Forecast of hydrogen price vs effective natural gas price

Below (Figure 9) is the comparison of natural gas and hydrogen price forecasts.
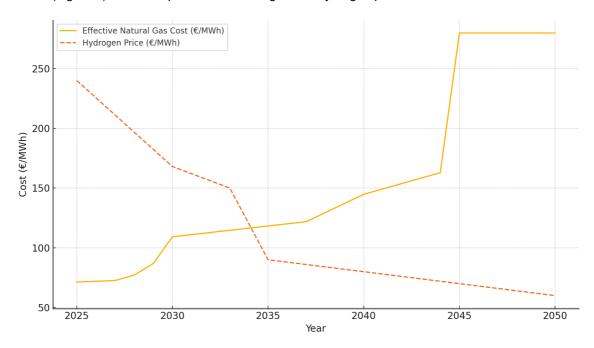
Figure 9: The comparison of hydrogen and natural gas prices for the years 2025-2050

Agent Attributes

Attributes are assigned to each agent to reflect differences in company strategy, decision-making, and resource capacity regarding hydrogen adoption. The table below summarizes the agent-specific attributes used in the model. The full dataset with assigned values can be found in Appendix A (Table 12).

Table 8: Overview of Agents' Attributes

Attribute	Description
Annual Energy Demand [MWh]	Total yearly energy consumption of the company
Capital Availability [€]	Financial resources available for hydrogen-related investment

Willingness to Adopt	Propensity to adopt hydrogen technologies based on internal motivations
Willingness to Invest	Openness to allocating capital for infrastructure such as storage
Importance of Energy Security	Perceived value of stable and independent energy supply
Risk Tolerance	Degree to which the company is comfortable with uncertainty and innovation
Peer Influence Sensitivity	Extent to which company behavior is influenced by the actions of peer firms
Regulatory Awareness	Understanding of policy incentives, obligations, and regulatory trends
Subsidy Responsiveness	Likelihood of reacting positively to financial incentives from public actors

Scenario Parameters

Scenario-specific parameters influence how agents perceive and behave under different governance models. These parameters shape the institutional context and directly affect adoption and investment behavior. The table below provides an overview of key parameters and their function in the model. Full scenario values are listed in Table 13 (Appendix A).

Table 9: Overview of Scenario Parameters

Parameter	Description
Energy Security	Perceived stability and autonomy in energy supply
Risk Associated	Level of financial, regulatory, and operational risk borne by the agent
Peer Influence	Degree to which adoption is affected by others' behavior
Regulatory Knowledge	Required familiarity with rules, permits, and compliance procedures
Subsidy Easiness	Perceived difficulty of accessing public subsidies for storage investments

4.5 Model Output and Key Performance Indicators (KPIs)

To evaluate the results of the simulation, the ABM utilizes a set of system-level and agent-level outputs at each simulation step. These outputs are used to compute Key Performance Indicators (KPIs) that capture adoption behavior, investment trends, infrastructure development, and the distribution of costs and benefits. KPIs serve as the reference for comparing the effectiveness, efficiency, and inclusivity of various governance configurations. They include:

1. **Hydrogen Storage Capacity**

This indicator measures the total hydrogen storage capacity (in kilograms) installed in the cluster at any point during the simulation. It captures the pace of infrastructure rollout and the extent to which storage investment aligns with hydrogen adoption trends.

2. Share of Hydrogen in the Energy Mix

This KPI reflects the percentage of total energy demand met by hydrogen on an annual basis. It allows tracking the integration of hydrogen into the industrial energy mix and measures how effectively storage enables decarbonization. It is calculated as:

$$Hydrogen\ Share\ [\%] = \frac{Hydrogen\ Storage\ Capacity\ (weekly\ buffer) * 52\ ^{weeks}/_{year}}{Total\ Annual\ Energy\ Demand} \times 100$$

3. *Hydrogen Adoption Rate*

This metric captures the proportion of industrial companies that have adopted hydrogen by the end of the simulation, including the year of adoption. It serves as a central indicator of progress toward decarbonization and the responsiveness of users to institutional, behavioral, and economic signals. The adoption rate is calculated as:

$$Adoption\ Rate\ [\%] = \frac{Number\ of\ Adopters}{Total\ Number\ of\ Users} \times 100$$

4. Storage Investment

This KPI measures the cumulative financial investment in hydrogen storage infrastructure throughout the simulation period. This includes all capital expenditure for construction and equipment, as well as annual operational expenditures related to the compression and maintenance of above-ground hydrogen tanks at operating pressures. It provides a comparative indication of cost magnitude across different ownership and governance models. The investment is computed as:

$$Storage\ Investment\ [€] = \sum_{i=1}^{years} Installed\ Capacity * \left(\frac{CapEx}{Payback\ Time} + OpEx * 52\ ^{weeks}/_{year}\right)$$

5. Net Economic Benefit (NEB)

The NEB represents the balance between the cost savings from switching away from natural gas and the expenses incurred from hydrogen storage and usage. It quantifies the economic value created by adopting hydrogen and investing in storage. NEB can be assessed at both the company and system-wide levels and will differ depending on the governance structure. It is calculated as:

$$NEB\ [€] = \sum Net\ Benefit - \sum Net\ Cost$$

5 Baseline Results

This chapter presents the results of the baseline simulation, where industrial companies individually decide whether to adopt hydrogen, without centralized coordination or shared infrastructure. These results serve as a reference point against which the outcomes of alternative storage governance scenarios are evaluated. By analyzing this uncoordinated setting, the chapter offers insights into how the hydrogen system evolves in the absence of institutional intervention in storage governance.

5.1 Simulation Results

The simulation results cover the adoption score, share of hydrogen in the energy mix, buildup of storage capacity, timing of adoption, storage infrastructure investments, and the resulting economic benefits of hydrogen integration.

Adoption Score
The average score of all companies in the cluster in the baseline model appears in Figure 10.
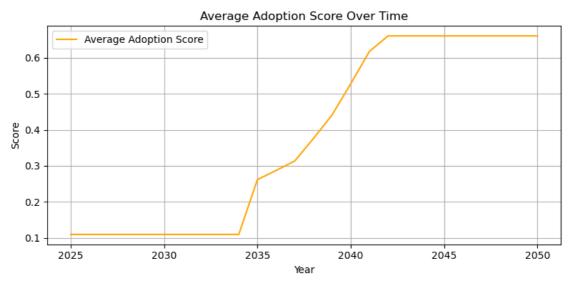
Figure 10: Adoption Score in the Base Run

This curve shows how industrial companies' attitudes towards hydrogen evolve over time. Initially, companies are strongly opposed due to high costs, limited access, and low acceptance. As infrastructure expands, prices drop, and acceptance increases, the adoption score rises. The completion of the national backbone around 2034 is a major enabler that boosts the adoption score. This connection between upstream and downstream parts of the value chain, as well as imports, reduces hydrogen prices further. Storage technologies begin to mature and become more accessible. All these factors together raise the adoption score for hydrogen, as perceived risks decrease and its appeal grows, especially as the price gap between hydrogen and natural gas narrows.

Hydrogen Share in Energy Mix

The hydrogen share refers to the proportion of total energy demand that is met by hydrogen. The larger the storage capacity, the more hydrogen can be stored weekly, resulting in a higher hydrogen utilization. Figure 11 below shows the evolution of the hydrogen share over time.
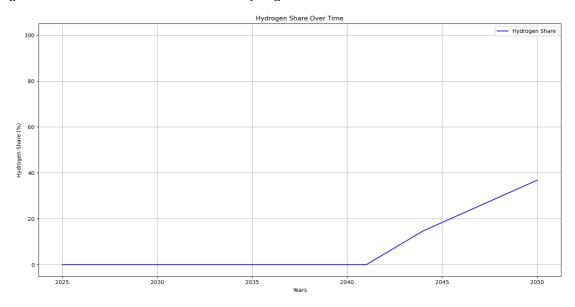
Figure 11: Evolution of Hydrogen Share in the Base Run

As shown in the graph, the hydrogen system has limited performance in the early stages, with hydrogen accounting for only a minor share of total energy consumption. Although storage technology and economics improve over time, the hydrogen share begins to rise only after the first storage investment is completed in 2041. While hydrogen becomes more cost-competitive than natural gas by around 2034, individual companies still delay adoption. This is because, under the model's behavioral logic, a company transitions only when its adoption score exceeds the threshold of 0.5. This score is influenced by factors such as perceived cost advantage, energy security benefits, regulatory awareness, peer adoption, and subsidy availability. Therefore, despite favorable cost signals, companies require multiple reinforcing incentives and a stronger sense of certainty before committing to the switch.

Between 2041 and 2050, the hydrogen share gradually increases, eventually reaching just below 38%. This steady growth reflects a cautious transition strategy within the baseline scenario. It suggests that companies diversify their energy sources gradually, keeping natural gas in their portfolios due to ongoing concerns over hydrogen storage costs, infrastructure maturity, and supply reliability. This conservative path highlights the influence of institutional and economic risk aversion in shaping trends in hydrogen adoption.

Storage Capacity, Energy Mix, and Adoption Timing

The following set of KPIs illustrates the buildup of hydrogen storage capacity, energy mix composition, and adoption timing over the simulation years. It helps determine at what pace storage is being developed and how it corresponds with the share of hydrogen in the energy mix. Note that, to be 100% dependent on hydrogen, the storage capacity of the cluster must reach at least 6,800 kg. Figure 12 illustrates these KPIs over the simulation period.
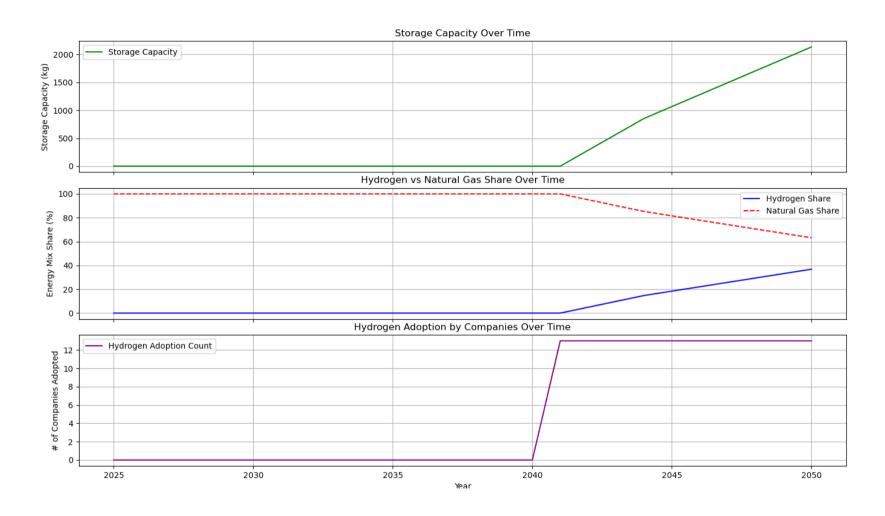
Figure 12: Evolution of Storage Capacity, Energy Mix, and Companies' Adoption Time

Figure 12 presents a composite of three critical indicators:

- **Storage Capacity**: Remains at zero until 2040, then expands in two clear steps following the collective adoption of hydrogen. The initial capacity ramp-up reflects company-level investments in modular above-ground tanks.
- **Energy Mix**: Natural gas remains the dominant source of heat for the entire period, gradually decreasing after investments are made into hydrogen storage. Then, hydrogen begins to gradually substitute for it. By 2050, hydrogen accounts for approximately 40% of the cluster's energy mix, with the remaining 60% still supplied by natural gas.
- **Adoption Count**: All 13 companies adopt hydrogen simultaneously in 2040. This synchronized shift is a direct result of the adoption score's emphasis on economic triggers, particularly the cost advantage of hydrogen over natural gas. Behavioral diversity is overridden in this case by techno-economic rationality.

Storage Investment per Company

Figure 13 presents the companies' cumulative investment for the entire simulation period. On the left vertical axis is the storage capacity in kilograms, whereas on the right axis is the total financial investment in €. This corresponds to the investment needed to achieve 38% of hydrogen in the energy mix in the cluster.
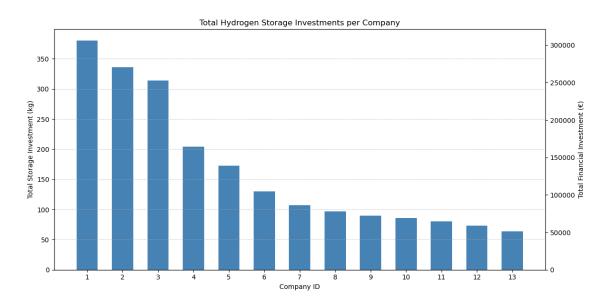
Figure 13: Total Investment in Storage per Company

As can be observed, the investment in hydrogen storage varies significantly across companies, primarily based on their energy demand and capital availability:

- Company 1, the largest and with the highest capital, invests in approximately 380 kg of storage capacity, which requires an investment of €300,000. This amount is substantial, primarily since it only covers the investment cost, and the company needs to supply hydrogen on top of that. Smaller companies often lack the financial resources for storage-related investments, which results in unfair treatment.
- Smaller firms such as Companies 12 and 13 invest in less than 100 kg each, which corresponds to around €50,000.

This disparity in investments reflects the limitations of a self-managed infrastructure model, where investment capacity is directly linked to firm size and available capital. Larger firms benefit from:
- Greater ability to absorb upfront CAPEX,
- Larger economies of scale,
- Faster returns due to higher hydrogen substitution volumes.

This creates a structurally unequal playing field that disadvantages smaller and medium-sized companies, reinforcing the need for a separate entity to take over storage infrastructure and give access to the users.

Annual Net Economic Benefit
Figure 14 below presents the annual net economic benefit per firm, calculated as the difference between the cost savings of using hydrogen and the total investment costs in the storage.
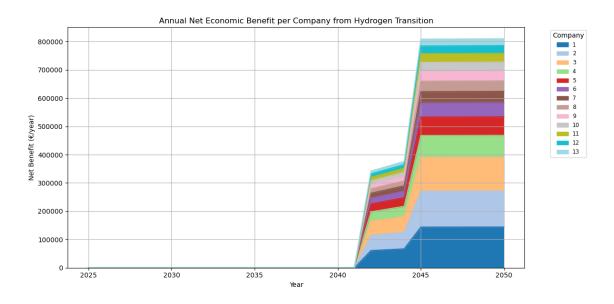
Figure 14: Annual Net Economic Benefit of Switching to Hydrogen

This stacked area chart shows the annual economic benefit for each company over time. Net economic benefit is defined as the cost savings from switching to hydrogen (including avoided CO_2 taxes) minus the cost of storage access and adoption investments. CAPEX is annualized over a 10-year amortization period, simulating the typical business case for industrial energy infrastructure.

Key observations:
- Benefits begin to accrue only after 2041, once hydrogen use starts.
- The benefit curve steepens between 2043 and 2050, corresponding to increased hydrogen usage and growing ETS prices, which raise the cost of natural gas.
- Larger companies dominate the benefit profile due to:
  - Greater storage volumes,
  - Larger absolute cost savings,
  - Higher return on investment in storage capacity.

Companies with higher demand (1–4) receive a larger net benefit than all other companies in the cluster combined. This is because they were able to invest more in capacity, which allows them to gain disproportionately greater benefits than companies that invested less.

Total Net economic benefit

Cumulative economic benefits, shown in Figure 15, reflect the long-term payoffs of early and large-scale adoption.
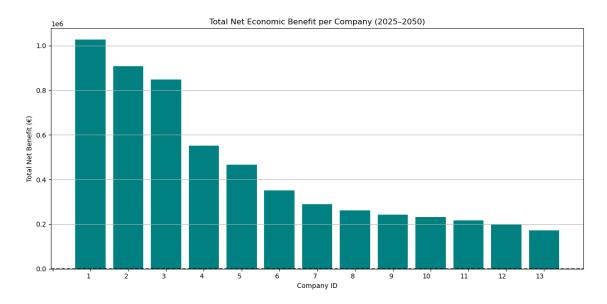
Figure 15: Total Cumulative Net Economic Benefit per Company

By 2050, total accumulated net economic benefits differ substantially across firms:

- Company 1 accumulates over €1 million in net benefits**,**
- Companies 2 and 3 earn over €850,000 each,
- In contrast, the smallest companies (10–13) accumulate benefits of less than €250,000.

Similar to previous KPIs, this result also reflects systemic inequality in the baseline model: companies with greater financial and operational capacity reap higher long-term rewards. These findings reinforce the need for alternative governance models that can distribute benefits more equitably and accelerate adoption among smaller players.

5.2   Reflection on the Results

The baseline highlights the systemic limitations of a decentralized and uncoordinated approach to hydrogen storage governance. The observed results of the simulation confirm patterns documented in the institutional and energy transition literature. Below is the reflection on the results from the institutional perspective.

Simultaneous Adoption Driven by Price Differences

All 13 industrial companies adopt hydrogen in 2040, suggesting that decision-making in the baseline scenario is highly sensitive to techno-economic signals, particularly the cost differential between hydrogen and natural gas. This reflects the model's adoption score formulation, where the $\Delta cost$ is weighted more heavily than behavioral factors. This result aligns with the notion of threshold-based innovation diffusion, where actors delay adoption until a clear economic advantage emerges (Rogers, 2003; Venkatesh et al., 2003). In rational-choice terms, this corresponds to bounded rationality, where decision-makers wait for sufficient clarity before deviating from the current norm (Simon, 1957).

From a policy perspective, this convergence around a future price point indicates a collective wait-and-see equilibrium, which is often observed during infrastructure transitions. As Frischmuth et al. (2024) argue, the lack of clear regulatory incentives for early adoption and investment in hydrogen storage leads to systemic inertia, especially in fragmented industrial regions.

Delayed Adoption Reflects Institutional Ambiguity

The delay in adoption until 2040 is not just due to agent behavior but also aligns with real-world institutional uncertainty. As mentioned in Chapter 2, institutional guidelines for hydrogen storage still lack clear roles, rights, or obligations for development in decentralized clusters (CMS Law, 2023; ACM, 2024). Without legal clarity, companies encounter high transaction costs, including permitting delays, ambiguous safety requirements, and legal liabilities—all of which serve as disincentives. Furthermore, limited visibility into long-term hydrogen pricing and subsidy trajectories exacerbates this effect. Companies hesitate to invest under policy ambiguity, especially without solid forward contracts or guaranteed infrastructure development (Stam et al., 2024). This underscores the need for institutional commitment mechanisms (North, 1990) to reduce uncertainty and enable early action. Stam et al. (2024) suggest that long-term policy stability and credible investment signals are essential in motivating private actors to take action under risk.

Larger Companies Benefit More

The simulation reveals significant variations in total hydrogen storage investment and net economic benefits across firms. Larger companies (1–3) invest more and gain more, while smaller companies lag behind. This outcome reflects the distribution of capital, which is directly linked to energy demand profiles. In the real world, this effect mirrors concerns that smaller industrial firms in Cluster 6 are less capable of participating in energy transitions without coordinated support or shared infrastructure. This also reflects the "Matthew Effect" in innovation systems, where actors with more resources gain more benefits over time (Merton, 1968; Markard et al., 2012). Without mechanisms for risk-sharing or collective ownership, smaller players are likely to be excluded from early benefits, worsening spatial and economic inequality in the hydrogen economy.

Low Hydrogen Share Despite All Companies Adopting

While all companies start adopting hydrogen in 2040, the total hydrogen share in the energy mix reaches only 38% by 2050, while the EU target is 100%. This partial adoption indicates that firms will continue to rely mostly on natural gas. This finding is rooted in infrastructure and operational constraints. In the baseline model, companies bear the full burden of CAPEX and OPEX. The high levelized cost of storage (LCoS), combined with limited economies of scale, discourages full substitution of natural gas. It also reflects the cautious behavior of the companies. Even after adopting hydrogen, agents may use it sparingly, viewing it as a strategic hedge rather than a complete replacement. This aligns with empirical insights from Hasankhani et al. (2024), who found that industrial actors in the Netherlands prefer hybrid energy portfolios during early transition phases due to perceived reliability risks and infrastructure immaturity.

Need for Central Storage Governance?

The simulation highlights that the self-managed baseline model creates a system where adoption is not only delayed but also unequal and inefficient. The results support arguments made in the literature that hydrogen storage is a networked infrastructure good, and thus should not be governed purely by individual actors (HyDelta, 2023; EBN-TNO, 2024). In centralized natural gas systems, storage is managed by public or regulated monopolies, allowing for shared access and cost recovery through regulated tariffs. Applying a similar model to hydrogen may enhance access, accelerate adoption, and mitigate investment risks, particularly for small- and medium-sized enterprises (SMEs). This hypothesis will be tested through the scenario simulation later in the report.

6   Uncertainty Analysis

This chapter presents the uncertainty analysis conducted on the baseline model to evaluate how variations in input parameters affect simulation outcomes. By adjusting parameters with high uncertainty, the analysis examines the robustness of the baseline configuration and identifies which factors most strongly influence the dynamics of hydrogen adoption within the industrial cluster.

6.1   Uncertain Parameters

This analysis targets parameters characterized by high uncertainty, either due to limited empirical data or the inherent difficulty of assigning precise values—particularly concerning stakeholder behavior. These parameters are selected due to their substantial impact on model outcomes and the considerable uncertainty surrounding their real-world values. For instance, the adoption threshold, which defines the point at which an agent considers hydrogen a viable option, is a conceptual construct lacking empirical calibration. Behavioral attributes assigned to agents are synthetically generated to capture heterogeneity in decision-making, yet they are not based on observed data from actual firms. The capital expenditure associated with above-ground hydrogen storage remains highly uncertain, as data is limited and subject to change due to technological innovation. Lastly, annual investment capital per company is based on an estimate, not derived from verifiable data on industrial firms. The parameters included in the analysis are listed in Table 10 below.

Table 10: Overview of the parameters and ranges for the uncertainty analysis

Parameter	Base Value	Uncertainty Range	Unit
Adoption Threshold	0.5	0.2 – 0.6	-
Agents' Behavioral Attributes	Depends on Agent	*(0.6 – 1.4)	-
Storage CAPEX	1073.43	600 – 1400	€/kgH$_2$
Annual Investment Capital	Depends on Agent	*(0.6 – 1.4)	€/year

6.2   Results of Uncertainty Analysis

Each parameter was varied independently to isolate its effect on the model's behavior through KPIs. The results of these variations are presented using comparative plots and are accompanied by interpretive discussion to evaluate their implications for the baseline scenario.

6.2.1   Adoption Threshold
The adoption threshold in the baseline was set at 0.5, which means that if, under the current conditions, the agent scores hydrogen at more than 50%, then he will adopt it. By lowering the thresholds, companies that score lower on hydrogen would be more likely to adopt. In the uncertainty analysis, the threshold was varied between 0.2 and 0.6 to maintain a consistent range. Figures 16 and 17 below illustrate how varying thresholds impact the adoption and overall integration of hydrogen in the energy system.
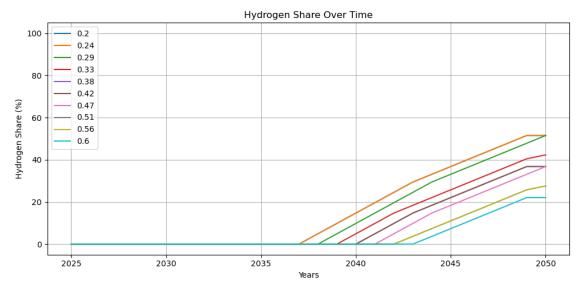
Figure 16: Hydrogen Share over Time under Various Adoption Thresholds
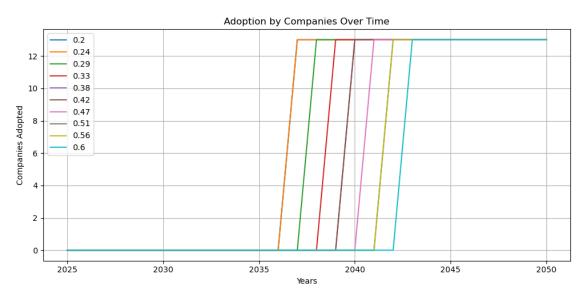
Figure 17: Adoption Timeline under Various Adoption Thresholds

As expected, lower threshold values enable quicker adoption. Compared to the base scenario, when companies adopt hydrogen in 2040, reducing the threshold to 20% will lead to adoption by 2036. Conversely, increasing the threshold to 60% will postpone adoption until 2042. This has a direct influence on the hydrogen share. The earlier companies adopt, the more capital they can allocate to storage investments. As a result, the hydrogen share rises from 38% to 52% in 2050. The same logic applies to delayed adoption, with the base hydrogen share dropping to 22% if companies wait to adopt until 2042.

6.2.2 Agents' Behavioral Attributes

For the behavioral uncertainty analysis, each agent's attribute was multiplied by a randomly selected factor ranging from 0.6 to 1.4. This procedure was applied over 50 independent simulation runs to generate a broad behavioral landscape. Key indicators such as hydrogen share and storage capacity were then analyzed using the 10th–90th percentile range, which captures the central 80% of simulation outcomes while excluding the

most extreme 10% at both tails. This approach helps filter out potential outliers or model artifacts that could distort interpretation. The resulting outcomes are presented in Figure 18 below.
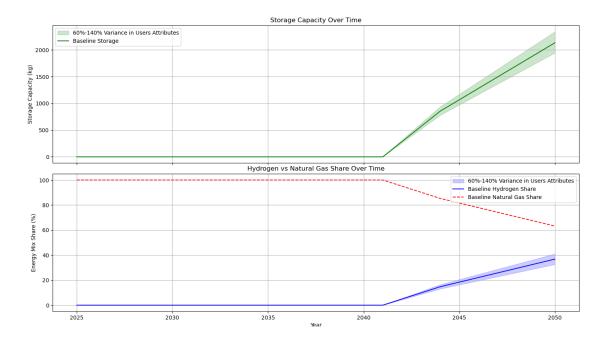
Figure 18: Storage Capacity Utilization and Hydrogen Share Under Behavioral Variations

As observed from the figure, the variation in company-level attributes has a relatively low impact on hydrogen storage investment and adoption outcomes. Despite introducing a significant variance in the attributes, the storage capacity and hydrogen share in the mix differ by only 5% in both upper and lower directions. The range of hydrogen share varies from 33% to 43% compared to the initial 38%.

6.2.3   Storage CAPEX

In the baseline scenario, CAPEX was set to €1073.43/kg H_2, which is a literature-based estimate from sector reports and academic studies (from Moran et al. (2023) and Steward (2009)). However, it is a particularly uncertain parameter, as values in the literature range from €600/kg H_2 to €1,400/kg H_2, depending on technology maturity, capacity, and production scale (Burke et al., 2024; Horizon Europe, 2023). Additionally, because the simulation includes future years, the CAPEX forecasts tend to lower the values and support them with future technological advancements. For instance, U.S. DOE estimates suggest current costs around $1323/kg H_2, while future forecasts project values as low as $200–300/kg H_2 as economies of scale and material innovations improve (Amos, 1998; Zhili, 2022).

In this analysis, CAPEX is varied across the range from €600 to €1400 per kg H_2 to evaluate how investment costs affect adoption behavior, storage development, and hydrogen integration. Figure 19 below illustrates the impact of this variation on storage capacity utilization and the corresponding hydrogen share (compared to the natural gas share) over time.
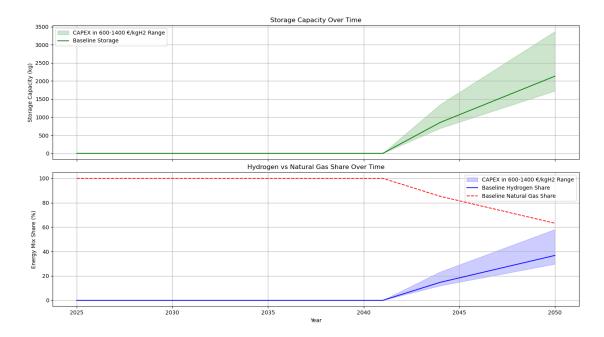
Figure 19: Storage Capacity Utilization and Hydrogen Share Under CAPEX Variations

Examining the simulation results, lower CAPEX values enable more widespread investment in storage infrastructure, leading to a higher hydrogen share. At a lower price per kg of H_2, companies can spend the same amount of annual capital on storage investment, which means more capacity is utilized each year. At €600/kg H_2, storage capacity increases from 2,100 kg to nearly 3,500 kg by 2050 with the same spending. This allows the hydrogen share to approach 60% by 2050. Conversely, at €1,400/kg, investment becomes unattractive for most firms, especially smaller ones, which delays adoption and limits the hydrogen share to around 30% by 2050. Notably, the same range of CAPEX variation results in disproportionately different outcomes. Large capital costs only slightly reduce the hydrogen share (by 6 percentage points), while lower costs can significantly boost the hydrogen share (by 19 percentage points).

6.2.4   Annual Investment Capital

In the baseline scenario, the annual investment capital value is fixed per agent and represents an estimate of the company's capital flexibility. However, in practice, the investment capacity is highly variable due to differences in cash flow and strategic capital planning. To reflect this uncertainty, the companies' annual investment budgets vary between 60% and 140% of their baseline capital. This allows us to observe how both tight capital constraints and greater financial flexibility affect hydrogen adoption and infrastructure development. Figure 20 below presents the effects on storage capacity and the hydrogen share in the energy mix over time.
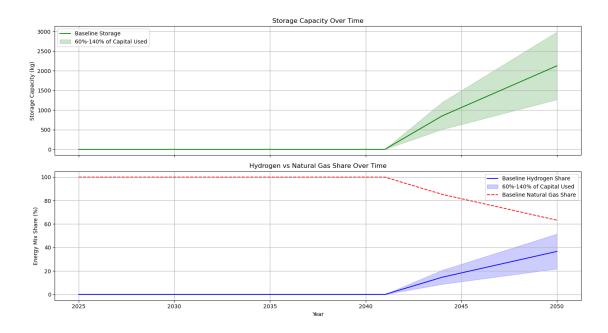
Figure 20: Storage Capacity Utilization and Hydrogen Share Under Capital Variations

The results show a clear pattern: firms with larger annual budgets invest in larger volumes, accelerating the hydrogen transition. If 140% of the current annual budget were spent on storage investment, the capacity would reach 3000 kg by 2050, compared to just 1300 kg when companies spend 60% of the budget. Similarly, the hydrogen share rises to over 50% in the high-budget case, while it stagnates around 20% under constrained capital.

6.3   Implications of Uncertainty Analysis

The uncertainty analysis demonstrates that a few key parameters exert significant influence over hydrogen adoption outcomes, while others have only a marginal effect. This differentiation is essential for designing effective and targeted policy interventions.

Adoption Threshold

The adoption threshold is a critical determinant of adoption timing and hydrogen share. Minor changes to this parameter shifted adoption by up to six years and altered the final hydrogen share by ±15 percentage points. Since the threshold reflects internal perceptions of hydrogen viability, supportive policies that reduce perceived risk—such as regulatory clarity, infrastructure guarantees, or long-term commitments—can accelerate adoption, even among cautious firms.

Agents' Behavioral Attributes

Behavioral heterogeneity among firms had only a marginal impact on aggregate outcomes. Despite wide variation in internal attributes, the hydrogen share changed by just ±5 percentage points. This suggests that external conditions matter more than company-specific traits. Consequently, policy frameworks should offer uniform support to all firms, ensuring that even less proactive companies can transition under the right conditions.

Storage CAPEX

Storage capital costs significantly affect investment behavior, particularly for smaller firms. Lowering these high upfront costs improves storage buildout and hydrogen integration. This can be addressed through technological advancements, public R&D funding, and financial mechanisms such as subsidies and standardization to foster economies of scale.

Annual Investment Capital

Financial capacity directly influences how much storage firms can deploy. Companies with greater liquidity invest earlier and at larger volumes, accelerating decarbonization. Policies that expand access to capital—via grants, low-interest loans, or collective investment schemes—are essential to ensure all firms can participate in the hydrogen transition.

Taken together, the analysis confirms that adoption outcomes are primarily shaped by system-level enablers: investment cost, available capital, and perceived viability. Behavioral variation becomes secondary in the presence of strong institutional support and favorable economics. These findings point to a clear policy imperative: reduce investment barriers, ensure regulatory clarity, and create inclusive financial mechanisms to accelerate the hydrogen transition across all types of industrial actors.

7 Scenario Results

This chapter presents the results of three scenarios that explore alternative institutional arrangements for hydrogen storage operation. While the baseline model assumed fully self-funded storage by individual companies, the experimental scenarios assign storage responsibility to either an external public (DSO) or private operator, or a shared industry initiative. Each scenario alters the ownership, financing, and access model, which in turn impacts adoption dynamics, investment size, and hydrogen utilization. Moreover, sensitivity analysis is performed to confirm that the results from running the scenarios and valid and comparable.

7.1   Scenario A: Distribution System Operator (DSO)

In this scenario, a public Distribution System Operator acts as the sole investor and operator of the hydrogen storage infrastructure. Unlike the decentralized approach in the baseline, storage is centrally owned and managed, enabling coordinated investment and shared access. The results of this scenario simulation are presented below.

Adoption and Storage Behavior
Figures 21 and 22 illustrate the hydrogen share, adoption timeline, storage growth, and energy mix composition.
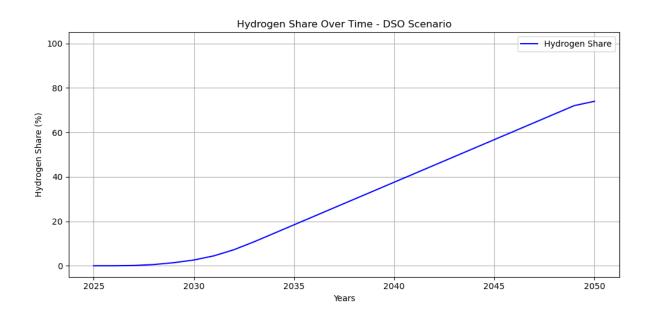

Figure 21: Evolution of Hydrogen Share in DSO Scenario
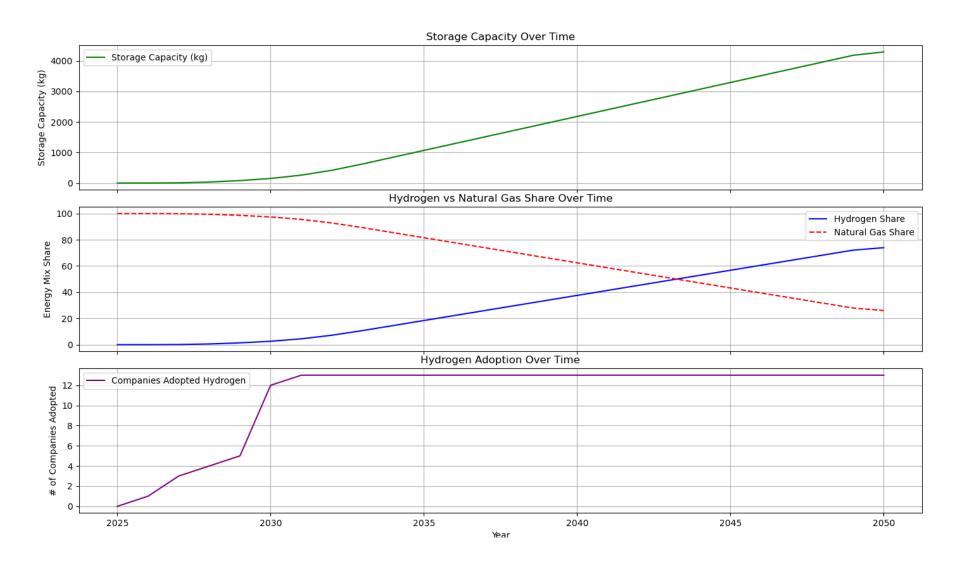
Figure 22: Evolution of Storage Capacity, Energy Mix, and Companies' Adoption Time

Compared to the baseline scenario, the DSO model results in:

- **Earlier adoption**: Companies begin adopting hydrogen around 2028, with all companies beginning to supply part of their needs by 2033. This is nearly a decade earlier than in the baseline.
- **Faster infrastructure scaling**: Storage capacity increases steadily, surpassing 4,000 kg by 2050, significantly more than the baseline capacity of ~2,100 kg.
- **Higher hydrogen penetration**: The hydrogen share reaches nearly 73% by 2050, compared to only 38% in the baseline. Natural gas share declines correspondingly.

This acceleration is primarily due to the reduced cost burden for companies and the risk-free access to infrastructure, both of which make adoption more attractive. Since the DSO handles storage, there is no competition in this part of the value chain; rather, it functions as a natural monopoly. The cost difference between natural gas and hydrogen is internalized, combined with LCoS, and reflected in the tariffs, allowing for an early ramp-up. The rate of acceleration is relatively slow due to a lack of competition.

Net Benefits

Figure 23 shows the cost-benefit balance from the DSO's perspective.
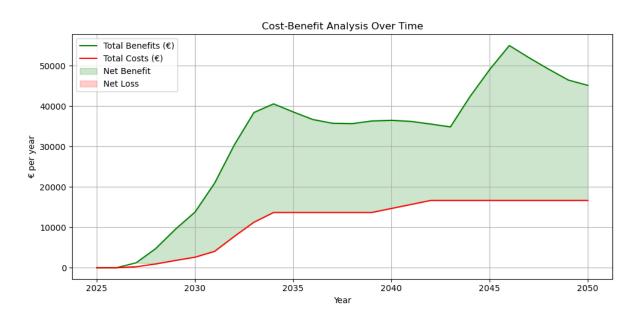
Figure 23: CBA of Investment into Storage

The Total Net Benefit of the CBA for hydrogen storage over the simulation period was calculated to be €530,922.78. It consists not only of financial benefits from DSO income and saved energy costs for users, but also social benefits, including reduced CO2 emissions, health benefits for citizens, and improved resilience. These were quantified and combined in CBA.

According to the CBA results, the cumulative net benefit grows year-on-year, with no periods of net loss. After 2028, the total annual benefits increase sharply until 2033. This can be explained by the fact that in 2033, the national backbone and the first large-scale UHS in salt caverns are planned to be completed; therefore, above-ground storage will become less critical. Storage-related costs remain relatively stable due to economies of scale and early investments. The CAPEX is distributed over the years of the business case, so there is no spike in the cost curve.

From the user perspective (Figure 24), the net economic benefit is positive for all 13 companies.
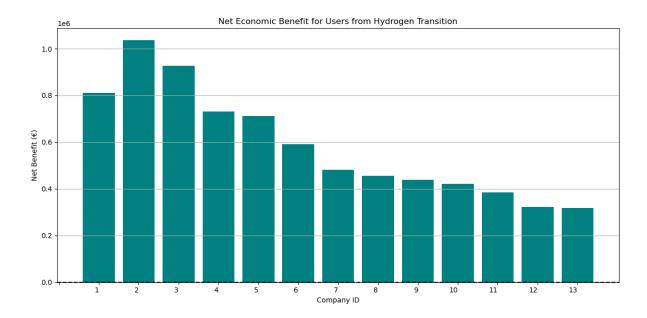
Figure 24: Total Cumulative Net Economic Benefit per Company in DSO Scenario

From the chart, it can be seen that larger companies still benefit the most from higher hydrogen consumption volumes due to the cost savings from reduced CO_2 emissions, but the disparity compared to baseline results is significantly less visible. On average, companies benefit more when DSO operates storage. This is primarily because having a central storage operator allows companies to access storage services without upfront financial commitments.

One of the critical features of this scenario is the timing of subsidies. The DSO begins investing in storage infrastructure during the early years of the simulation, when government subsidies are at their peak. As a result, the LCoS is substantially lower for investments made during this period. While users still pay for storage indirectly through the hydrogen price, they avoid the burden of direct investment costs. Importantly, these lower LCoS values remain fixed for 20 years, the duration of the infrastructure's payback period. This creates a strong incentive for early adoption, particularly for smaller or more risk-averse companies that might otherwise delay transition due to capital constraints.

DSO-led storage may initially pose a short-term financial drawback as early adopters may incur temporary losses when hydrogen is still more expensive than natural gas. For example, Company 1 was the earliest adopter due to its high energy demand and strategic orientation. However, its early entry also meant bearing greater costs during the initial years when hydrogen was still relatively expensive. Consequently, its total net benefit is slightly lower than that of Company 2, which was adopted shortly afterward under more favorable cost conditions. This highlights how the timing of adoption and energy consumption profiles affect individual outcomes. As hydrogen prices fall and natural gas prices rise over time, the economic outlook improves.

This institutional model is particularly effective for enabling participation from smaller firms that lack the economies of scale or internal financing needed to build independent storage systems. By externalizing investment risk and leveraging subsidy windows, the DSO approach ensures more equitable access to infrastructure and accelerates system-wide adoption.

7.2   Scenario B: Private Third-Party Operator

Under this institutional arrangement, a private investor enters the hydrogen value chain as an independent storage operator. This form of vertical unbundling allows new market actors to specialize in storage services, aligning with the principles of liberalized energy markets. The outcomes of this governance configuration are presented below.

Adoption and Storage Behavior

Figures 25 and 26 illustrate the evolution of hydrogen share, cumulative adoption, energy mix transition, and storage capacity buildup under the third-party scenario.
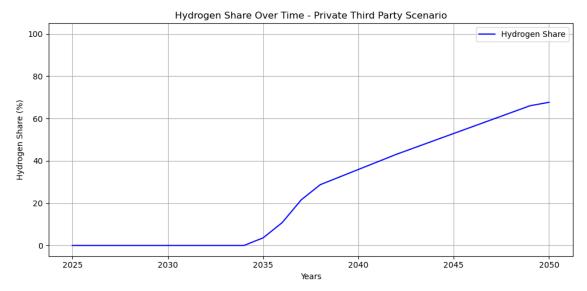
Figure 25: Evolution of Hydrogen Share in Third-Party Investor Scenario

The contracted capacities for all companies in the cluster are as follows:
- Companies 1, 2, and 3 each contracted for a total of 700 kg of hydrogen storage.
- Companies 4 and 5 each contracted for a total of 350 kg of hydrogen storage.
- Company 6 contracted a total of 275 kg of hydrogen storage.
- Companies 7, 8, 9, 10, and 11 each contracted for a total of 175 kg of hydrogen storage.
- Companies 12 and 13 each contracted for a total of 130 kg of hydrogen storage.

Compared to the baseline scenario, this model exhibits:
- **Faster adoption**: Companies start adopting hydrogen in 2034 – seven years earlier than in the base run, but later than when DSO is in charge.
- **Faster infrastructure growth**: Storage reaches almost 4,000 kg by 2050, which is significantly higher than the baseline and slightly lower than the DSO scenario.
- **Higher hydrogen penetration**: The hydrogen share reaches 68% by 2050, which is significantly higher than the baseline's 38% and slightly below the DSO scenario (73%).

The delay in adoption is driven by the need for investor confidence and contract aggregation. The operator only builds new storage modules when there is a sufficient number of committed users. This introduces market frictions, particularly for smaller companies that must wait for bundled contracts to become viable. However, competition and profit motives result in greater efficiency and responsiveness compared to the monopolistic structure, particularly in later years when the market matures.
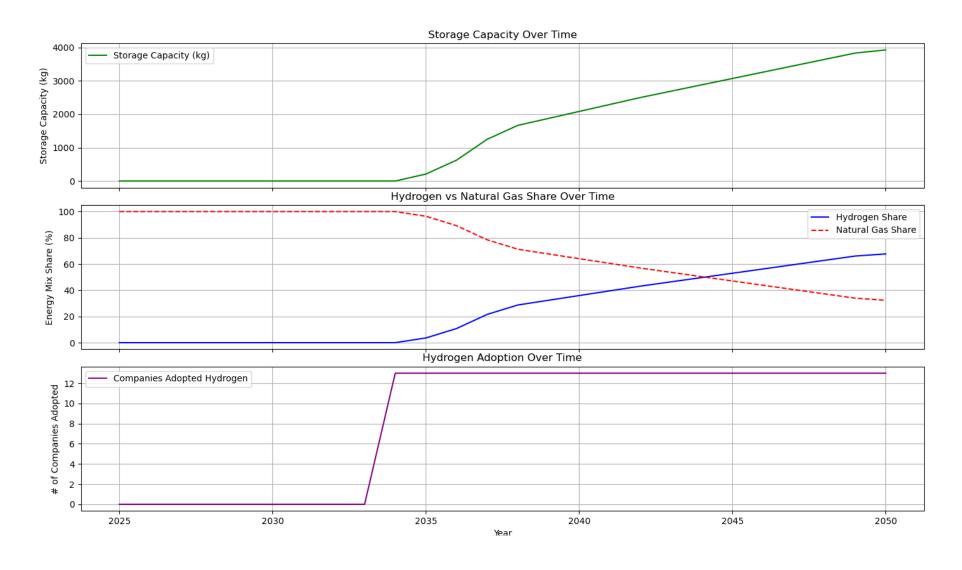
Figure 26: Storage Capacity, Energy Mix, and Hydrogen Adoption over Time

Net Benefits

Figure 27 presents the cumulative net benefit for the private storage operator over the simulation period.
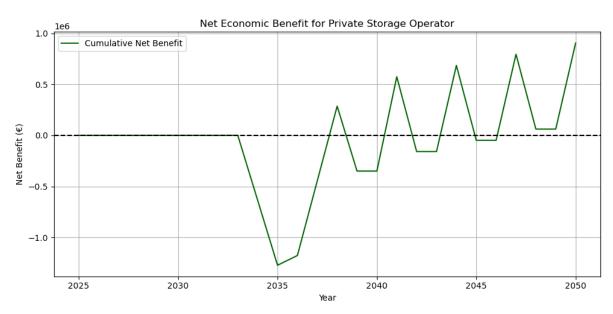
Figure 27: Cumulative Net Economic Benefit for the Investor

The investor experiences an initial period of financial loss due to the large upfront CAPEX in years with limited adoption. Once the storage is complete, revenues from access fees begin to outweigh costs. The investor's success is tied to the number of users, efficient capacity scaling, and maintaining a stable access fee that is attractive yet profitable. Over time, the cumulative benefit becomes strongly positive and reaches €904,754.74 by 2050. Compared to the total cost of €4,745,818.55, the Return on Investment is equal to

$$ROI = \frac{\text{Total Net Benefit}}{\text{Total Cost}} = \frac{€904,754.74}{€4,745,818.55} = 19\%.$$

From the user's perspective, the net economic benefit varies depending on the timing of adoption and the bundle size. Figure 28 shows the per-company benefit outcomes.
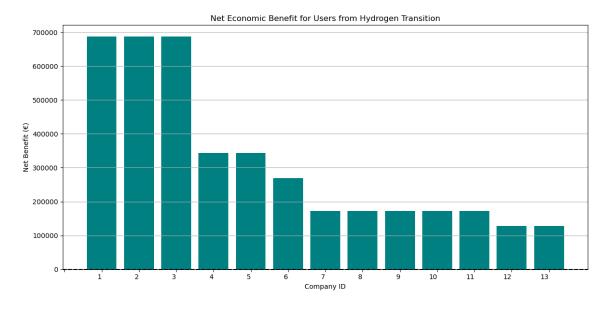
Figure 28: Total Net Economic Benefit per Company in Third-Party Scenario

Compared to the DSO scenario, companies in this governance model experience lower net economic benefits due to higher access fees. These fees include a profit margin for the private operator, who must ensure a viable business case and return on investment. As a result, the total cost of hydrogen (including storage) is higher for end-users.

Because access is provided through standardized contract-based bundles, companies with similar energy demand secure equal storage access and thus similar economic outcomes. However, this standardization also creates greater disparities between large and small firms. Larger companies are better positioned to commit early to larger bundles due to greater capital and demand, while smaller firms often face delays or settle for less cost-efficient options. As a result, the economic gap between early adopters and smaller players is more pronounced than in the DSO scenario.

Nonetheless, this governance model offers a clear improvement over the baseline. By shifting investment responsibility to the private operator, smaller firms avoid the high upfront costs of infrastructure, gaining access to storage they might otherwise be unable to afford. This enables broader participation and reduces barriers to entry for capital-constrained companies.

7.3   Scenario C: Shared Investment Model

In this scenario, industrial companies do not rely on an external operator to provide hydrogen storage infrastructure. Instead, they collectively coordinate to co-invest in modular storage facilities based on their aggregated capital and demand, and let the industrial park utility operator distribute the hydrogen to the users. The results of this governance on the system behavior are shown below.

Adoption and Storage Behavior
Figure 29 presents the evolution of the hydrogen share in the shared investment scenario, while Figure 30 illustrates storage capacity, energy mix, and the adoption timeline. Both figures can be seen below.
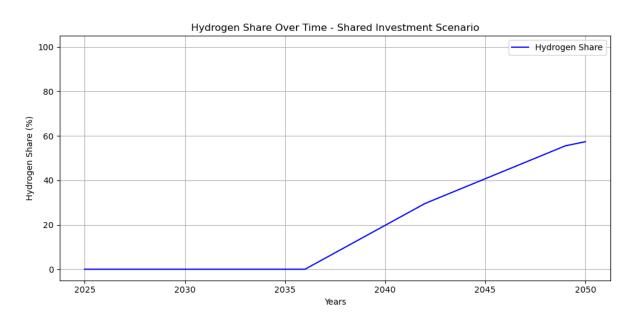
Figure 29: Hydrogen Share Over Time in Shared Investment Scenario
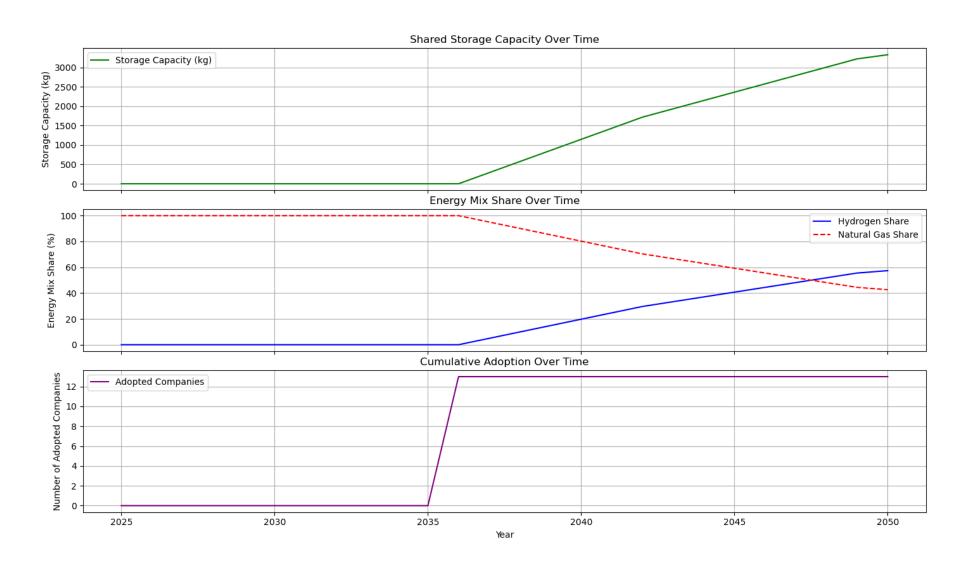
Figure 30: Storage Capacity, Energy Mix, and Adoption Timeline in Shared Investment Scenario

Compared to the baseline, the shared scenario results in:

- **Faster adoption**: All companies in the cluster form of the investment group and made their first investment in hydrogen in 2035. This is four years prior to the adoption in the base run.
- **More storage investments**: Storage capacity reaches approximately 3,300 kg by 2050, which is less than in the DSO scenario (4,100 kg), but more than the baseline (2,100 kg).
- **Higher hydrogen penetration**: The hydrogen share reaches 58% by 2050. While lower than in the DSO or private investor scenarios, it is still a significant improvement over the baseline by 20 percentage points.

The faster adoption can be explained by the fact that when more companies decide to invest in a shared facility, it encourages others to join. The sense of participating in an initiative strengthens companies' resolve, enabling them to take on more risk, which leads to quicker adoption. Once they commit to the shared investment, they are willing to allocate a larger portion of their capital to storage investments, knowing it will benefit the entire cluster.

Compared to external operators, lower storage utilization can be explained by larger transaction costs due to the negotiation and coordination in decentralized decision-making. This is especially evident when comparing it with a third-party scenario where adoption happens around the same time, but storage capacity offtake proceeds more quickly. This is because the centralized governance works very efficiently, especially during the processes of permitting, building, and negotiating with other actors.

Investment Per Company
Figure 31 below illustrates the total hydrogen storage investment made by each company under the shared scenario, highlighting the differences in contribution levels across firms.
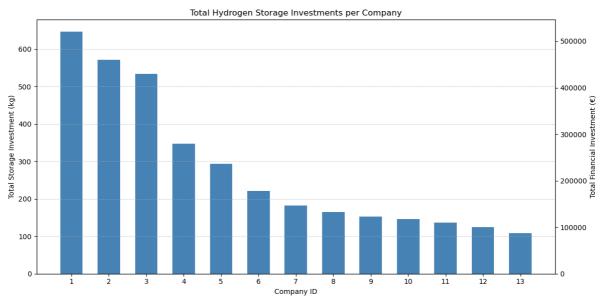
Figure 31: Total Hydrogen Storage Investment Per Company

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The investment size is nearly double that of the baseline scenario, meaning almost twice the capacity has been installed. The earlier adoption enabled benefits from larger subsidies, resulting in a lower cost per kg invested compared to the base case. The results also show that the shared model reduces investment inequality. In a shared scenario, larger-budget companies invest more to benefit the cluster, which accelerates the transition. They are motivated to do so because other companies with less capital express their intention to transition and join the shared investment model. Compared to the baseline, where companies invest separately, shared ownership results in more balanced investment levels. The difference between the largest and smallest investors is smaller, indicating a fairer distribution of infrastructure costs. The collective model's capital threshold guarantees that no investment is initiated unless the minimum requirements are met, reducing underutilized capacity and free riding. This makes the shared model more financially efficient and inclusive, especially for medium-sized firms, while keeping the larger companies assured that others will contribute.

Net Economic Benefit
Figure 32 presents the total net economic benefit for each company in the shared scenario, capturing the financial gains from transitioning to hydrogen after accounting for their respective investment contributions.
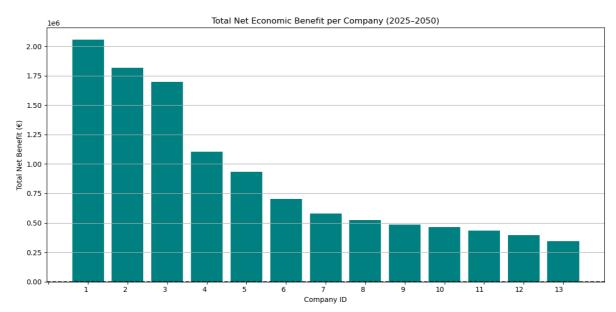
Figure 32: Net Economic Benefit per Company in Shared Investment Scenario

Results show that the shared governance model provides a strong financial incentive for nearly all participants. Larger companies naturally reap higher benefits due to greater hydrogen substitution volumes. Still, smaller companies also profit, thanks to early access and shared infrastructure. Total benefit levels for the users are higher than in all other scenarios, but it comes at the cost of having to invest more. The key driver behind these results is the collaborative nature of investment. The timing is crucial so that all companies agree to invest simultaneously. Companies want to fit in the time when subsidies for storage projects are still high and when the hydrogen price becomes lower. This trade-off is challenging to achieve, but if successful, companies can generate a substantial profit from the

transition. By synchronizing adoption and spreading infrastructure costs, companies reduce per-unit investment burden while still gaining access to storage.

This scenario reflects the potential of decentralized governance in regional industrial clusters. Its success depends on:
- The ability to coordinate among companies with diverse resources and risk absorption,
- Effective capital pooling mechanisms and contract enforcement to prevent free riding,
- The timing of group formation and subsidy optimization,
- Administrative capacity to handle joint permitting and construction processes.

Overall, the shared investment model offers a promising hybrid approach: it lacks the simplicity and scale of centralized models but makes the hydrogen transition more accessible and collectively beneficial. It may be particularly effective in industrial clusters where no single public or private entity is willing to take on the role of storage operator.

7.4 Scenario Comparison

This section compares the outcomes of the three governance scenarios with the baseline model and with each other. The comparison is based on key indicators such as hydrogen adoption rate, storage capacity, investment distribution, and economic benefits.

Hydrogen Adoption Trajectories

Figure 33 illustrates the hydrogen share over time for all scenarios. The DSO scenario leads to the fastest and most extensive hydrogen utilization, followed by the private investor and shared investment models. The baseline scenario lags significantly behind all others.
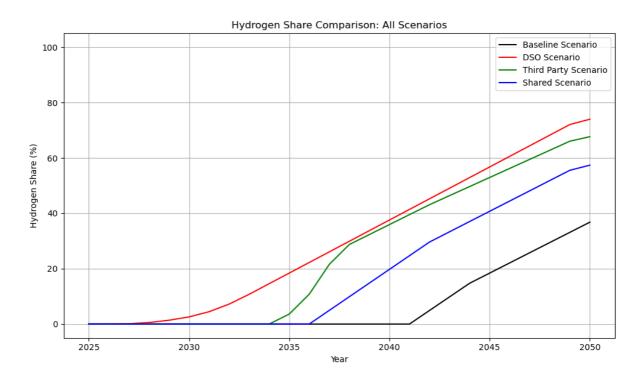
Figure 33: Hydrogen Share Comparison Across All Scenarios

The four scenarios exhibit different hydrogen adoption trajectories. The baseline scenario performs the weakest, with hydrogen reaching only about 38% of the energy mix. This is attributed to the uncoordinated institutional framework, where each firm independently bears the full risk and cost of storage infrastructure without any coordination or support mechanisms. As a result, adoption is delayed and uneven across the cluster.

In contrast, the DSO scenario attains the highest hydrogen share, reaching about 73% by 2050. This strong performance stems from early adoption, beginning around 2028, facilitated by centralized planning, public subsidies, and non-profit pricing. The DSO model eliminates investment risk for users and accelerates infrastructure development through coordinated and timely decisions, particularly during periods of substantial public financial support.

The third-party investor scenario also performs well, reaching a hydrogen share of about 68% by 2050. Adoption starts later due to the need for contract aggregation and investor assurance before committing to infrastructure development. Despite these initial delays, the market-driven model allows for efficient scaling once companies decide to enter into contracts for access to storage.

The shared investment scenario yields a moderate outcome, with hydrogen accounting for about 58% of the total energy mix by 2050. Adoption is synchronized across companies and starts around 2036, following the formation of the first co-investment group. Although the absence of an external operator poses coordination challenges, the model effectively pools capital through collective action. However, delays caused by negotiations and acquiring permits slow infrastructure deployment compared to more centralized or market-based approaches.

Scenarios Implications

The three governance models differ in how they distribute benefits, promote inclusivity, and share risks among stakeholders. Regarding *net economic benefits* for users, the shared investment model yields the highest returns. This is mainly because companies gain directly from infrastructure ownership and can strategically time their investments to match periods of generous subsidies. The DSO model also provides significant user benefits by removing the need for capital investment, although profits are slightly lower due to the lack of direct ownership. The third-party investor model results in the lowest net benefit for users, as profit margins are embedded in the access fees, which increase the overall cost of hydrogen for companies.

Equity and inclusivity also differ across models. The DSO and shared scenarios are more accommodating to smaller firms. In the DSO model, public investment guarantees universal access regardless of firm size or capital availability. Similarly, the shared model allows smaller companies to participate by pooling resources with others, promoting fairer distribution of costs and benefits. In contrast, the private investor scenario creates bigger gaps: larger companies secure contracts earlier and in greater volumes, while smaller firms often face hurdles due to limited capital and access constraints.

Risk allocation varies across different scenarios. In the DSO model, all investment risk is internalized by the public operator, protecting companies from financial exposure. The private investor model shifts some of this risk through contractual arrangements, with firms taking on payment obligations in exchange for access. In the shared model, risk is distributed collectively among participants, as

companies jointly finance and operate the infrastructure. This fosters a sense of shared responsibility but also requires robust coordination mechanisms to prevent unequal burden-sharing or underperformance. Table 11 below presents an overview and comparison of the scenario simulation results.

Table 11: Results Comparison Between Scenarios

Scenario	Adoption Time (Years)	Storage Capacity (kg) in 2050	Hydrogen Share (%) in 2050	Net User Benefit	Equity
Baseline	2041	~2,100	38%	Medium, skewed	Low
DSO	2028–2033	~4,100	73%	High	High
Private Investor	2034	~4,000	68%	Medium	Medium
Shared	2036	~3,300	58%	Medium – High	High

7.5   Scenarios Sensitivity Analysis

To ensure that the simulation results across the governance scenarios are comparable, a structural sensitivity analysis is conducted. It allows to determine whether observed differences in system outcomes can be attributed to institutional design, rather than to inconsistencies in the model's logic or setup.

Each scenario modifies only the institutional configuration, specifically the ownership structure, investment coordination mechanisms, and access rules, while all global parameters remain fixed. For instance:
- The same set of 13 industrial agents is used, with identical behavioral traits, capital availability, and energy demand.
- Exogenous factors such as hydrogen price trajectories, subsidy schemes, ETS pricing, and natural gas costs are synchronized across simulations.
- Agent decision-making logic, including how adoption scores are computed, remains structurally identical.
- Storage technology (pressurized tanks) is held constant, with uniform CAPEX, OPEX, and efficiency values.
- The simulation period (2025–2050) and KPI measurement logic are the same across all scenarios.

The scenarios vary exclusively at the institutional level, reshaping the coordination environment in which agents operate without altering their underlying logic. Differences in ownership, investment responsibility, and access pricing modify how incentives, risks, and constraints are distributed across actors. However, because the agents themselves remain identical, these variations only affect how they respond to different opportunity structures—not whether they are fundamentally different decision-makers. For example, smaller firms consistently delay adoption in scenarios where it requires upfront

investments due to budget limitations, but when the access costs are structured, whether through tariffs on hydrogen or via a contracted fee, the adoption is triggered earlier. These behavioral shifts emerge endogenously from the governance context, validating that observed system differences are driven by institutional design rather than modeling inconsistency.

This modeling structure enables a controlled and interpretable comparison of institutional performance. It reflects the principle in institutional economics that governance arrangements shape actors' and the system's behavior by reallocating coordination costs and property rights (Williamson, 2000). Each scenario is grounded in a real-world analogue: the DSO case represents a regulated natural monopoly; the third-party case models liberalized infrastructure markets; and the shared investment scenario mirrors cooperative governance structures found in local energy initiatives (Jaag & Trinkner, 2011). The intentional variation across these empirically inspired designs allows the results to inform policy and strategy without compromising the comparability of findings.

8 Discussion

This chapter interprets the simulation results within broader academic, policy, and industrial contexts. By connecting model outcomes to theoretical frameworks and practical implications from literature, it highlights key lessons for researchers, policymakers, and industrial actors.

8.1 Interpretation of Key Results

The simulation results illustrate how institutional design shapes the trajectory of hydrogen adoption in decentralized industrial clusters. While all scenarios demonstrate a clear improvement over the status quo, the underlying dynamics behind each pathway reveal important distinctions. A central observation across all cases is that hydrogen adoption is driven by demand-side behavior. Since the model is scoped from the user perspective, the offtake of hydrogen only accelerates once companies are ready to adopt, reflecting real-world patterns where downstream actors in the value chain tend to transition later. This framing explains the initially slow rise in hydrogen share across all scenarios and underscores that adoption is not solely constrained by technical or supply capacity but rather by economic feasibility, institutional confidence, and strategic coordination.

In scenarios where a designated investor, either public or private, provides hydrogen storage infrastructure, adoption occurs earlier and more rapidly. The reason lies in the redistribution of investment risk. When companies do not need to finance and construct their own storage, their willingness to adopt hydrogen increases. This is especially impactful for smaller firms, which typically face steeper capital constraints. Instead of having to pay upfront capital costs, they engage through predictable access fees, which are easier to incorporate into operational budgets. In contrast, when storage governance is decentralized and left to industrial users, whether individual or shared, companies are required to self-finance storage, which presents higher thresholds for participation. This results in delayed adoption, particularly among smaller firms, and a more uneven distribution of hydrogen use across the cluster.

Moreover, although the model does not explicitly simulate reinforcing dynamics, such as the feedback loop between growing adoption, increased demand, and market confidence, the behavioral logic suggests that these mechanisms are at play. In both the DSO and private investor scenarios, users are more assured of infrastructure availability and continuity. In practice, this assurance would likely trigger self-reinforcing loops: early adopters increase market activity, which justifies further investment, reduces costs, and attracts new users, accelerating the transition. The model captures the direction of these effects, even if it cannot reflect their full system-level amplification.

8.2 From Literature Perspective

The findings of this study align with and expand on existing academic literature related to energy transitions, infrastructure governance, and institutional design. At its core, the research confirms well-established insights from transition theory, particularly the notion that institutional arrangements can either promote or hinder the adoption of sustainable technologies. Similar to arguments presented in strategic niche management (SNM) and the multi-level perspective (MLP), early adopters in this study

are influenced not only by price signals but also by the stability, trust, and supportiveness of the socio-technical environment around them. The more robust and coordinated the institutional setting, the fewer obstacles there are to adoption. This supports claims in the literature that highlight the significance of regime-aligned infrastructure and enabling institutions in scaling innovation (Geels, 2014; Kanger et al., 2020). For example, the DSO model aligns with the concept of "protective spaces" for experimentation, where the public operator protects early adopters from full market exposure, thereby reducing perceived risks (Smith & Raven, 2012). This explains why adoption tends to start earlier and occurs more uniformly when the public sector takes on a coordinating role.

The results of this simulation also add nuance to the debate on market liberalization in infrastructure provision. The private storage operator, while profit-driven, still delivers strong adoption outcomes due to its contractual clarity and investment incentives. This supports perspectives from institutional economics (Williamson, 2000), suggesting that private actors can play a pivotal role in infrastructure transitions, provided that transaction costs are minimized through well-designed contracts. However, the scenario also demonstrates the limitations of such models for inclusivity: without proper regulatory mechanisms to ensure access for smaller players, liberalized systems can result in market failures, resulting in imperfect information and inequalities, a concern noted in both critical transition studies and policy design literature (Avelino & Rotmans, 2009; Meadowcroft, 2011).

What distinguishes this research is the combination of behavioral modeling with institutional variation, bridging a gap between techno-economic optimization models and more qualitative institutional frameworks. The agent-based model used here translates theoretical expectations about actor behavior under different institutional settings into measurable outcomes, such as adoption rates, storage investment, and hydrogen share. In doing so, it provides an operational view of institutional performance, which is often lacking in high-level policy discussions.

8.3   From Policy Perspective

For policymakers seeking to foster an inclusive and timely hydrogen transition, the governance of hydrogen storage infrastructure emerges as a strategic lever, not only for coordinating investments but also for shaping market behavior and distributing benefits among industrial actors. The findings of this study emphasize that institutional structures and the allocation of property rights are not merely technical details but fundamental design choices that influence the trajectory and equity of the transition.

Central to this is the question of who should own and control the storage infrastructure. When storage is governed as a public good, it becomes easier for everyone to access, not just the most prominent players, thereby reducing barriers to entry for smaller firms and aligning infrastructure development with societal goals, such as decarbonization, security of supply, and regional economic inclusion. From a policy design standpoint, the way storage is institutionalized fundamentally determines how incentives translate into behavior. Ownership models influence who makes decisions, who bears risk, and how costs are recovered. For example, property rights allocated to a neutral, regulated actor enable long-term planning and equitable access, whereas market-driven ownership favors modular expansion but often leads to differentiated access and higher costs for risk-averse actors. This suggests that the institutional environment must be tailored to the policy goals: whether the priority is speed, efficiency, or inclusivity.

Equally important are the complementary instruments used to steer system dynamics. Subsidies, for instance, can be powerful enablers of infrastructure rollout, but their impact depends heavily on institutional capacity to act on them. Actors must be coordinated enough to mobilize capital before subsidy windows close. Without mechanisms for aggregation, available subsidies may go underutilized or be captured by a small subset of well-positioned firms. Rather than offering extensive subsidies, policymakers must direct funding differentially across the value chain: supporting early adopters and smaller firms. This targeted approach ensures that institutional asymmetries, such as differences in capital availability or administrative capacity, do not promote exclusion. For example, supporting a storage operator who offers access contracts at transparent, regulated prices may be more effective than subsidizing individual firms to build their own assets.

This forces regulators to design the market's institutional structure, including assigning roles and responsibilities, and regulating the activities of specific players. The level of regulation is crucial for the rollout of the hydrogen market. Whether it will be a natural monopoly or a competitive market will determine the emergence of formal rules and informal norms between the players. If access to hydrogen storage is governed by contracts, auctions, or capacity bundles, then regulatory safeguards are needed to ensure fair participation and price transparency. In liberalized settings, this may involve mandating open-access rules, price caps, or minimum capacity allocations for SMEs. In more regulated settings, the focus shifts to ensuring governance accountability and cost recovery without suppressing adoption incentives.

8.4   From Industry Perspective

For industrial actors considering the transition to hydrogen, this study emphasizes that strategic positioning is not just about timing or cost, but essentially about understanding the institutional context and aligning internal decision-making with the changing institutional structure. When a company comprehends these institutional settings, it is more likely to benefit from following the rules. Knowing how much risk to incur or the optimal timing for transition all stem from the governance model, allowing firms to achieve long-term benefits.

One of the clearest insights for industry is that governance models directly affect the level of commitment required from companies. In systems where infrastructure is provided through third-party access (TPA), firms are not required to make large upfront investments. This lowers the entry barrier, especially for firms that are capital-constrained or cautious about locking in resources in an uncertain regulatory environment. In such cases, companies should adopt a watchful but proactive stance, monitoring infrastructure rollouts and subsidy frameworks while preparing internally for rapid adoption when access becomes viable. Participating early can yield long-term cost advantages, particularly if fees remain fixed over time.

In contrast, when the burden of developing infrastructure falls on firms themselves, strategic coordination becomes essential. Companies must assess not only their own readiness but also that of their peers. This requires trust among companies within a cluster, transparent communication, and a shared willingness to pool resources. For larger firms, there may be reputational and structural benefits to leading such coalitions, especially if they can shape the terms of the investment and gain early

access to cost reductions from economies of scale. Smaller firms, on the other hand, may find their best entry point in aligning with cooperative platforms or forming joint investment vehicles.

A key lesson for industrial companies is that the energy transition is not an instant but a cumulative and iterative process. It requires developing flexible strategies that allow for the gradual integration of hydrogen into their energy mix. This may involve phasing capital expenditures, renegotiating contracts for larger supplies over time, or combining hydrogen with other low-carbon technologies. Crucially, companies should monitor not only hydrogen prices but also policy timelines, infrastructure developments (such as the national backbone), and the behavior of other companies. In contexts where reinforcing dynamics are likely to emerge, such as when large-scale adoption drives down costs and accelerates supply expansion, firms that delay may miss critical cost windows or find themselves locked out of limited infrastructure.

9   Conclusion

This final chapter synthesizes the main findings of the study. It begins by answering the research questions, followed by practical recommendations. It then discusses the study's limitations and proposes directions for future research.

9.1   Answering the Research Questions

To address the main research question—*'Which hydrogen storage ownership model is most likely to enhance the adoption of hydrogen by Cluster 6 companies?'*—it is necessary to first answer the sub-questions.

SQ1: What formal regulations and policies govern hydrogen (storage) in the Netherlands?
In the Netherlands, hydrogen policies are shaped by a mix of national strategies, energy laws, and evolving operational standards. Key documents such as the National Hydrogen Strategy (2020), the Cluster Energy Strategies (CES), and the Energy Act (which combines and revises the Gas and Electricity Acts) establish the institutional and legal framework for hydrogen production, storage, and transportation. These documents outline the roles of hydrogen producers, grid operators, and industrial stakeholders in a developing hydrogen value chain, emphasizing the need to increase low-carbon hydrogen supplies, promote regional adoption, and reduce regulatory uncertainty. They provide the roadmap for scaling up the production (electrolysers) capacity and the timeline of the national backbone construction. However, many issues, such as governance structures for above-ground hydrogen storage, remain unaddressed. This poses a challenge for hydrogen offtake because above-ground storage is a good initial step toward industrial decarbonization until sufficient capacity in UHS salt caverns is developed. Currently, without clear rules, companies are responsible for arranging their own storage, complying with safety regulations, and obtaining lengthy permits. This process is costly and deters companies from transitioning, as it requires significant effort and capital to achieve sustainability. This situation urges regulators to develop the most effective ownership model to support a large-scale transition.

SQ2: Who are the actors involved, and what are their interactions and responsibilities in the emerging hydrogen system in a decentralized industrial cluster?
The emerging hydrogen system in decentralized industrial clusters consists of several key actor groups, each with distinct roles, responsibilities, and interdependencies. These include industrial companies, hydrogen producers, infrastructure operators, and regulators. Together, they constitute the full hydrogen value chain, spanning demand, infrastructure, supply, and governance. Industrial companies represent the demand side of the system. They seek to adopt hydrogen to replace natural gas in their production processes as they must commit to the Dutch and EU decarbonization goals. However, their decision to adopt hydrogen depends on several key factors, including access to storage infrastructure, cost certainty, subsidy availability, and confidence in widespread acceptance of hydrogen. In the early stages of the transition, industrial companies are generally risk-averse and hesitant to engage in capital-intensive investments in storage unless clear benefits and stability are guaranteed.

Hydrogen producers are upstream entities responsible for generating green hydrogen. They operate electrolysers that are powered by nearby renewable energy sources or electricity from the grid. In decentralized clusters, production can be integrated within the park or connected via pipelines to external production centers. They are responsible for delivering consistent volumes of hydrogen to the users through the physical infrastructure of grid operators. Because they rely on downstream commitments of uncertain users and infrastructure coordination, they struggle with capacity planning and scaling.

Grid operators are responsible for developing and maintaining the physical infrastructure needed to transport hydrogen, as well as delivering the energy downstream. While Gasunie (TSO) focuses on national and cross-border transmission of pressurized gas (through pipelines of the newly formed hydrogen backbone), DSOs are more relevant for localized distribution within the built environment and industrial clusters.

Storage plays a vital coordinating role, bridging the gap between hydrogen supply (producers) and demand (users), and ensuring reliability and flexibility in the system. Currently, no specific entity is designated to operate storage, so this part of the value chain is omitted. Dutch government officials plan to appoint a party to operate storage facilities, but there is no legislation in place to confirm this. The role of the operator would include planning, financing, permitting, constructing, and operating hydrogen storage infrastructure.

Regulators define the legal and institutional framework within which all other actors operate. Their responsibilities include crafting national and regional hydrogen strategies, allocating subsidies, enforcing safety and environmental standards, and determining market rules for hydrogen. They decide the degree of liberalization of storage, whether it should be considered a natural monopoly or accessible to anyone. Through policies such as the Energy Act, the Hydrogen Strategy, and sectoral cooperation codes, regulators influence how the system functions by establishing property rights, institutional rules, and financial instruments.

Interactions among actors are influenced by the institutional framework and the allocation of rights and responsibilities. If the system were highly centralized, like natural gas, coordinating activities between stakeholders would be easier. However, with multi-energy systems, coordination becomes more complex because of the many multi-directional activities happening upstream and downstream. Therefore, energy storage has become even more important, yet there are no clear guidelines on how it should operate. With a centralized storage operator (similar to natural gas), industrial companies interact with a single infrastructure provider while regulators monitor the fairness and efficiency of these interactions. Conversely, in a liberalized energy system, users organize the storage connection on their own – they can either set it up independently or through an external party.

SQ3: Which agents, institutional rules, and technical structures regarding hydrogen storage should be incorporated into the Agent-Based Model (ABM)?
To model the institutional dynamics of hydrogen storage adoption, the Agent-Based Model (ABM) developed in this research integrates three core components: (1) agents, (2) institutional rules, and (3) technical structures.

(1) Agents

The ABM focuses on industrial companies as agents, representing the demand side of the hydrogen value chain. This is to simulate adoption from the end-user perspective, which has not been sufficiently incentivized. Thirteen distinct companies are modeled, each with diverse characteristics to reflect realistic variations. Agents differ in energy demand due to their operational size, investment capital for sustainability, and internal strategies for adopting technological innovations. Some companies are more cautious and hesitant, or risk-averse, towards hydrogen, while others are more willing to adopt new technologies. The model allows agents to assess their environment and make informed decisions based on their internal attributes. Once they view hydrogen as a promising opportunity, they will consider investing resources into storage.

(2) Institutional rules

The model represents the status quo, where storage is financed and operated individually by industrial firms without external coordination. The institutional rules in this scenario assume that companies make their own decisions about adoption and investment independently. Storage investments are entirely self-funded, with no shared financing or third-party access. Once a company decides to invest, it experiences a delay during which the storage infrastructure is approved and constructed. After that, the full capacity becomes operational, and the company can receive hydrogen from the provider, store it for short-term use, and utilize it for its production processes. The current institutional framework assumes that individual industrial companies bear full costs and risks, with uncertainty surrounding the widespread adoption of hydrogen.

(3) Technical structure

The technicalities include a physical storage facility that needs to be deployed and financed. To that end, the model incorporates a series of technical and economic parameters grounded in recent literature and policy trajectories. For instance, the capital expenditure for installing hydrogen storage is fixed per kilogram of storage capacity, reflecting average estimates for pressurized tanks. Once storage is installed, it incurs ongoing operational expenses, which account for maintenance, inspection, and operational handling. To reflect investment planning over time, the storage infrastructure is amortized over a 10-year period, which spreads capital repayment evenly across that horizon.

The model also includes energy pricing dynamics to mimic real-world economic signals. The price of hydrogen starts high and decreases over time, reflecting expected cost reductions from technological learning, economies of scale, and a maturing market. Meanwhile, the natural gas price features a dynamic CO_2 pricing component, calculated using the EU Emissions Trading System (ETS), with emissions priced according to an evolving carbon cost trajectory that reaches high costs to discourage natural gas use.

Subsidies serve as a policy tool to encourage investment in storage. The initial capital subsidy rate is high to attract early investments, then decreases over time and is fully phased out after 2040. This decreasing support system reflects a transitional policy approach, where early investments are highly promoted, while later entrants are expected to depend more on market viability.

SQ4: What are the possible storage governance models?
The research identifies three potential hydrogen storage governance models: public-led (DSO), market-led (third-party investor), and collaborative (shared investment). These models offer various setups for

determining who should be authorized to handle storage and whether all stakeholders would benefit from it.

The public-led model, represented in this study by the DSO, assumes centralized ownership and operation of hydrogen storage by a publicly mandated actor. This model is grounded in the logic of natural monopolies and public interest infrastructure, where planning, financing, and access are coordinated to ensure equitable participation and alignment with policy goals. It reflects a proactive, top-down governance structure in which the operator internalizes investment risk, and users pay regulated tariffs based on the levelized cost of storage (LCoS).

In a market-based model, storage is liberalized and unbundled from the state-owned grid operator. Here, private entities participate in the hydrogen value chain as storage infrastructure operators, building and renting out storage capacity for profit. This approach emphasizes contractual access, profit incentives, and market responsiveness. Storage is considered a competitive service rather than a public good, with access governed by market rules such as storage bundles and negotiated fees.

The last proposed model features the shared investment model, which simulates a bottom-up cooperative structure. In this setup, companies form cooperatives and collaboratively plan and fund the development of modular storage facilities, pooling capital and sharing capacity based on their energy needs. This governance structure depends on mutual coordination, trust, and timing. Instead of centralized control or market contracts, governance here relies on consensus and collective rules.

SQ5: Which key performance indicators (KPIs) should be used to assess hydrogen adoption?
To evaluate the effectiveness of selected hydrogen storage ownership models on hydrogen adoption, several key performance indicators (KPIs) were selected based on their relevance to both system-level outcomes and stakeholder-specific benefits.

The most informative KPI for adoption is the hydrogen share in the total energy mix of industrial companies. This indicator directly captures the degree to which firms transition from fossil fuels to hydrogen. As hydrogen use increases, the share reflects the pace and extent of decarbonization. It also indirectly reveals the effectiveness of institutional and economic arrangements in enabling that transition.

A second key indicator is the total installed storage capacity, measured in kilograms of hydrogen. This reflects the scale of infrastructure development over time and shows how quickly capacity is utilized. It also reveals how well the system is prepared to meet future hydrogen demand.

At the company level, the net economic benefit is a financial metric that measures the total cost savings from switching to hydrogen, minus the expenses incurred through investment or access to storage (depending on the scenario). This helps determine whether and how different actors benefit financially under each governance model.

Additional indicators include the year a company started using hydrogen, which provides insights into the transition timing; the distribution of investments per company, which reveals equity implications; and, in scenarios involving external operators, the operator's benefit.

Main Research Question: Which hydrogen storage ownership model is most likely to enhance the adoption of hydrogen by 'Cluster 6' companies?

The comparative analysis of the three storage ownership models reveals that institutional design has a profound influence on the adoption of hydrogen in decentralized industrial clusters. While each model enables significant improvements over the current state, their impact varies across dimensions such as adoption speed, equity, financial outcomes, and systemic coordination.

A model where a public grid operator operates storage scores highest in terms of adoption timing and system-wide decarbonization. Companies begin adopting hydrogen by 2028, and by 2050, the hydrogen share in the cluster's energy mix reaches approximately 73%. Public operator, acting as a non-profit entity, internalizes investment risk and capital costs, allowing firms, especially smaller ones, to access infrastructure through regulated storage fees. The DSO also times investments to align with peak subsidy periods, lowering the Levelized Cost of Storage (LCoS). In addition, this governance model yields the highest net social benefit, as shown through the cost-benefit analysis, which includes not only economic gains but also environmental and social benefits. From a systems integration perspective, this model offers the most inclusive and stable path forward.

However, this does not imply that the DSO-governed storage is universally optimal. The shared investment model offers distinct advantages, particularly in terms of individual net economic benefit for participating companies. Although the total hydrogen share reaches a slightly lower level, companies co-invest in infrastructure and directly benefit from favorable subsidy timing and shared capital expenditures. This model fosters trust and collaboration among firms and demonstrates how decentralized governance can be effective when coordination mechanisms are strong. It also reduces investment disparities, offering a more equitable structure than when investing individually.

The private investor scenario introduces a market-based solution that balances profit-seeking behavior with infrastructure growth. Adoption begins later than in the DSO model but still earlier than the baseline. Although access fees are higher due to profit margins, this model shows that vertical unbundling and liberalized access can deliver high adoption levels if contracting is efficient. It is especially attractive for industrial clusters with active private actors willing to invest under clear and stable regulatory frameworks. Furthermore, this model offers a viable business case for new entrants into the hydrogen storage market, promoting competition and innovation.

Each model thus presents trade-offs: the DSO model maximizes social benefit and early adoption, but does not yield the highest returns for the companies. On the other hand, the shared model provides the highest financial returns to users but results in greater disparity and unequal contribution to the storage investment. The private investor model demonstrates scalable market-driven efficiency, but companies do not receive high financial benefits. Taking into account the institutional and financial barriers faced by small and medium-sized firms, the complexity of coordination in early-stage markets, and the pressing need for rapid decarbonization, the DSO-led governance appears to be the most likely to enhance hydrogen adoption in 'Cluster 6'. It offers the clearest institutional assurance, the lowest adoption barriers, and the broadest system-wide benefits, making it the most robust configuration for supporting an inclusive and accelerated hydrogen transition.

9.2   Recommendations

The findings of this research lead to a few strategic and policy recommendations aimed at supporting the adoption of hydrogen in Cluster 6. These recommendations target both institutional design and policy instruments and are based on the comparative performance of the different storage governance models tested.

1.   Specify a Designated Storage Operator in the Regulatory Framework

The policymakers must establish a specific governance model and enforce it in practice. Whether it involves public or private operators or shared ownership, it is essential to incorporate it in policy documents so that companies are less hesitant and more confident in considering a transition to hydrogen. This would serve as a stimulus to encourage the energy-intensive industrial sectors to adopt green hydrogen in their processes, given its ability to decarbonize heavy industries. Based on this study, the most beneficial governance model involves a public system operator to coordinate and finance hydrogen storage infrastructure, thereby significantly reducing upfront investment risk for industrial firms. Such institutional arrangements enable earlier and broader adoption, and provide more equity for smaller and medium-sized enterprises (SMEs). Therefore, national or regional governments should consider making hydrogen storage a natural monopoly or allowing public-private partnerships with strong public oversight.

2.   Regulate Storage Component of the Value Chain

Regardless of the level of liberalization of hydrogen storage, the market regulator (ACM) must ensure that access to information remains transparent and fair. No market failures should occur, as this would undermine the competitive practice. For a natural monopoly, the ACM must ensure that the operator delivers the best services and does not misuse its authority. For a competitive market, ACM must regulate, for example, through ex-ante measures, such as price caps on access fees, equal opportunity for SMEs, and mandatory and open tendering for a private storage operator at a cluster, which would maximize institutional efficiency and ensure fairness for all market participants. Regulatory frameworks must also guard against market concentration and ensure that profit-seeking behavior does not undermine public objectives.

3.   Administrative Simplicity and Availability of Storage Incentives

To facilitate the transition to hydrogen, policymakers must ensure the process is straightforward and appealing for energy users. Otherwise, companies may not view it as in their best interest to switch to more sustainable practices. Instead of only punishing non-adopters by taxing fossil fuels, the government should offer incentives for companies to adopt hydrogen and other carbon-free solutions. This includes providing clear information about available financial tools, streamlining the permitting process, and establishing strong and clear safety protocols. Perhaps a dedicated agency could be established to assist companies in obtaining the necessary permits and safety certificates.

Offering subsidies for infrastructure investment is essential to boost investor confidence and attract more players to the market. Early adopters should receive additional benefits, as research indicates that demand-side delays slow down adoption. If people view hydrogen as a practical alternative to natural gas, it will become more widely accepted and standardized. Although electrolyzer capacities are rapidly expanding within the national strategy, delayed adoption can create a mismatch between upstream and downstream processes, thereby compromising the effectiveness of the transition. Policymakers must ensure storage subsidy schemes are transparent and accessible, regardless of the

governance model, whether it is centralized operators ot individual ownership. Simplifying the application and distribution process for subsidies will be crucial to overcome the barrier and enable large-scale utilization.

4. Demand-Responsive and Behavior-Driven Policies

Hydrogen storage infrastructure should not be developed solely based on projected supply-side availability. Since the end users ultimately utilize the storage capacity, policy planning must be responsive to demand-side behavior. The companies are not just energy consumers but mostly production-oriented entities whose decisions are shaped by internal priorities. For them, energy must be affordable, accessible, and secure, not just technically available.

This requires a fundamental shift in hydrogen policy design. Instead of assuming a common adoption logic based on economic or technical feasibility, policymakers must understand the behavioral aspects of industrial adoption. Firms vary in evaluating risks and benefits, influenced by capital, risk tolerance, strategy, and perceptions. Thus, policy frameworks must be more behavior-driven. This includes not only offering financial incentives but also designing institutional environments that build trust, reduce uncertainty, and align with company values. Understanding companies' needs allows for more aligned and robust strategies for scaling up hydrogen adoption. Bottom-up approaches, such as agent-based modeling, combined with stakeholder engagement and behavioral diagnostics, can help policymakers anticipate how companies will respond to different policies and how these responses affect the emergent behavior of the system. By embedding these insights into infrastructure planning, governments can avoid underutilized investments and ensure that policies are both inclusive and effective.

9.3 Limitations and Future Work

While this study offers valuable insights into the institutional dynamics of hydrogen storage adoption, several limitations must be acknowledged. First, the model adopts a demand-side focus, meaning that upstream factors such as hydrogen production capacity, transport constraints, and supply-side price dynamics are not explicitly modeled. While this scoping allows for a deeper exploration of end-user behavior and institutional governance, it omits potential bottlenecks that may arise from limited supply, fluctuating production costs, or infrastructure gaps. These supply-side dynamics are particularly relevant when assessing system-wide feasibility and coordination.

Second, while the model includes agent heterogeneity through varied behavioral attributes (e.g., risk tolerance, investment motivation), these parameters are **synthetically** assigned and remain static throughout the simulation. This simplification excludes dynamic processes such as learning, adaptation, or evolving firm strategies. Moreover, industrial companies are modeled as a single type of agent, despite the substantial variability in operational needs, decision-making processes, and hydrogen demand profiles across sectors such as chemicals, food processing, or metal industries. This limits the model's ability to represent sector-specific adoption patterns.

Third, the three institutional scenarios used in the simulation are intentionally idealized to reflect distinct governance logics. The DSO is modeled as a neutral, non-profit actor, while the private investor pursues profit-maximization. Although grounded in energy market literature, real-world institutions often behave more ambiguously, influenced by politics, bureaucracy, or lobbying.

Fourth, the model is only validated internally for uncertainty in choosing parameters and for scenario comparability. While this approach confirms the consistency and robustness of the simulation logic, external validation, such as confronting the simulation results against real-world data or stakeholders evaluating model outputs, was not conducted. Stakeholder interviews were used to shape the institutional logic and scenario design, but the simulation results themselves were not presented back to the stakeholders for validation. This creates a gap between conceptual alignment and empirical credibility.

Lastly, the model does not account for future exogenous shocks or policy shifts that could significantly influence hydrogen adoption, such as evolving CO_2 pricing regimes, the rise of nuclear hydrogen, changing subsidy frameworks, or broader macroeconomic developments.

To overcome the limitations mentioned above, future research should explore the following directions:
- Coupling supply-demand dynamics and integrating transport networks.
- Modeling heterogeneous governance structures across multiple clusters.
- Empirically calibrating agent behaviors using real-world data.
- Conducting external validation with stakeholders and experts.
- Simulating possible future policies that might influence system behavior to include more variety in the results.

9.4   Use of Artificial Intelligence in the Research

Artificial intelligence (AI), particularly OpenAI's ChatGPT, played a supportive role in this research project. While the researcher independently conducted the core analytical and conceptual tasks, such as model design, scenario development, data analysis, and interpretation, AI was used to improve the overall clarity, efficiency, and quality of the thesis. The AI's main contribution was in refining and structuring the text. ChatGPT helped enhance sentence flow, refine phrasing, and improve the readability of academic arguments without changing their intended meaning. This was especially helpful when writing complex institutional reflections or presenting simulation results in a clear and consistent narrative.

AI also played an important role in supporting the technical documentation of the ABM. While the model was developed independently in Python, ChatGPT assisted in building a structure and creating classes and functions specific to the Mesa library, as well as helping plot the results and debug errors during simulations. This saved a lot of time that I could use to make my code more advanced and coherent.

Beyond code-related tasks, ChatGPT helped shape the structure of the report's chapters. By offering suggestions on how to position findings or frame strategic and policy implications, it contributed to the development of a more structured and compelling narrative. However, all content ideas, arguments, and analytical choices were ultimately based on the researcher's own interpretation of simulation outputs and literature.

In conclusion, AI significantly improved the efficiency and quality of the research process while being fully guided by the researcher. Its contributions remained within the scope of textual refinement, technical support, and structural feedback. The usage of AI allowed more time and attention to be devoted to the substantive and interpretive aspects of the research.

Bibliography

ACM. (2024, December 12). ACM publishes explanation of new rules regarding third-party access to hydrogen terminals. ACM.nl. https://www.acm.nl/en/publications/acm-publishes-explanation-new-rules-regarding-third-party-access-hydrogen-terminals

Agastya Hydrogen. (2025, April 8). Hydrogen storage: the key to unlocking a green energy future. https://agastyah2.com/hydrogen-storage-solutions/

Ajzen, I. (1991). The theory of planned behavior. Organizational Behavior and Human Decision Processes, 50(2), 179–211. https://doi.org/10.1016/0749-5978(91)90020-T

Amos, W. A. (1998). *Cost of storing and transporting hydrogen* (NREL/TP-5700-2510). National Renewable Energy Laboratory. https://doi.org/10.2172/6574

Avelino, F., & Rotmans, J. (2009). Power in transition: An interdisciplinary framework to study power in relation to structural change. European Journal of Social Theory, 12(4), 543–569. https://doi.org/10.1177/1368431009349830

Berenschot. (2022). *Versnelling van de waterstofeconomie: De rol van decentrale overheden*. https://www.berenschot.nl

Better-tech. (2024, September 25). The lowest bidder wins the order: Is energy storage unprofitable or does it have amazing gross margins? https://www.better-tech.net/news/the-lowest-bidder-wins-the-order-is-energy-storage-unprofitable-or-does-it-have-amazing-gross-margins#:~:text=In%20the%20first%20half%20of%20this%20year%2C,high%20growth%20rate%20in%20the%20future%20.%22

Blagrave, P., & Furceri, D. (2021). The macroeconomic effects of electricity-sector privatization. Energy Economics, 100, 105245. https://doi.org/10.1016/j.eneco.2021.105245

BloombergNEF. (2025, March 6). Europe's New Emissions Trading System Expected to Have World's Highest Carbon Price in 2030 at €149, BloombergNEF Forecast Reveals. https://about.bnef.com/blog/europes-new-emissions-trading-system-expected-to-have-worlds-highest-carbon-price-in-2030-at-e149-bloombergnef-forecast-reveals/#:~:text=BloombergNEF%27s%20(BNEF%27s)%20EU%20ETS%20II%20Market%20Outlook,a%20result%2C%20leading%20to%20significant%20emissions%20abatement.

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. Proceedings of the National Academy of Sciences, 99(Suppl 3), 7280–7287. https://doi.org/10.1073/pnas.082080899

Burke, A., Ogden, J., Fulton, L., & Cerniauskas, S. (2024). Hydrogen Storage and Transport: Technologies and Costs. In Institute of Transportation Studies, UC Davis (UCD-ITS-RR-24-17). https://escholarship.org/content/qt83p5k54m/qt83p5k54m_noSplash_8bb1326c13cfb9aa3d0d376ec26d3e06.pdf?t=s9oa2u

CE Delft. (2022). *The role of hydrogen in industrial decarbonisation*. https://cedelft.eu/publications/

CIEP. (2022). Hydrogen policy in the Netherlands: An integrated approach. Clingendael International Energy Programme. https://ciep.energy/media/pdf/uploads/ZlrEOzv8hlcsJ446bdufMwnQfOXm9ymB6hpETq0i.pdf

CMS Law. (2023). *Netherlands: Towards a Hydrogen Market Framework*. https://cms.law

Colaluce, L. (2024, October 15). The price of electricity generation with green hydrogen rises and approaches 250 €/MWh. Strategic Energy Europe. https://strategicenergy.eu/aumento-costo-hidrogeno-verde/#

Crown. (2023). Hydrogen transport and storage cost report. https://assets.publishing.service.gov.uk/media/659e600b915e0b00135838a6/hydrogen-transport-and-storage-cost-report.pdf

Czitrom, V. (1999). One-Factor-at-a-Time versus Designed Experiments. The American Statistician, 53(2), 126–131. https://doi.org/10.2307/2685731

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319–340. https://doi.org/10.2307/249008

Di Micco, S., Romano, F., Jannelli, E., Perna, A., & Minutillo, M. (2023). Techno-economic analysis of a multi-energy system for the co-production of green hydrogen, renewable electricity and heat. International Journal of Hydrogen Energy, 48(81), 31457–31467. https://doi.org/10.1016/j.ijhydene.2023.04.269

Dimitrova, M. (2024, April 26). What is the EU ETS 2 price forecast for 2030? Homaio. https://www.homaio.com/post/what-is-the-eu-ets-2-price-forecast-for-2030

EBN-TNO. (2024). *Underground Hydrogen Storage in the Netherlands*. Retrieved from https://www.earthdoc.org/content/papers/10.3997/2214-4609.202421118

Edelenbos, J., & Klijn, E. (2005). Managing stakeholder involvement in decision making: A comparative analysis of six interactive processes in the Netherlands. Journal of Public Administration Research and Theory, 16(3), 417–446. https://doi.org/10.1093/jopart/mui049

EIA. (November 18, 2021). Carbon Dioxide Emissions Coefficients by Fuel. https://www.eia.gov/environment/emissions/co2_vol_mass.php

Eicke, L., & De Blasio, N. (2022). Green hydrogen value chains in the industrial sector—Geopolitical and market implications. Energy Research & Social Science, 93, 102847. https://doi.org/10.1016/j.erss.2022.102847

Elestor. (n.d.). Cost of storage. https://elestor.com/technology/cost-of-storage

Enserink, B., Bots, P. W. G., van Daalen, C., Hermans, L. M., Kortmann, L. J., Koppenjan, J., Kwakkel, J. H., Ruijgh-van der Ploeg, M. P. M., Slinger, J., & Thissen, W. A. H. (2022). Policy Analysis of Multi Actor Systems. (2nd edition ed.) TU Delft OPEN Publishing. https://doi.org/10.5074/T.2022.004

Epstein, J. M., & Axtell, R. (1996). Growing artificial societies: Social science from the bottom up. MIT Press.

Eslamizadeh, S., Ghorbani, A., & Weijnen, M. (2023). Establishing industrial community energy systems: Simulating the role of institutional designs and societal attributes. Journal of Cleaner Production, 419, 138009. https://doi.org/10.1016/j.jclepro.2023.138009

European Commission. (2023a). IPCEI Hy2Use Factsheet. https://ec.europa.eu

European Commission. (2023b). Cost of hydrogen production. European Hydrogen Observatory. https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production

Fishbein, M., & Ajzen, I. (1975). Belief, attitude, intention and behavior: An introduction to theory and research. Reading, MA: Addison-Wesley.

Frischmuth, F., Berghoff, M., Braun, M., & Haertel, P. (2024, April 19). Quantifying seasonal hydrogen storage demands under cost and market uptake uncertainties in energy system transformation pathways. arXiv.org. https://arxiv.org/abs/2404.12974

Fu, P., Pudjianto, D., Zhang, X., & Strbac, G. (2020). Integration of Hydrogen into Multi-Energy Systems Optimisation. Energies, 13(7), 1606. https://doi.org/10.3390/en13071606

FuelCellsWorks. (2025). *The Netherlands Implements RED III Targets for Green Hydrogen Consumption*. https://fuelcellsworks.com/2025/03/18/green-hydrogen/the-netherlands-implements-red-iii-targets-for-green-hydrogen-consumption-with-important-exemption-for-users-without-a-hydrogen-grid-connection

Gasunie. (2022). *Hydrogen infrastructure: A national backbone*. https://www.gasunie.nl/en/projects/hydrogen-backbone

Gbangbola, O. H. (2022). *Understanding Electrolysers and the Netherlands Hydrogen Strategies*. SSRN. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4887902

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. Research Policy, 33(6–7), 897–920.

Geels, F. W. (2014). Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. Theory, Culture & Society, 31(5), 21–40. https://doi.org/10.1177/0263276414531627

Ghorbani, A., Bots, P., Dignum, V., & Dijkema, G. (2013). MAIA: A framework for developing agent-based social simulations. Journal of Artificial Societies and Social Simulation, 16(2). https://doi.org/10.18564/jasss.2166

Government of the Netherlands. (2020). *Government Strategy on Hydrogen*. https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen

Government of the Netherlands. (2023). *Climate Policy*. https://www.government.nl/topics/climate-change/climate-policy

Han, J., Wang, J., He, Z., An, Q., Song, Y., Mujeeb, A., Tan, C., & Gao, F. (2023). Hydrogen-powered smart grid resilience. Energy Conversion and Economics, 4(2), 89–104. https://doi.org/10.1049/enc2.12083

Hasankhani, M., van Engelen, J., Celik, S., & Diehl, J. C. (2024). Unveiling complexity of hydrogen integration: A multi-faceted exploration of challenges in the Dutch context. Journal of Cleaner Production, 434, 139927.

Horizon Europe. (2023). Advanced materials for hydrogen storage tanks. Horizon-europe.gouv.fr. https://www.horizon-europe.gouv.fr/advanced-materials-hydrogen-storage-tanks-34822

HyDelta. (2023). HyDelta 3.0 Reports and Results. https://www.hydelta.nl

Hydrogen Europe. (2024). Hydrogen Infrastructure Report 2024. https://hydrogeneurope.eu

HyLaw. (2019). National Policy Paper: Netherlands. https://www.hylaw.eu/files/2019-03/HyLAW_National%20Policy%20Paper_Netherlands.pdf

Høyland, S. A., Kjestveit, K., & Skotnes, R. Ø. (2023). Exploring the complexity of hydrogen perception and acceptance among key stakeholders in Norway. International Journal of Hydrogen Energy, 48(21), 7896-7908.

IRENA. (2020). Green hydrogen cost reduction. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

Jaag, C., & Trinkner, U. (2011). A general framework for regulation and liberalization in network industries. Chapters. https://ideas.repec.org/h/elg/eechap/12961_3.html

Kanger, L., Sovacool, B. K., & Noorkõiv, M. (2020). Six policy intervention points for sustainability transitions: A conceptual framework and a systematic literature review. Research Policy, 49(7), 104072. https://doi.org/10.1016/j.respol.2020.104072

Karlsson, M., Gebremedhin, A., Klugman, S., Henning, D., & Moshfegh, B. (2008). Regional energy system optimization – Potential for a regional heat market. Applied Energy, 86(4), 441–451. https://doi.org/10.1016/j.apenergy.2008.09.012

Koirala, B. P., Koliou, E., Friege, J., Hakvoort, R. A., & Herder, P. M. (2015). Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. Renewable and Sustainable Energy Reviews, 56, 722–744. https://doi.org/10.1016/j.rser.2015.11.080

Lei, H., Thomas, J., Curnick, O., Shivaprasad, K., Roy, S., & Xing, L. (2024). Integrating Green Hydrogen into Building-Distributed Multi-Energy Systems with Water Recirculation. Applications in Energy and Combustion Science, 100318. https://doi.org/10.1016/j.jaecs.2024.100318

Li, Z., Zhang, W., Zhang, R., & Sun, H. (2020). Development of renewable energy multi-energy complementary hydrogen energy system (A Case Study in China): A review. Energy Exploration & Exploitation, 38(6), 2099–2127. https://doi.org/10.1177/0144598720953512

Ligmann-Zielinska, A., Kramer, D. B., Cheruvelil, K. S., & Soranno, P. A. (2014). Using uncertainty and sensitivity analyses in socioecological Agent-Based models to improve their analytical performance and policy relevance. PLoS ONE, 9(10), e109779. https://doi.org/10.1371/journal.pone.0109779

Liu, K., Xu, Z., Gao, F., Wu, J., & Guan, X. (2023). Coordination optimization of hydrogen-based multi-energy system with multiple storages for industrial park. IET Generation, Transmission & Distribution, 17(6), 1190–1203. https://doi.org/10.1049/gtd2.12726

Macal, C. M., & North, M. J. (2010). Tutorial on agent-based modeling and simulation. Journal of Simulation, 4(3), 151–162. https://doi.org/10.1057/jos.2010.3

Mallapragada, D. S., Gençer, E., Insinger, P., Keith, D. W., & O'Sullivan, F. M. (2020). Can Industrial-Scale Solar Hydrogen Supplied from Commodity Technologies Be Cost Competitive by 2030? Cell Reports Physical Science, 1(9), 100174. https://doi.org/10.1016/j.xcrp.2020.100174

Mantulet, G., Peffen, A., & Cail, S. (2023, November 24). Carbon price forecast under the EU ETS: Is the current design of the EU ETS suited for post-2030 deep decarbonization? Enerdata. https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. Research Policy, 41(6), 955–967.

Meadowcroft, J. (2011). Engaging with the politics of sustainability transitions. Environmental Innovation and Societal Transitions, 1(1), 70–75. https://doi.org/10.1016/j.eist.2011.02.003

Meegahapola, L. (2023). Grid Integration of Hydrogen Electrolyzers and Fuel-Cells: Opportunities, Challenges and Future Directions. *IEEE Smart Grid Bulletin*. Retrieved from https://smartgrid.ieee.org/bulletins/march-2023-1/grid-integration-of-hydrogen-electrolyzers-and-fuel-cells-opportunities-challenges-and-future-directions

Mensah, G., Opoku, R., Davis, F., & Obeng, G. Y. (2024). Techno-economic analysis of green hydrogen production and electric vehicle charging using redundant energy on a solar photovoltaic mini-grid. Cleaner Energy Systems, 100165. https://doi.org/10.1016/j.cles.2024.100165

Merton, R. K. (1968). *The Matthew effect in science: The reward and communication systems of science are considered*. *Science*, 159(3810), 56–63.

Moran, C., Deane, P., Yousefian, S., & Monaghan, R. F. (2023). The hydrogen storage challenge: Does storage method and size affect the cost and operational flexibility of hydrogen supply chains? International Journal of Hydrogen Energy, 52, 1090–1100. https://doi.org/10.1016/j.ijhydene.2023.06.269

Morchid, M., Cherqaoui, M., & Issami, J. (2025). Determinants of Technological Innovation Adoption: An Overview of Modern Theories. African Scientific Journal. Volume 03, Num 28. pp: 0617 – 0634.

Mulder, M., Perey, P., Moraga, J. L., & Centre for Energy Economics Research (CEER). (2019). Outlook for a Dutch hydrogen market: economic conditions and scenarios. In CEER Policy Papers (Vol. 5) [Report]. University of Groningen. https://www.rug.nl/cenber/blog/ceer_policypaper_5_web.pdf

Nationaal Waterstof Programma. (2023). *Voortgangsrapportage 2023*. https://nationaalwaterstofprogramma.nl

NedZero. (2024, April 9). The new energy law: what is it about? https://nedzero.nl/en/news/the-new-energy-law-what-is-it-about

Nikolic, I. (2009). Co-evolutionary Method for Modelling Large Scale Socio-Technical Systems Evolution. PhD Dissertation, TU Delft.

North, D. C. (1990). *Institutions, institutional change and economic performance*. Cambridge University Press.

OECD. (2021). Policies for a Carbon-Neutral Industry in the Netherlands. OECD Publishing.
https://doi.org/10.1787/6813bf38-en

Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2021). Hydrogen production, storage, utilization, and environmental impacts: a review. Environmental Chemistry Letters, 20(1), 153–188.
https://doi.org/10.1007/s10311-021-01322-8

PBL (Netherlands Environmental Assessment Agency). (2022). *Climate and Energy Outlook 2022*. https://www.pbl.nl

QG&M Law. (2024). *Dutch Energy Act Passed by Senate*. https://qgmlaw.com/publications/dutch-energy-act-passed-by-senate

Railsback, S. F., & Grimm, V. (2019). Agent-based and individual-based modeling: A practical introduction (2nd ed.).
Princeton University Press.

Rheinmetall. (n.d.). Multiple-Element Gas Container (MEGC).
https://www.rheinmetall.com/en/products/hydrogen/hydrogen/storage-and-transport-systems/multiple-element-gas-container-megc

Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.

RVO. (2022). *NL Dutch Solutions for a Hydrogen Economy*. Retrieved from https://www.rvo.nl/files/file/2022-05/NL-Dutch-solutions-for-a-hydrogen-economy-V-April-2022-DIGI.pdf

RVO. (2023a). Subsidies and Programmes: SDE++, DEI+, OWE. https://www.rvo.nl

RVO. (2023b). *Cluster Energy Strategy (CES)*. Retrieved from https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/industrie/cluster-energie-strategie

S&P Global Ratings. (2023). Dutch Electricity and Gas Transmission and Distribution Framework: supportive. In S&P Global Ratings (pp. 1–3) [Report]. https://www.enexisgroep.nl/media/jyscjl5r/rating-direct-report-20230307.pdf

Schlund, D., Schulte, S., & Sprenger, T. (2022). The who's who of a hydrogen market ramp-up: A stakeholder analysis for Germany. Renewable and Sustainable Energy Reviews, 154, 111810.

Sheshinski, E. (2003). Privatization and its Benefits: Theory and evidence. CESifo Economic Studies, 49(3), 429–459.
https://doi.org/10.1093/cesifo/49.3.429

Simon, H. A. (1957). *Models of man: Social and rational*. Wiley.

Smith, A., & Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. Research Policy, 41(6), 1025–1036. https://doi.org/10.1016/j.respol.2011.12.012

Sprenkeling, M. & HyDelta. (2023). HYDelta 2_D10.2 Stakeholder perspectives on the societal embeddedness of the development and deployment of hydrogen technologies in the Netherlands. https://publications.tno.nl/publication/34640809/BKRYH8/sprenkeling-2023-stakeholder.pdf

Stam, R., Van Der Linde, C., & Stapersma, P. (2024). Hydrogen policy in the Netherlands: Laying the foundations for a scalable hydrogen value chain. In The Geopolitics of Hydrogen. Studies in Energy, Resource and Environmental Economics (pp. 165–189). Springer. https://doi.org/10.1007/978-3-031-59515-8_9

Steward, D. M. (2009). Scenario Development and Analysis of Hydrogen as a Large-Scale Energy Storage Medium. https://www.researchgate.net/publication/228336554_Scenario_Development_and_Analysis_of_Hydrogen_as_a_Large-Scale_Energy_Storage_Medium

TNO. (2023). Hydrogen Storage: Enabling Flexibility in Renewable Energy Systems. https://www.tno.nl/en/newsroom/insights/2023/01/hydrogen-storage-flexibility

TNO. (n.d.). Large-scale storage and transport of hydrogen: Hydrogen storage and transport. tno.nl/en. https://www.tno.nl/en/sustainable/industry/carbon-neutral-industry/clean-hydrogen-production/storage-transport-hydrogen/

Trading Economics. (n.d.). EU Natural Gas TTF. https://tradingeconomics.com/commodity/eu-natural-gas

United Nations. (2015). Sustainable Development Goals. Retrieved from https://sdgs.un.org/goals

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. MIS Quarterly, 27(3), 425–478. https://doi.org/10.2307/30036540

Walters, D. E., & Wiseman, H. J. (2025, January). Self-regulation in emerging and innovative industries. Retrieved from https://scholarship.law.tamu.edu/facscholar/2160?utm_source=scholarship.law.tamu.edu%2Ffacscholar%2F2160&utm_medium=PDF&utm_campaign=PDFCoverPages

WaterEnergySolutions. (2022, March). CES Cluster 6: Cluster Energie Strategie. Retrieved from https://www.nldigital.nl/wp-content/uploads/sites/3/2023/11/Cluster-Energie-Strategie-Cluster-6.pdf

Williamson, O. E. (2000). The new institutional economics: Taking stock, looking ahead. Journal of Economic Literature, 38(3), 595–613. https://doi.org/10.1257/jel.38.3.595

Xia, Q., Zou, Y., & Wang, Q. (2024). Optimal capacity planning of Green Electricity-Based Industrial Electricity-Hydrogen Multi-Energy system considering variable unit cost sequence. Sustainability, 16(9), 3684. https://doi.org/10.3390/su16093684

Zhang, T., Cao, K., & Wei, Y. (2021). A review of agent-based modeling in energy systems. Renewable and Sustainable Energy Reviews, 135, 110180. https://doi.org/10.1016/j.rser.2020.110180

Zhili, F. (2022). Economically Viable Intermediate to Long Duration Hydrogen Energy Storage Solutions for Fossil Fueled Assets (NETL Report 22FERD_ES_Feng). WE New Energy Inc. https://netl.doe.gov/sites/default/files/netl-file/22FERD_ES_Feng.pdf

Appendix A

Table 12: Agents' Attributes Values

Company	Annual energy demand [MWh]	Capital availability		Willingness to Adopt	Willingness to Invest	Perceived Importance of Energy Security	Risk tolerance	Peer Influence Sensitivity	Regulatory Awareness	Subsidy responsiveness
1	1715	€	175 000.00	0.87	0.94	0.92	0.89	0.3	0.85	0.87
2	1630	€	155 000.00	0.67	0.86	0.85	0.76	0.36	0.88	0.67
3	1460	€	145 000.00	0.69	0.68	0.88	0.69	0.42	0.8	0.77
4	945	€	95 000.00	0.75	0.71	0.79	0.59	0.5	0.91	0.84
5	811	€	80 000.00	0.77	0.88	0.84	0.78	0.58	0.77	0.8
6	608	€	60 000.00	0.53	0.57	0.8	0.54	0.66	0.81	0.76
7	496	€	50 000.00	0.44	0.58	0.69	0.43	0.72	0.67	0.65
8	469	€	45 000.00	0.68	0.72	0.81	0.55	0.78	0.74	0.52
9	452	€	42 000.00	0.31	0.66	0.77	0.75	0.82	0.77	0.75
10	435	€	40 000.00	0.13	0.55	0.74	0.81	0.85	0.66	0.59
11	397	€	37 000.00	0.74	0.16	0.81	0.64	0.87	0.63	0.81
12	332	€	34 000.00	0.46	0.35	0.78	0.39	0.91	0.69	0.67
13	300	€	30 000.00	0.4	0.41	0.66	0.6	0.96	0.6	0.66

Table 13: Scenario Parameters Values

Scenario	Energy Security	Risk Associated	Access to Infrastructure	Peer Influence	Regulatory Knowledge	Subsidy Easiness
Baseline	0.9	0.87	0.35	0.15	0.94	0.75
DSO	0.74	0.4	0.85	0.77	0.3	0.88
Private third party	0.82	0.52	0.7	0.75	0.47	0.81
Shared	0.9	0.79	0.5	0.97	0.79	0.84

Appendix B

Table 14: Price and Policy Forecast for Simulation Period

Year	Hydrogen price (€/MWh)	Natural gas price incl. tax (€/MWh)	ETS tax (€/tCO2)	Subsidy level (%)
2025	240.02	71.36	71.11	
2026	225.62	71.99	72.41	80
2027	211.22	72.62	73.7	
2028	196.82	77.14	83.0	
2029	182.42	86.86	103.0	
2030	168.02	109.21	149.0	70
2031	162.02	111.03	152.73	
2032	156.02	112.84	156.46	
2033	150.02	114.65	160.19	
2034	120.01	116.46	163.91	
2035	90.01	118.27	167.64	
2036	88.01	120.09	171.37	
2037	86.01	121.9	175.1	25
2038	84.01	129.53	190.8	
2039	82.01	137.16	206.5	
2040	80.01	144.79	222.2	
2041	78.01	149.31	231.5	
2042	76.01	153.83	240.8	
2043	74.01	158.35	250.1	
2044	72.01	162.87	259.4	
2045	70.01	279.8	500.0	0
2046	68.01	279.8	500.0	
2047	66.01	279.8	500.0	
2048	64.01	279.8	500.0	
2049	62.01	279.8	500.0	
2050	60.01	279.8	500.0	

Note:

Hydrogen prices are forecasted based on Colaluce (2024), Collins (2023), and Mulder et al. (2019)
Natural gas price taken from Dutch TTF (Trading Economics, n.d.)
The ETS tax forecast is based on Dimitrova (2024), Mantulet et al. (2023), and BloombergNEF (2025)
Subsidy levels estimated from RVO (2023a)