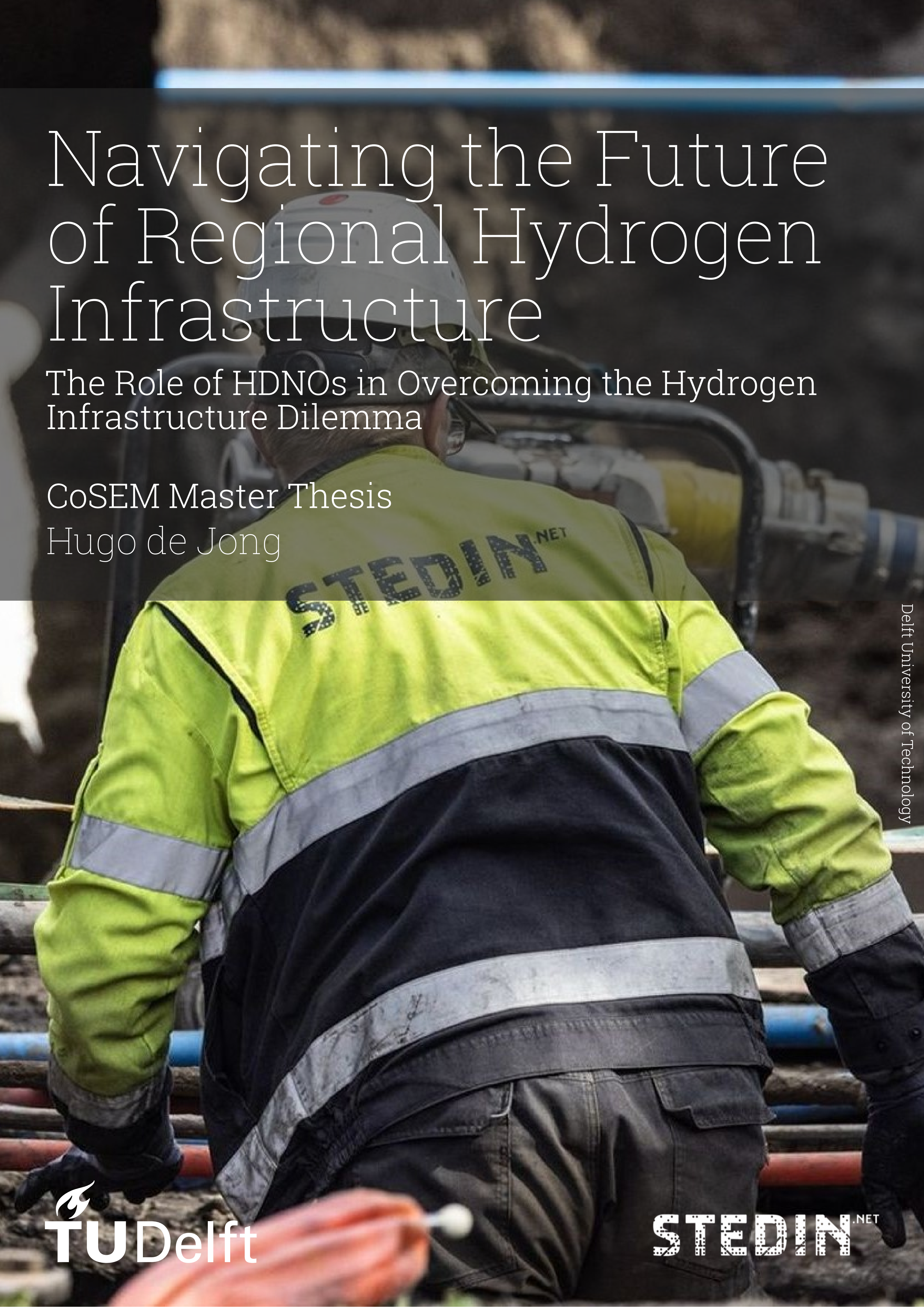

Navigating the Future of Regional Hydrogen Infrastructure

The Role of HDNOs in Overcoming the Hydrogen Infrastructure Dilemma

CoSEM Master Thesis

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The Role of HDNOs in Overcoming the Hydrogen Infrastructure Dilemma

by

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Cover: Technician Inspecting Utility Pipelines, adapted from [142]
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Preface

Before you lies the master thesis *"Navigating the Future of Regional Hydrogen Infrastructure: The Role of HDNOs in Overcoming the Hydrogen Infrastructure Dilemma"*. This thesis marks the conclusion of my journey through the MSc Complex Systems Engineering and Management program at Delft University of Technology.

I've always been interested in how technical solutions can help tackle complex societal problems, and the energy transition is one of the biggest challenges of our time. In exploring this field, I became particularly interested in the role hydrogen could play in the decarbonization of the regional industry. For my final academic project, I decided to focus on hydrogen infrastructure and used agent-based modeling to investigate how it might develop. The method proved to be a valuable learning experience, one that strengthened my abilities as a modeler and system thinker. Most importantly, it showed me that embracing uncertainty and iteration is often key to finding effective solutions.

I had the opportunity to conduct my research at Stedin, which added a valuable real-world dimension to this project. I am especially grateful to Arjen Jongepier and Edward Droste for giving me the opportunity to pursue this thesis within the organization and for supporting the project from its earliest stages, when it was still little more than a collection of initial ideas. Through our regular sparring sessions, we gradually shaped the research into something meaningful, not just academically but also in terms of practical value for Stedin. Their guidance, feedback and enthusiasm were instrumental in turning the concept into a thesis that contributes to ongoing discussions within the company, rather than ending up in a drawer.

I would like to extend my sincere thanks to Amineh Ghorbani and Zofia Lukszo for their thoughtful input throughout our meetings. Their academic expertise and critical insights helped ground this thesis in a strong theoretical and methodological framework. Their feedback consistently challenged me to think more deeply and refine my arguments, greatly enhancing the overall quality of the work. I am especially grateful to Renske van 't Veer for her constant support, clear guidance, and timely feedback. Her practical advice and sharp eye for detail were invaluable in helping me navigate moments of uncertainty and stay focused throughout the research process.

I would also like to thank the entire department of *Systeem- en Netstrategie* at Stedin, as well as the other colleagues with whom I worked during my time there, for their help and contributions to my research. It was a pleasure to conduct my thesis at Stedin, an environment that offered both valuable insight into the energy transition and an engaging setting to work in.

I want to thank the other Stedin thesis students as well for the fun moments, shared frustrations, and mutual support along the way. Going through the process with others who understood the ups and downs made a real difference, and I am grateful to have made some great new connections in the process.

Finally, I want to thank my friends and family for their support, encouragement, and belief in me throughout this process. Your presence, whether offering advice, motivation, or just being present, has meant a lot.

I wish you a pleasant reading experience.

Hugo de Jong
Delft, June 2025

Summary

The Netherlands is in the middle of a major energy transition, with the aim of reducing greenhouse gas emissions by 55% by 2030 and attaining full climate neutrality by 2050. Hydrogen is increasingly seen as a key enabler in this shift, offering a clean fuel alternative to natural gas, especially in industrial sectors where electrification is not feasible. To support this ambition, the Dutch government is supporting large-scale hydrogen production and the development of a national hydrogen infrastructure. Led by HyNetwork Services, the planned hydrogen backbone will be rolled out in phases, ultimately connecting five major industrial clusters, as well as key cross-border links and storage sites by 2033 and beyond.

While the national hydrogen backbone is designed to connect five large industrial clusters, it overlooks a major segment of Dutch industry: the many medium-sized industrial sites scattered across the country, collectively referred to as Cluster 6. These firms, active in sectors such as food, chemicals, metals, and glass, are not slated to have direct access to the hydrogen network. As a result, they face substantial barriers to adopting hydrogen, including long distances to the infrastructure and high connection costs. Electrification is often not a viable alternative because many of these sites are based on high-temperature or high-energy processes that are technically difficult to electrify. Combined with the ongoing congestion of the electricity grid, this leaves few practical decarbonization pathways. Despite their considerable potential to reduce emissions, these companies remain dependent on fossil fuels due to the lack of timely and viable low-carbon options.

This situation reflects a deeper coordination challenge. Medium-sized industries cannot commit to adopting hydrogen without access to infrastructure, while infrastructure providers cannot justify building regional pipeline networks without a sufficient concentration of demand. No operator will build a full network for a single user; demand must be visible and justifiable at scale. This chicken-and-egg dynamic is further compounded by regulatory uncertainty: the role of regional Hydrogen Distribution Network Operators (HDNOs) has not yet been formally defined, leaving existing Distribution System Operators (DSOs) without a clear mandate or framework for anticipatory action. As a result, the hydrogen transition risks stalling across a substantial part of the industrial sector, unless this coordination deadlock can be resolved through more proactive planning approaches. This thesis addresses this challenge by asking:

”How do proactive versus reactive rollout strategies by Hydrogen Distribution Network Operators (HDNOs) shape the societal costs and benefits of hydrogen infrastructure for regional medium-sized industrial users?”

The coordination failure in Cluster 6 is not unique. Similar patterns of mutual hesitation between supply and demand have slowed down infrastructure transitions in other sectors, such as electric vehicles and public transport. Studies consistently show that technological readiness and latent demand are not enough to trigger rollout: early coordination, credible signals, and targeted policy support are often required to break through inertia. These dynamics are well documented in theories of network effects, path dependence, and real options, which explain how uncertainty and fragmented incentives can stall adoption.

What makes regional hydrogen infrastructure particularly challenging is the need to build it from scratch in areas with dispersed and uncertain demand. Unlike current electricity or gas networks, which can expand incrementally, hydrogen pipelines require upfront investment in entirely new systems. These investments are difficult to justify when potential users are spread over a wide area and have not yet committed. In the traditionally demand-driven energy system of the Netherlands, this creates a structural barrier: firms need infrastructure to adopt hydrogen, but infrastructure will not be built without visible and concentrated demand. Without a shift toward more anticipatory planning, the hydrogen transition risks leaving much of the regional industry behind.

To explore how this gap might be addressed, this thesis develops a conceptual agent-based model that simulates HDNO decision making under different investment strategies. The model focuses on the specific coordination challenge in Cluster 6 and examines how proactive versus reactive rollout approaches affect infrastructure efficiency, hydrogen adoption, and broader societal outcomes under real-world constraints.

The model treats infrastructure rollout as a dynamic outcome of decentralized, expectation-driven behavior. Firms make adoption decisions based on cost, proximity to infrastructure, and timing, while a unified infrastructure planner combining the roles of Hydrogen Distribution Network Operator (HDNO) and Distribution System Operator (DSO) evaluates whether demand signals justify investment. This formulation reflects the interdependence between energy carriers in the real world. The model explores three stylized rollout strategies: reactive, where investment follows confirmed demand; proactive, where rollout anticipates it; and delay, where no infrastructure is built.

These strategies are evaluated using a Societal Net Present Value (SNPV) metric that captures both direct financial costs and broader societal outcomes, including emissions reductions and avoided grid reinforcements. By incorporating constraints such as workforce capacity and investment cycles, the model highlights how timing and institutional network operator design influence system-wide outcomes.

The simulation results show that proactive HDNO investment strategies can significantly accelerate the rollout of regional hydrogen infrastructure. In the initial experiments, even modest anticipatory investment, governed by a proactivity parameter β, helps overcome coordination failures, accelerating adoption and improving societal outcomes. Although early rollout involves higher upfront costs, these are offset over time by faster emissions reductions and more efficient infrastructure use. In contrast, reactive strategies that depend solely on confirmed demand lead to delayed, fragmented development and fail to catalyze widespread decarbonization.

Additional experiments highlight the critical role of timing. A well-placed, short proactive window aligned with the investment cycles of the companies can trigger full adoption, while delays often push the companies toward irreversible alternatives such as electrification. Policy design also matters: hydrogen subsidies are more effective when paired with visible hydrogen infrastructure, whereas electricity subsidies tend to fragment adoption and reduce network efficiency. The results emphasize that effective decarbonization depends not just on financial incentives, but on coordinated timing between infrastructure availability and firm-level decisions.

These findings point to a clear conclusion: timing and coordination are critical to unlocking the hydrogen transition for medium-sized industries. To break the current deadlock, infrastructure planning must move beyond reactive logic and instead take on a shaping role, providing credible signals that enable firms to act.

Based on these findings, the thesis recommends that future HDNOs adopt a proactive and spatially targeted rollout strategy. Instead of waiting for confirmed demand, limited infrastructure should be deployed in high-potential industrial areas in anticipation of firms' decarbonization investment cycles. This approach improves network utilization, lowers per-connection costs, and delivers greater societal value than reactive or heavily subsidized strategies. If existing DSOs are to take on this role, they will need a clear mandate, mechanisms for cost recovery, and the institutional flexibility to act on credible but incomplete demand signals. Early stage planning tools, stakeholder coordination, and targeted pilot projects can help enable selective implementation while managing investment risk.

Policymakers must enable this strategy by front-loading regulatory clarity and financial support. The legal frameworks should clearly define HDNO responsibilities, allow anticipatory investment, and support regional coordination. Crucially, incentives must be timed to coincide with visible infrastructure rollout - not delayed until after demand appears. At the same time, medium-sized firms should prepare internally and collaborate regionally to increase their visibility and influence infrastructure planning. When well-timed infrastructure is paired with strategic incentives, it can drive widespread adoption, accelerate decarbonization across dispersed regions like Cluster 6, and ensure a more balanced and impactful energy transition.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ABM	Agent-Based Modeling
ACM	Authority for Consumers and Markets
CAPEX	Capital Expenditure
COSEM	Complex Systems Engineering and Management
DSO	Distribution System Operator
EU ETS	European Union Emissions Trading System
FTE	Full-Time Equivalent
HDNO	Hydrogen Distribution Network Operator
HNS	HyNetwork Services
HP	High Pressure
HTNO	Hydrogen Transmission Network Operator
KPI	Key Performance Indicator
LCOH	Levelised Cost of Hydrogen
LP	Low Pressure
MV	Medium Voltage
NPV	Net Present Value
OPEX	Operational Expenditure
P2G	Power-2-Gas
PRS	Pressure Reduction Station
RAB	Regulated Asset Base
ROI	Return on Investment
SNPV	Societal Net Present Value
TSO	Transmission System Operator
WACC	Weighted Average Cost of Capital

1 Introduction

The introductory chapter begins by presenting the background context (Section 1.1), followed by a statement of the problem (Section 1.2). It then identifies the knowledge gap and formulates the research questions (Section 1.3), along with the chosen research approach (Section 1.4). The chapter also outlines the practical and scientific contributions of the study (Section 1.5) and its relevance to the CoSEM program (Section 1.6). Finally, it concludes with an outline of the report (Section 1.7).

1.1. Background

The Netherlands is committed to cutting greenhouse gas emissions by 55% by 2030 and achieving climate neutrality by 2050 [95]. Hydrogen is positioned to play an important role in this transition [68]. As a clean energy carrier, it does not produce direct greenhouse gas emissions when used in hydrogen fuel cell vehicles or industrial applications and offers a versatile alternative fuel for key sectors such as industry, transportation and heating [46, 117]. In addition to its role as a direct fuel, hydrogen facilitates energy storage through Power-to-Gas (P2G), enabling surplus renewable energy from solar and wind sources to be efficiently stored and utilized when needed [13, 58]. Therefore, to accelerate the integration of renewable energy sources, the Netherlands has set ambitious hydrogen goals, with the aim of achieving 3 to 8 GW of electrolysis capacity by 2030 and increasing to 45 GW by 2050 [95]. To facilitate this transition, hydrogen project development in the Netherlands has increased in recent years. In June 2023, the Dutch government expanded subsidies for renewable hydrogen production, committing an initial € 998.33 million for 2024 to support at least 200 MW of electrolysis capacity, with additional funding expected for subsequent years [94].

In response, the private sector has expressed strong interest in developing large-scale hydrogen production facilities. Among the most prominent initiatives, Air Liquide and TotalEnergies announced a joint investment of € 600 million in two electrolyte facilities to be built in Zeeland and Maasvlakte, with a combined annual production target of 45,000 tonnes of green hydrogen by 2029 [140]. Similarly, Shell's 200 MW Holland Hydrogen I and Eneco's planned 800 MW Eneco Electrolyzer reflect comparable ambitions, with an estimated annual output of approximately 22,000 and 85,000 tonnes, respectively [114, 64]. More projects, including several North Sea initiatives, are being implemented to further strengthen the country's hydrogen infrastructure [126, 26]. However, despite this industrial momentum, most projects have yet to reach a final investment decision. Developers often cite barriers such as policy uncertainty, limited visibility of demand, high cost of connection to the grid, and delays in the delivery of critical infrastructure [143, 144]. As a result, several projects have faced delays, scale reductions, or design changes, indicating that current policy and institutional frameworks are not yet fully aligned with the needs of large-scale hydrogen deployment.

To improve the alignment between national hydrogen ambitions and the infrastructure required to carry out large-scale projects, the Ministry of Economic Affairs and Climate designated Gasunie's subsidiary, HyNetwork Services (HNS), in 2022 to lead the development of a national hydrogen transport network [71]. Following two years of consultation, the proposed backbone is set to be rolled out in four phases.

It will connect five major industrial clusters, hydrogen storage sites and neighboring countries, allowing large-scale hydrogen transport and cross-border decarbonization efforts, as shown in Figure 1.1 [65].

Figure 1.1: Overview of the planned national hydrogen network in the Netherlands, highlighting key industrial clusters, cross-border links, and strategic infrastructure nodes essential for enabling large-scale hydrogen transport and decarbonization.

The first phase of the national hydrogen backbone is expected to be completed in 2026 in Rotterdam, where a 32 kilometer hydrogen pipeline will connect the Tweede Maasvlakte to Pernis, as can be seen in Figure 1.2. By 2030, the network is expected to be operational in Noord-Nederland, Noordzeekanaalgebied, and Zuidwest-Nederland. This includes the integration of the HyStock storage facility in Noord-Nederland and the first cross-border hydrogen connection with Belgium at Zelzate. Between 2031 and 2033, the network will extend further through the Delta Rhine Corridor, linking Rotterdam, Moerdijk, and Chemelot in Limburg with Germany and Belgium. This expansion will create a fully connected system between industrial clusters and international markets. After 2033, additional connections and new pipelines will be added in regions with rising hydrogen demand. These developments will strengthen the capacity of the backbone and ensure long-term supply security [65].

Although the national hydrogen backbone focuses on the five major industrial clusters, Cluster 6 industries, consisting of 450 medium-sized and dispersed facilities in the Netherlands, face significant challenges in adopting hydrogen as a sustainable energy source [81]. These companies, which produce essential goods such as food, chemicals, metals, glass, ceramics, and waste management services, are distributed throughout the country and rely heavily on fossil fuel infrastructure, making their transition to hydrogen particularly challenging. Key barriers to hydrogen adoption include high connection costs due to the distance from the planned hydrogen infrastructure and limited access to hydrogen networks [81, 136]. The lack of a dedicated hydrogen pipeline for Cluster 6 industries means that many will likely miss their 2030 hydrogen integration targets [81]. However, grid congestion further complicates other decarbonization efforts by delaying the electrification of processes and integrating green hydrogen.

Despite the significant challenges faced by Cluster 6 industries, particularly the limited feasibility of electrification due to severe grid congestion, these sectors have considerable potential for CO_2 reductions through the adoption of hydrogen. Many of these industries operate processes that are difficult to electrify using current technologies. A shift from natural gas to green hydrogen could reduce their emissions by more than 50% by 2030 [81]. However, with limited access to hydrogen infrastructure and constrained electrification options due to network congestion, many companies are forced to rely on interim or suboptimal solutions. This underscores the urgent need to develop a regional energy infrastructure that can support the decarbonization of these highly energy-intensive, hard-to-abate industries.

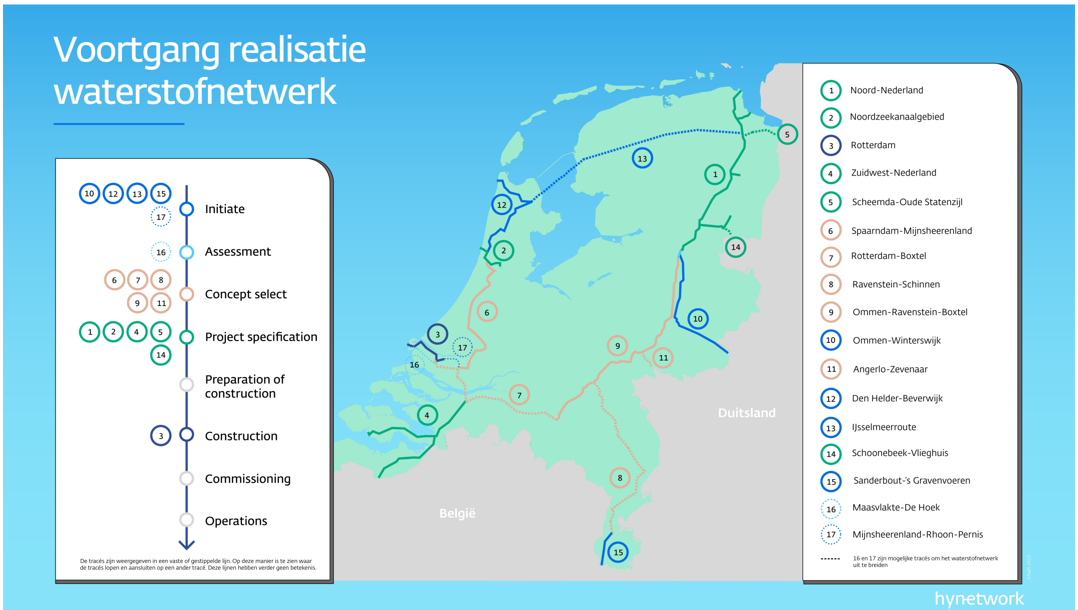

Figure 1.2: Timeline and geographic phasing of the hydrogen backbone rollout in the Netherlands, illustrating how the infrastructure will gradually expand across industrial regions from 2026 to 2033 and beyond.

The urgency of developing regional hydrogen connections raises the fundamental question of who will oversee and manage the regional hydrogen distribution network. Although HyNetwork has been designated as the hydrogen transmission network operator (HTNO) responsible for the national hydrogen backbone, the governance of regional hydrogen distribution networks remains uncertain in the Netherlands. On 21 May 2024, the Council of the EU formally adopted the European Hydrogen and Decarbonized Gas Market Package, establishing a regulatory framework for hydrogen network operations [41]. The H2 Directive (Directive (EU) 2024/1788) requires Member States to define governance structures for regional hydrogen networks. Unlike hydrogen transmission network operators, hydrogen distribution network operators (HDNOs) are not required to be legally independent entities [41]. Instead, the directive requires HDNOs to maintain separate accounting records to ensure financial transparency and prevent cross-subsidization between hydrogen and natural gas operations. This approach allows for synergies between natural gas and hydrogen distribution networks, while ensuring clear financial reporting and regulatory oversight [41].

The directive acknowledges that joint operation of hydrogen and natural gas networks can be beneficial as it enables cost efficiencies and infrastructure synergies. However, the Dutch Ministry of Climate Policy and Green Growth has not yet determined the governance model for the Dutch regional hydrogen distribution. To explore viable approaches, the Ministry has commissioned research that identified five potential models for the deployment of regional infrastructure [66]:

- Multiple network operators, including regional gas network operators (Gas-RNBs).
- Multiple network operators under open competition.
- A single network operator, such as HyNetwork Services (HNS).
- A single network operator as a joint venture of gas network operators.
- A single network operator selected through a tender process.

Regulatory uncertainty over who is responsible for regional hydrogen networks continues to delay investment. Without clear rules on who will develop, manage, and oversee these networks, infrastructure providers remain reluctant to commit [100]. At the same time, the lack of guaranteed market demand adds to their hesitation [66].

In mature sectors such as electricity and gas, DSOs are legally required to connect users under the aansluitplicht set out in Article 23 of the Dutch Electricity Act [91]. This obligation ensures that the infrastructure is delivered once a valid request is made. However, no such obligation currently exists for hydrogen. In the absence of a designated hydrogen distribution operator and matching legal instruments, the rollout remains uncertain and highly risk-sensitive.

The European Commission recommends evaluating the ”energy-economic necessity” of hydrogen networks through joint planning between electricity and gas operators [93]. This helps ensure that infrastructure expansion aligns with national goals in energy and climate. But in practice, pipelines cannot be developed speculatively; they require realistic demand forecasts and credible planning. However, businesses are unlikely to switch to hydrogen without a stable supply and competitive pricing, while infrastructure providers cannot justify major investments without firm offtake agreements. This creates a classic chicken-and-egg dilemma. Companies need infrastructure to commit, but infrastructure providers need commitment to build [66, 63]. Resolving this challenge will require regulatory clarity, strategic coordination between stakeholders, and early-stage policy support to reduce investment risks and unlock the development of regional hydrogen networks [56].

1.2. Problem Statement

The Netherlands is currently investing in a national hydrogen transport backbone to connect major industrial clusters. However, this top-down focus leaves a critical gap: there is no clear strategy for how medium-sized industries, particularly those outside the core clusters, will access hydrogen infrastructure [81]. These industries, spread across the country and often faced with grid congestion or reliance on high-energy fuels, are risk exclusion from the hydrogen transition despite their significant decarbonization potential.

This infrastructure gap is due to unresolved governance and investment uncertainties. While HyNetwork Services (HNS) has been appointed as the national hydrogen transmission network operator (HTNO), no decision has been made on who will oversee regional hydrogen distribution. The EU's Hydrogen and Decarbonised Gas Market Package (Directive (EU) 2024/1788) requires Member States to establish governance structures for regional networks, commonly known as Hydrogen Distribution Network Operators (HDNOs), but the Netherlands is still evaluating several models [41, 66]. Until this governance question is resolved, regional infrastructure planning is likely to remain stalled, leaving medium-sized industries without certainty of future access, even once the national backbone is in place.

At the same time, existing network operators typically follow a reactive investment logic, based on a legal obligation to connect end users only after receiving a formal request [91]. Although effective for mature gas and electricity networks, this approach is poorly suited to an emerging and uncertain technology like hydrogen. Firms will not commit to hydrogen use without infrastructure, but operators will not lay down an entire new energy infrastructure without justifiable demand, a classic coordination failure.

This policy deadlock undermines progress on regional hydrogen rollout and risks delaying industrial decarbonization. The current uncertainty - about who builds, who pays, and when - is slowing investment and planning, especially for infrastructure that serves scattered medium-scale demand. If left unresolved, the Netherlands could miss a key opportunity to decarbonize its mid-sized industrial base in time to meet decarbonization targets.

1.3. Knowledge Gap and Research Questions

Section 1.2 highlighted institutional and investment uncertainties that hinder the regional rollout of hydrogen infrastructure in the Netherlands. This section now turns to the corresponding scientific gap.

Although hydrogen infrastructure planning has gained academic momentum, most studies emphasize national-scale systems and large industrial clusters. These models typically assume coordinated action by transmission system operators (TSOs), treating demand as centralized and relatively predictable [97, 5, 132]. As such, they rely on top-down optimization frameworks to identify cost-effective backbone configurations and long-term transition pathways [48, 146, 79].

In contrast, the deployment of regional hydrogen is characterized by a heterogeneous and spatially dispersed demand, where infrastructure decisions are more decentralized and exposed to uncertainty

[100]. In this context, Hydrogen Distribution Network Operators (HDNOs) are expected to play a key role in connecting medium-sized industrial users. However, the strategic behavior of these operators, particularly in deciding whether to invest proactively based on anticipated demand or reactively in response to confirmed requests, remains underexplored in the academic literature.

While some recent studies have begun to address spatial and institutional complexities at the local level \cite{ates2024, vanderkeur2023hydrogen}, most still do not explicitly model the network operator as an actor with its own decision-making logic. Instead, infrastructure rollout is often treated as a background condition or a centrally planned input, rather than as the outcome of strategic coordination. This overlooks the coevolutionary dynamics between network rollout and industrial adoption, commonly referred to as the chicken-and-egg problem. The resulting coordination failure is especially pronounced in fragmented industrial regions, where no central actor aggregates demand or guarantees access. Without early infrastructure commitments, adoption remains stalled; yet, without adoption, infrastructure is unlikely to materialize.

The central scientific gap, therefore, lies in understanding to what extent different HDNO rollout strategies, ranging from reactive to proactive, can help overcome the coordination deadlock in regional hydrogen deployment. This includes not only the nature of the strategies themselves, but also the timing of their implementation and the extent to which institutional inertia delays action. Specifically, the objective is to examine how these interacting factors shape system outcomes over time, including infrastructure utilization, adoption rates, and societal costs.

The study is guided by the following overarching research question:

> *”How do proactive versus reactive rollout strategies by Hydrogen Distribution Network Operators (HDNOs) shape the societal costs and benefits of hydrogen infrastructure for regional medium-sized industrial users?”*

To operationalize this question, the thesis addresses six subquestions:

1. What are the conceptual trade-offs between proactive and reactive HDNO rollout strategies for regional hydrogen infrastructure in the short and long term?
2. How can the societal costs and benefits of these rollout strategies be defined and evaluated in a regional industrial context?
3. How can HDNO decision making be modeled in the context of regionally distributed industrial demand?
4. How do variations in the timing and scale of the HDNO rollout strategies influence the societal outcomes of the development of regional hydrogen infrastructure?
5. How do proactive policy instruments affect HDNO rollout strategies in regional hydrogen systems?
6. What role can existing DSOs play in enabling the regional rollout of hydrogen infrastructure?

The analysis considers consequences for three key actor groups: (i) medium-sized industrial firms seeking to decarbonize; (ii) the HDNO as infrastructure investor and operator; and (iii) the public sector, concerned with financial, environmental, and energy security outcomes.

By investigating these questions, the thesis contributes to a more realistic and policy-relevant understanding of how regional hydrogen networks can emerge. The objective is to inform both regulatory design and infrastructure planning strategies to ensure that medium-sized industrial regions are not left behind in the hydrogen transition. This analysis is grounded in a case study of Cluster 6 in the Netherlands, providing empirical context to explore regional dynamics while retaining broader applicability.

1.4. Research Approach

Integrating hydrogen infrastructure into the Dutch energy system involves complex technical, regulatory, and societal challenges. These challenges are difficult to address using traditional research methods alone. Qualitative approaches often lack the ability to make predictions, while quantitative optimization models may overlook important dynamics such as feedback loops, changing behaviors, and institutional uncertainty [134]. To fully understand how different actors and decisions influence the system as a whole, a systems thinking perspective is needed.

Simulation modeling supports this perspective by providing a structured way to explore how systems behave over time, especially under uncertainty [122]. Unlike top-down models that assume centralized control, simulation allows for decentralized decision making, where different actors interact and adapt to each other. This is essential when studying infrastructure transitions that depend on both technical and institutional coordination.

Within this approach, Agent-Based Modeling (ABM) is used to capture the behavior of individual actors, such as infrastructure providers, medium-sized industrial companies, and public authorities, each with their own goals, constraints, and limited information. ABM is particularly well suited to model systems in which outcomes emerge from local decisions and interactions, rather than from a central plan [104]. It can represent adaptive behavior, strategic interaction, and the evolution of institutions over time.

To build the model, a system exploration phase is first performed using academic studies, government reports, and industry documents. This helps identify key actors, their roles, and the dependencies between them. The stakeholder analysis then maps out the incentives and constraints that each actor faces. These insights are refined through expert interviews, helping to ensure that agent behaviors in the model reflect realistic assumptions [25].

The simulation is built in NetLogo, a platform designed to model decentralized and adaptive systems. Agents follow decision rules that allow them to react to changes in the market, regulation, or the actions of other agents. Real-world data, such as industrial hydrogen demand in regions such as Cluster 6, are used to create scenarios and check whether the model behaves in line with observed trends.

1.5. Research Contribution

This thesis makes three main contributions to the academic and policy discourse on regional hydrogen infrastructure.

1. *Conceptual contribution:* The study takes the well-known chicken-and-egg problem in infrastructure development as its analytical starting point and builds a structured understanding of how it emerges in regional contexts. By focusing on the mutual dependency between industrial demand and infrastructure rollout, the research highlights how institutional uncertainty and fragmented demand can stall progress in areas outside of the major industrial clusters. The thesis then explores how different strategic approaches, specifically proactive versus reactive rollout by infrastructure providers, can influence system development over time. This perspective brings new conceptual clarity to coordination failures in regional hydrogen transitions and provides a foundation for evaluating institutional and behavioral responses to those failures.
2. *Methodological contribution:* The thesis develops an Agent-Based Model (ABM) to simulate the strategic interaction between distribution system operators and medium-sized industrial firms in the context of the implementation of regional hydrogen infrastructure. The model focuses on varying levels of HDNO proactiveness, ranging from reactive, demand-following strategies to anticipatory, proactive planning as the core decision variable. It captures how local feedback loops between infrastructure rollout and industrial adoption shape long-term system trajectories. This modeling approach enables a systematic exploration of how different HDNO strategies affect spatial rollout patterns, the emergence or resolution of coordination failures, and the resulting societal costs and benefits.
3. *Policy and practical contribution:* The study contributes to ongoing planning and policy discussions on how regional hydrogen infrastructure can be developed in support of industrial decarbonization. By examining how different rollout strategies affect spatial system outcomes, it highlights the importance of coordinated area-based approaches in overcoming adoption barriers and improving infrastructure efficiency. These insights are relevant to current debates on institutional design under Directive (EU) 2024/1788, and can support actors involved in energy system coordination. In particular, existing DSOs can use these findings to inform regional prioritization and long-term investment planning among energy carriers.

Together, these contributions aim to bridge the gap between high-level policy ambitions and the practical challenges of regional hydrogen rollout, supporting both scholarly understanding and real-world decision-making.

1.6. Relevance for CoSEM

This research aligns closely with the objectives of the Complex Systems Engineering and Management (CoSEM) program by addressing a real-world infrastructure transition challenge at the intersection of technology, institutions, and actor behavior. The rollout of regional hydrogen networks is not simply a matter of engineering feasibility; it is a complex sociotechnical problem that involves interdependent decisions by infrastructure providers, industrial users, and public authorities under uncertainty.

The study contributes to CoSEM's emphasis on system integration and institutional design by examining how different strategic choices, particularly proactive versus reactive roll-out strategies, shape long-term results for regional energy infrastructure. It applies systems thinking to map actor dependencies and coordination failures, and uses Agent-Based Modeling (ABM) to simulate decentralized, adaptive decision making in the absence of centralized control. This allows for the exploration of emergent dynamics and policy-relevant insights that traditional optimization models may overlook.

In addition, the project reflects the CoSEM ethos of bridging academic insight and policy relevance. By addressing a timely governance question under Directive (EU) 2024/1788 and providing decision support for regional prioritization and infrastructure planning, the research offers practical value to actors of the energy system. In doing so, it demonstrates how interdisciplinary methods, from institutional analysis to computational modeling, can be combined to inform complex transition strategies in the energy domain.

1.7. Outline of the Report

This thesis begins in Chapter 2 by examining the hydrogen infrastructure dilemma, focusing on the chicken-and-egg dynamic between supply and demand, and the role of DSOs in addressing coordination failures in fragmented industrial regions. Chapter 3 outlines the research approach, explaining the rationale for using Agent-Based Modeling (ABM) to simulate decentralized decision making and interactions among DSOs, medium-sized companies, and policymakers.

Chapter 4 presents the conceptual model, defining agent behaviors, investment logic, and the feedback mechanisms that drive infrastructure rollout. Chapter 5 implements the model as a simulation, detailing the baseline assumptions, key inputs, and performance indicators.

Chapter 6 explores the robustness of the model through sensitivity analysis, investigating how variations in constraints and incentives influence outcomes. Chapter 7 presents the simulation results, comparing proactive and reactive DSO strategies and evaluating their impact on adoption rates, infrastructure utilization, and societal value.

Chapter 8 offers a broader reflection on the theoretical and policy implications of the results and identifies directions for future research. Finally, Chapter 9 synthesizes the main findings, answers research questions, and discusses the practical implications for regional hydrogen deployment.

2
Literature Review

This chapter builds on the introduction's framework of the challenges associated with hydrogen infrastructure deployment, specifically addressing the complex interdependence between infrastructure availability and technology adoption, commonly referred to as the chicken-and-egg dilemma. While Chapter 1 highlighted institutional uncertainties and coordination issues hindering regional hydrogen rollout, this literature review delves into the theoretical foundations underpinning these dynamics. It further examines similar infrastructure adoption dynamics in other sectors, reviews strategic planning approaches by Distribution System Operators (DSOs), contrasts proactive and reactive rollout strategies for Hydrogen Distribution Network Operators (HDNOs), and identifies the key financial, operational, and regulatory constraints affecting hydrogen infrastructure deployment. Finally, the chapter establishes the research gap that this thesis addresses, providing an essential context for the modeling and analysis presented in subsequent chapters.

2.1. Theoretical Background on the Chicken-and-Egg Problem

Infrastructure transitions often face a chicken-and-egg dilemma: companies delay adoption without infrastructure, while providers hesitate to invest without demand. This interdependence creates a feedback loop that slows change and reinforces fossil-based systems. Models show how such dynamics can slow transitions [18], as seen in electric mobility, where limited charging networks and vehicle uptake hold each other back [129]. Similar patterns in sectors such as energy and communications highlight the need for coordinated infrastructure planning [86].

One explanation comes from *network effects*—the idea that the value of a system increases as more users participate [35]. In network industries, additional users create direct or indirect benefits for others by increasing the number of complementary connections, services, or components. In the hydrogen context, more users improve the economics of infrastructure, such as fueling stations, pipelines, and storage, while a stronger infrastructure network encourages further adoption. However, these feedback loops only become self-sustaining once a critical mass is reached. Without it, uptake tends to stall and early investments struggle to break even [50].

Another barrier is *path dependence*. Energy systems, regulations, and business practices are often built around fossil fuels. Even when better alternatives emerge, early choices and increasing returns can lock in existing technologies, making change slow and costly [27, 6].

Game theory helps explain why coordination often fails in infrastructure transitions. In a *Stag Hunt*, all players benefit the most from cooperating - for example, if both DSOs and industrial users invest simultaneously - but uncertainty about the actions of others can lead to inaction, even when mutual cooperation is preferable [133]. In a *Prisoner's Dilemma*, cooperation is structurally blocked: even if joint action would be better for all, the dominant strategy is to act independently, leading to suboptimal outcomes [80]. Experiments confirm that coordination failure can occur even when multiple equilibria are known and cooperation is beneficial, due to strategic uncertainty and risk aversion [62].

Real options theory complements this by framing investment as a flexible decision under uncertainty, where delaying commitment can have strategic value [31]. In the hydrogen sector, high sunk costs, irreversibility, and long asset lifetimes encourage deferral, as actors wait for greater certainty around demand, technology, and regulation. Although early investments could unlock broader benefits for the system, individual firms may rationally choose to wait, reinforcing the need for policy instruments that reduce uncertainty or incentivize early action.

To address these challenges, *mechanism design theory* provides tools for creating institutions that align private incentives with public goals. Rather than assuming ideal conditions, it begins with desired outcomes, such as high infrastructure utilization, and asks what rules or contracts would lead rational actors to choose those outcomes [89]. Practical instruments like matching grants, off-take agreements, demand aggregation, and public-private partnerships can help reduce individual risk and promote collective action. These are especially important in sectors such as hydrogen, where high fixed costs, long repayment periods, and natural monopoly characteristics make coordinated investment and supportive regulatory frameworks essential [73, 60].

All of this unfolds within the broader context of system transitions. The *multi-level perspective (MLP)* explains how innovations such as hydrogen typically emerge in protected niche environments and must compete with established technologies, institutional structures, and broader societal trends such as climate policy or energy security concerns [45]. Building on this, *transition management* emphasizes the importance of long-term coordination through pilots, experimentation, and adaptive planning. Its goal is to guide sustainable change while avoiding early lock-ins to suboptimal technologies or system designs [85].

Building on the theoretical foundations discussed above, Figure 2.1 illustrates how the chicken-and-egg dilemma in infrastructure transitions can be understood as a reinforcing feedback loop between technology adoption and infrastructure investment. Adoption signals demand, justifying investment ("demand signaling"), while infrastructure enhances adoption through network effects and social validation. This loop captures the interdependence at the core of the transition challenge. Game theory explains why the loop often does not activate: in a stag hunt, actors hesitate despite mutual benefits; in a prisoner's dilemma, cooperation is structurally blocked. Real options theory supports this delay, as uncertainty makes waiting rational. The left side of the figure represents external drivers—such as policy incentives—that can initiate adoption, while the right side reflects macro-level pressures like climate goals, drawn from the multi-level perspective. Mechanism design theory underpins the role of targeted interventions that shift incentives and unlock the loop. As such, the figure offers a conceptual bridge from theory to the agent-based modeling developed in the following chapters.

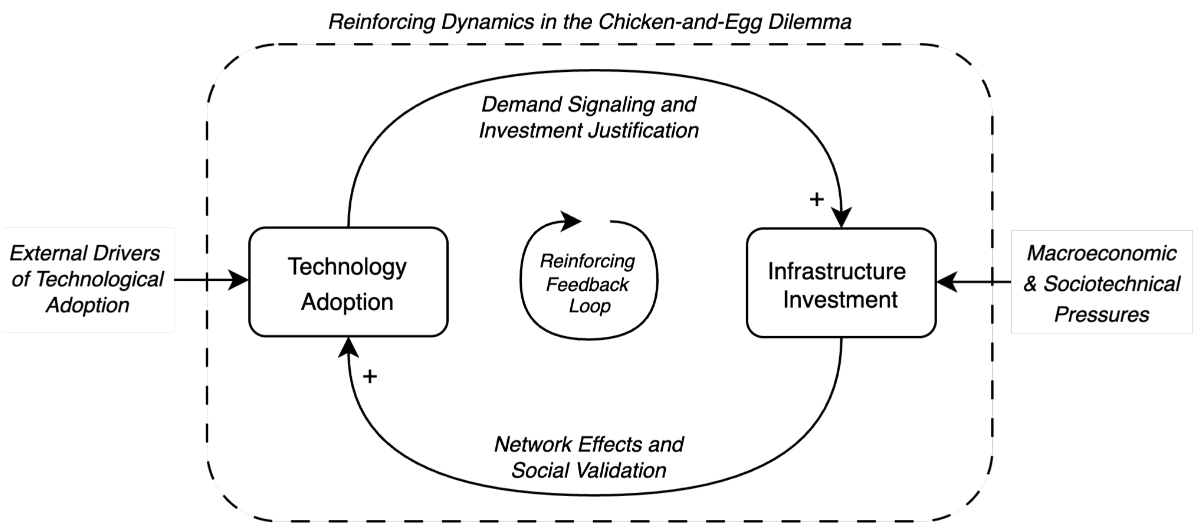

Figure 2.1: Theoretical model of the chicken-and-egg dilemma in technology adoption and infrastructure investment.

2.2. The Chicken-and-Egg Problem Across Different Markets

The theoretical dynamics outlined above are not just abstract constructs—they are observable in real-world sectors where the adoption of infrastructure and technology is tightly coupled. Markets such as electric vehicles (EVs), telecommunications, and public transportation reveal how coordination failures can delay systemic change.

In the EV sector, adoption has often lagged due to limited charging infrastructure, while providers hesitate to invest without clear demand, a feedback loop that slows progress [55]. Consumers also cite concerns about range, cost and reliability [74]. Telecommunications shows a similar pattern: network expansion is frequently postponed in low demand or rural areas due to uncertain returns, while users remain offline without adequate infrastructure, deepening digital divides despite strong network effects [20]. In public transport, unreliable or infrequent service reduces ridership, weakening the case for further investment, especially in low-density areas or during delays such as COVID-19 [139].

These examples highlight the limitations of relying solely on market signals to drive infrastructure development. Historical experience also demonstrates that targeted intervention can effectively overcome this challenge. A well-known example is the Dutch rollout of natural gas in the 1960s. Following the discovery of the Slochteren gas field, the government implemented a comprehensive national strategy. It established Gasunie to coordinate the supply, mandated the conversion of households to city gas, and secured long-term transfer agreements with industrial users. By aggregating demand and reducing investment uncertainty, these coordinated measures helped resolve the chicken-and-egg dilemma and accelerated infrastructure deployment [107].

To replicate such outcomes, many sectors now employ targeted mechanisms, including subsidies, regulatory mandates, and public-private partnerships, to shift incentives and reduce the risk of early-stage investment, particularly in emerging technologies and infrastructure projects [131, 141, 123]. At the same time, adaptive technologies, such as smart charging systems, predictive analytics for resilient networks, and modular infrastructure planning, play a critical role in enhancing flexibility and responsiveness in the face of environmental and technological uncertainties [127, 82, 8].

These cases support the main argument of this chapter: infrastructure transitions require more than demand and available technology. They depend on proactive infrastructure providers and institutional tools that enable action ahead of confirmed demand and help break the coordination deadlock that often stalls investment and adoption.

2.3. The Role of Infrastructure in Systemic Climate Mitigation

While hydrogen serves as a central example in this thesis, the challenges it illustrates are part of a broader transformation: the need to build several infrastructure systems for green energy sources. However, the stakes go far beyond the immediate deployment dilemma. Hydrogen represents a broader class of climate mitigation technologies that require large-scale, long-lived infrastructure and that once built shape not only energy systems, but also institutions, spatial planning, and societal outcomes.

Increasingly, scholars and policy makers recognize that the infrastructure for climate mitigation is not just a technical matter but a systemic one [111, 118]. These decisions define future options, affect who bears risk and who captures value, and determine whether the transition will be inclusive and effective. As such, infrastructure must be evaluated not only for emissions or cost efficiency, but also on its contribution to long-term societal goals.

To support this broader perspective, Cohen et al. [24] propose a conceptual framework linking climate mitigation strategies to the Sustainable Development Goals (SDGs). Their model highlights the co benefits and potential trade-offs of different mitigation actions, ranging from fuel switching and energy efficiency to behavioral change. Figure 2.2 visualizes how these actions generate systemic impacts across employment, health, governance, and environmental quality.

In this framework, the transition from natural gas to hydrogen in industrial sectors is categorized as a 'Fuel Change' (Category B). Although its primary goal is emission reduction, this transition affects many other domains.

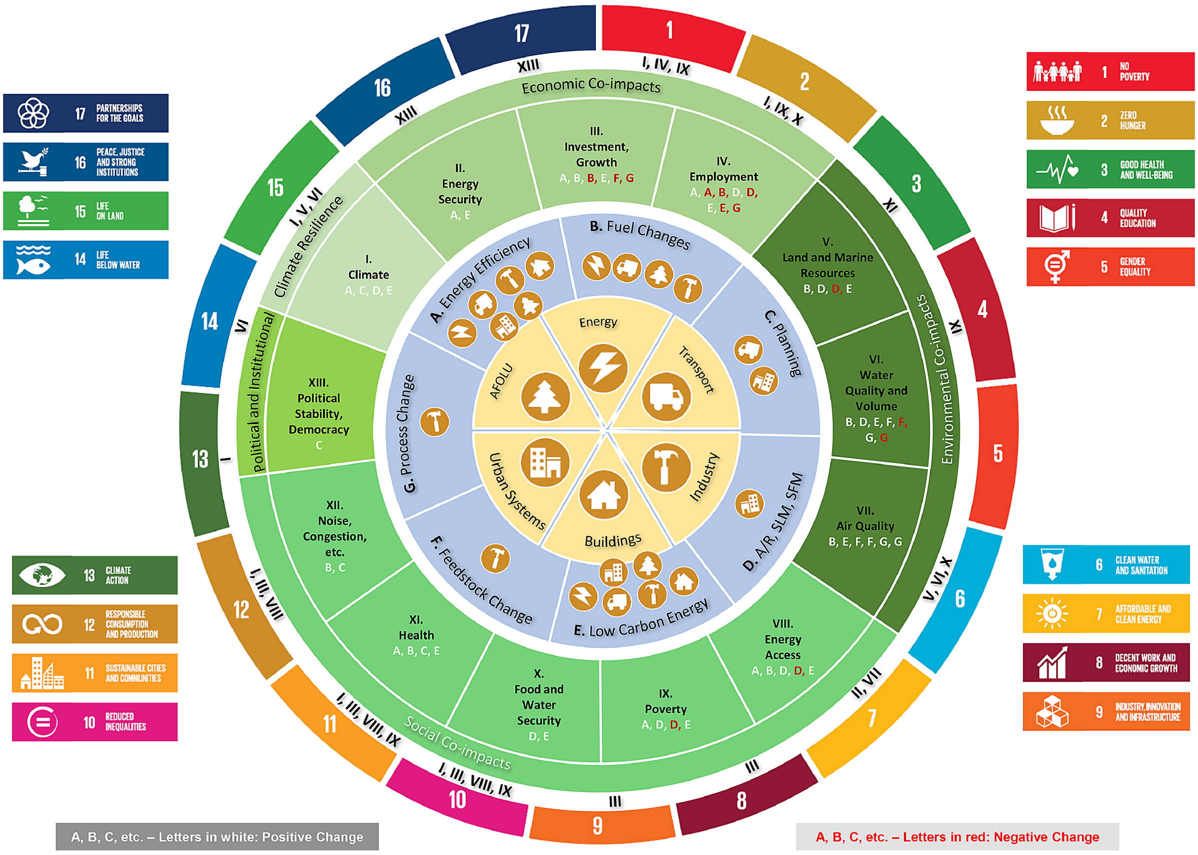

Figure 2.2: Co-benefits and adverse side effects of mitigation actions with links to the SDGs, adapted from Cohen et al. [24]

- *Investment Growth*: The rollout of hydrogen can stimulate capital formation in electrolysis, pipeline networks, storage systems, and end-use applications. It can also support industrial competitiveness and national energy security by reducing dependence on fossil imports [57, 119, 4, 3].
- *Employment*: The expansion of hydrogen infrastructure generates jobs across the value chain, from renewable energy generation to construction, retrofitting, and system integration [57, 4].
- *Environmental Quality*: Switching to hydrogen reduces local air pollutants such as particulates and SO_x, improving air quality. While hydrogen combustion can produce NO_x, this can be effectively mitigated using technologies such as staged combustion or gas recirculation, as demonstrated in the Gersen, Essen, and Wolff [47].
- *Water Use and Quality*: Hydrogen production generally reduces the risks of water contamination compared to fossil fuels, but electrolysis processes can raise concerns about water availability and efficiency [119].
- *Energy Access and System Flexibility*: Hydrogen can act as a balancing vector in renewable-heavy systems, enabling seasonal storage and off-grid industrial applications [57, 3].
- *Health and Quality of Life*: Reductions in combustion emissions improve respiratory health and reduce noise pollution, especially in urban or industrial zones [57, 119, 4].

However, the literature also highlights risks and trade-offs:

- *High Capital Costs*: Hydrogen infrastructure requires significant upfront investment. Without clear policy support or coordinated demand, early stage financing may be difficult to secure [57, 119].
- *Labor Market Disruption*: Transitioning away from fossil fuels can displace workers in the gas extraction, refining, and related sectors. Without active reskilling and just transition policies, this could exacerbate regional inequalities [4, 3].

This body of theory suggests that the climate mitigation infrastructure must be evaluated through a multi-dimensional lens. Although CO_2 reduction is central, so are also the societal, economic and institutional impacts that shape the durability and legitimacy of transition pathways. For hydrogen infrastructure, in particular, this means that rollout strategies, whether proactive or reactive, cannot be judged by technical feasibility alone. They must also be assessed for how they advance or constrain systemic change.

The next section builds on this insight by examining how system operators, particularly distribution system operators (DSOs) and the emerging hydrogen distribution network operators (HDNOs), can navigate these complex trade-offs in planning for hydrogen roll-out under uncertainty.

2.4. Expansion Planning by Network Operators

Network operators are central to energy transitions, particularly in contexts where infrastructure and demand must evolve together. Traditionally, planning has followed a reactive model, responding to connection requests, minimizing costs, and adhering to fixed regulatory frameworks. Although this has worked in mature sectors like electricity and gas, it is less suited to emerging domains such as hydrogen, where demand is uncertain, dispersed, and dependent on timely infrastructure availability.

Distribution System Operators (DSOs) provide a relevant point of reference. Originally focused on connection and maintenance of the network, many are now adopting more strategic roles. International examples from Slovenia, the UK, and Canada show DSOs experimenting with stakeholder-led and anticipatory planning to better align infrastructure with projected demand and reduce investment risk [115, 51]. This signals a broader shift: from passive operators to facilitators of systemic change.

Academic literature reflects this trend. Kabiri-Renani et al. [75] emphasize the importance of aligning local and national planning, while others highlight the role of distributed flexibility - such as storage, demand response, and aggregation of consumers - as 'virtual capacity' to reduce physical grid expansion [90, 43]. These approaches enable more adaptive, resilient infrastructure development under uncertainty.

However, structural constraints remain. Fragmented governance, strict cost control mechanisms, and limited institutional mandates often prevent operators from taking action before demand is confirmed. Many still rely on just-in-time planning models, which are poorly suited to the needs of emerging energy carriers. To overcome these limitations, scenario-based planning and multiactor decision making tools are increasingly viewed as essential [75].

Although this section focuses on regional network operators in general, the insights are directly applicable to hydrogen. Hydrogen Distribution Network Operators (HDNOs), which are still in the early stages of institutional and regulatory development, will face similar but often more severe planning and coordination challenges. Unlike established DSOs, HDNOs will operate without mature legal mandates or planning frameworks, making proactive investment even harder to justify. However, the experience of DSOs offers valuable lessons. It highlights the structural tensions between risk, timing, and accountability that will also shape HDNO decision making. The next section builds on this foundation to examine the core strategic choices facing HDNOs in planning regional hydrogen rollout.

2.5. Proactive and Reactive HDNO Rollout Strategies

Hydrogen Distribution Network Operators (HDNOs) face a fundamental strategic challenge: when and how to invest in infrastructure under conditions of fragmented demand, policy uncertainty, and weak planning mandates. Unlike traditional utilities, HDNOs operate in a landscape where user connections are not yet compulsory, and no established protocols guide infrastructure timing. In this context, rollout decisions are highly consequential, not just technically or financially, but institutionally and politically [75, 113].

Rather than a binary choice, rollout strategies are better understood along a spectrum of DSO 'activation', reflecting the extent to which system operators participate in shaping the future energy system [34]. Highly active DSOs move beyond traditional asset management, playing coordinating roles in integrating new technologies, enabling decarbonization, and interacting with other system actors. This activation is not defined solely by the timing of investment decisions, but by the breadth of functions a DSO takes on and the degree of strategic engagement with system transformation. At one end of the spectrum, DSOs may adopt a more proactive stance, coordinating investment and innovation ahead of confirmed demand. Others may act more reactively, relying on demand signals or congestion to trigger operational responses. For example, flexibility services can serve as an adaptive tool to address system constraints without committing to capital intensive reinforcement, especially where uncertainty or cost considerations dominate planning decisions [90]. Similarly, demand-driven mechanisms can be used to manage short-term needs under uncertainty [43]. Where a DSO or HDNO is placed along this spectrum depends on regulatory structures, investment incentives, and the institutional capacity to manage complexity and risk [34, 90, 43].

This section explores the strategic trade-offs embedded in roll-out decisions. It distinguishes between short-term and long-term considerations and shows how early choices shape not just system costs, but the broader dynamics of market formation. The focus is especially relevant for emerging hydrogen clusters like Cluster 6, where market signals alone may be too weak to guide infrastructure investment without deliberate coordination [66, 56].

2.5.1. Short-Term Trade-Offs

In the short term, HDNOs must choose between two strategic postures: acting early to accelerate system formation, or holding back to reduce financial and political exposure. Each approach distributes uncertainty differently and raises distinct challenges for regulatory and societal justification.

A *proactive* strategy involves investing in infrastructure before demand is confirmed. This can help break coordination deadlocks by sending credible signals to potential users, lowering adoption barriers, and creating early network effects [35, 18]. Such early action may be essential in fragmented hydrogen markets, where no single actor can independently trigger system formation [75]. However, this approach carries short-term risks. If uptake fails to materialize, public funds may be tied up in underused infrastructure, leading to scrutiny over efficiency, fairness, and legitimacy [7, 1]. Because these investments are often financed through taxes or regulated tariffs, they must be defensible not just technically and economically, but also politically and socially [113].

In contrast, a *reactive* approach delays investment until user commitments are secured. This aligns with real options theory: under uncertainty, waiting preserves flexibility and reduces the risk of locking in suboptimal infrastructure paths [31]. For publicly mandated operators, this posture makes investments easier to justify to regulators, auditors, and policymakers [83]. Yet caution has costs. Without visible infrastructure, potential users may hesitate, reinforcing coordination failures and slowing the emergence of viable hydrogen systems [129, 56].

In sum, proactive strategies aim to catalyze momentum but face high justification burdens under uncertainty. Reactive strategies minimize early risk but may miss critical timing windows. Finding the right balance is central to short-term HDNO planning [75, 113].

2.5.2. Long-Term Considerations

While short-term decisions are shaped by risk and justification pressure, long-term consequences hinge on how early infrastructure choices influence the structure and resilience of the future hydrogen network.

A well-targeted *proactive* rollout can lay the foundation for a coherent and scalable system. Early investment enables spatial alignment between production, transport, and demand; helps secure key routes; and allows time to resolve permitting or land use constraints. Over time, this can reduce retrofit costs, encourage industrial clustering, and align infrastructure with broader decarbonization strategies [75, 76, 43].

However, long-term exposure also increases. If demand does not emerge, or if the policy or technology directions change, early infrastructure may become obsolete or underutilized [86]. This is a real concern in the hydrogen markets, where uncertainty remains about carrier formats (e.g. gaseous, liquid, or chemical vectors) and end-use applications [48, 90].

A *reactive* approach avoids this exposure by scaling infrastructure as demand patterns become clearer. It preserves optionality and avoids lock-in to designs that may not suit future needs [84]. But slow or fragmented implementation risks establishing fossil alternatives, increasing future costs, or creating bottlenecks if the infrastructure needs to catch up quickly [138]. In this way, excessive caution may undermine climate targets and industrial competitiveness [45, 56].

Ultimately, long-term strategy is not just about avoiding stranded assets; it is about enabling a transition pathway that is coherent, adaptive, and aligned with societal goals.

2.5.3. Implications for Strategy

The literature often frames rollout strategy as a balancing act between short-term risk management and long-term system development. This tension is fundamentally about timing: how to make decisions today under uncertainty while enabling the infrastructure needed for future transformation.

Reactive strategies are widely understood to reduce immediate financial and political risk by deferring investment until demand is confirmed. While this can help avoid stranded assets, it may also slow progress or reduce the ability to influence how systems evolve. More proactive approaches, those that anticipate future needs, can accelerate deployment and support innovation, but require stronger coordination, better planning tools, and clearer routes for political and regulatory justification.

Rather than a binary choice, much of the literature describes a spectrum of strategic proactiveness. Operators are seen as positioning themselves along this spectrum depending on factors like demand certainty, regulatory structure, and system maturity. In some cases, anticipatory investment in high-potential regions is seen as justified; in others, more flexible, demand-responsive approaches may be preferable [76, 18]. This logic draws on both the theory of real options, which emphasizes the preservation of flexibility in uncertain contexts, and the transition theory, which highlights the value of experimentation through pilots and niche projects [85, 89].

Critically, the literature emphasizes that such calibrated strategies depend on enabling conditions. Scenario-based planning tools, adaptive regulatory frameworks, and public-private risk-sharing arrangements are often cited as essential supports for managing uncertainty without stalling development [75, 123]. Without these, even well-intentioned strategies may fall short of delivering infrastructure at the pace and scale required for hydrogen deployment.

The next section explores how these strategic orientations interact with financial, operational, and regulatory constraints in practice.

2.6. Constraints for Hydrogen Network Rollout

While HDNOs do not yet exist as formal entities and may differ from traditional Distribution System Operators (DSOs) in structure and mandate, they will likely operate under similar regulatory and institutional conditions. Some sort of government-imposed rules will shape their investment decisions, just as they do for DSOs today. For this reason, the constraints currently facing DSOs, financial, operational, and regulatory, offer a useful reference point to anticipate the barriers that will affect the deployment of hydrogen networks. This section draws on the DSO experience to examine these constraints and their implications for future HDNO planning.

2.6.1. Financial Constraints

In the Netherlands, Distribution System Operators (DSOs) for gas and electricity operate under a revenue cap framework regulated by the Authority for Consumers and Markets (ACM). This model, rooted in the Gas and Electricity Acts, calculates allowable income using a building block approach that includes four main components: operational expenditure (OPEX), capital expenditure (CAPEX), depreciation, and fair return on the regulated asset base (RAB) [10].

Figure 2.3 illustrates how these components shape the total regulatory cost base. CAPEX and OPEX reflect infrastructure and operational spending and must be justified in bi-annual investment plans. Depreciation defines how infrastructure costs are recovered over time, with the ACM allowing degressive methods to prevent costs from being pushed onto a shrinking customer base as gas demand declines. The Cost of Capital is determined by a combination of the Weighted Average Cost of Capital (WACC) and the Regulated Asses Base (RAB).

To promote efficiency, the ACM enforces an x-factor that reduces allowed revenue annually, rewarding DSOs that operate below cost projections. A q-factor adjusts returns based on service quality, prevent-

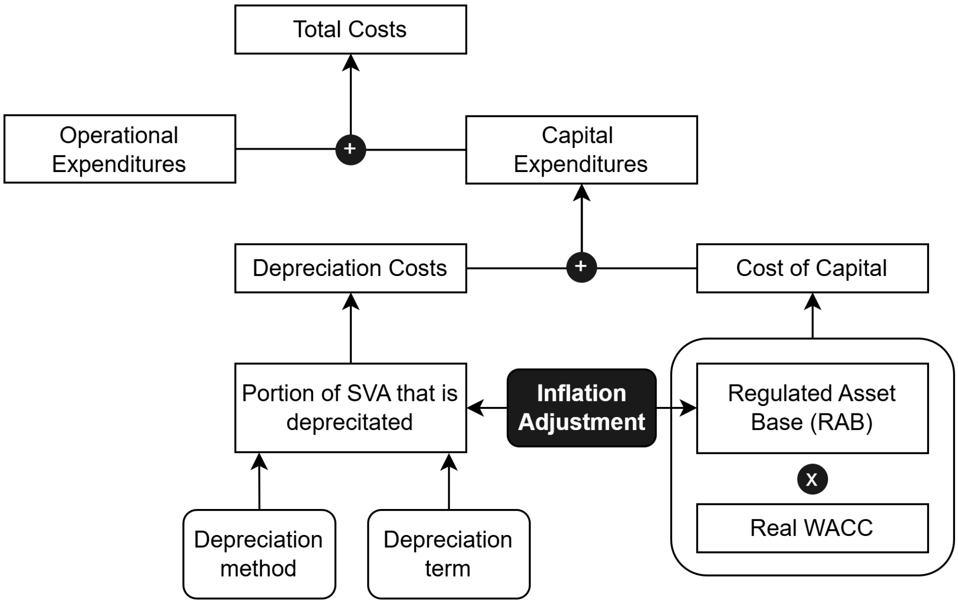

Figure 2.3: Composition of regulatory costs, including depreciation and capital returns via WACC, adapted from [10].

ing cost-cutting at the expense of safety or reliability [11]. The framework also includes retrospective corrections for volatile inputs, such as inflation or the risk-free rate, which is now tied to Dutch 20-year bonds with a floor of 0.5% following a court ruling in 2023 [10].

Importantly, DSOs are allowed to recover costs related to the decommissioning of outdated infrastructure, such as the removal of outdated gas lines [10]. This ensures that removal of the current system is treated as part of the energy transition, rather than a financial liability.

Access to financing is not a major hurdle for DSOs. As low-risk, regulated entities, they can usually obtain favorable loans, especially with government guarantees [53]. The real constraint lies in justification: because DSOs recover costs through consumer tariffs, any spending, especially on proactive infrastructure, must be rigorously defensible. Even when early investment is beneficial, the lack of confirmed demand or policy backing makes it difficult to prove that such expenditures are both necessary and efficient.

In the context of hydrogen, financial regulation is less developed. DSOs are currently not permitted to distribute hydrogen directly. However, affiliated entities within network companies may participate in pilot projects under strict regulatory supervision. The ACM has shown flexibility here, supporting initiatives such as the hydrogen heating pilot in Hoogeveen to evaluate residential use cases [11]. These pilots are important, but they operate under temporary frameworks. The absence of a comprehensive hydrogen regulation introduces financial and legal uncertainty, complicating planning for large-scale rollout.

While financial prudence and compliance are essential, it is clear that funding access itself is not the most limiting factor. Rather, the need for regulatory and political justification, rooted in the tariff-based financing structure, makes proactive investment in hydrogen infrastructure difficult without strong demand signals or a clearer legal mandate.

2.6.2. Operational Constraints

Although HDNOs have not yet been formally established, they are expected to face many of the same operational challenges currently encountered by Distribution System Operators (DSOs). These challenges, ranging from spatial limitations and labor shortages to permitting delays and supply chain constraints, determine whether infrastructure plans can be realized in practice and thus offer a practical lens for anticipating barriers in hydrogen rollout.

In the Netherlands, one of the most densely populated countries in Europe, underground space in urban areas is already congested with water, sewer, telecom, and gas networks [69], which complicates the installation of new pipelines for electrification or hydrogen. The land for substations and routes is similarly limited, competing with housing, agriculture, and other uses [53]. Advanced techniques such as trenchless drilling and GIS-based planning are often required to identify viable infrastructure paths.

Even when physical space is available, regulatory complexity contributes to delays. Projects must navigate multiple permits, zoning restrictions, and environmental assessments [102], while also aligning with national transition strategies through coordination at the municipal, regional, and national levels [101]. The pressure on space is further intensified by competing demands from offshore wind, solar parks and hydrogen storage [101], prompting calls for streamlined permits while safeguarding critical land uses [102].

DSOs also face persistent resource constraints. Operators like Stedin report structural shortages of skilled personnel, including engineers, technicians, and project managers, that limit the execution capacity [53]. Supply chain disruptions have further delayed key components like transformers and cables, adding cost and uncertainty [53].

Together, these constraints constitute the growing *feasibility gap* which represents the discrepancy between planned infrastructure projects and the capacity to implement them feasible by 2030 [32]. With electricity demand projected to increase 180 to 250% by 2050 [101, 53], grid congestion already restricts new connections and backfeed capacity. Although interim solutions such as demand management and decentralized energy hubs provide partial relief, they cannot substitute for timely and sufficient physical infrastructure expansion [53].

2.6.3. Regulatory Constraints

Beyond physical and financial limitations, infrastructure rollout is fundamentally shaped by the regulatory environment. In emerging sectors like hydrogen, where market roles, rights, and responsibilities remain undefined, legal uncertainty becomes a major obstacle to long-term planning and investment. For prospective HDNOs, this challenge is particularly acute. Unlike existing DSOs, which operate under established legal mandates for gas and electricity, HDNOs will depend on new legislation to determine what infrastructure they are allowed to build, who they can connect, and how investment costs can be recovered. Without such a mandate, even technically sound and economically viable projects may be blocked or delayed due to legal ambiguity.

In the Netherlands, the regulatory framework for hydrogen distribution is still under development. Although hydrogen is widely recognized as a key pillar of the national energy transition, current legislation, namely the Gas Act (Gaswet) and the Electricity Act (Elektriciteitswet) do not provide DSOs with a formal mandate to operate hydrogen networks [91, 92]. These acts lack a clear legal foundation for hydrogen distribution, leaving network operators without defined responsibilities or rights in this emerging sector. As a result, proactive planning is limited, and early-stage infrastructure efforts remain largely confined to pilot projects operating under temporary exemptions.

In response, the Dutch government is preparing a new *Energy Act (Energiewet)*, which will unify the Gas and Electricity Acts into a single, modernized legislative framework [121]. This reform aims to eliminate inconsistencies between the two existing laws, update outdated provisions, and align definitions with evolving European legislation. However, the version scheduled to take effect on 1 January 2026 does not yet include a dedicated chapter on hydrogen infrastructure. Instead, hydrogen regulation is expected to be introduced in a future amendment, which will incorporate provisions from the EU Decarbonization Package and national policy decisions on hydrogen market organization [59].

In particular, the draft Energy Act proposes a provision allowing subsidiaries of grid operators to construct and operate hydrogen terminals, storage facilities, and infrastructure for import, export, and conversion. Although these activities are generally reserved for private parties, the proposal allows public participation if private investment lags, helping to prevent delays in the development of the hydrogen market [72]. The proposal remains under parliamentary debate and, if passed, will form the legal foundation for subsequent hydrogen-specific regulation.

Meanwhile, DSOs rely on temporary frameworks. The Temporary Hydrogen Pilot Framework (THPF), issued by ACM, allows DSOs to conduct pilot projects under strict safety and consumer protection conditions [12]. In parallel, the Hydrogen Guidelines *(Richtsnoeren Waterstof)* offer technical and safety recommendations for early stage infrastructure planning [120].

Several DSOs have already launched pilot initiatives across the country [16]:

- Lochem pilot, led by BBSB and Liander, exploring hydrogen in protected urban zones;
- Wagenborgen pilot, organized by Enexis to test hydrogen for residential heating;
- Hoogeveen pilot, a collaboration between Rendo, Gasunie, and Essent to convert a neighborhood to hydrogen-based heating;
- Stad aan 't Haringvliet, the largest pilot, involving Stedin, Gasunie, and other stakeholders aiming to convert an entire town to hydrogen.

These pilots are designed to generate technical, economic and societal insights that can inform future regulation and infrastructure development.

Despite ongoing pilot efforts, the absence of a comprehensive regulatory framework continues to constrain long-term planning for hydrogen networks. Until the Energy Act is enacted and extended to cover hydrogen infrastructure explicitly, DSOs - and, by extension, future HDNOs - remain limited to small-scale projects under temporary exemptions [59, 72]. This reliance on provisional instruments results in a fragmented legal environment in which actors lack clarity on permissible activities, cost recovery mechanisms, and connection mandates. For prospective HDNOs, this uncertainty undermines the ability to make credible investment plans, secure stakeholder commitments, and align infrastructure timing with emerging demand. As such, the lack of regulatory clarity does not merely delay implementation; it structurally limits the scope for proactive system development.

In addition to clarifying DSO mandates, the regulatory framework must also address the issue of third-party access (TPA) to hydrogen infrastructure. Two main approaches are under consideration: regulated third-party access (rTPA), where infrastructure owners are legally obliged to provide access under fixed conditions; and hybrid negotiated third-party access (hnTPA), which allows for negotiated agreements within a regulatory framework. Recent research highlights that while rTPA offers transparency and non-discriminatory access, it may limit investment flexibility and increase complexity for emerging hydrogen markets. In contrast, hnTPA provides room for tailored agreements and dynamic coordination, which could better align with early-stage infrastructure rollouts in fragmented industrial regions like Cluster 6 [78]. A well-chosen TPA regime will be crucial for balancing open access with investment security and system coherence as the hydrogen network scales up.

2.7. Identified Research Gap

The reviewed literature emphasizes the conceptual foundations of the chicken-and-egg dilemma in infrastructure deployment, highlighting theoretical explanations such as network effects, game theory, and real options theory. While these theories provide a robust understanding of why coordination failures occur, the specific role of proactive versus reactive investment strategies by Hydrogen Distribution Network Operators (HDNOs) remains notably underexplored, especially in the current regulatory and institutional context of system operators.

Previous studies and empirical cases in comparable sectors have illustrated the complexities and potential strategies to overcome infrastructure coordination issues, focusing primarily on generalized policy interventions or centralized planning frameworks. However, they do not adequately address the specific decision-making processes or strategic actions that HDNOs can take within existing regulatory constraints and operational realities.

Furthermore, existing research on distribution system operators (DSOs) underscores the emerging shift toward proactive infrastructure investment strategies to better anticipate future demand and reduce uncertainties. However, this research primarily centers on mature sectors like electricity or gas, leaving a distinct knowledge gap regarding how similar proactive or reactive strategies might function for hydrogen infrastructure. This is particularly critical given hydrogen's unique characteristics, regulatory ambiguity, and the fragmented nature of regional medium-sized industry demand.

Consequently, there is a clear and specific gap in the current understanding of how proactive or reactive HDNO strategies can effectively resolve the chicken-and-egg dilemma in the regional rollout of hydrogen infrastructure. Addressing this gap requires examining how these strategic decisions interact with the prevailing institutional and regulatory constraints, which influence both immediate infrastructure investments and long-term system evolution. This thesis explicitly targets this underresearched area, contributing to both theoretical insights and practical strategies necessary for the timely deployment of regional hydrogen networks.

In addition, the literature often evaluates hydrogen infrastructure through narrow techno-economic criteria, overlooking its role in shaping broader societal outcomes. As the hydrogen transition becomes increasingly framed as a form of systemic climate mitigation, it is critical to define and apply multidimensional metrics that reflect this ambition. These metrics must account for societal, environmental and institutional impacts, not only emissions reduction or financial returns. Without appropriate evaluation frameworks, roll-out strategies risk being misaligned with the long-term goals of sustainable and equitable transformation. This thesis addresses this secondary gap by integrating such metrics into the assessment of HDNO planning strategies.

3 Methodology

This chapter outlines the methodological approach used to analyze how different strategies of system operators can help overcome the chicken-and-egg dilemma in the decentralized implementation of the hydrogen infrastructure under uncertainty. Given the need to capture adaptive behavior, strategic interaction, and system-level feedback, Agent-Based Modeling (ABM) is used as the primary method. Section 3.1 introduces ABM, its theoretical foundations, its use in relevant literature, and its fit for this research. Section 3.3 details the development and validation of the simulation model.

3.1. Agent-Based Modeling (ABM)

Agent-Based Modeling (ABM) is a computational approach used to simulate the behavior of individual actors, known as agents, and their interactions within a system. Each agent follows its own decision rules and can adapt based on its environment and other agents. Through repeated interactions, agents generate emergent system-level patterns such as cooperation, innovation, diffusion, or lock-ins [14, 104]. Unlike top-down or equation-based models that assume aggregate or centralized behavior, ABM allows bottom-up modeling of heterogeneity, feedback, and adaptation, making it particularly suitable for complex, decentralized systems operating under uncertainty [130].

In academic literature, ABM has been widely used to study complex systems composed of interacting actors. In the fields of energy, infrastructure, and sustainability, ABMs help to explore how consumers, firms, and regulators respond to policy changes, market dynamics, and technological change [54, 110, 112]. A key strength of ABMs is their ability to simulate a range of behavioral assumptions and policy scenarios, revealing tipping points, feedback loops, and path dependencies that would be difficult to capture using traditional modeling approaches [87, 49].

ABM is especially valuable for analyzing sociotechnical transitions, long-term shifts shaped by the interplay of technologies, institutions, markets, and user practices. These systems are characterized by path dependence, institutional inertia, and non-linear system responses [23]. ABM makes it possible to represent how local interactions and decisions scale up to system-level outcomes. Figure 3.1 illustrates how ABMs can simulate transitions, showing how policy interventions, actor behavior, and infrastructure interact in feedback-rich environments.

This modeling approach is well suited to analyzing:

- The co-evolution of technologies, institutions, and user behavior [23, 105];
- Emergent patterns such as lock-ins and tipping points [104];
- Feedback dynamics, including expectation-driven investments and adaptive policymaking [23];
- The impact of agent heterogeneity on the effectiveness of policy instruments [105].

In the context of the deployment of hydrogen infrastructure, where investment decisions are fragmented, timing is uncertain, and actor coordination is weak, ABM provides a framework for analyzing how local actions shape systemic outcomes. It is particularly suited to studying the core problem of this thesis: the

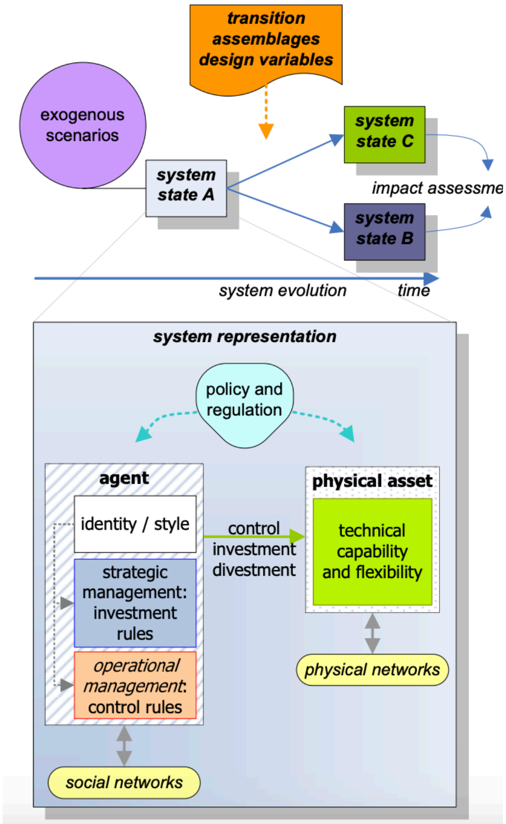

Figure 3.1: Framework for assessing system transitions with agent-based models, adapted from Chappin and Dijkema [23].

chicken-and-egg dilemma, where infrastructure is delayed due to lack of demand, and demand fails to materialize without visible infrastructure. By modeling agents' strategies, feedbacks, and expectations, ABM helps explore how different interventions or coordination mechanisms might unlock this deadlock and support a successful transition.

3.2. Suitability of ABM for This Research

The implementation of a regional hydrogen infrastructure for medium sized industries is a highly decentralized and uncertain process. DSOs, industrial users, and policymakers make strategic choices, reacting not only to formal regulations and market prices, but also to each other's behavior over time [81]. The success or failure of infrastructure deployment depends on how these local decisions interact, sometimes reinforcing, sometimes stalling progress. Capturing such decentralized, adaptive, and feedback-driven dynamics requires a modeling approach that allows decisions to remain at the actor level and lets system outcomes emerge from their interactions.

Agent-Based Modeling (ABM) is particularly suited to this task. In this research, it enables individual HDNOs and industrial firms to be modeled as autonomous agents, each following decision rules based on their expectations, constraints, and local conditions. This actor-based approach reflects the diversity of strategies and behaviors observed in Cluster 6 industries and HDNOs. In addition, ABM captures feedback mechanisms that are central to the problem. Infrastructure investments influence adoption rates, and adoption, in turn, reshapes investment incentives - a dynamic that plays out over time rather than being fixed in advance [18, 56]. Unlike traditional top-down or optimization models, ABM does not require specifying a predetermined equilibrium. Instead, it allows different transition pathways to emerge based on the interaction of agents under changing conditions.

Flexibility is another important reason for choosing ABM. As the regulatory framework for hydrogen infrastructure remains in development, with upcoming changes in *Energiewet*, it is essential to use a method that can incorporate changes in external conditions during simulation runs and capture how agents adapt to new policies or incentives [21].

Finally, ABM supports scenario exploration, which is critical given the uncertainties about future hydrogen demand, cost developments, and policy interventions. By systematically varying assumptions, ABM helps reveal how different proactive or reactive strategies by HDNOs affect long-term outcomes for society, such as network utilisation, connection costs, and emissions reduction [49].

For these reasons, ABM is the most appropriate methodological choice for this research. It matches the decentralized, heterogeneous, adaptive and feedback-rich nature of the challenge of deploying hydrogen infrastructure, providing a credible basis for analyzing how different HDNO strategies impact societal outcomes.

3.3. Modeling Methodology

This section describes the process followed to design, build, and test the agent-based simulation model used in this research. The methodology includes the conceptual development of the model, the collection and preparation of input data, and the strategies used to handle uncertainty and validate model behavior.

3.3.1. Model Conceptualization and Formalization

The conceptual model used in this research is presented in Chapter 4. It is based on the academic literature reviewed in Chapter 2, which identifies key actors, system interactions, and decision-making processes involved in the deployment of hydrogen infrastructure.

The model uses the framework by Cohen et al. [24] to link mitigation actions to Sustainable Development Goals. This provides the evaluation logic for the simulation and ensures that rollout strategies are assessed not only on infrastructure utilization or cost, but also on their impact on employment, public health, and long-term system resilience. This aligns with the understanding of hydrogen infrastructure as a systemic form of climate mitigation, as discussed in Section 2.3.

The model was refined through consultations with energy sector experts, including representatives from Stedin, Alliander, Enexis, and Netbeheer Nederland. Table 3.1 summarizes these engagements. These meetings were used to validate assumptions, adjust agent behavior, and align the model with operational and regulatory conditions relevant to potential HDNOs, including DSOs that may take on this role.

Where direct data on decision-making behavior was unavailable, assumptions were based on sector reports and analogies to similar infrastructure transitions, such as the rollout of electric vehicle charging networks. These assumptions were reviewed with experts to ensure they reflected actual practices while maintaining the necessary simplifications of agent-based modeling.

Table 3.1: Overview of Expert Consultations for Model Development

Expert / Group	Affiliation	Role	Engagement Frequency
Arjen Jongepier	Stedin	Energy System Strategist	Bi-weekly
Edward Droste	Stedin	Regulatory Economics & Market Design	Bi-weekly
Frank van Alphen	Netbeheer Nederland & Stedin	Network and System Strategist Hydrogen	One-time meeting
Duncan de Vries	Stedin	Innovation Expert	One-time meeting
Chantal Spierings	Enexis Group	Business Consultant	One-time meeting
Axel Schnoeckel	Firan	Business Developer	One-time meeting
Stijn Kromwijk	Zeeuwind	Business Developer	One-time meeting
Arjan van Voorden	Stedin	Asset Management Expert	One-time meeting

3.3.2. Data Collection

The model supports both synthetic and real-world data input. For exploratory purposes, hypothetical regions can be simulated using randomized firm data, including spatial coordinates and energy demand.

However, for the main analysis in this thesis, real-world data is used from a specific area within Cluster 6.

The input dataset contains 16 industrial companies located in the municipality used as a case study, provided by Stedin. This area was selected because it is currently being explored as a potential location for hydrogen infrastructure, making it a realistic candidate for regional hydrogen rollout among medium-sized industrial users. Each firm is classified as a grootverbruiker (large gas consumer), and its annual energy consumption is based on its current contractual gas usage. This data includes geospatial coordinates and serves as the basis for estimating infrastructure needs and firm-level investment decisions.

All companies are treated using uniform behavioral assumptions, such as retrofit costs and payback thresholds, based on expert input, literature, and analogies with similar transitions. Firm-specific attributes or identifiers are not used, ensuring confidentiality and generalizability.

Additional input parameters, including infrastructure costs, fuel price trajectories, carbon pricing, and regulatory constraints, are derived from public sources and sector reports. A complete overview of these assumptions is provided in Appendix A and discussed further in Chapter 5.

To assess the robustness of the model, an one-factor-at-a-time (OFAT) sensitivity analysis is performed. This method systematically explores how variation in key parameters affects model outcomes, helping to identify tipping points and evaluate the influence of uncertainty. The method and results are discussed in detail in Chapter 6.

3.3.3. Software Implementation

The model was built in `NetLogo`, a platform that is well suited to simulate the behavior of decentralized, rule-based agents and visualizing spatial dynamics [145]. It is fully parameterized to support both synthetic and real-world data, enabling rapid testing of alternative assumptions and policy settings. This setup allows flexible exploration of rollout strategies under uncertainty.

The NetLogo interface is shown in Figure 3.2.

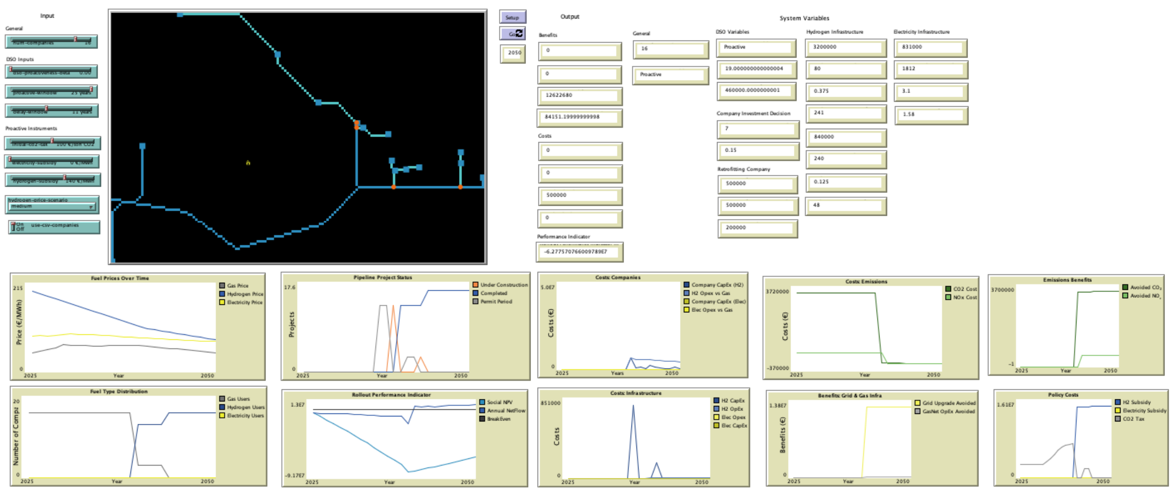

Figure 3.2: NetLogo model interface showing agent layout and simulation controls.

3.3.4. Model Verification

To ensure that the simulation model was correctly implemented in accordance with the conceptual design, a range of verification activities were conducted throughout development. These aimed to confirm that individual agents behaved as intended, that decision rules were executed accurately, and that the model outputs were consistent with theoretical expectations.

Agent behaviors were first tested in isolation through unit tests, where specific functions such as investment decisions and subsidy applications were checked for logical consistency. Subsequently, interaction tests were performed using simplified configurations with a limited number of agents. These tests enabled focused observation of feedback mechanisms and emergent dynamics in controlled settings. In addition, extensive debugging and code tracing were used to validate that the implemented decision logic matched the conceptual flow diagrams and theoretical assumptions laid out in earlier stages.

These verification steps were applied iteratively, allowing for continuous refinement of the internal logic and technical structure of the model.

3.3.5. Sensitivity Analysis

The primary objective of this sensitivity analysis is to investigate how uncertainty in the key parameters of the model affects the result of the model. Once these parameters are better understood, the final model can serve as a reference case against which different rollout scenarios can be tested. In this way, the sensitivity analysis supports an iterative modeling approach, gradually building a more reliable and nuanced understanding of the system under study.

The method used is a one-factor-at-a-time (OFAT) sensitivity analysis. This approach begins with a nominal set of parameter values, which is the model discussed in Chapter 6, and explores the effect of changing a single parameter while keeping all others constant. As a local method, OFAT is particularly suitable for identifying tipping points, nonlinearities, and parameter-specific sensitivities [17]. By sweeping each selected parameter across a defined range and comparing the resulting model outputs, it becomes possible to isolate the influence of individual parameters. These variations are visualized to assess the shape and strength of the response, indicating whether the behavior of the model is robust, sensitive, or context-dependent.

3.3.6. Model Validation

Because the rollout of hydrogen infrastructure is forward-looking, empirical validation is not possible. Instead, the model was validated through expert feedback, literature comparison, and face validity checks.

Experts from Stedin, who were closely involved throughout the project, provided repeated input on assumptions and logic, confirming the model's alignment with operational realities. Additional consultations with Enexis, Firan, Netbeheer Nederland, and Zeeuwind helped refine behavioral rules and contextual accuracy in earlier development stages.

To ensure external plausibility, the behavior of the model was compared to established transition dynamics and policy reports. Repeated runs confirmed that expected system responses, such as accelerated adoption after early infrastructure rollout, were consistently recurring. These combined steps provide confidence that the model is a credible tool for the exploration of scenarios under uncertainty.

3.4. Experiment Setting

To assess how HDNO strategies affect the rollout of hydrogen infrastructure under uncertainty, this section outlines the experimental setup used to address Research Sub-questions 4 and 5. Each experiment isolates a key strategic dimension, demand anticipation, timing, and policy context, to test how DSOs might unlock the chicken-and-egg dilemma identified in Chapters 1 and 2.

Experiment 1: Anticipating Demand

This experiment tests how the scale of HDNO proactiveness, modeled using a demand weighting factor, affects infrastructure rollout. Higher weights reflect greater reliance on expected (unconfirmed) demand, while lower weights represent reactive strategies based on actual commitments. The outcomes are evaluated in terms of overall societal costs and benefits.

*"4. What effect does the timing and **scale** of proactive and reactive DSO decision making have on the societal costs and benefits of the rollout of hydrogen infrastructure in Cluster 6?"*

Experiment 2: Timing of Investment

This experiment examines how the timing of the HDNO action impacts the rollout performance. It compares early investment (after initial demand signals) with delayed responses. The goal is to explore the trade-offs between early commitment and reduced risk under uncertainty.

*"4. What effect does **the timing** and scale of proactive and reactive DSO decision making have on the societal costs and benefits of the rollout of hydrogen infrastructure in Cluster 6?"*

Experiment 3: Policy Instruments
This experiment analyzes how hydrogen subsidies, electricity subsidies, and a CO_2 tax affect the business case for industrial retrofitting and hydrogen adoption. Evaluate whether these instruments incentivize early adoption and influence HDNO investment decisions under uncertainty.

*"5. What is the effect of different **proactive regulatory instruments** for hydrogen development in Cluster 6?"*

Together, these experiments provide a structured framework to explore how timing, proactiveness, and policy design influence the dynamics and outcomes of hydrogen infrastructure deployment.

3.4.1. Evaluating Model Outcomes

To assess the systemic impact of different rollout strategies, this study applies a unified evaluation framework that balances societal costs and benefits over time. As discussed in Chapters 1 and 2—particularly Section 2.3—the hydrogen transition involves more than financial efficiency. It affects long-term societal goals including decarbonization, health, employment, and energy system resilience.

To reflect these dimensions, the evaluation uses a composite metric: *Societal Net Present Value (SNPV)*. This indicator aggregates monetized benefits and costs into a single scalar, supporting the structured comparison of rollout strategies under uncertainty. Its general structure is defined as:

$$\text{Societal Net Present Value} = (B_{\text{direct}} + B_{\text{indirect}}) - (C_{\text{direct}} + C_{\text{indirect}})$$

With the following conceptual components:

- B_{direct}: direct benefits, such as avoided CO_2 emissions and reduced NO_x pollution;
- B_{indirect}: indirect benefits, such as job creation, innovation spillovers, public health improvements, avoided grid reinforcement, and reduced operational costs in gas infrastructure;
- C_{direct}: direct costs, including capital and operational expenditures for hydrogen and electricity infrastructure;
- C_{indirect}: indirect costs, including transitional inefficiencies, increased firm-level OPEX, and costs from continued reliance on fossil systems.

Not all of these elements will be included in the operational metric by default. Their inclusion is determined by (i) whether they can be meaningfully represented within the agent-based modeling framework and (ii) whether expert feedback supports their materiality and traceability in the context of Cluster 6.

In Chapter 5, this structure is operationalized using agent behavior and traceable cost streams. The included components, such as emissions pricing, infrastructure costs, firm investments, and avoided system expenditures, are specified in detail. Dimensions that cannot be robustly quantified are acknowledged but excluded from the formal metric.

This approach enables transparent scenario comparison while capturing the broader societal value of rollout strategies beyond technical and financial performance.

4 Conceptual Agent-Based Model

This chapter presents the conceptual agent-based model developed to simulate how regional hydrogen infrastructure either progresses or stalls. It begins by placing the model within the broader hydrogen value chain, then narrows the focus to the critical interface between infrastructure and end use. It identifies the coordination failure between HDNOs and industrial users, outlines each agent's decision-making logic, and describes the feedback loops that emerge from their interaction. The chapter concludes with key modeling assumptions that form the foundation for the simulation analysis in the chapters that follow.

4.1. Bottleneck Identification: Hydrogen Value Chain

The rollout of hydrogen infrastructure in the Netherlands occurs within a broader value chain spanning production, transportation, storage, and end use (Figure 4.1). Although each stage plays a role in the energy transition, this thesis focuses specifically on the interface between transportation and end use, where coordination failures most acutely hinder progress.

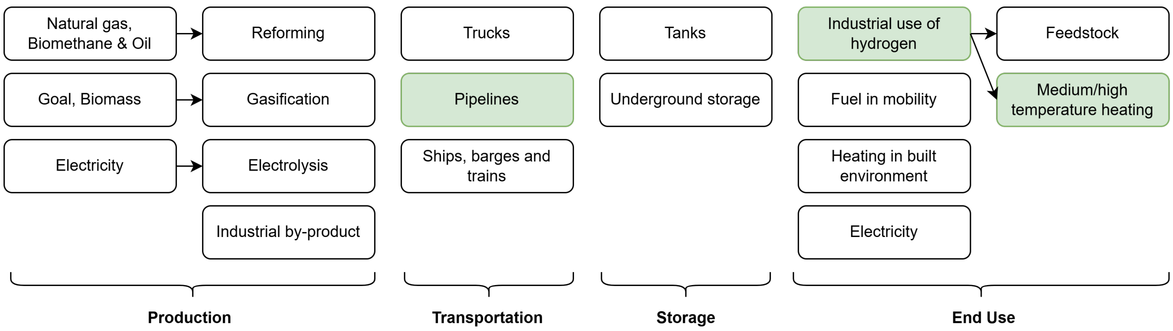

Figure 4.1: The Hydrogen Value Chain, adapted from [9] and [77]

Hydrogen can be produced through methods such as electrolysis or reforming and transported via pipelines, trucks, ships, or trains. It may be stored in tanks or underground facilities before being used in sectors such as transport, heating, electricity, and, in particular, industry. Early demand is expected to be concentrated in industrial applications, especially for feedstock replacement and high-temperature processes.

The model focuses specifically on the transport and end-use stages, where regional infrastructure must connect industrial users to the national hydrogen backbone. This choice reflects prior findings that regional coordination challenges, especially between HDNOs and industrial actors, are a key bottleneck in hydrogen adoption.

As shown in Figure 4.2, the envisioned hydrogen system depends on extending the national backbone

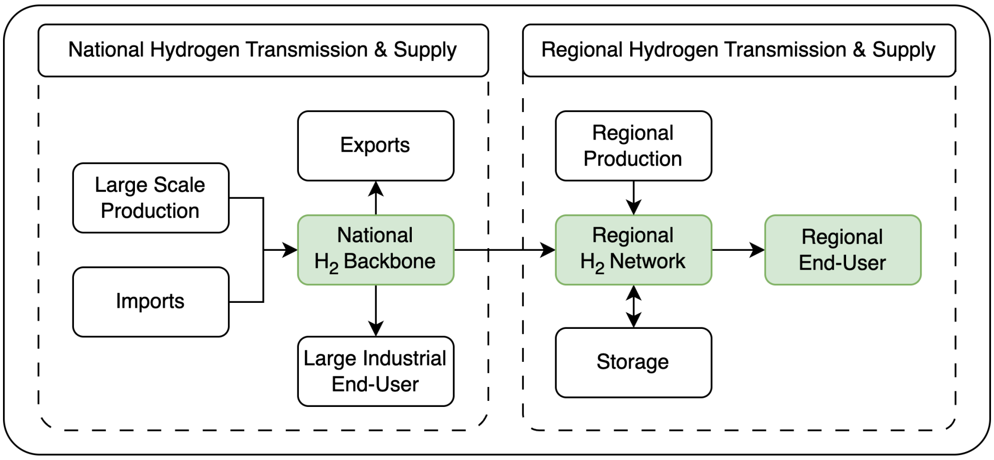

Figure 4.2: Schematic representation of the hydrogen transmission and supply system.

through regional networks to reach industrial users. While HyNetwork Services oversees the national rollout, the regional layer remains institutionally undefined. No governance model or operator mandate has been established, leaving uncertainty over who is responsible for connecting medium-sized dispersed users. This gap, represented by the red cross, reflects the missing regional link. Fragmented authority, spatially scattered demand, and unclear investment responsibilities further increase perceived risks. Infrastructure providers hesitate without firm demand, while industrial users delay adoption without guaranteed access. As discussed in Chapter 1 and Chapter 2, this is less a technical problem than a failure of justification: neither HDNOs nor companies can credibly act without clear signals that the other will follow.

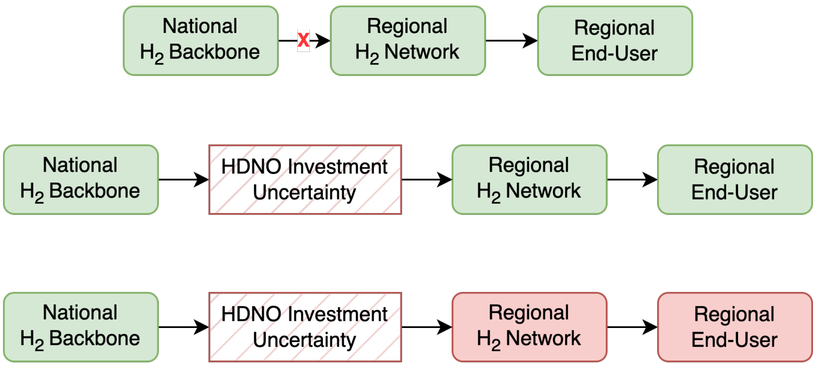

Figure 4.3: Investment uncertainty among HDNOs at the regional level.

Figure 4.3 shows how the lack of regional governance becomes a structural bottleneck. While the national network advances under a clear mandate, regional infrastructure stalls due to mutual hesitation. HDNOs will not invest without credible demand, and companies won't commit without nearby infrastructure. Long-distance connections are often too expensive and deepen the standstill. This is less a technical or economic impasse than a breakdown in mutual justification: each actor requires assurance that the other will move first. This misalignment sets the stage for understanding the behavioral feedback loops at the heart of the model.

4.2. Coordination Failure: Chicken-and-Egg Dilemma

The delay in regional hydrogen rollout stems from a reinforcing feedback loop: without infrastructure, companies are reluctant to switch to hydrogen; without visible demand, HDNOs hesitate to invest. This interdependence creates a self-reinforcing bottleneck. The core issue is not technical feasibility or regulatory barriers, but how decentralized actors perceive risk and anticipate each other's moves, a dynamic that reflects the chicken-and-egg dilemma introduced in Chapter 2.

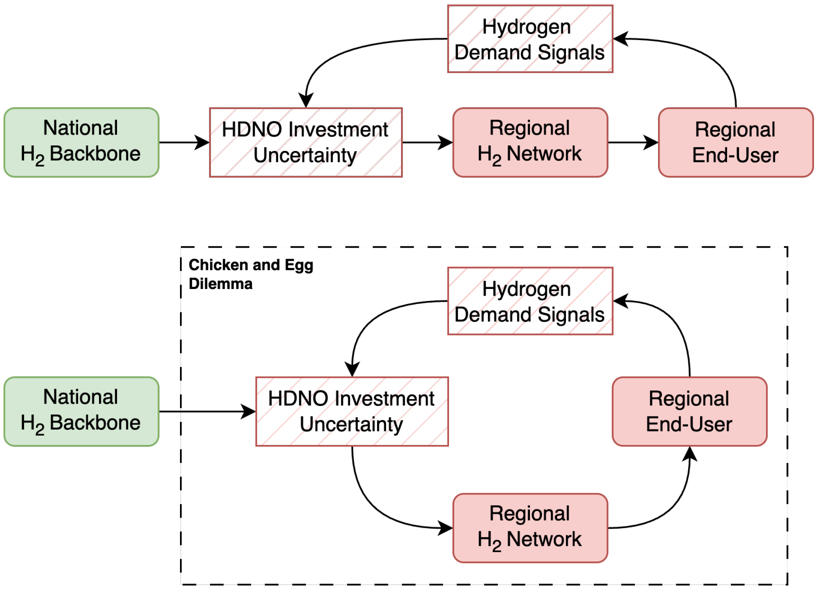

Figure 4.4: Zoomed-in system view highlighting missing regional links and the emergence of investment uncertainty.

As shown in Figure 4.4, this chicken-and-egg dilemma plays out in a tightly coupled subsystem. The lower panel highlights the loop that drives regional stagnation: The uncertainty of HDNO investment leads to a lack of infrastructure, which limits industrial uptake, further reducing demand signals, and strengthening uncertainty. This systemic feedback, while institutionally grounded, is inherently behavioral in nature.

In traditional models, uncertainty is often treated as an external condition - a fixed background risk. In contrast, this simulation treats uncertainty as something that emerges from the decisions of strategic actors. As shown in Figure 4.5, HDNOs decide whether to invest based on perceived demand, while companies decide whether to adopt hydrogen based on infrastructure availability. These choices are interdependent: each actor adjusts its expectations in response to the other. Over time, this creates a feedback loop where investment and adoption coevolve, sometimes reinforcing progress, and other times amplifying delays.

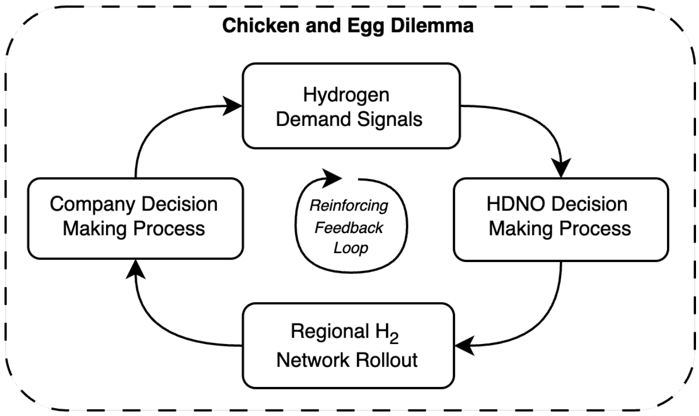

Figure 4.5: Chicken-and-egg feedback loop between HDNO decision-making and industrial hydrogen demand signals.

In this formulation, HDNOs investment uncertainty and industrial demand are not static inputs but dynamic outcomes of agent interaction. The regional rollout emerges from this interplay, enabling the simulation to capture how coordination failures evolve and under what conditions they might be overcome.

This conceptualization forms the foundation of the agent-based model. By modeling coordination failure as the result of interacting and decentralized decisions by HDNOs and industrial users, the simulation explores how variations in investment logic, demand signaling, and timing can influence the emergence or resolution of the chicken-and-egg dilemma. The next section builds on this formulation by specifying how the two core agent types, HDNOs and industrial users, make decisions within the model framework.

4.3. Key Decision-Making Processes

Building on the coordination loop described above, the simulation models decision-making as an interactive process between two types of agents: industrial companies and HDNOs. Each responds not only to immediate economic incentives but also to evolving behavior in its environment, forming a feedback loop of demand signaling and infrastructure response.

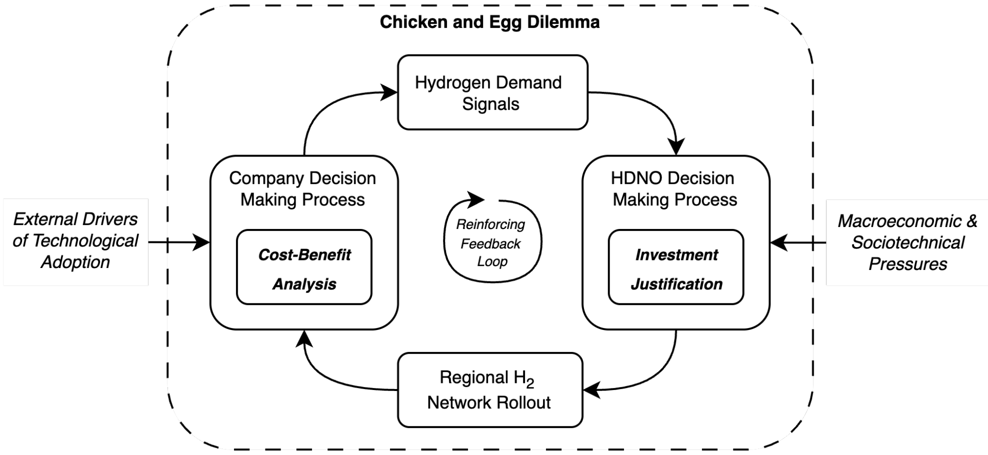

Figure 4.6: Overview of mutual decision processes between industrial companies and the HDNO.

As Figure 4.6 illustrates, industrial companies evaluate hydrogen adoption through an internal cost-benefit analysis, shaped by external drivers such as carbon pricing, subsidies, and fuel cost projections. If the expected return exceeds their threshold, they submit a letter of intent, generating hydrogen demand signals.

However, HDNOs assess whether infrastructure rollout is warranted. Their investment justification depends on the strength of aggregated demand signals, available resources, and broader macroeconomic and sociotechnical pressures. Depending on the strategy, the HDNO decides whether to proceed with development in a given region.

This coupled structure allows infrastructure availability and industrial adoption to co-evolve over time. Rather than treating demand and rollout as fixed inputs, the model derives them from within the system through agent interaction, capturing how regional systems stall or accelerate based on the alignment of incentives, expectations, and timing.

The following sections formalize each of these decision processes in detail.

4.4. Dynamic Feedback Between Demand and Infrastructure

Regional hydrogen development does not follow a linear path. Instead, it evolves through feedback loops between industrial demand and DSO investment decisions. As shown in Figure 4.7, these loops can reinforce either momentum or inertia, depending on how infrastructure availability, perceived benefits, and company interest interact.

When companies show early interest, DSOs are more likely to invest. The new infrastructure lowers connection costs and strengthens the business case for switching, encouraging further adoption. This can create a virtuous cycle in which demand and rollout reinforce each other.

But this dynamic cuts both ways. If DSOs build too soon, without firm commitments, the result may be underused assets and stranded costs. Reactive strategies based on confirmed letters of intent may take longer, but bring greater certainty. By investing only when demand is more secure, DSOs reduce risk,

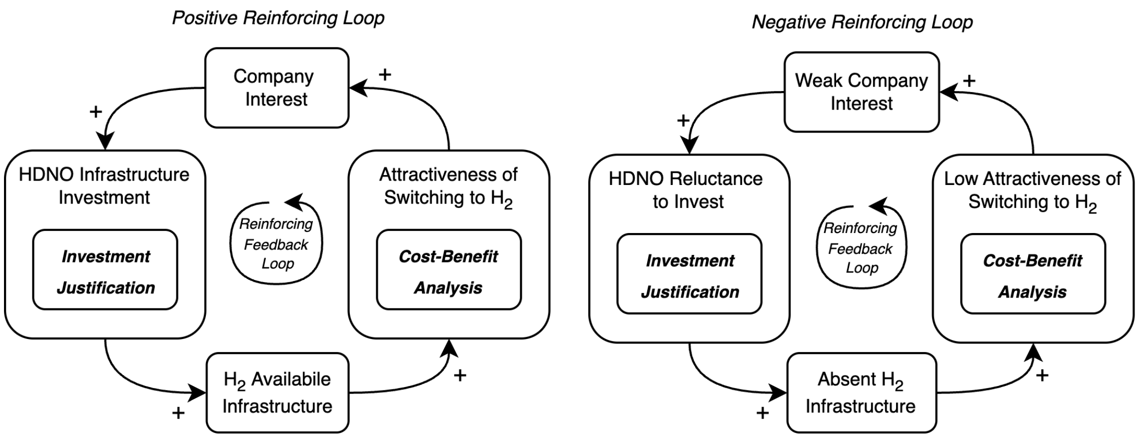

Figure 4.7: Dynamic feedback loop between demand signals and infrastructure development.

attract upfront capital (e.g., connection fees), and avoid overextending limited resources. For public DSOs, tasked with serving the public interest, this cautious approach can be especially valuable.

Even strong positive feedback can have downsides. Rapid rollout may lock regions into hydrogen pathways as better alternatives emerge or overshoot actual needs. On the other hand, weak signals and hesitant investment can trap regions in a cycle of delay, even when modest intervention might have broken the deadlock.

Small differences in timing, strategy, or local conditions can lead regions toward very different outcomes, from fast infrastructure build-out to prolonged inaction. By simulating how infrastructure and demand respond to one another over time, the model captures this divergence. It highlights how uncertainty, expectations, and the timing of key decisions shape the trajectory of the hydrogen transition.

4.5. Overview and Formalized Conceptual Model

The previous sections outlined the coordination dilemma between industrial actors and hydrogen distribution network operators (HDNOs), highlighting the feedback loops that shape infrastructure rollout under uncertainty. This section formalizes those dynamics into a structured simulation model.

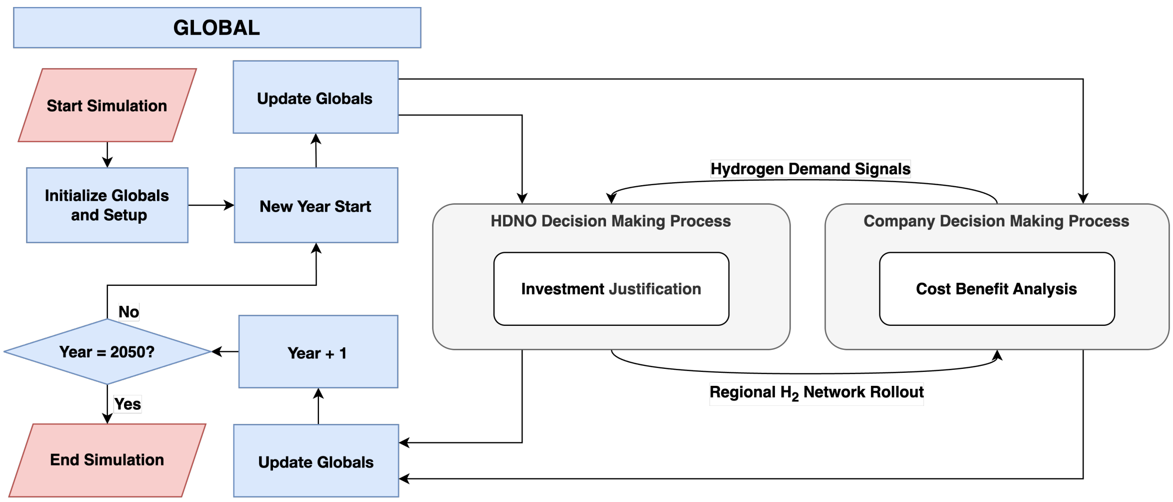

Figure 4.8: High-level simulation structure, showing annual interactions between global parameters, company decisions, and HDNO investment logic.

Figure 4.8 shows a high-level overview of the model. The simulation runs in annual steps, starting with updates to global parameters such as fuel prices, subsidies, and carbon taxes. These influence the behavior of two main agent types: industrial companies and the HDNO. Companies evaluate whether switching from natural gas to hydrogen is financially attractive and, if so, submit a letter of intent as a hydrogen demand signal. The HDNO then assesses whether effective demand justifies infrastructure investment, recognizing that a complete network cannot be built for a single firm and requires an aggregated demand base.

While this figure focuses on hydrogen-specific coordination, modeling only a Hydrogen Distribution Network Operator (HDNO) would neglect critical dynamics. Industrial regions are not choosing between hydrogen and nothing—they are navigating multiple decarbonization pathways, including electrification and, in some cases, continued use of gas. These options compete and interact both strategically and spatially. To reflect this broader planning landscape, the simulation abstracts the infrastructure coordinator as a unified Distribution System Operator (DSO), responsible for investment decisions across electricity, hydrogen, and potentially gas networks.

Although this abstraction extends beyond the current legal mandate of Dutch DSOs, it is grounded in emerging policy developments. The EU Hydrogen and Decarbonised Gas Market Directive (EU) 2024/1788 explicitly permits the integration of hydrogen distribution into existing operator structures. Similarly, recent national analyzes emphasize the need for regionally coordinated multi-carrier infrastructure governance [100]. The model of HDNO and DSO as a single agent is therefore not only a forward-looking simplification; it aligns with institutional trends and enables the exploration of carrier-agnostic rollout strategies, infrastructure prioritization, and decision-making under uncertainty.

This modeling choice directly supports the research objective: to examine how infrastructure planning shapes and is shaped by overlapping transition pathways. Capturing these interdependencies is essential to understanding the strategic dynamics of regional decarbonization.

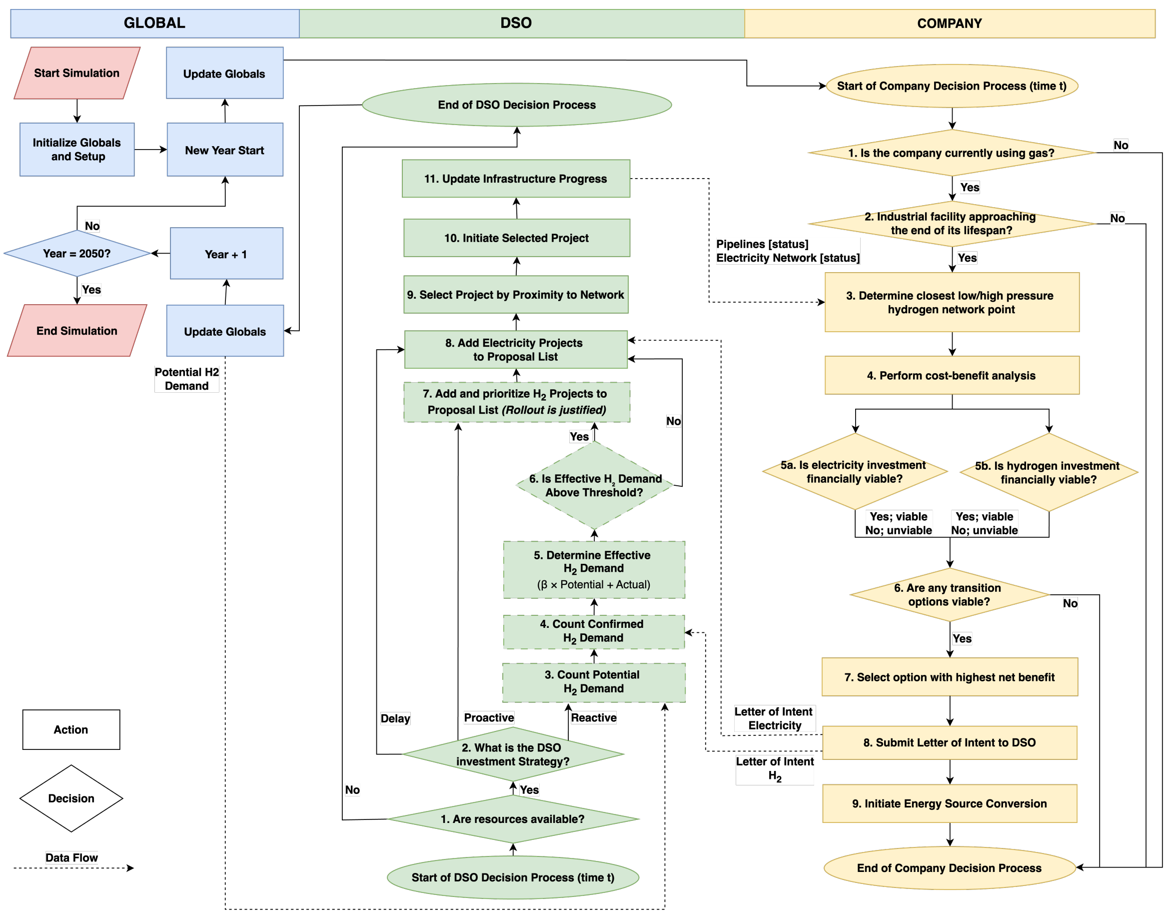

Figure 4.9: Formalized annual simulation logic, showing detailed decision-making flow for the global environment, DSO, and company agents.

Figure 4.9 shows the detailed decision-making logic within each annual cycle. The company module evaluates the feasibility of switching based on asset lifetime, infrastructure proximity, and financial returns. If conditions are met, a letter of intent is submitted. The DSO then processes demand signals, selects an investment strategy (reactive, proactive, or delay), and initiates infrastructure rollout based on thresholds, available resources, and spatial prioritization.

4.6. Company Decision-Making Process

The industrial companies in the model act as individual agents that consider switching from natural gas to hydrogen or electricity only when their existing installation approaches the end of its technical lifetime. This reflects the investment logic of companies, which typically aligns major energy decisions with asset replacement cycles. At that point, the firm weighs whether the long-term benefits, such as avoided gas costs, CO_2 tax savings, and potential subsidies, justify the costs of retrofitting and connecting to an alternative network.

Although technical connection is always possible, availability and cost vary depending on the infrastructure rollout and distance to the network. Especially in reactive DSO strategies, limited local infrastructure can make adoption prohibitively expensive. As a result, switching behavior is shaped not only by energy prices and policy incentives, but also by spatial factors and infrastructure timing.

As shown in Figure 4.10, each firm follows a structured decision process. First, it checks whether it is eligible to consider switching: This occurs only when it still uses gas and its asset is nearing end-of-life. Second, it determines the costs of connection to hydrogen and electricity, based on proximity to existing infrastructure. Third, it conducts a complete cost-benefit analysis, weighing expected annual benefits, such as fuel savings, CO_2 tax reductions, and probabilistic subsidies, against capital, operational, and connection costs (see Table 4.1). Finally, if either energy carrier meets the firm's investment criteria (payback period and ROI), a letter of intent is submitted. Otherwise, the firm reinvests in gas and re-evaluates in later years.

This structured decision logic ensures that the switch emerges from a combination of firm-specific conditions, infrastructure implementation, and external drivers. In particular, firms located near planned infrastructure face lower connection costs and are more likely to adopt early, reinforcing local demand. These localized decisions aggregate into regional demand signals that influence the planning of the DSO infrastructure, closing the coordination loop described above.

Cost-Benefit Formulation for Investment Decisions

Each year, companies assess whether switching from natural gas to hydrogen or electricity is financially viable. This decision is based on a structured cost-benefit analysis that weighs expected benefits against total discounted costs over the investment horizon. A firm proceeds with the switch only if both the payback period and return on investment exceed predefined thresholds. Otherwise, it reinvests in a new gas installation and re-evaluates the decision in a future asset cycle.

The evaluation includes the following components:

Annual benefits

- *Avoided gas cost*, calculated when the alternative energy price is lower than the gas price. This depends on the difference between P_{gas} and either P_{H2} or P_{elec}, and scales with the firm's annual energy demand E.
- *CO_2 tax savings*, derived from the avoided emissions of switching fuels. This depends on the carbon tax level T_{CO2}, the emission factor EF_{CO2}, and energy demand E.
- *Expected subsidy*, which reflects policy support and is calculated as a probabilistic term. It combines the expected subsidy size (S_{H2} or S_{elec}) with the probability of receiving it (p_{subsidy}) and is also proportional to E.

Costs

- *Operational cost*, incurred annually when hydrogen or electricity is more expensive than natural gas. It depends on the price gap ($P_{\text{H2}} - P_{\text{gas}}$ or $P_{\text{elec}} - P_{\text{gas}}$) and scales with demand E.

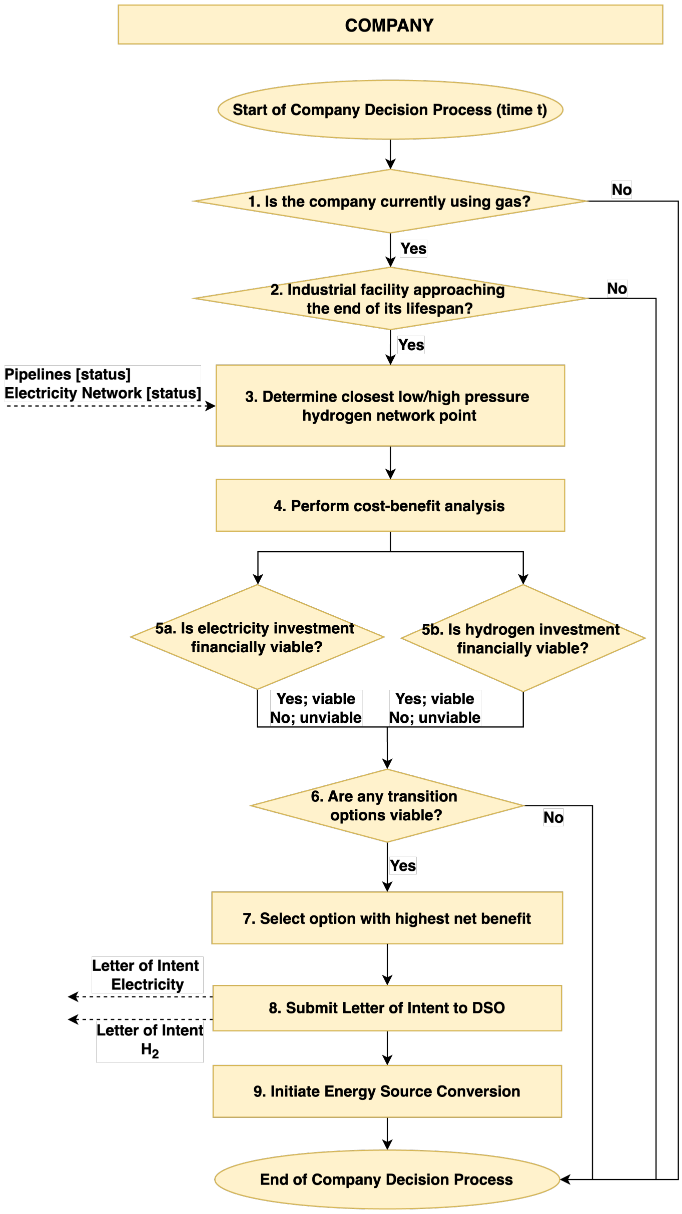

Figure 4.10: Company decision flowchart: annual evaluation of energy switching options based on fuel use, asset status, infrastructure proximity, and financial feasibility.

- *Retrofitting cost*, a one-time capital expense required to convert internal systems. This varies across firms and is represented by $C_{\text{retrofit,H2}}$ or $C_{\text{retrofit,elec}}$.
- *Connection cost*, which depends on distance to the network D, using a linear cost rate (c_{H2} or c_{elec}). For hydrogen, an additional component $\delta_{\text{PRS}} \cdot C_{\text{PRS}}$ may apply if a pressure regulation station is needed.

Component	**Hydrogen Transition**	**Electricity Transition**
Annual Benefits		
Avoided Gas Cost	$B_1 = \max(0,\, P_{\text{gas}} - P_{\text{H2}}) \cdot E$	$B_1 = \max(0,\, P_{\text{gas}} - P_{\text{elec}}) \cdot E$
CO_2 Tax Benefit	$B_2 = E \cdot EF_{\text{CO2}} \cdot T_{\text{CO2}}$	$B_2 = E \cdot EF_{\text{CO2}} \cdot T_{\text{CO2}}$
Expected Subsidy	$B_3 = E \cdot S_{\text{H2}} \cdot p_{\text{subsidy}}$	$B_3 = E \cdot S_{\text{elec}} \cdot p_{\text{subsidy}}$
Total Annual Benefit	$B = B_1 + B_2 + B_3$	$B = B_1 + B_2 + B_3$
Costs		
Operational Cost	$C_1 = \max(0,\, P_{\text{H2}} - P_{\text{gas}}) \cdot E$	$C_1 = \max(0,\, P_{\text{elec}} - P_{\text{gas}}) \cdot E$
Retrofitting Cost	$C_2 = C_{\text{retrofit,H2}}$	$C_2 = C_{\text{retrofit,elec}}$
Connection Cost	$C_3 = D \cdot c_{\text{H2}} + \delta_{\text{PRS}} \cdot C_{\text{PRS}}$	$C_3 = D \cdot c_{\text{elec}}$
Total Discounted Cost	$C = \sum_{t=1}^{T} \frac{C_1}{(1+r)^t} + C_2 + C_3$	$C = \sum_{t=1}^{T} \frac{C_1}{(1+r)^t} + C_2 + C_3$
Decision Criteria		
Net Benefit	$NB = B - C$	$NB = B - C$
Payback Period	$PP = \frac{C}{B - C_1}$	$PP = \frac{C}{B - C_1}$
Return on Investment	$ROI = \frac{NB}{C}$	$ROI = \frac{NB}{C}$

Table 4.1: Cost-benefit evaluation for industrial transition to hydrogen or electricity, including expected subsidies for both carriers

Two key attributes differentiate firms in the model: their annual energy demand (E) and their spatial location (x, y). These characteristics shape the underlying variables that determine the cost-benefit outcome of switching.

- *Fuel price differentials* ($P_{\text{gas}} - P_{\text{H2}}$, $P_{\text{gas}} - P_{\text{elec}}$) affect the potential fuel savings or extra costs. Although global in value, their financial impact scales directly with firm-level energy demand E, making energy-intensive firms more sensitive to fuel price changes.
- *Carbon tax level* (T_{CO2}) applies equally between firms but produces larger savings for those with higher demand E, as their avoided emissions are greater.
- *Subsidy size and uncertainty* ($S_{\text{H2}}, S_{\text{elec}}, p_{\text{subsidy}}$) represent the modeled probabilistic policy incentives. Although not firm-specific, the expected benefit scales again with E, and stochastic variation introduces differences even among otherwise similar firms.
- *Retrofitting cost* (C_{retrofit}) varies between firms according to the compatibility of the internal systems and the scale of their operations. Larger and more energy-intensive firms typically require more extensive retrofitting, resulting in higher costs.
- *Distance to infrastructure* (D) is determined by spatial location. Firms closer to hydrogen or electricity networks face lower connection costs (C_3), and in the case of hydrogen, may also avoid pressure regulation costs ($\delta_{\text{PRS}} \cdot C_{\text{PRS}}$). Thus, early infrastructure rollout benefits nearby firms and creates spatial clustering effects.

As simulation progresses, global trends, such as declining hydrogen prices and increasing CO_2 taxes, make switching more attractive over time. This dynamic ensures that even firms that initially reinvest in gas may reconsider in later years as the economics shift in favor of cleaner carriers.

This framework ensures that the switching results emerge from firm-specific conditions, including energy intensity, spatial location, policy exposure, and access to infrastructure. The evaluation logic is summarized in Table 4.1.

To determine transition viability, the model computes three evaluation metrics:

- *Net Benefit (NB)*: the total benefit minus total cost.
- *Payback Period (PP)*: the number of years needed to recover the investment.
- *Return on Investment (ROI)*: the net benefit as a fraction of total cost.

Only if the payback period is shorter than a predefined threshold and the ROI exceeds a minimum acceptable level will the company proceed to submit a letter of intent to the DSO. These thresholds are based on values from the literature that reflect typical return expectations and investment horizons for industrial firms. The exact values used in this model are introduced in Chapter 5. If either condition is not met, the company reinvests in a new gas installation and delays the transition until that asset approaches the end of life.

This cost-benefit framework ensures that fuel switching decisions respond directly to changes in fuel prices, policy incentives, and infrastructure rollout. Crucially, when infrastructure is planned in a given area, nearby companies face significantly lower connection costs, which can tip the cost-benefit calculation in favor of switching. This mechanism captures how early infrastructure planning can unlock clustered adoption and supports evaluation of how industrial actors respond under different spatial and policy scenarios.

4.7. HDNO Decision-Making Process

In the Dutch energy system, Distribution System Operators (DSOs) are legally required to connect users to the electricity grid under a *connection obligation*, as codified in Article 23 of the Electricity Act [91]. This obligation requires that DSOs fulfill connection requests within a defined period -typically 18 weeks for small consumers - with longer, case-specific timelines for large users regulated by the ACM. As such, the system operates under a fundamentally reactive planning logic: the infrastructure is delivered in response to confirmed individual requests rather than proactive system-wide planning.

Unlike electricity and gas, hydrogen currently lacks a designated Distribution System Operator (HDNO) and is not covered by a formal connection obligation. As a result, there is no institutional mechanism that guarantees firms access to hydrogen infrastructure, even if they are willing to switch. Although it is often assumed that similar rights will eventually apply, such expectations remain speculative. As noted in [78], the legal framework for hydrogen is still in development, and the division of responsibilities for the implementation and access of infrastructure has not yet been formally defined. In principle, hydrogen connections could be organized through a future obligation or arranged via private contracts, but neither approach has been formalized.

However, introducing a connection obligation for hydrogen would not necessarily result in an efficient system. When electricity, gas, and hydrogen all remain viable parallel options, the infrastructure landscape risks becoming fragmented. Firms may be connected to different carriers in isolated locations, leading to underutilized networks and reduced returns on public investment. Because hydrogen requires the construction of an entirely new distribution system, efficient deployment is heavily dependent on spatial coordination and demand clustering. A reactive, request-driven approach, as used for mature carriers like electricity, can delay infrastructure development, hinder economies of scale, and ultimately slow the transition.

Modeling only a hydrogen distribution operator in isolation would fail to capture the interdependency of infrastructure decisions between energy carriers. Industrial firms choose between hydrogen, electricity, and gas based on a combination of retrofit costs, relative prices, and local infrastructure availability. These choices are not made in isolation; the rollout of one carrier affects the perceived viability of others. Ignoring these interdependencies risks producing fragmented infrastructure, inefficient allocation of public resources, and a slower overall transition.

To reflect this interconnected reality, the simulation introduces a *unified DSO agent* responsible for coordinating the deployment of hydrogen, electricity and gas infrastructure within a single decision-making framework. This setup enables the model to test three stylized investment strategies:

- *Reactive mode:* Hydrogen infrastructure is initiated only when a sufficient number of letters of intent have been submitted. This represents a strict interpretation of the current legal logic, mirroring the *connection obligation* for electricity and gas.
- *Proactive mode:* Projects are started in anticipation of demand based on spatial clustering and suitability, without waiting for confirmed requests. Electricity connections in those areas are deferred, under the assumption that they will transition to hydrogen.
- *Delay mode:* No hydrogen infrastructure is built. This reflects the current institutional vacuum, where no HDNO has been appointed and DSOs are not yet active in hydrogen planning.

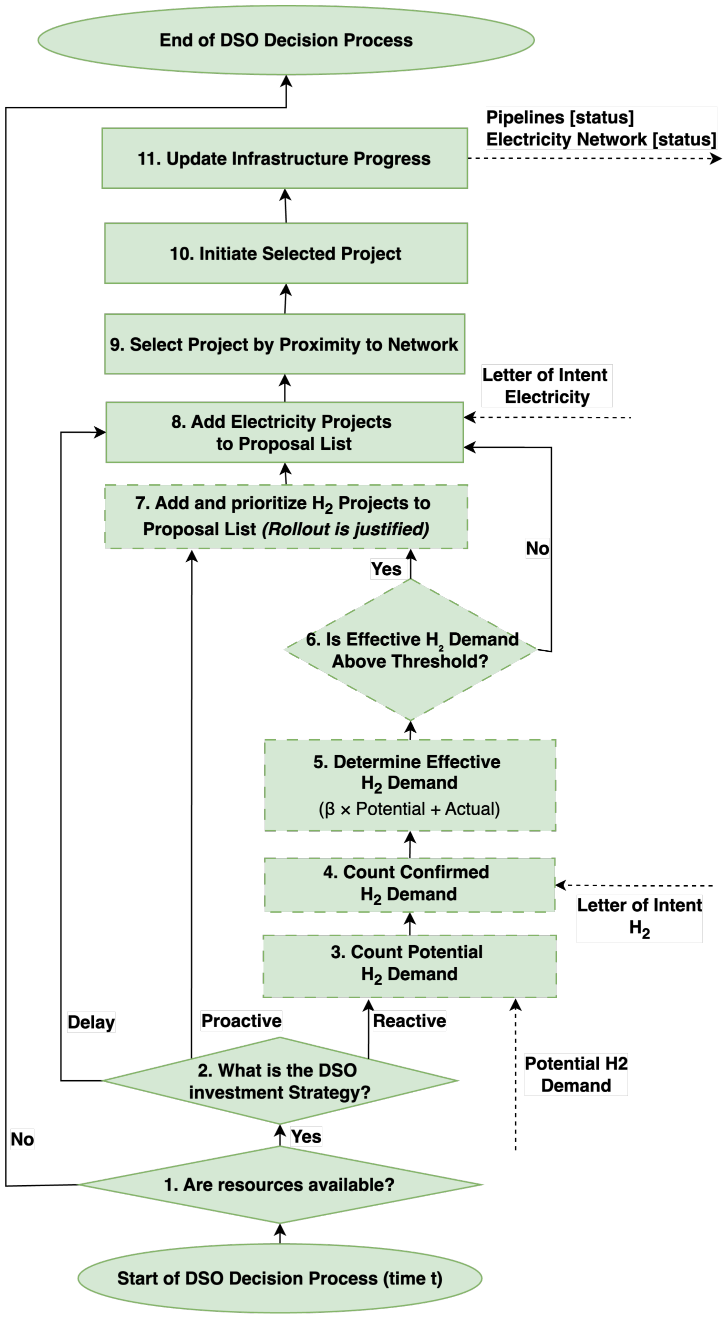

Figure 4.11: DSO infrastructure planning process: Annual decision logic for hydrogen and electricity project rollouts.

Each year, the DSO first checks the available planning capacity. If labor, budget, or other resource constraints are binding, new projects are postponed. The model includes the legally mandated *connection obligation* for electricity, requiring DSOs to realize connections upon request. However, hydrogen lacks such a legal obligation. As a result, the implementation of hydrogen infrastructure in the *reactive mode* follows a more cautious justification logic based on effective demand:

$$D_{\text{eff}} = D_{\text{conf}} + \beta \cdot \min(D_{\text{pot}}, D_{\text{thresh}})$$

Here, D_{conf} represents the confirmed demand through letters of intent, D_{pot} is the number of potentially switchable firms in the area, and D_{thresh} is the minimum aggregate demand required to justify investment. The parameter $\beta \in [0, 1]$ reflects the willingness of the DSO to consider anticipated, but not yet confirmed, demand. The minimum function ensures that the speculative potential does not disproportionately influence investment decisions. Since hydrogen is a new energy carrier without a formal roll-out mandate, the infrastructure cannot be justified for a single company alone; it must serve a credible cluster of current or expected users.

If the effective demand in an area exceeds the threshold, it becomes eligible for hydrogen rollout. This reflects the preference of the DSO for coordinated, clustered infrastructure development, aligned with the national hydrogen backbone. Unlike electricity, where the connection obligation requires the service of individual users, hydrogen infrastructure requires collective justification. Public investments will not support the implementation of an entire regional network for a single firm; a broader user base is needed to ensure efficient use of resources.

When both hydrogen and electricity projects are triggered in the same area, they are planned in parallel unless resource constraints, such as limited labor, materials, or budget, prevent full execution. In that case, hydrogen projects that meet the justification threshold are prioritized, reflecting the strategic value of clustered deployment. If total project demand exceeds annual capacity, projects that cannot be executed are not automatically deferred but must reapply the following year. This setup reflects real-world constraints on construction capacity, while allowing delayed projects to be reconsidered in future years.

These delays can affect company behavior. Infrastructure construction often spans multiple years, while companies face hard deadlines tied to the end-of-life of their existing assets. If hydrogen is not available when a firm must reinvest, it may switch to electricity or remain on gas, locking in that choice for another full asset cycle. This limits the emergence of hydrogen clusters, even when local interest is high.

This framework captures the importance of timing, spatial coordination, and strategic prioritization in rollout decisions. By comparing proactive, reactive, and inactive strategies within a unified DSO framework, the model highlights how institutional choices shape the speed, geography, and efficiency of the hydrogen transition.

4.8. Conceptual model assumptions

To retain analytical clarity while capturing the essential coordination dynamics between industrial actors and the distribution system operator (DSO), the model is built on a set of simplifying assumptions. These abstractions are not intended to reproduce the full complexity of real-world systems but rather to define an experimental setting in which key interaction mechanisms can be examined systematically. The assumptions are grouped into three main categories: decision timing and firm behavior, infrastructure representation, and market and policy context.

Decision timing and firm behavior.

- All agents, companies and DSO, make decisions on an annual, synchronized time basis. Each simulation tick represents one year, aligning with typical industrial and infrastructure planning cycles. Within each year, companies revise their cost-benefit analysis in response to newly planned infrastructure, particularly updated connection costs. These updates allow firms to reflect the most recent network layout in their investment decisions, even before the next simulation year begins. However, no further intra-year iterations or decision cycles take place.

- Firms only consider fuel switching when an installation approaches the end of its technical lifetime. This models real-world investment inertia by tying decisions to the equipment replacement cycle.
- Firms act independently and do not coordinate their decisions. However, local infrastructure spillovers are captured: firms benefit from nearby hydrogen conversions through reduced connection costs, encouraging spatial clustering.
- Hydrogen adoption is triggered by letters of intent submitted to the DSO. These serve as binding commitments conditional on infrastructure access and enable the DSO to assess effective demand.
- Industrial energy demand is assumed to be constant over time. Firms maintain fixed gas consumption until transition, after which hydrogen use remains stable.
- Once converted to hydrogen, firms do not revert to gas or other carriers. Transitions are considered irreversible within the model horizon.
- All firms are technically capable of retrofitting for hydrogen. No limitations from R&D readiness or sector-specific constraints are modeled.
- Firm decision logic is sector-neutral. Variations in process temperature or industrial subsector are not represented.
- Firms have no influence on policy or regulatory design. Market and policy conditions are externally defined and remain unchanged throughout the simulation.

Infrastructure representation.

- Hydrogen is delivered exclusively via newly constructed low- and high-pressure distribution pipelines branching from the national backbone. Alternative transport methods such as trucks or rail are excluded, focusing the model on local pipeline infrastructure.
- The DSO is represented as a single actor, assigned the role of Hydrogen Distribution Network Operator (HDNO), responsible for all infrastructure planning, investment, and rollout decisions. Commercial third parties are not modeled in the construction or operation of hydrogen pipelines. This simplification enables a clear comparison of reactive, proactive, and delayed strategies without introducing inter-operator dynamics.
- All quantities, costs, demand, supply, are modeled as annual averages. Intraannual variability, such as hourly demand peaks, renewable fluctuations, or price volatility is not included.
- Once constructed, the pipelines are assumed to remain operational for the full model horizon. No failures, maintenance, or renewal cycles are considered.
- Hydrogen storage is excluded from the model. The infrastructure is designed to match the average annual demand, and short-term or seasonal balancing is beyond the scope of the analysis.
- Multiple regional connection points are assumed to the national backbone. Firm connections are routed from these points and the expansion of the local network prioritizes efficient spatial clustering to reduce costs.

Market and policy context.

- Hydrogen, electricity and gas prices follow fixed exogenous trajectories reflecting broader trends. Local demand does not affect these prices, allowing focus on infrastructure-driven dynamics.
- Policy conditions, such as taxes, subsidies, and regulations, remain constant throughout the simulation. Scenario variations are applied externally, without internal policy feedbacks.
- The DSO is assumed to act as the Hydrogen Distribution Network Operator (HDNO), reflecting the strong interdependence between electricity, gas, and hydrogen systems. This role supports coordinated planning across carriers and leverages existing infrastructure expertise.
- Tariffs for gas, electricity, and hydrogen are assumed to be equal and do not influence connection decisions. Instead, connection choices are driven by infrastructure costs and timing. No explicit tariff structure is modeled, and revenues from user tariffs are not tracked. This reflects the assumption of a single DSO responsible for all carriers, ensuring tariff neutrality across the system.

- The connection of the system to the backbone is initiated once three firm commitments are received. After this link is established, additional firm connections require only one new request.
- The network expansion follows a threshold-based logic that prioritizes spatial proximity. Strategic behavior such as lobbying, pricing competition, or political intervention is not modeled.
- All infrastructure costs are borne by the HDNO and participating companies. No co-funding or subsidies from public entities are assumed within the base case.

Together, these simplifying assumptions create a controlled setting in which to explore how industry and DSO interact. Their influence on model behavior is examined in detail in Chapters 5 and 6, where several of the assumptions are relaxed or modified in different scenarios.

4.9. Model Overview

To provide a structured overview of the simulation architecture, Table 4.2 applies the ODD (Overview, Design concepts, and Details) protocol developed by Grimm et al. [52]. This framework standardizes the documentation of agent-based models and supports transparency and replicability. The table summarizes the model's purpose, agent attributes, decision logic, spatial and temporal scales, initialization routines, key inputs, and internal submodels, as implemented in the Regional Hydrogen-Infrastructure ABM.

Table 4.2: ODD framework for the Regional Hydrogen-Infrastructure ABM following Grimm et al. [52]

	Model-specific description
1 · Purpose	Test how three planning strategies by a future multi-carrier Distribution System Operator (DSO) affect coordination with industrial firms and shape the regional rollout of hydrogen and electricity infrastructure in the Netherlands. The model evaluates: • *Reactive window*: infrastructure is built in response to confirmed demand and partially weighted potential demand, using parameter β. • *Proactive window*: infrastructure is built without waiting for confirmed commitments. • *Delay*: no hydrogen infrastructure is developed.
2 · Entities, state variables & scales	The model includes two primary agent types: *industrial companies* and a *regional Distribution System Operator (DSO)*. *State variables and annual decision logic:*

	Industrial Company	**Distribution System Operator**
Attributes	• Location (x, y) • Annual demand E • Remaining installation lifetime L • Investment Triggers $\text{ROI}_{\min}$, $\text{PP}_{\max}$	• Operational Capacity K • Strategy $S \in \{\text{reactive}, \text{proactive}, \text{delay}\}$ • Potential Demand Sensitivity β • Minimum Demand threshold D_{thresh}
Decision logic	1. If installation lifetime L nearing lifetime, consider switching from gas to hydrogen or electricity. 2. Evaluate both alternatives through full cost–benefit analysis. 3. If at least one option meets: $\text{ROI} \geq \text{ROI}_{\min}$ and $\text{Payback} \leq \text{PP}_{\max}$, submit a Letter of Intent (LoI) for the energy carrier with higher net benefit. 4. If no option is viable, continue using gas and decrement lifetime: $L \leftarrow L - 1$. 5. If $L = 0$ and neither alternative is viable, reinvest in a new gas installation and reset lifetime L.	1. Check whether sufficient planning capacity is available. 2. If strategy is *delay*, skip hydrogen rollout. 3. If strategy is *proactive*, prioritize hydrogen rollout without full confirmation. 4. If strategy is *reactive*: • For each region, calculate effective hydrogen demand: $D_{\text{eff}} = D_{\text{conf}} + \beta \cdot \min(D_{\text{pot}}, D_{\text{thresh}})$ • If $D_{\text{eff}} \geq D_{\text{thresh}}$, add the region to the hydrogen project proposal list. 5. Add electricity connections to the proposal list based and proceed investments.

Scales	*Spatial scale:* rectangular world $0 \leq x \leq 150,\ 0 \leq y \leq 100$ patches with km_per patch $= 0.05$. This corresponds to a 7.5×5.0 km industrial corridor. *Temporal scale:* discrete annual ticks (1 tick $= 1$ year); simulation starts in 2025 and stops when year ≥ 2050, providing a 25-year horizon that can be extended for scenario work.
3 · Process overview & scheduling	Each simulation year (2025–2050), the model updates prices and policy inputs, lets firms evaluate switching and submit letters of intent, checks DSO capacity, queues and executes eligible projects, updates routing using A* path-finding, and logs outputs.
4 · Design concepts	The model captures a coordination failure between firms and the DSO through a chicken-and-egg loop: demand depends on infrastructure, and infrastructure depends on demand. Rollout and adoption emerge from decentralized, rule-based decisions. Firms switch if ROI and payback thresholds are met; the DSO invests if clustered demand justifies it. Dynamics include inertia, clustering, and path dependence. Agents are heterogeneous and non-adaptive; stochasticity arises from update order and subsidy uptake.
5 · Initialization	Firms are initialized with (x, y) location, demand, and lifetime from baseline data. Backbone nodes are mapped from GIS onto the grid. All firms start on gas; DSO parameters are set per scenario; simulation begins in 2025.
6 · Input data	Includes time-series data (fuel prices, CO_2 tax, subsidies), spatial data (firm and backbone locations), infrastructure cost and workforce parameters, and behavioral thresholds. Full details in Appendix B.
7 · Submodels	Firms evaluate switching via ROI and payback; DSOs schedule projects based on demand and strategy. A* routing updates distances; rollout is capacity-limited. Prices and policies update annually.

5

Baseline Agent Based Model

This chapter defines the baseline configuration of the simulation model by specifying key input parameters at the global, DSO and company levels. Building on the behavioral structure outlined in Chapter 4, it sets the stage for scenario analysis by operationalizing fuel prices, infrastructure costs, policy incentives, and system constraints. All values are sourced from the literature or expert input, where available, with assumptions made explicit. A complete overview of the variables is provided in the Appendices A and B.

5.1. Model Input Classification

Each simulation run begins by initializing the model environment, including agent states, infrastructure parameters, and the surrounding market and policy conditions. These input variables are organized into three main categories that correspond to the scope of influence within the simulation architecture. The full list of parameters is provided in Appendix A.

- *Global parameters:* These inputs define the overall simulation context, encompassing time control, policy settings (e.g., subsidies, CO_2 tax), fuel price trajectories, inflation, emission factors, and infrastructure cost and performance parameters. They include fixed and time-varying values and serve as external conditions that shape agent decision-making and system dynamics.
- *DSO-level parameters:* This set includes variables that govern the strategic behavior and operational capacity of the distribution system operator. Covers investment modes (proactive, reactive, delayed), scenario-defined time windows, a proactiveness coefficient (β), and internal resource constraints such as workforce and material availability. These inputs influence when and where the DSO expands the infrastructure.
- *Company-level parameters:* These parameters define the characteristics and internal state of the industrial firms in the model. They include fixed attributes such as location, energy demand and installation age, as well as dynamic variables that track connection status, investment viability, and financial performance of technology transitions.

5.2. Model Input Parameters

Several input parameters require further explanation due to their influence on the behavior of the model or the way they are implemented. This section provides additional details on how these parameters are defined, sourced, and used in the simulation.

5.2.1. Green Hydrogen Price Scenarios

Expert consultations identified the price of hydrogen as the most influential factor in company decisions to switch fuels, highlighting the importance of operational expenditure. The HyRegions study reports a wide 2030 cost range - from €1.8 to €15 per kg_{H2}—reflecting differences in technology and location in obtaining hydrogen [66]. To simplify the data for modeling, three representative scenarios are decided based on the key sources mentioned in the HyRegions report [101, 19, 96, 22].

Table 5.1: Projected hydrogen production costs under different cost scenarios

Year	Low-cost (€/kg)	Medium-cost (€/kg)	High-cost (€/kg)
2025	6.0	7.0	8.5
2030	5.0	6.5	8.0
2035	4.5	5.5	7.0
2040	4.0	5.0	6.5
2050	3.0	4.0	5.5

These values represent estimated wholesale delivery prices to industrial end-users, including transport and balancing costs. The scenarios are implemented as an annual time series from 2025 to 2050, with linear interpolation between listed years. Prices are converted to €/MWh using an energy content of 33.33 kWh/kg to match the economic calculations of the model. When no price variation is applied in the scenario analysis, the medium-cost trajectory is used as the default.

5.2.2. Hydrogen Subsidy

The model includes a fixed subsidy for hydrogen consumption, expressed in €/MWh and applied to the amount of green hydrogen used by industrial agents. A 25-year average value is used to support a consistent evaluation of investment metrics such as NPV and ROI.

Although most current support schemes target hydrogen production, they offer useful proxies for estimating end-use incentives. In the Netherlands, the OWE scheme provides up to €9/kg for green hydrogen produced via electrolysis, covering both capital and operational costs for 5–10 years [103]. Similarly, the European Innovation Fund's 2023 pilot auction (IF23) awarded support to seven RFNBO hydrogen production projects with a clearing price of €0.48/kg, or approximately €14.4/MWh using an energy content of 33.33 kWh/kg. For the upcoming 2024 auction (IF24), the ceiling price is set at €4/kg, corresponding to roughly €120/MWh [39].

These reference points suggest that real-world support mechanisms span a range of approximately €14–270/MWh, or €0.48–9.00/kg, depending on the award scheme and project characteristics. Given the uncertainty inherent in future policy design and market conditions, and rather than adopting these extremes, the model applies more moderate values within this range. Based on this policy context, the model implements four stylized subsidy scenarios between €2.5/kg and €6.50/kg (equivalent to €83.25/MWh to €216.45/MWh). These average long-term values, chosen to cover the expected policy support range, are summarized in Table 5.2.

Table 5.2: Average subsidy levels used in the model under different scenarios

Scenario	None	Low	Medium	High
Average Subsidy Level (€/MWh)	0	83.25	149.85	216.45

These values are not direct conversions of individual policy schemes, but serve as representative averages for long-term scenario analysis. In addition, to avoid overly optimistic investment signals, the model assumes that only 75% of the firms receive subsidies by default [61], introducing a probabilistic element into the firm-level decision logic.

5.2.3. Dutch CO_2 Tax

The Dutch CO_2 tax, introduced in 2021, functions as a national supplement to the EU Emissions Trading System (ETS), ensuring large industrial emitters face a minimum effective carbon price. In the model, this tax follows the official Dutch policy trajectory and extends it in line with long-term climate goals. Year-specific rates are applied to better reflect investment incentives and regulatory pressure.

In the model, the EU ETS is not modeled as a separate market. Instead, tax values include both the Dutch CO_2 Tax and anticipated ETS prices, capturing the full effective carbon cost faced by emitters.

The official schedule increases the combined CO_2 price from €30/tonne in 2021 to €125 by 2030 (an average rise of €10.56/year [109]). Post-2030, the model assumes a continued linear increase to €250 by 2040, reflecting expert projections and alignment with EU climate policy.

To simulate the national target of a 90% reduction in industrial emissions by 2040–2050, the model imposes a prohibitive CO_2 tax of €10,000/tonne from 2041 onward. This value is not derived from emission volume calculations or marginal abatement cost curves, but serves as a model-internal enforcement mechanism. It ensures that firms do not invest in new fossil-based installations after 2040, effectively simulating a regulatory phase-out of gas technologies. In this way, the CO_2 tax acts as a hard constraint to enforce compliance with the long-term climate goal, rather than a market-determined price signal.

The model tests sensitivity to early-phase pricing using the following scenarios:

Table 5.3: Carbon price assumptions under different scenarios

Scenario	2025–2029 (€/tCO_2)	2040 (€/tCO_2)	2041+ (€/tCO_2)
Low	100	250	10,000
Medium	150	250	10,000
High	200	250	10,000

By embedding the CO_2 tax directly in agent-level cost calculations, the model captures how carbon pricing influences technology choices, investment timing, and fossil fuel phase-out - in accordance with current Dutch policy and the broader EU decarbonization goals.

5.2.4. Hydrogen Infrastructure

The model uses a two-tier regional hydrogen infrastructure: new high-pressure pipelines for shared transmission and repurposed low-pressure natural gas pipelines for *last mile* distribution. High-pressure lines are newly built to allow phased adoption; repurposing would force all connected users to switch at once, limiting flexibility. In contrast, low-pressure lines typically serve individual users or small clusters, making them well suited for gradual, cost-effective reuse. This setup is aligned with both the technical feasibility and the incremental nature of industrial decarbonization.

Pipeline Cost Parameters

Table 5.4 summarises the capital and operational expenditure assumptions by pipeline type. Values are based primarily on HyRegions [66]. For new low-pressure pipelines, CAPEX is estimated using the observed difference in annual connection fees for high-capacity low-pressure and high-pressure gas connections, as published by Enexis Netbeheer [36], which suggests that high-pressure infrastructure is approximately 94% more expensive. This yields a baseline CAPEX of €1.65 million/km. Repurposing costs are assumed to be 30% of new CAPEX, following estimates from DNV [33].

Table 5.4: Hydrogen pipeline cost parameters by type

Pipeline Type	CAPEX (M€/km)	OPEX (%/yr)
High-pressure (new)	3.20	0.25
High-pressure (repurposed)	0.84	–
Low-pressure (new)	1.65*	1.00
Low-pressure (repurposed)	0.50**	3.33

* Estimated from cost ratios published by Enexis Netbeheer [36].
** Assumed to be 30% of new CAPEX based on DNV [33].

Construction Speed

Construction rates follow HyRegions [66], which estimates that a complete regional network can be completed in seven years under a proactive rollout. The model assumes annual construction capacities of 80 km/year for high-pressure pipelines and 240 km/year for low-pressure pipelines, based on an approximation from the HyRegions [66] rollout scenario of approximately 171 km/year on a national level. The faster rate for low-pressure systems reflects their simpler installation requirements, fewer safety restrictions, and greater spatial flexibility.

Workforce Requirements

Construction workforce requirements are based on Evida and CE Delft [42], which estimate 0.333 full-time equivalents (FTE) per kilometre of hydrogen pipeline for a national-scale rollout. To account for differing construction methods, the model applies 0.375 FTE/km for new high-pressure pipelines and 0.125 FTE/km for repurposed low-pressure lines. These figures reflect sectoral norms in labour intensity and mechanisation.

Material Requirements

Steel demand is derived from pipe wall volume and density calculations discussed in HyRegions [66]. For high-pressure pipelines (20” diameter, 20 mm wall), total steel required is approximately 241 t/km. Low-pressure lines (8” diameter, 10 mm wall) require around 48 t/km. These values are critical for estimating both capital costs and embodied emissions.

Table 5.5: Technical specifications and material requirements of hydrogen pipelines

Pipeline Type	Pressure (bar)	Diameter (inch)	Wall Thickness (mm)	Material* (t/km)
High-pressure (new)	80	20	20	241
Low-pressure (repurposed)	30	8	10	48

* Steel use is calculated geometrically from pipe wall dimensions and steel density (7,850 kg/m³).

Summary of Hydrogen Pipelines

Table 5.6 summarizes the key pipeline parameters used in the model for the two configurations implemented: new high-pressure pipelines for transmission and repurposed low-pressure pipelines for distribution.

Table 5.6: Summary of hydrogen pipeline parameters used in the model

Pipeline Type	CAPEX (M€/km)	OPEX (%/yr)	Material (t/km)	Construction (km/yr)	Workforce (FTE/km)
High-pressure (new)	3.20	0.25	241	80	0.375
Low-pressure (repurposed)	0.50	3.33	48	240	0.125

Pressure Reduction Stations

Pressure reduction stations (PRS) are included in the model to account for pressure transitions between high-pressure (HP) and low-pressure (LP) hydrogen pipelines. A unit CAPEX of €0.23 million per station is assumed, based on the estimated cost of € 1.5 million for HP-to-HP valve stations [135], scaled down using the same cost ratio applied between the repurposed HP and LP pipelines (approximately 15%).

No additional workforce, material requirements, construction time, and OPEX are assigned to PRS, as these are considered embedded in the pipeline construction parameters already defined [66]. This avoids double-counting and ensures consistency in resource allocation across infrastructure components.

5.2.5. Electricity Infrastructure Parameters

The model uses underground medium-voltage (MV) cables to represent the electrical infrastructure, reflecting the Dutch practice that the entire MV network is underground due to reliability and spatial planning considerations [98]. Parameters are not included to test electrification feasibility but to quantify trade-offs under limited DSO resources and to compare rollout dynamics with hydrogen infrastructure.

Cable Cost Parameters

The capital expenditure for underground medium-voltage (MV) cables varies substantially between projects and sources. Recent data from the European energy regulator ACER offers a grounded reference point: according to a 2023 corrigendum to the Unit Investment Cost report, the average capital cost for a 110–150 kV underground cable with one circuit is €830,658 per km [116]. For operational expenditure, Madigan et al. [88] report that O&M costs for underground transmission lines typically amount to 0.15% of the capital cost annually. This corresponds to an annual OPEX of approximately €1,246 per kilometer, assuming the ACER capital cost baseline.

Construction Speed

The national build speed for medium voltage cables is 1,812 km/year [99], reflecting the combined output of the six Dutch DSOs. To align with the regional scope of the model, this is scaled to 302 km/year, assuming an even distribution between operators. While actual rollout capacity varies between DSOs due to geography, organizational structure, and local conditions, the model assumes a uniform rate to reflect the general pace of regional development. This simplification overlooks DSO specific differences, but is necessary to constrain infrastructure expansion to realistic levels.

Workforce Requirement

Netbeheer Nederland estimates a shortage of 28,000 technicians by 2029 to implement a wide-ranging electricity infrastructure program, including medium and low voltage cables, transformer stations, public charging infrastructure, and new consumer connections [99]. This total includes direct hires and subcontracted personnel, such as mechanics, engineers, and project managers.

In 2024, Dutch DSOs installed 1,812 km of underground medium voltage (MV) cable and 1,938 km of low voltage cable indicating that the MV cable constitutes approximately 48% of the total length of the new cable. However, cable rollout is only one component of the overall workload. The infrastructure agenda also includes over 100,000 new connections, nearly 2,500 transformer substations, and extensive low-voltage grid reinforcement through the *neighborhood-scale* strategy [99].

To allocate technician effort specifically to the construction of MV cables, the model conservatively assumes that 16% of the total technician shortage applies to this task. This implies an available labor pool of 4,480 FTEs over the five-year period from 2024 to 2029. We assume that each technician contributes a full-time workload (1.0 FTE), in line with the figures reported by Netbeheer Nederland.

Given a steady national build rate of 1,812 km/year, the average workforce requirement per km of MV cable is:

$$\text{Workforce/km} = \frac{4,480 \text{ FTE}}{5 \text{ years} \times 1,812 \text{ km/year}} \approx 0.49 \text{ FTE/km} \tag{5.1}$$

This figure reflects the average full-time labor intensity required to deliver the MV cable infrastructure, adjusted for the division of the workforce in the broader electricity system.

Table 5.7: Summary of electricity infrastructure parameters used in the model

Cable Type	CAPEX (€/km)	OPEX (%/yr)	Material (t/km)	Construction (km/yr)	Workforce (FTE/km)
MV underground cable	830,658	0.15	1.58	302	0.49

Material Requirement

Underground medium voltage cables require approximately 0.82 tonnes of aluminum and 0.66 tonnes of copper per kilometer, according to estimates from Deetman et al. [29]. Combined, this results in a total material intensity of 1.58 t/km.

These input material values are used to estimate capital and resource requirements associated with the installation of MV cables, ensuring consistency in infrastructure cost calculations and enabling direct comparison with hydrogen pipelines.

Summary of Electricity Infrastructure

Table 5.7 summarizes the key parameters used in the model for underground medium-voltage (MV) electricity cables, which represent the regional electric infrastructure in the simulation.

5.2.6. Coordinate Conversion

Firm locations were provided by Stedin in RD (Rijksdriehoekscoördinaten) coordinates, expressed in meters. To align these with the NetLogo simulation environment, the coordinates were linearly transformed to a 150 × 100 patch grid, with each patch representing 50 meters. This transformation preserved spatial relationships and ensured that distances in the model reflect real-world geography.

The conversion was carried out externally, using a fixed origin and scale based on the bounding box of the study area. The resulting patch coordinates were imported via CSV and assigned in NetLogo using setxy, enabling accurate placement of firms and spatially grounded infrastructure rollout.

5.3. Model Outputs

The model generates annual outputs at three levels: Company, Infrastructure (DSO), and Global, capturing agent behavior, infrastructure rollout, and system-wide developments. An overview is provided in Table 5.8.

Table 5.8: Model outputs by system level

Level	Key Outputs
Company	Technology adoption (hydrogen, electrification) Payback period and ROI Firm-level CO_2 and NO_x emissions Timing of fuel switching decisions
Infrastructure (DSO)	Annual rollout of pipelines and cables (km) Utilization of workforce and materials vs. available capacity Unfulfilled connection requests and project status
Global	Total emissions and carrier shares (hydrogen, electricity, gas) Market price trends (hydrogen, electricity, gas) Cumulative public subsidies and CO_2 tax revenues Societal Net Present Value (SNPV)

A complete overview of variable definitions and units is provided in Appendix B.

5.4. Model Output Evaluation

This section explains how the Hydrogen Infrastructure Rollout Indicator, introduced in Section 3.4.1, is operationalized within the simulation model. It is implemented as an annually computed balance of monetized costs and benefits, referred to as the Net–Flow, which anchors the model's multidimensional results in measurable outputs. The Net–Flow captures system-wide impacts across infrastructure, firms, and society, including both direct and indirect effects of hydrogen deployment. When aggregated over time and discounted to a base year, it yields a single scalar: the Societal Net Present Value (SNPV), in accordance with Dutch and EU infrastructure appraisal guidelines.

The indicator was developed through an iterative process that combined theoretical exploration with expert consultation (see Chapter 3), to ensure both analytical rigour and policy relevance. While the conceptual rationale for using a system-level key performance indicator is discussed in Sections 2.3 and 3.4.1, this section focuses on the specific modeling choices underpinning the Net–Flow, including expert-informed assumptions and the structural constraints inherent to the agent-based modeling approach.

Disaggregation of NPV Components

The SNPV is computed by summing the discounted annual Net-Flow values over the simulation horizon (2025–2050). Each annual Net-Flow is constructed from the output streams generated by the agent-based simulation and is structured as shown in Equation 5.2. Inclusion of each component is based on relevance, data quality, and expert judgement.

The following cost-benefit streams constitute the Net-Flow:

- *Infrastructure investment costs*: Capital expenditures for hydrogen infrastructure ($C^{\text{H2}}_{\text{infra,CAPEX}}$) and electric grid upgrades ($C^{\text{Elec}}_{\text{infra,CAPEX}}$), recorded by the DSO agent. Hydrogen costs include Pressure Reduction Stations, while electric costs reflect grid reinforcement. Both vectors are included to enable comparative scenario analysis.
- *Operational costs*: Recurring expenditures for operation and maintenance of hydrogen and electricity networks ($O^{\text{H2}}_{\text{infra}}, O^{\text{Elec}}_{\text{infra}}$).
- *Firm investment costs*: Capital costs associated with adopting hydrogen, electrification, or continuing with gas-based operations ($C^{\text{H2}}_{\text{firm,CAPEX}}, C^{\text{Elec}}_{\text{firm,CAPEX}}, C^{\text{Gas}}_{\text{firm,CAPEX}}$), differentiated by firm characteristics and transition timing.
- *Change in operating costs*: Changes in firms' operational expenditures relative to the gas baseline (ΔO_{firm}), allowing the model to isolate fuel switching effects without double counting.
- *Environmental externalities*: Monetized firm-level emissions of CO_2 and NOx, based on projected EU ETS prices and health-related valuations. Avoided emissions are recorded as benefits ($B_{\text{CO2,avoided}}, B_{\text{NOx,avoided}}$), reflecting tangible economic gains.
- *Grid-related savings*: Benefits derived from deferring electric grid upgrades ($B_{\text{grid,upgrade avoided}}$) and gas network operational costs ($B_{\text{gasnet,OPEX avoided}}$), conditional on system-level load thresholds.

These elements together form a complete annual ledger of system-level costs and benefits. The series is discounted to the 2025 base year using a rate of $r = 4\%$, consistent with international infrastructure planning standards [2]. This approach enables an integrated comparison between infrastructure costs, firm-level investment dynamics, environmental outcomes, and network effects.

The Net–Flow at each time step t is defined as:

$$
\begin{aligned}
\text{NetFlow}_t = \; & - C^{\text{H2}}_{\text{infra,CAPEX}}(t) - C^{\text{Elec}}_{\text{infra,CAPEX}}(t) \\
& - O^{\text{H2}}_{\text{infra}}(t) - O^{\text{Elec}}_{\text{infra}}(t) \\
& - C^{\text{H2}}_{\text{firm,CAPEX}}(t) - C^{\text{Elec}}_{\text{firm,CAPEX}}(t) \\
& - \Delta O^{\text{H2}}_{\text{firm}}(t) - \Delta O^{\text{Elec}}_{\text{firm}}(t) \\
& - C^{\text{Gas}}_{\text{firm,CAPEX}}(t) \\
& - C_{\text{CO2}}(t) - C_{\text{NOx}}(t) \\
& + B_{\text{CO2,avoided}}(t) + B_{\text{NOx,avoided}}(t) \\
& + B_{\text{grid,upgrade avoided}}(t) + B_{\text{gasnet,OPEX avoided}}(t)
\end{aligned} \tag{5.2}
$$

Each term is discounted using:

$$
\text{DiscountFactor}_t = \frac{1}{(1+r)^{t-2025}}, \quad \text{where } r = 0.04 \tag{5.3}
$$

The Societal Net Present Value is calculated as:

$$
\text{SNPV} = \sum_{t=2025}^{2050} (\text{DiscountFactor}_t \cdot \text{NetFlow}_t) \tag{5.4}
$$

While the Societal Net Present Value (SNPV) is a useful metric because it accounts for both costs and benefits over time, its interpretation is shaped by the model's discounting structure. Since all outcomes are discounted to 2025 and the time horizon ends in 2050, benefits that occur later, such as avoided emissions or long-term savings, carry less weight than near-term effects. If the evaluation window extended further, for example to 2060, the relative value of long-term benefits would increase. Within the current setup, this means that strategies involving earlier investments tend to score higher SNPV values, simply because their payoffs occur sooner.

At the same time, structural dynamics like technological lock-ins and path dependencies are still present in the model. The point at which firms switch fuels has long-term implications for the system, regardless of when costs or benefits are realized. This means that while SNPV tends to reward early action, the relative differences between strategies remain meaningful, especially in terms of coordination, timing, and system evolution. Therefore, SNPV is best used to compare the effectiveness of different rollout strategies, rather than to draw firm conclusions about the absolute benefits of acting early.

Exclusion of Alternative KPIs

Several conventional KPIs were evaluated during model design but ultimately excluded in favor of a systemic, forward-looking assessment framework. For example, the Levelised Cost of Hydrogen (LCOH) provides a clear benchmark to compare production costs across technologies but does not account for externalities, infrastructure interactions, or system-level impacts, limitations identified in the literature on energy project evaluation [30]. Similarly, financial indicators such as Net Present Value (NPV) and Return on Investment (ROI) focus on project-specific outcomes and are less suitable for capturing the broader spatial and temporal effects relevant to DSO strategy.

Macroeconomic indicators like job creation and GDP impact were also reviewed but excluded due to attribution challenges. While such effects may be present, they are difficult to quantify at the regional level and are not considered decisive in evaluating the credibility or feasibility of hydrogen rollout strategies. Instead, the model applies a holistic framework that integrates agent-level decisions and system-level outcomes over time, in line with the strategic and infrastructure-oriented scope of the analysis.

5.5. Model Implementation Assumptions

While the parameters and structure of the baseline model are specified in detail throughout this chapter, several underlying assumptions remain implicit but are essential for correct interpretation. These are included here for completeness and academic transparency:

- Input parameters are treated as exogenous and scenario-defined; agents cannot influence fuel prices, taxes, or subsidies.
- No firm-level heterogeneity beyond the defined input variables is considered (e.g., differences in risk preferences, strategic interactions, or political influence).
- Firms base investment decisions on their own economic calculations, wherein the connection costs are dynamically influenced by the actions of other firms.
- Electricity and hydrogen infrastructure are assumed to scale linearly with demand; no network congestion, pressure loss, or technical failures are modelled.
- Embodied emissions from infrastructure construction are not accounted for; only operational emissions and avoided emissions are monetised in the cost–benefit evaluation.
- All outputs are reported as average yearly values; no intra-annual dynamics such as seasonal demand fluctuations or short-term price volatility are included.

5.6. Model Availability

The full NetLogo implementation of the agent-based model is publicly available on GitHub:

`https://github.com/HugodeJong00/HydrogenABM`

6

Sensitivity Analysis

In sociotechnical systems, the results of the models are often highly sensitive to assumptions about the behavior of the actors and the constraints of the system. Given the uncertainty, interdependencies, and emergent dynamics of such systems, sensitivity analysis is essential to evaluate the robustness of the model and to support the justified selection of parameter values.

This chapter presents a sensitivity analysis of the agent-based model (ABM) developed in this research, which simulates the behavior of the distribution system operator (DSO) in response to decentralized industrial hydrogen demand. As Broeke, Voorn, and Ligtenberg [17] and Borgonovo et al. [15] emphasize, the complexity and flexibility of ABMs require systematic exploration of key assumptions to ensure interpretability and reliability.

The sensitivity analysis in this chapter serves two main purposes: (1) to assess how model outcomes respond to uncertainty in critical input assumptions, and (2) to identify empirically plausible parameter settings for use in the baseline scenario. To strengthen the real-world relevance of this exploration, parameter choices and ranges are informed by available literature, expert input, and sector-specific reports.

6.1. Sensitivity Analysis Parameters

To generalize beyond the case study, this analysis uses a randomized synthetic region rather than a specific real-world location. Firm characteristics such as spatial position and energy demand are randomly generated to reflect plausible industrial clustering and demand variation. These randomized attributes support broader generalizability and reduce the risk of overfitting to a single case.

Table 6.1: Randomized context parameters

Parameter	Name	Nominal value	Range	Unit
Number of firms	`num-firms`	`13`	`Fixed`	`count`
Energy consumption	`energy-consumption`	`Random`	`[5,000; 15,000]`	`MWh`
Company coordinates	`setxy`	`Random`	`[0;150], [0;100]`	`-`

To ensure generalizability beyond a single real-world case, the model simulates a synthetic industrial region with randomized firm locations and energy demands. Energy use is sampled uniformly between 5,000 and 15,000 MWh, centered around the sectoral average for medium-sized firms [81]. The model includes 13 firms, reflecting the upper bound of observed cluster sizes in Dutch hydrogen demand regions, which typically host between 3 and 13 firms [66]. This setup represents a dense but realistic scenario, allowing for meaningful exploration of rollout dynamics without overfitting to a specific context.

This randomized setup serves two purposes: (1) to allow exploration of model dynamics across a diverse set of regional configurations, and (2) to ensure that results are not biased by the specifics of any single empirical case.

In contrast to these randomized context parameters, the sensitivity analysis focuses on a defined set of input parameters that are both uncertain and highly consequential for model behavior. These were selected due to their empirical uncertainty, their interdependence with other system components, and their strong influence on rollout speed and infrastructure adoption outcomes. The selection was guided by expert consultation and review of the literature to ensure empirical relevance and plausibility.

Table 6.2: Parameters included in sensitivity analysis

Parameter	Name	Nominal value	Range	Unit
Demand threshold	`demand-threshold`	0.5	[0; 1]	-
DSO workforce cap	`dso-workforce-cap`	15	[1; 22]	FTE
DSO material cap	`dso-material-cap`	400,000	[200,000; 500,000]	kg

The demand threshold defines the minimum share of firms that must express interest before the DSO initiates infrastructure rollout, reflecting institutional caution toward irreversible investment under uncertain demand, as discussed in Chapter 1 and 2. This mirrors real-world governance practices, where infrastructure development, particularly for hydrogen, is often delayed until sufficient local commitment justifies public or regulated investment. The model adopts a regional rollout strategy in line with the Dutch decarbonization goals, using 2050 as the evaluation horizon. Within this context, the demand threshold represents a tipping point: the minimum level of early interest required to make infrastructure deployment economically viable, measured as a positive net present value (NPV) by 2050 under a reactive strategy. Identifying this point, the model links the strategic rollout timing to both institutional decision making logic and long-term societal cost–benefit considerations.

The remaining two parameters, DSO workforce capacity (in FTE) and material availability (in kilograms of pipeline infrastructure), represent the most critical constraints for the implementation of energy infrastructure, as highlighted in the literature review (Chapter 2). These parameters directly link the model to the real-world *feasibility gap* identified in recent national infrastructure assessments. According to DNV [32], only 72% of the necessary infrastructure investments are expected to be realized by 2030 under the current constraints in the workforce and supply chain, which implies a 28% shortfall due to practical constraints on execution capacity [32]. This percentage is used in the model as a reference point: Simulations test which combinations of workforce and material capacity allow, on average, 72% of firms (approximately 9 out of 13) to adopt hydrogen by 2030. This approach anchors the sensitivity analysis in empirical system bottlenecks and ensures that the modeled rollout scenarios reflect realistic implementation barriers.

By independently varying each sensitivity parameter while maintaining the others constant, the analysis isolates their individual impact on infrastructure deployment dynamics. This enables the identification of tipping points, thresholds, and non-linearities, providing input for baseline assumptions and informing strategy design under uncertainty.

6.2. Results of Sensitivity Analysis

This section presents the results for the three parameters: the demand threshold, workforce capacity, and material availability.

6.2.1. Demand Threshold

The demand threshold defines the minimum share of firms that must express commitment before the DSO initiates the rollout of the hydrogen infrastructure. This reflects institutional caution under uncertainty, capturing the point at which investment becomes justifiable in a reactive deployment scenario.

Figure 6.1 shows how this parameter affects both adoption dynamics and economic performance. Lower threshold values trigger earlier deployment, allowing firms to adopt hydrogen sooner and leading

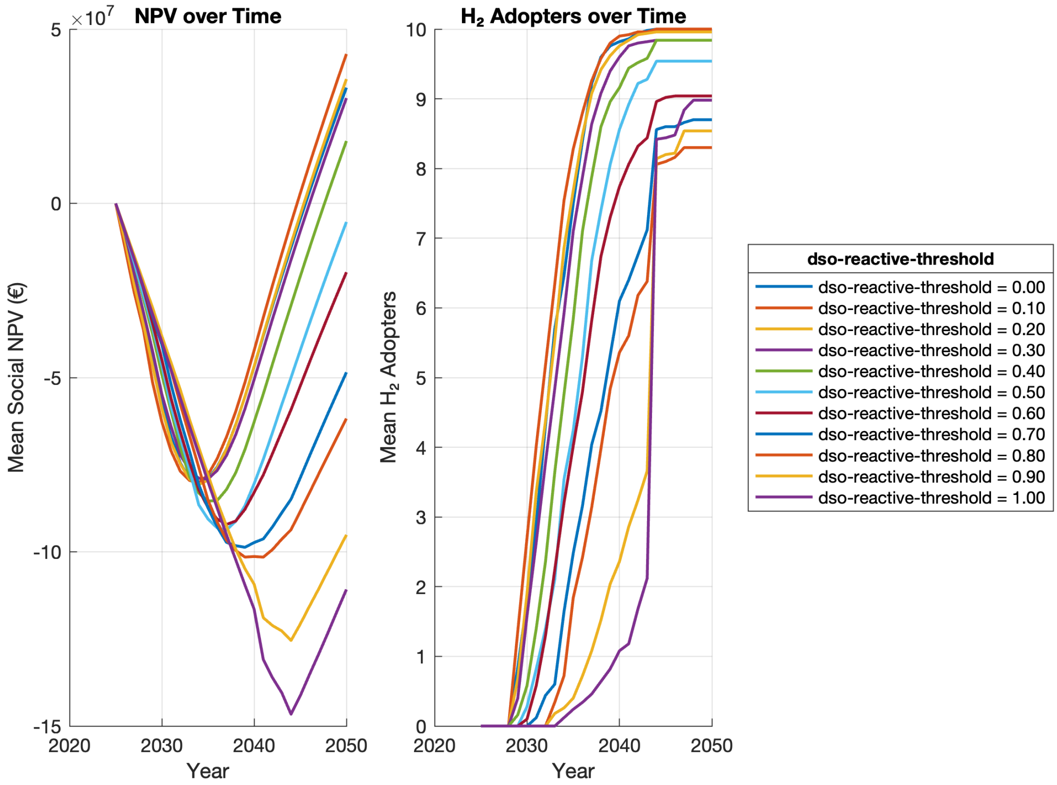

Figure 6.1: Sensitivity analysis results for the demand threshold. *Left:* Mean societal NPV over time. *Right:* Mean number of hydrogen adopters over time. Lower thresholds lead to earlier and broader adoption, improving long-term returns.

to stronger net present value (NPV) outcomes by 2050. In contrast, higher thresholds delay rollout—especially at extreme values (e.g., 1.0), where infrastructure is deployed only if all firms commit. This results in significant delays and limited adoption.

Figure 6.2 further confirms this pattern, comparing the mean NPV across all threshold levels in 2050. Thresholds at or below 0.4 consistently yield positive societal returns. Above 0.5, outcomes decline rapidly, and values above 0.7 lead to substantial net losses. These results clearly indicate a tipping point: below a certain level of early demand, reactive infrastructure rollout fails to generate sufficient returns within the model horizon.

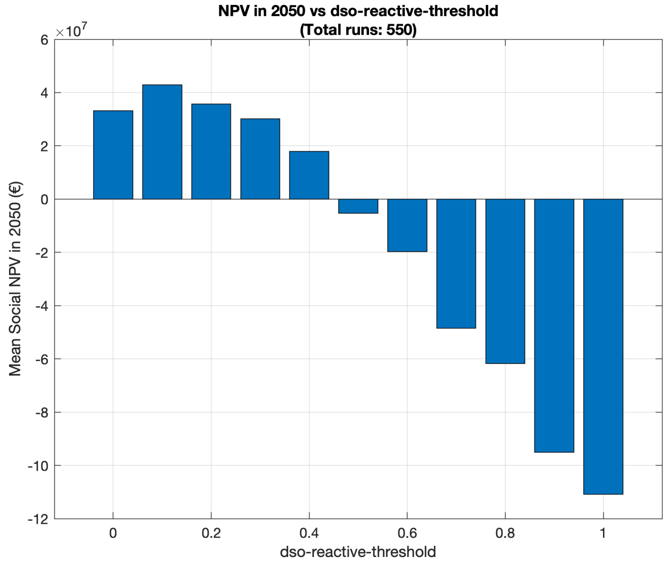

Figure 6.2: Mean societal NPV in 2050 as a function of the reactive threshold. Positive outcomes occur only for thresholds below 0.5.

Based on this analysis, a threshold value of `0.4` is selected for the baseline scenario. This represents the minimum level of early interest at which the DSO still achieves a positive NPV by 2050. It reflects a cautious but economically justified tipping point: balancing the risk of premature investment with the need to initiate rollout before adoption stalls. This value will serve as a reference in the modeling experiments that follow.

6.2.2. DSO Workforce and Material Constraints

In addition to demand-side uncertainty, the rollout of hydrogen infrastructure is limited by the operational capacity of the DSO. Two internal constraints are considered: the availability of skilled workforce (FTE) and the supply of pipeline materials (kg). These are the most prominent real-world barriers to infrastructure delivery, as discussed in Chapter 2.

Recent national assessments project that, under current constraints, only 72% of the necessary energy infrastructure will be realized by 2030 [32]. This benchmark is used in the model to assess which combinations of workforce and material availability enable approximately 9 out of 13 firms to adopt hydrogen within that timeframe.

Figure 6.3 shows the effect of workforce capacity on adoption. At low levels (e.g., 1–5 FTE), adoption remains far below the feasibility benchmark. As capacity increases, rollout accelerates, with a clear saturation point around 16–17 FTE. Beyond this, additional capacity yields minimal gains.

Material constraints show a similar pattern (Figure 6.4). Below 400,000 kg, adoption plateaus well under the benchmark. Around 450,000 kg and above, the target is reached. Beyond this point, returns diminish.

Both constraints exhibit clear tipping points, beyond which additional resources yield diminishing returns. Based on the analysis, baseline values of 16 FTE and 470,000 kg are selected, as they enable the model to reproduce a 72% hydrogen adoption rate by 2030—aligned with national feasibility assessments. These values are retained for the subsequent modeling experiments to ensure that the analysis reflects real-world implementation limits. Overall, the sensitivity results establish empirically grounded baseline assumptions and highlight critical thresholds, providing a robust foundation for the scenario-based analysis that follows.

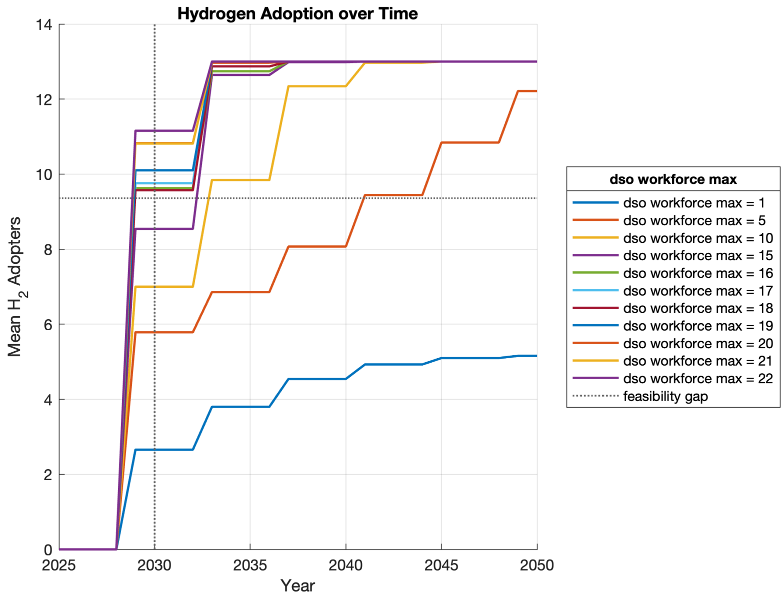

Figure 6.3: Hydrogen adoption over time at different DSO workforce capacities. Horizontal line: 72% adoption benchmark. Vertical line: 2030.

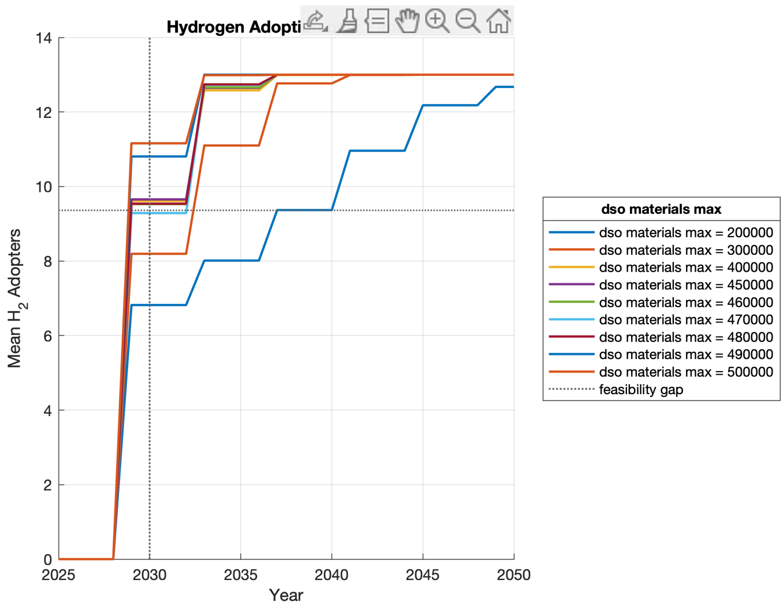

Figure 6.4: Hydrogen adoption over time at different DSO material constraints. Horizontal line: 72% adoption benchmark. Vertical line: 2030.

7
Results

This chapter presents the simulation results, showing how DSO investment strategies affect the rollout of the regional hydrogen infrastructure. The experiments investigate how shifting both the timing and intensity of proactive investment influences adoption, efficiency, and societal value, thereby analyzing the coordination dilemma at the heart of this thesis.

The rollout sequences used to structure these experiments, the combination of delay, proactive and reactive phases, are illustrated in the Appendix C. Although the order of phases is fixed, their durations are varied systematically across experiments, including cases where the delay or proactive window is set to zero.

7.1. Experiment 1 — Impact of the Scale of Proactiveness

The first experiment explores how accounting for potential demand influences the timing and benefits of the deployment of hydrogen infrastructure. In the agent-based model, the DSO decides whether to initiate pipeline construction based on a combination of confirmed demand D_{conf} and a weighted portion of potential demand D_{pot}, where the weighting is governed by the proactivity parameter $\beta \in [0, 1]$. This parameter reflects the extent of anticipatory behavior: Lower values indicate a reactive approach, while higher values reflect increasingly speculative investment decisions.

As expected, the first result shows that anticipatory investment can significantly accelerate infrastructure rollout. In the model, the system operator adopts a reactive stance at $\beta = 0$, responding only to confirmed demand. Under this logic, where infrastructure is justified solely on the basis of submitted letters of intent, no rollout occurs before 2044. Figure 7.1 shows that even a modest increase in $\beta = 0.1$ - allowing partial consideration of potential demand - accelerates the first connection by 12 years, to 2032. Further increases yield diminishing but still notable gains, with rollout stabilizing around 2029 once β exceeds 0.4.

This result clearly illustrates the earlier-described chicken-and-egg dilemma. By easing its investment threshold and responding to incomplete demand signals, the system operator can launch the rollout before firm commitments materialize. In doing so, the provider makes the pivotal move on the supply side to resolve coordination failure: building infrastructure even without hard guarantees.

To assess whether this initial move leads to broader system effects, potentially triggering a strengthening cycle of infrastructure rollout and the adoption of clean fuel, we turn to the NPV trajectories shown in Figure 7.2. Several general observations can be made. Each strategy incurs early societal costs, reflecting the burden of continued fossil fuel emissions. However, these costs begin to diverge over time as a result of differences in the timing and scale of deployment, whether for hydrogen or electricity. Following this initial dip, green fuel adoption gradually increases and the societal benefits of reduced emissions start to materialize. Although the overall pattern of early costs followed by delayed gains is consistent between strategies, the timing, depth, and scale of these effects differ significantly, a dynamic we now explore in more detail.

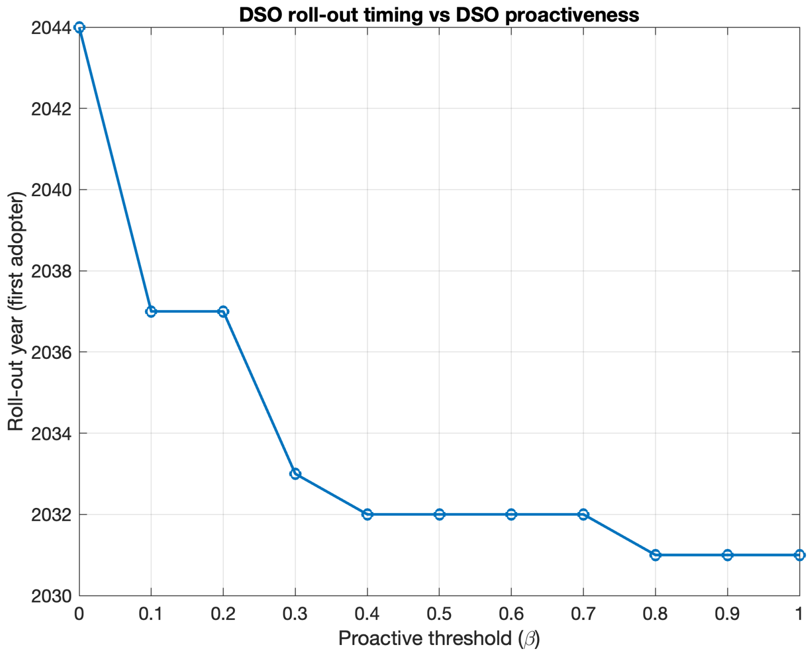

Figure 7.1: Year in which the first cluster connection is built as a function of the pro-active threshold β.

In particular, the rollout of each strategy remains costly at the regional level, and by 2050, the benefits fail to fully offset cumulative costs in nearly all cases. This is largely due to the system still operating under a reactive DSO model, where rollout depends on confirmed and potential firm requests, preventing the deployment of the most efficient infrastructure network. In Section 7.2, which explores a proactive rollout scenario, overall system costs are significantly lower, and long-term transition values become positive.

Now that we have analyzed the general rollout pattern, we turn to the different strategies, specifically the variation in β values, as shown in Figure 7.2. High-β strategies, which reflect anticipatory investments, frontload their infrastructure spending. This is clearly visible in the figure: the NPV curves for higher β values show a much steeper initial decline, indicating higher early costs. However, this also results in earlier completion of the infrastructure and earlier realization of societal benefits from reduced fossil fuel emissions. These strategies begin to accumulate positive effects sooner and over a longer period. This behavior, seen in the earlier and shallower dips in the NPV curves, is partly explained by basic discounting: acting earlier enables benefits to accrue sooner and for a longer duration, improving long-term outcomes.

However, more important is what the shape of the NPV curves reveals. As shown in Figure 7.2, reactive strategies with low values of β produce deeper and more prolonged troughs compared to the earlier and shallower declines observed with more anticipatory approaches. This indicates that reactive rollouts are not only more costly as a result of extended fossil fuel use but also structurally less efficient. Because rollout decisions depend on an effective demand threshold shaped by β, higher values allow the DSO to act on partial demand signals and identify promising routes earlier. This enables a more coherent clustered infrastructure deployment. In contrast, low-β strategies rely solely on confirmed demand, resulting in fragmented, piecemeal rollout. Over time, this lack of coordination leads to a disjointed energy landscape, where firms adopt different technologies at different moments, increasing system costs and delaying the realization of societal benefits.

This coordination effect becomes even more visible when looking at long-term outcomes. As Figure 7.3 shows, higher β values are associated with a higher number of hydrogen adopters and a higher societal NPV by 2050, following a clear upward trajectory. These outcomes reflect the benefits of synchronized adoption: When many firms transition around the same time, the infrastructure is used more efficiently,

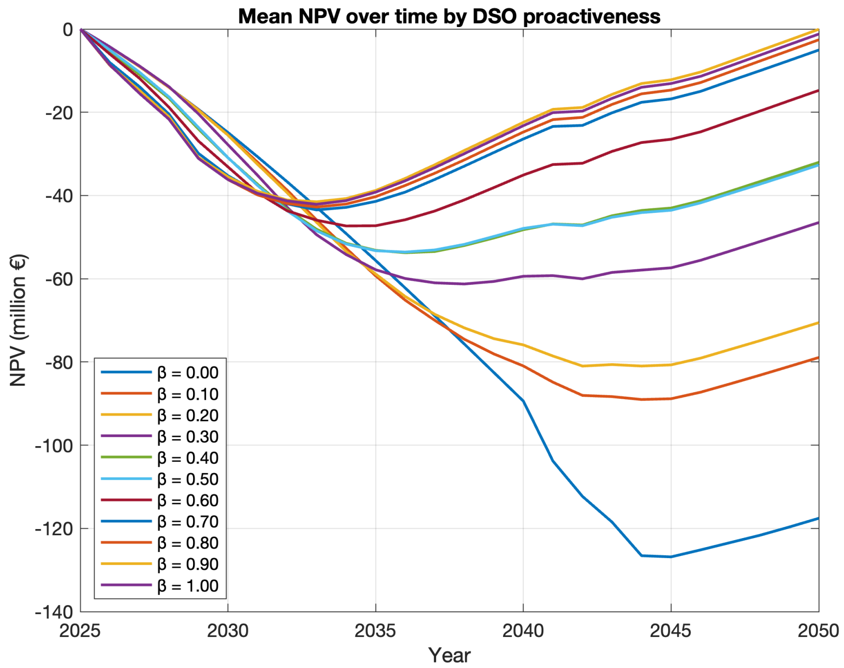

Figure 7.2: Mean cumulative societal NPV over time for different values of β for a reactive DSO.

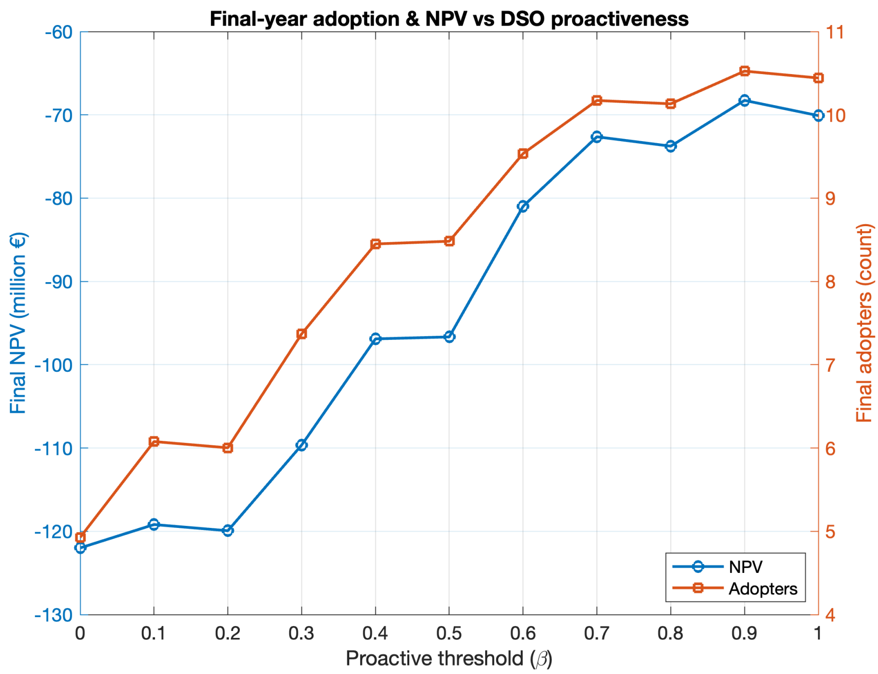

Figure 7.3: Final-year (2050) societal NPV and number of adopters versus β. Left axis: NPV (blue); right axis: number of adopting firms (orange). Error bars show ± 1 standard error.

redundancy is minimized, and the value of the network increases. In short, Figures 7.2 and 7.3 together highlight a central insight: the more forward-looking the strategy, the shorter and shallower the cost period, the greater the success of adoption and the stronger the overall outcome of the system.

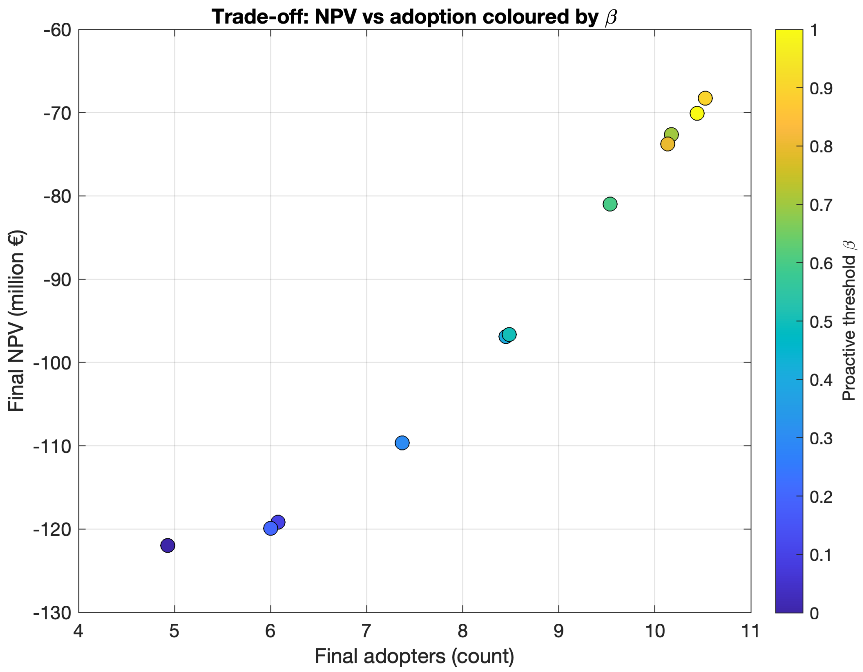

Figure 7.4: Trade-off between final cumulative societal NPV and total number of adopters by 2050, with color indicating proactivity level β.

A final point of interest concerns how much potential demand is efficient to anticipate when planning infrastructure in high-potential areas. Figure 7.4 shows the trade-off between the final adoption of hydrogen and the societal NPV, with points colored by the level of proactiveness. The figure reveals a strong positive relationship: as the number of adopters increases, so does the net societal value. The results improve markedly once around 70% of potential demand is considered and stabilize between 80–100%, suggesting that a moderate level of anticipation is sufficient to trigger coordinated adoption and unlock substantial benefits throughout the system. Beyond this range, additional speculation offers limited returns while increasing the risk of underutilized infrastructure. In practice, strong societal outcomes can be achieved without relying on fully speculative planning simply by accounting for a significant but not exhaustive share of potential demand.

7.2. Experiment 2 — Investment Timing

This section explores how the timing of investment decisions, specifically the delay in the initiation of the rollout and the length of the proactive planning window, affects the effectiveness of the deployment of hydrogen infrastructure for medium-sized industries. By systematically varying these parameters, the experiment reveals their influence on adoption dynamics, infrastructure utilization, and long-term societal outcomes.

7.2.1. Isolated Effect of Proactive Windows

As shown in Figure 7.5, three different hydrogen adoption trajectories emerge depending on the size of the proactive window. In the fully reactive scenario (proactive window = 0), the adoption is slow and is mainly driven by external market forces such as increasing CO_2 taxation and decreasing hydrogen prices. Without anticipatory infrastructure development, uptake remains limited until around 2043, when economic signals become strong enough to trigger widespread switching.

Introducing a moderate proactive window (1–4 years) significantly alters this dynamic. The infrastruc-

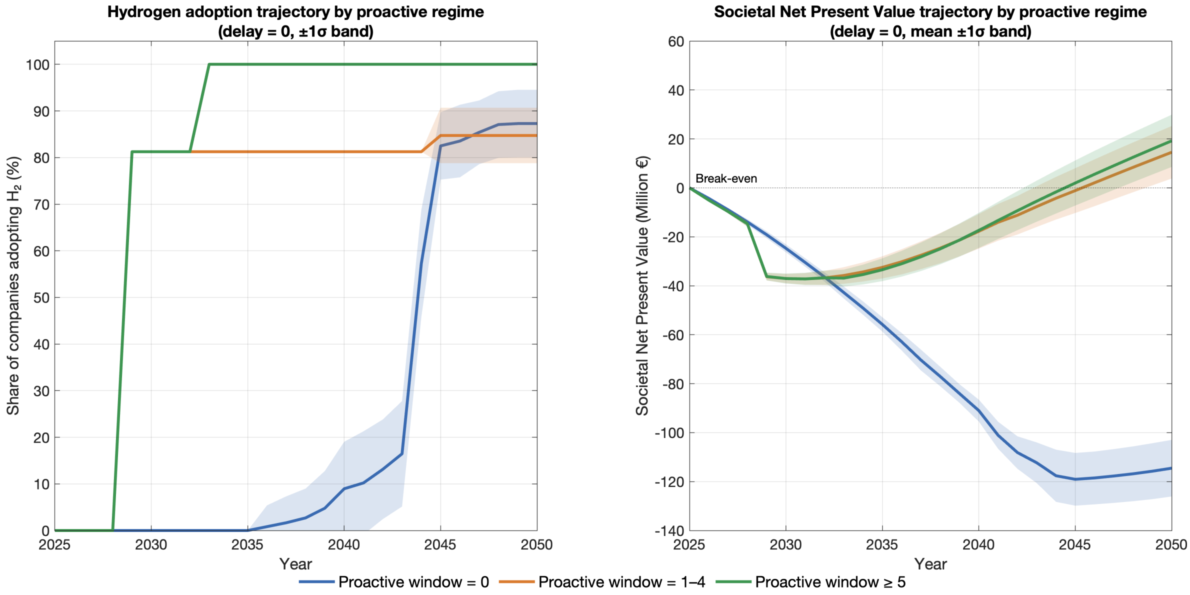

Figure 7.5: Hydrogen adoption (left) and societal NPV (right) under varying degrees of DSO proactiveness (delay = 0).

ture is constructed earlier, allowing a first wave of adopters to connect approximately four years after the first proactive year. However, the effect is only partial: Although early adopters benefit, many companies continue to delay until economic incentives become stronger, resulting in a staggered and incomplete transition.

In contrast, when the proactive window is extended to five years or more, the system undergoes a full transformation. A second construction cycle is triggered, and all potential hydrogen users are connected in a coordinated manner. This leads to adoption of 100% by 2035, demonstrating how an anticipatory rollout can overcome coordination deadlock and accelerate the system-wide transition.

The societal consequences of these strategies are illustrated in the right panel of Figure 7.5, which shows the evolution of the societal Net Present Value (NPV). All scenarios initially decline due to the inclusion of societal costs, namely the costs associated with continued CO_2 and NO_x emissions. Proactive strategies experience a steeper early decline in NPV as a result of high upfront infrastructure investments in the construction of a regional hydrogen infrastructure. However, these investments enable faster adoption and earlier emission reductions, allowing NPV to recover more quickly, reaching break-even by 2045 and continuing to rise thereafter.

In contrast, the reactive strategy delays both investments and benefits. The infrastructure is deployed gradually in response to individual company requests, preventing early clustering and resulting in fragmented rollout. As a result, pipelines are often laid down to serve only a few firms, while nearby potential users remain unconnected for years. This leads to prolonged under-utilization, compounding inefficiencies already discussed. Combined with the continued societal costs from delayed emissions reductions, the reactive scenario remains in negative NPV territory throughout the modeled period and never reaches the break-even point.

These differences are also highlighted in Figure 7.6, which compares the final adoption rate in 2050 with the corresponding societal NPV for each simulation run. Although reactive and moderately proactive regimes often achieve similar levels of final adoption, the timing of investment proves to be a critical differentiator. The moderately proactive regime consistently outperforms the reactive one in terms of societal NPV, as a more early rollout allows benefits, such as reductions in emissions and earlier infrastructure utilization, to materialize sooner.

The effect is most pronounced in the highly proactive regime (proactive window ≥ 5), which reaches full adoption by 2050 and delivers the highest societal returns. Early, broad rollout enables full network utilization, improves system efficiency, reduces per-user infrastructure costs, and accelerates emission reductions. However, the results also show that the most critical change occurs with the first proactive

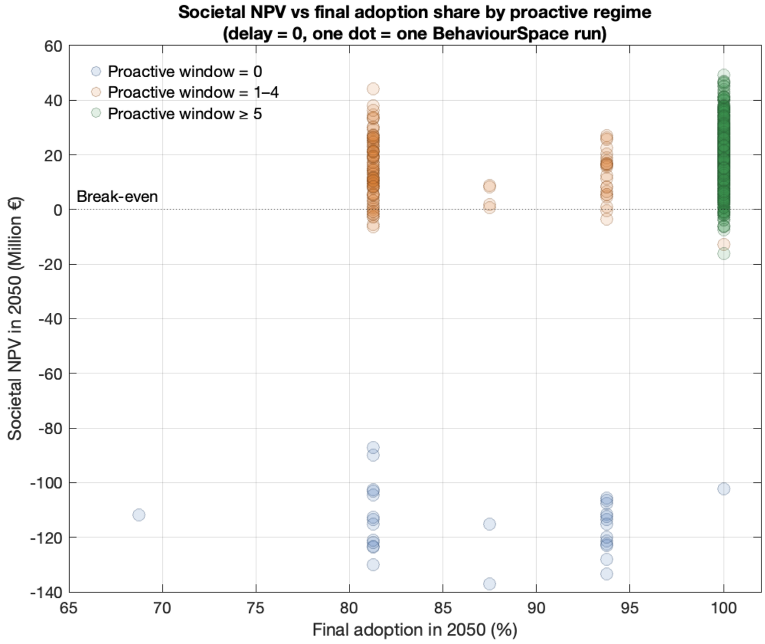

Figure 7.6: Final hydrogen adoption vs. societal NPV in 2050, grouped by proactive regime (delay = 0). Each dot represents a single behaviorSpace run.

step. Even a limited early rollout is enough to break the coordination deadlock and put the system on a more favorable trajectory. Although the reactive strategy may eventually catch up in terms of adoption, its delayed action leads to prolonged infrastructure inefficiencies and postponed societal benefits, making it significantly less effective within the modeled time frame.

7.2.2. Isolated Effect of Delay Windows

Figure 7.7 shows the impact of varying delay windows on hydrogen adoption and the net present value (SNPV), assuming that there is no proactive investment window. Similarly to the effect of proactive windows, delay regimes also shape distinct system trajectories. When the delay is limited to 0-15 years, the drivers of the external market, such as CO_2 taxation and hydrogen subsidies, remain effective in pushing a large share of companies toward hydrogen adoption. However, once the delay exceeds 15 years, the adoption curve drops sharply.

With a 16-year delay, we already see a notable decline in the share of companies adopting hydrogen. This trend accelerates in the 17–19 year delay range, where most companies have already chosen electrification as their decarbonization strategy. In the longest delay scenario (20–25 years), only a small fraction of companies adopt hydrogen, indicating that the window of opportunity for hydrogen infrastructure to play a meaningful role has effectively closed. In these cases, the absence of timely infrastructure forces firms to decarbonize via electrification, leaving hydrogen out of the equation.

This finding underscores the risk of excessive delay: once companies are pushed to act, whether due to climate targets, regulatory pressure, or cost incentives, they will choose the most available and feasible option. If hydrogen is not accessible by that time, the market opportunity is lost.

The societal NPV curves in Figure 7.7 on the right further illustrate the consequences of delayed action. Scenarios with minimal delay enable earlier infrastructure rollout, which leads to earlier emission reductions and, consequently, a less severe decline in societal value. In contrast, longer delays shift hydrogen adoption so far into the future that benefits cannot accumulate meaningfully within the modeled horizon. In addition, societal costs increase due to widespread electrification, a more expensive and less efficient route for many firms under current assumptions.

Importantly, this also implies that the timing of decarbonization targets is important. In the current model, companies are effectively forced to make a decarbonization decision starting around 2040. If

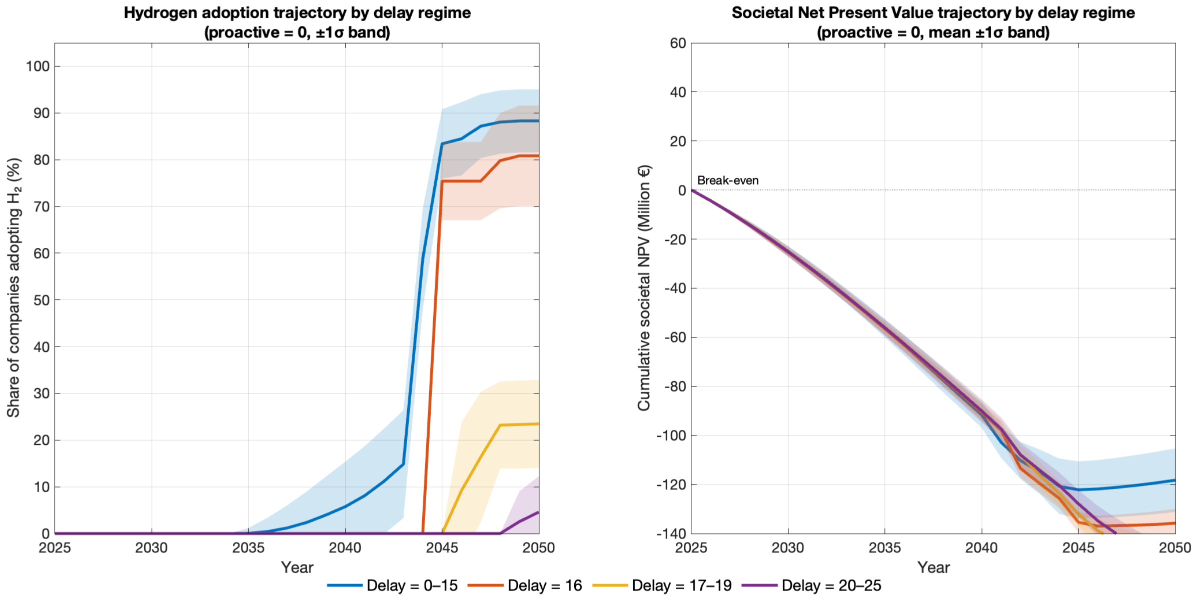

Figure 7.7: Hydrogen adoption (left) and cumulative societal NPV (right) by delay regime (proactive window = 0).

this forced decision-making were to occur earlier, due to tighter climate policy or changing market conditions, the adoption curves would shift accordingly, bringing the transition point forward. As such, delays in the implementation of hydrogen infrastructure become even more critical. Once firms commit to alternative technologies, the hydrogen option is effectively foreclosed, regardless of whether the infrastructure becomes available later.

Figure 7.8 reinforces this point. Across all delay regimes, late infrastructure rollout limits the achievable societal benefits within the 2050 horizon. This is particularly evident in scenarios with delays exceeding 15 years, where adoption drops sharply and NPV remains low. By the time infrastructure becomes available, many companies have already locked into alternative decarbonization pathways, most often electrification, leaving hydrogen unable to play a meaningful role. The result is higher transition costs, fragmented system development, and the loss of coordinated rollout potential. These findings underscore that enabling early adoption is not just advantageous but essential to preserving hydrogen as a viable decarbonization option.

7.2.3. Combination of Delay and Proactive Windows

In practice, rollout strategies rarely involve immediate action without delay or an indefinite postponement followed by a purely reactive approach. A more realistic pathway involves some degree of institutional delay, followed by the implementation of a proactive hydrogen infrastructure strategy. The interplay between delay and proactiveness is critical in shaping adoption outcomes and infrastructure efficiency.

Figure 7.9 presents the adoption trajectories clustered by their temporal shape, grouping combinations of delay and proactive windows that result in similar system behavior. The clusters reveal how different timings lead to characteristic adoption patterns.

Scenarios with *short delays and high levels of proactiveness* show a sharp increase in hydrogen adoption shortly after the delay period ends. Likewise, *moderate and medium delays followed by moderate proactiveness* result in a similarly rapid transition, though slightly later in time. In both cases, the increase in adoption aligns with a period (approximately 2035-2040) when market conditions, such as higher CO_2 prices, hydrogen subsidies, and improved cost competitiveness, support hydrogen uptake. The infrastructure constructed during this window can be used effectively, as companies are ready to switch and can connect without interruption, which can be clearly seen in the medium delay & moderate proactive pathways.

As the delay extends further, the shape of the adoption curve changes. When infrastructure is rolled

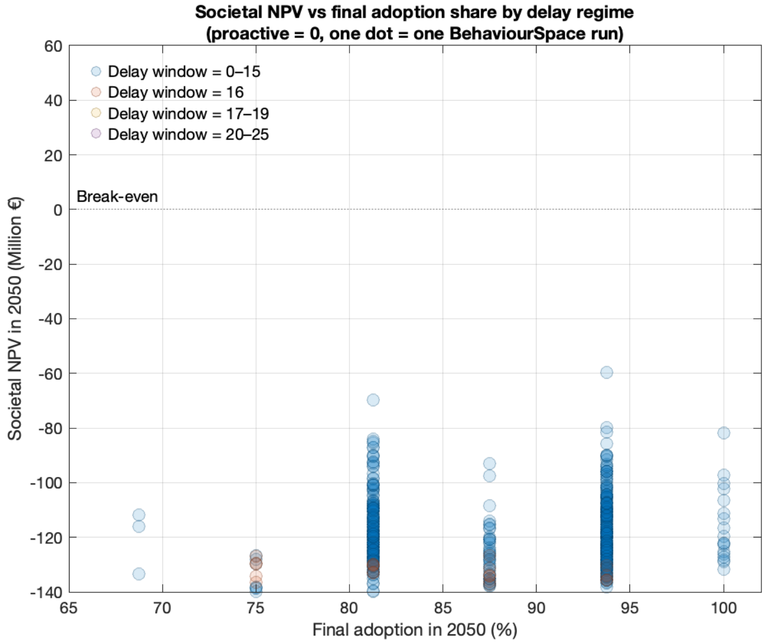

Figure 7.8: Final hydrogen adoption vs. societal NPV in 2050, grouped by delay regime (proactive window = 0). Each dot represents a single behaviorSpace run.

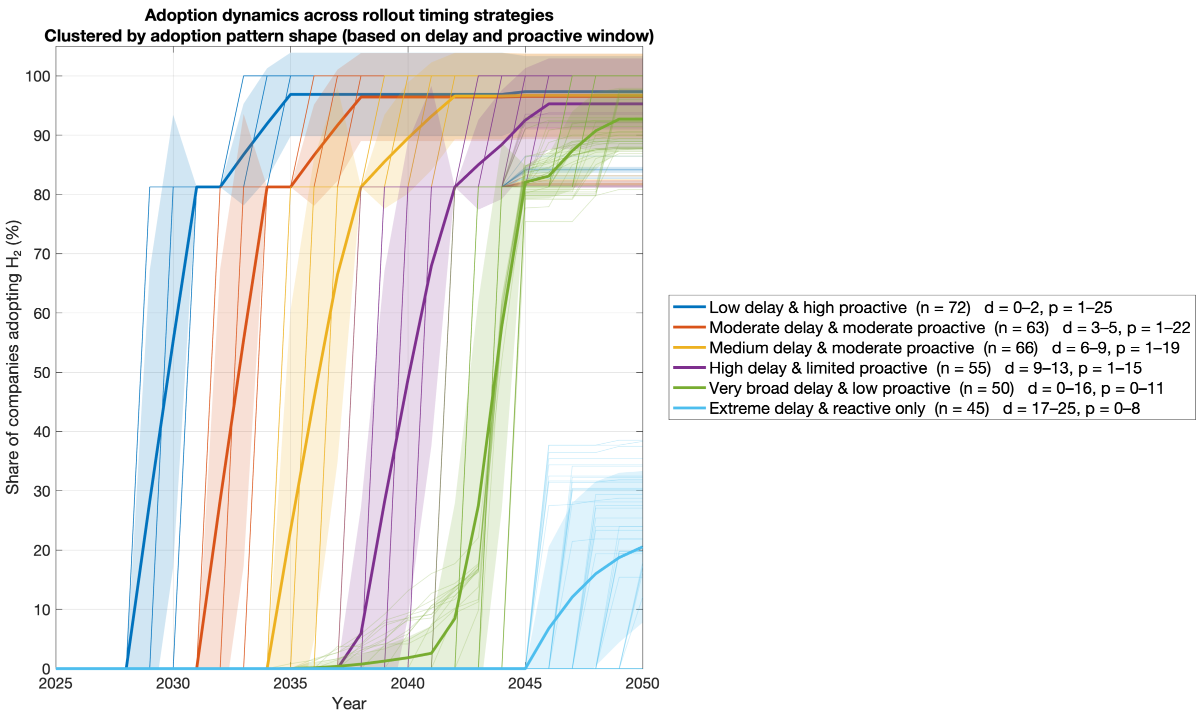

Figure 7.9: Adoption dynamics across rollout timing strategies, clustered by adoption pattern shape.

out later, a growing portion of companies have already transitioned to electrification, reducing the number that eventually adopt hydrogen, as can be seen in the *very broad delay & low proactive pathway.* This leads to a slower and more limited increase in hydrogen users and indicates a lower overall utilization of infrastructure. In clusters with larger delays and more limited proactiveness, adoption is more fragmented and a mix of energy carriers begins to emerge.

In the case of *extreme delays*, even if a proactive window is included, the overall behavior of the system becomes effectively *reactive*. By the time the planning phase begins, many firms are already under pressure to decarbonize and have committed to alternative technologies, most commonly electrification. In this context, infrastructure rollout no longer anticipates future demand, but instead reacts to decisions that have already been made. As a result, hydrogen plays only a marginal role in the transition, and the infrastructure is left underused.

The societal implications of these adoption trajectories are reflected in the corresponding cumulative Net Present Value (SNPV) results, as shown in Figure 7.10. Across the different timing clusters, distinct differences in cost and benefit realization emerge.

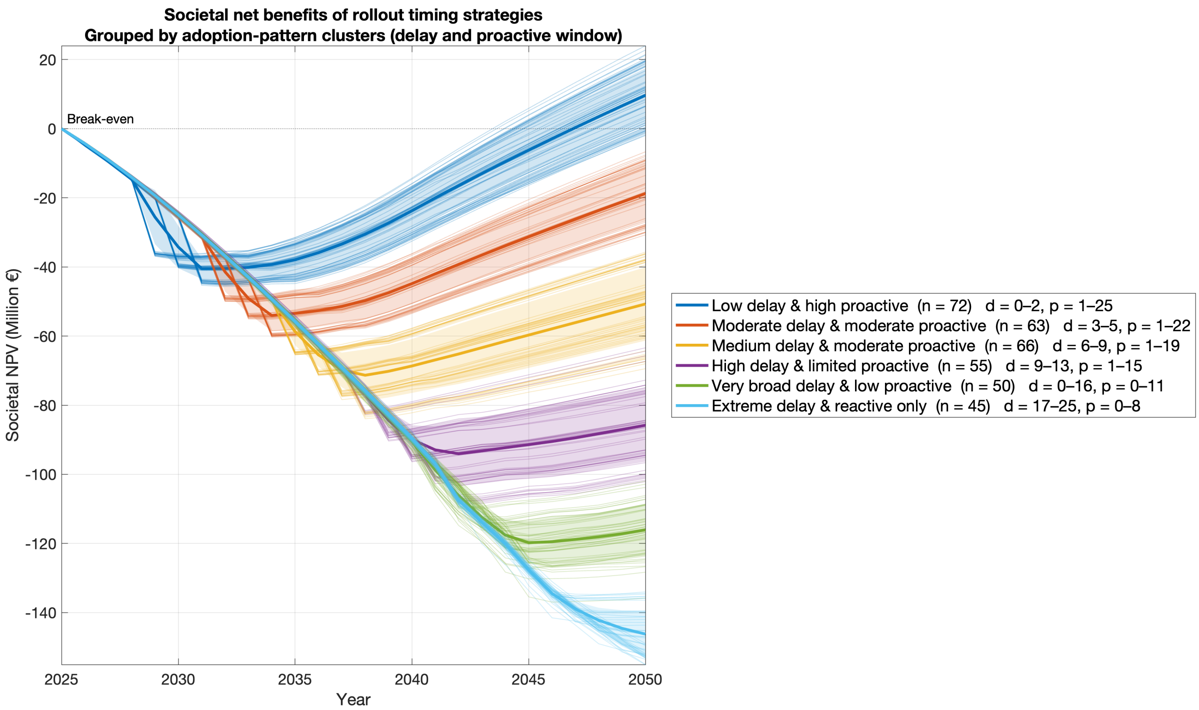

Figure 7.10: Societal net benefits of rollout timing strategies, grouped by adoption-pattern clusters (delay and proactive window combinations).

Scenarios with low delay and high proactiveness show a steep initial drop in NPV, driven by upfront infrastructure investments. However, these strategies also completed their rollout earlier, allowing the system to gain societal benefits, primarily from the reduction of CO_2 and NO_x emissions, sooner. This leads to a recovery of NPV over time, with several runs reaching break-even before 2050 and many continuing to improve steadily thereafter.

As delay increases and proactiveness decreases, this recovery becomes less pronounced. Infrastructure investments are made later, adoption is slower, and benefits are realized in the future. This delays the break-even point and reduces the present value of future gains due to discounting. As a result, the SNPV curves flatten and remain lower throughout the period.

Moderate delays can still allow for meaningful recovery, provided that rollout is followed by a proactive and well-timed infrastructure strategy. In such cases, the SNPV trajectory can be shifted upward, even if adoption begins later. Crucially, this depends on acting before firms make irreversible decarbonization decisions. If infrastructure deployment occurs too late—after companies have already committed to electrification or other alternatives—the opportunity for hydrogen to play a significant role declines sharply. This dynamic is clearly visible in the *extreme delay* scenario, where proactive planning arrives too late to meaningfully alter the course of adoption.

An additional observation is that once the infrastructure is in place and achieves high levels of utilization, typically with adoption rates between 80% and 100%, the shape of the NPV curve becomes relatively insensitive to the exact level of adoption. This suggests a kind of binary effect: once a sufficiently large share of the network is proactively laid down, the majority of societal benefits are already being captured. In this context, the decisive factor is not the precise adoption rate, but the act of deploying the infrastructure itself, which unlocks the long-term value of the system.

7.3. Experiment 3: The Role of Proactive Policy Instruments

This experiment examines how targeted policy instruments can help overcome the chicken-and-egg dilemma that often hinders low-carbon infrastructure deployment. We focus on three possible policy levers in the Dutch climate policy: a hydrogen consumption subsidy, an electricity subsidy, and the initial industrial CO_2 tax rate. Each instrument is tested at four levels: none, low, medium, and high, as specified in Section 5.

We evaluated the effectiveness of these instruments under two rollout scenarios. The first is a reactive scenario, in which the infrastructure is expanded only in response to demonstrated firm-level demand. The second introduces a partially proactive approach in which the DSO makes five years of upfront investment before reverting to reactive behavior. By comparing these scenarios, we assess how the timing and nature of policy interventions influence long-term fuel adoption and overall societal welfare.

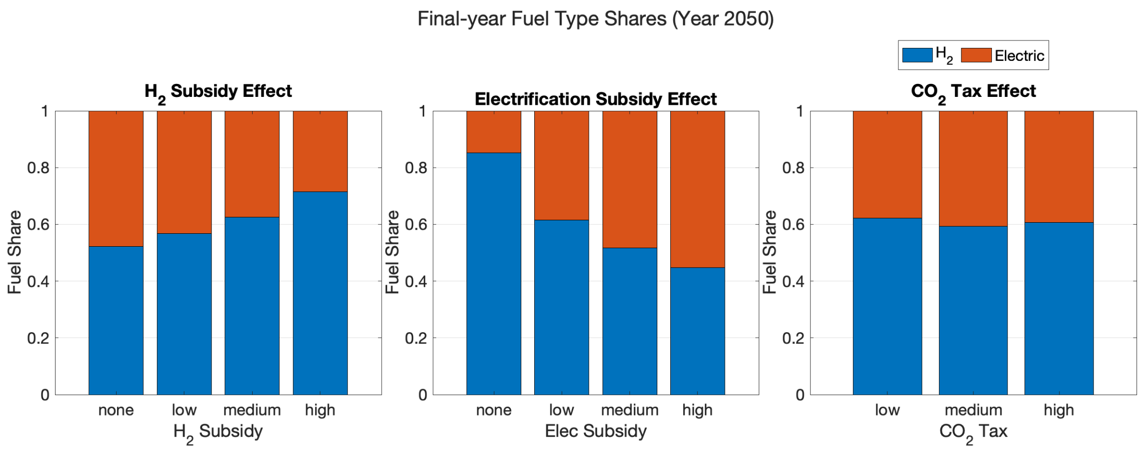

Figure 7.11: Fuel type shares among companies in 2050 under different subsidy and tax scenarios.

In the reactive scenario, the aim is to understand how different price signals, without any proactive infrastructure planning, impact the adoption of low-carbon fuels and overall societal welfare. The results, summarized in Figures 7.11 and 7.12, reveal how each policy lever influences both the industrial fuel mix by 2050 and the cumulative societal Net Present Value (SNPV) of hydrogen deployment.

Figure 7.11 shows the projected shares of hydrogen and electricity in the industrial energy mix. As expected, higher hydrogen subsidies lead to a steady increase in hydrogen adoption from about 50% without support to roughly 70% under the highest subsidy level. This pattern reflects how price incentives stimulate firm-level demand, which in turn triggers infrastructure expansion. As more companies choose hydrogen, this growing user base reinforces the rollout, helping to overcome the chicken-and-egg dynamic from the demand side. The resulting spatial clustering around the hydrogen network improves infrastructure utilization and reduces connection costs per firm.

In contrast, even a modest electricity subsidy keeps hydrogen adoption steady at around 60%, while higher electricity support reduces hydrogen's share to below 45%. In these cases, firms shift toward electrification, which results in more dispersed and less predictable connection requests. This fragmentation makes it harder for the DSO to coordinate infrastructure development and bundle connections efficiently, undermining opportunities for economies of scale and driving up per-connection costs.

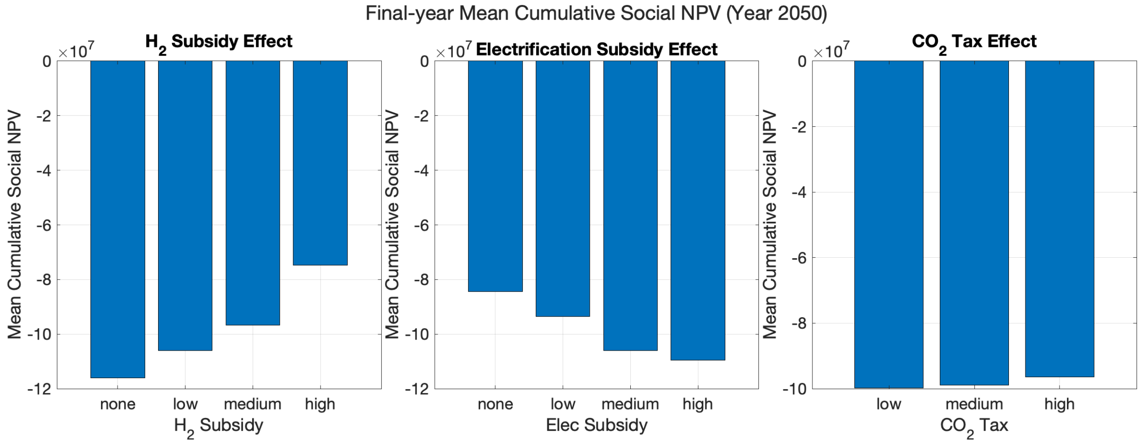

Figure 7.12: Final-year mean cumulative societal NPV (Year 2050) under varying hydrogen subsidy, electricity subsidy, and initial CO_2 tax levels.

Adjusting the initial CO_2 tax consistently reduces the dependence on natural gas but has minimal impact on the balance between hydrogen and electricity, which remains close to 60/40% across all levels. This suggests that, in its current form, the CO_2 tax lacks the directional force needed to steer firms toward a specific low-carbon pathway.

Figure 7.12 shows how the results of the fuel mix in each policy scenario translate into broader welfare effects. The hydrogen subsidy supports a more concentrated shift toward hydrogen, reinforcing spatial clustering among firms and enabling more efficient infrastructure deployment. Importantly, it also accelerates adoption: by improving the short-term economic case for hydrogen, firms switch earlier, prompting earlier infrastructure rollout. As a result, the system begins to benefit sooner from reduced CO_2 and NO_x emissions, extending the period over which societal cost savings can accumulate. This combination of spatial coordination and temporal acceleration helps mitigate connection costs and improves infrastructure utilization, partially offset by the fiscal burden of the subsidy.

In contrast, electricity subsidies lead to a more fragmented energy landscape, with firms splitting between electricity and hydrogen. This lack of alignment undermines the potential for spatial coordination, inflates per-firm infrastructure costs, and erodes the efficiency gains typically associated with networked rollout. The resulting inefficiencies are clearly visible in the societal NPV, which suffers under increasingly mixed adoption patterns. Changes in the initial CO_2 tax, while moving firms away from natural gas, do not generate a decisive preference between carriers, leaving the energy mix, and thus the infrastructure rollout, diffuse and suboptimal from a system-wide perspective.

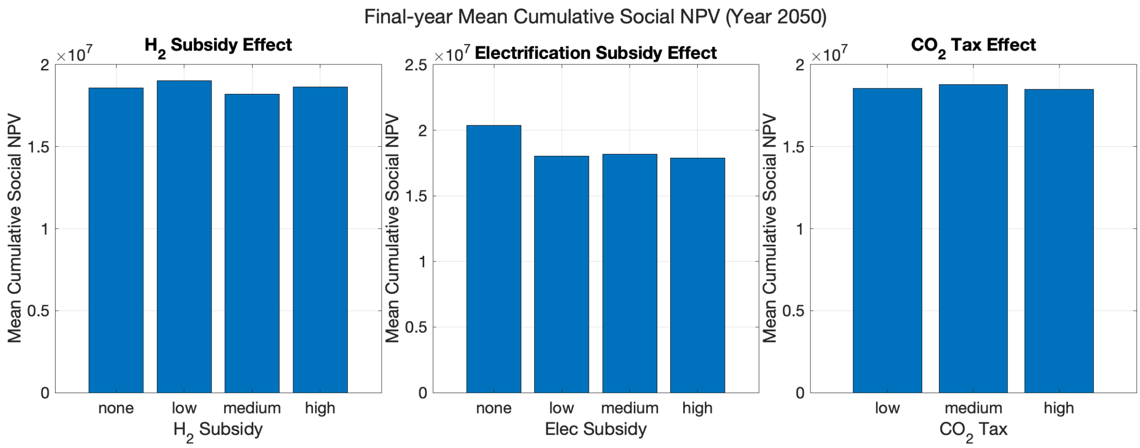

Figure 7.13: Final-year mean cumulative societal NPV (Year 2050) under a scenario with five years of initial proactive rollout followed by reactive behavior.

To assess the importance of timing, we then consider a partially proactive rollout in which the DSO makes five years of upfront infrastructure investments before reverting to reactive decision-making. As shown in the results of Section 7.2, this early action is sufficient to achieve 100% the adoption of hydrogen by 2050.

Figure 7.13 shows that this early burst diminishes the marginal effect of subsequent price instruments. With hydrogen pipelines in place largely, additional hydrogen subsidies yield only modest welfare gains. In contrast, curtailing electricity subsidies now improves NPV, since the proactive window already established a robust hydrogen backbone and avoided many grid reinforcement costs. The initial CO_2 tax remains ineffective, as the dependences on the fuel choice path harden during the proactive period, leaving little room for the tax to redirect investment.

Together, these results show that while carrier-specific incentives, particularly hydrogen subsidies, can be more effective than broad, technology-neutral signals in a reactive setting, their impact remains limited without timely infrastructure availability. The most effective way to address the chicken-and-egg dilemma is not simply to make low-carbon options more affordable but to complement those incentives with anticipatory infrastructure rollout. A brief and well-timed phase of proactive investment enables clustering, unlocks network effects, and lays the groundwork for efficient, market-driven adoption.

However, this coordination is most effective when the implementation of the infrastructure aligns with external market signals such as rising CO_2 prices and targeted subsidies. As shown in Experiment 2, when the infrastructure is already in place as firms begin to face economic or regulatory pressure to decarbonize, adoption accelerates and the infrastructure reaches full utilization more quickly. This synchronization shortens the period of underutilization and allows societal benefits from reduced emissions to begin to accrue earlier. In contrast, when rollout lags behind or incentives are misaligned, firms may choose alternative technologies, weakening the potential of hydrogen to scale.

This dynamic, visible in long-delay scenarios, highlights that timing, sequencing, and alignment between infrastructure deployment and broader climate policy are just as critical as the scale of financial support. Most importantly, it reinforces that without infrastructure in place at the right moment, the reinforcing cycle of coordinated adoption and network expansion cannot take hold. Effective decarbonization strategies must therefore treat infrastructure and incentives as complementary, time-sensitive levers.

8 Discussion

This chapter interprets the results from Chapter 7 and reflects on their implications for theory, modeling, and practice. Section 8.1 reflects on academic questions; Section 8.2 considers societal relevance.

8.1. Academic reflection

This section brings together academic contributions (Section 8.1.1) and methodological insights (Section 8.1.2).

8.1.1. Knowledge Contribution

The findings presented in Chapter 7 connect directly to the theoretical perspectives and institutional challenges outlined in Chapter 2 and Chapter 1. Rather than offering a conclusive assessment, this section reflects on how the simulation results interact with existing academic debates and policy developments in the context of regional hydrogen infrastructure planning.

A central insight from the results is that even modest anticipatory investment can break the coordination deadlock. Limited early action - before demand is fully confirmed - shapes firms' expectations: Once credible infrastructure is visible, adoption begins, demand strengthens, and further expansion becomes easier to justify. In game-theoretic terms, this shifts the system from a cautious "wait-and-see" equilibrium to coordinated action, akin to a Stag Hunt, where actors move only when they believe others will too [133].

The findings also nuance real options theory [31]. While the standard logic emphasizes the value of waiting under uncertainty, the results suggest that small, early investments can themselves create future value—not just by preserving flexibility, but by shaping the conditions under which others act. Early infrastructure sends a credible signal, unlocks network effects, and helps avoid lock-in to less efficient technologies. Historical examples like the Dutch natural gas rollout of the 1960s illustrate this dynamic, where targeted public investment catalyzed widespread uptake [107].

In addition, the results demonstrate that the timing of the intervention has greater leverage than its magnitude. In Experiment 2 and 3, a short, well-timed, proactive investment window led to higher societal benefits than later, larger subsidies alone. This observation reinforces ideas from transition management [85], which emphasize the importance of policy sequencing and the visibility of action. It also resonates with the practical challenges discussed in Chapter 1: Despite substantial allocations of hydrogen subsidies in the Netherlands in 2024, many industrial developers remain hesitant to proceed [143]. The model helps explain this gap by showing that visible infrastructure plays a crucial role in derisking private decisions, an insight aligned with mechanism design literature [89], where institutional coordination tools are required to shift incentives under strategic uncertainty.

The results indicate that *when* support arrives and can matter at least as much as *how much* support is offered. In Experiments 2 and 3, a brief, front-loaded phase of proactive construction, five years of pipeline rollout, delivered a higher societal NPV than scenarios relying solely on large subsidies. Once a credible backbone is in place, even modest incentives are enough to trigger adoption; conversely, generous subsidies have little impact if firms still face the risk of being stranded without a connection. This sequencing effect aligns with the insights of transition management theory [85], which emphasizes that structural change depends on the timing and visibility of interventions. Early, tangible action, such as infrastructure deployment, can shift expectations and reduce uncertainty, allowing coordinated change. In this light, the results help explain the limited uptake of recent Dutch hydrogen subsidies: Without visible infrastructure, firms remain hesitant even when financial support is available.

Across the experiments, a 'hybrid' strategy, an initial burst of proactive construction followed by demand-led expansion, performs well only when two conditions align. First, infrastructure must become visible early enough to influence firms before they commit to alternative technologies. Second, supportive price signals, such as increased CO_2 costs, favorable hydrogen prices, or targeted subsidies, must be present to make switching attractive. When either element is missing, the hybrid approach effectively reverts to a reactive rollout: adoption slows, coordination falters, and infrastructure is underused. These findings echo the shift toward anticipation yet adaptive planning emerging in European DSO practice [113]. They also reinforce a key planning insight: visible infrastructure is necessary but not sufficient for effective decarbonization—it must be aligned with broader market and policy signals to enable coordinated uptake.

Finally, by integrating a societal net present value (SNPV) metric that accounts for emissions and air quality externalities, the model links to the broader literature on climate infrastructure as a systemic mitigation tool [24]. The early rollout scenarios deliver not only financial benefits but also earlier realization of cobenefits related to the environment and the stakeholders involved. These outcomes extend the evaluation of infrastructure beyond narrow cost-benefit logics and support the framework for the hydrogen rollout as part of a multidimensional sustainability transition.

8.1.2. Methodological Reflection

The use of Agent-Based Modeling (ABM), as outlined in Chapter 3, was essential to capture decentralized decision making, feedback loops, and uncertainty in the deployment of hydrogen infrastructure. It enabled simulation of how local actions by DSOs and firms interact to shape system-wide outcomes, particularly with respect to timing, coordination, and the emergence of adoption patterns [23, 104].

This bottom-up modeling approach provided advantages over conventional top-down methods by incorporating bounded rationality, spatial heterogeneity, and adaptive behavior [87, 49]. It allowed testing of how proactive infrastructure strategies might address the chicken-and-egg dilemma in fragmented industrial settings and revealed how investment timing can act as a critical lever in shaping long-term societal outcomes.

Among the key insights was the importance of timing in determining whether the hydrogen infrastructure provides meaningful benefits. In many scenarios, the results showed a binary-like pattern: if the infrastructure was deployed and adopted on a sufficient scale, societal gains materialized; if not, the benefits remained largely unrealized. This pattern hinges on successfully breaking the reinforcement feedback loop between infrastructure investment and technology adoption. At first glance, it might look like a simple tipping point dynamic. However, further examination suggests that this binary effect is not solely structural: it emerges from how infrastructure timing aligns with external pressures facing firms. Market signals such as increasing CO2 costs, hydrogen subsidies, and regulatory deadlines determine when companies must choose a decarbonization path. If hydrogen infrastructure is in place before that decision moment, widespread adoption remains feasible. If not, firms pivot to alternatives, and the opportunity for hydrogen narrows.

This finding reframes the idea of a hard tipping point into something more conditional: a window of opportunity shaped by both infrastructure rollout and broader systemic context. Synchronizing deployment with the decision points of the firms is, therefore, crucial, an interaction the model was particularly suited to capture. Although some of the sharp transitions observed may be partly influenced by the use of discrete time steps and threshold-based behavior by the model, they remain illustrative of the kinds of dynamics that can emerge under institutional and policy constraints in the real world.

This points to a broader methodological issue. While the sensitivity analysis (Section 3.3.5) tested the robustness of the model parameters, it did not fully clarify whether the observed timing effects are inherent to the decentralized dynamics or shaped by the model's decision-making structure. Future research could address this by testing alternative behavioral rules, introducing stochastic elements to investment timing, or using more continuous adoption thresholds. These approaches would help determine how stable the observed patterns are under different assumptions. It would also be useful to examine how changes in discount rates, the societal valuation of emissions reductions, or different cost–benefit weightings affect timing thresholds and the emergence or breakdown of feedback loops.

Lastly, the model incorporates several simplifying assumptions, including uniform decision rules across firms and stylized agent typologies. Empirical validation was limited to expert feedback and face plausibility (Section 3.3.6), reflecting the current lack of detailed data on the implementation of hydrogen infrastructure at the regional scale. Although these limitations constrain the predictive power, they are consistent with the purpose of the model as a scenario-based exploration tool.

In summary, ABM was well suited to investigate how decentralized actors and timing strategies coevolve in the early stages of hydrogen infrastructure rollout. The results demonstrate how infrastructure decisions interact with external pressures to shape the system trajectories. However, especially when interpreting timing effects, conclusions should be considered directional rather than definitive, pending further methodological refinement and empirical testing.

8.2. Societal Reflection

Although this research was grounded in the context of Cluster 6 and used regional data provided by Stedin, its relevance extends far beyond a single geography or network operator. The central coordination dilemma, how to initiate infrastructure rollout in the absence of guaranteed demand, is present in much of the Netherlands and Europe. In regions where hydrogen demand is still emerging and spatially fragmented, the challenge of acting under uncertainty is particularly acute.

Infrastructure decisions do more than shift costs; they determine which decarbonization pathways remain open. Waiting for confirmed demand often comes too late; firms lock into electrification or other alternatives, and hydrogen loses out. Conversely, overly speculative rollouts risk stranded assets. The best results occur when a short burst of upfront infrastructure – just enough to make the network visible – aligns with market and policy signals (e.g., rising CO2 prices, competitive hydrogen costs, or targeted subsidies). In that window, firms switch en masse, pipelines reach high utilization, and societal value is maximized. If either element is missing, if pipes appear without economic pressure, or incentives precede a credible backbone, adoption stalls, and underutilization persists.

This choreography is especially critical for medium-sized industrial firms, which lack the capacity to build infrastructure themselves or bear early commitment risks. Without visible and reliable hydrogen connections at their decision point, driven by policy deadlines, cost pressures, or climate targets, these firms default to electrification or transitional fossil options, locking in less efficient and costlier system outcomes. Targeted, proactive infrastructure deployment can prevent this lock-in by matching supply to latent demand before opportunity windows close.

From a societal perspective, the implication is clear: to make hydrogen a real option for industry, public institutions must do more than follow demand—they must help shape it. This requires not only cost-effective rollout, but also strategic timing and credible signaling. Infrastructure in this sense is not just enabling; it is establishing priorities. If delivered with intent and foresight, it can move the needle: not only in emissions reduction, but in how firms perceive their options, how sectors coordinate, and how transitions unfold across fragmented landscapes.

In short, this research suggests that public value in infrastructure-led transitions comes not just from efficiency, but from the ability to unlock collective action. The medium-sized industry will not decarbonize through flagship projects alone. It will do so when institutions create the right conditions, at the right time, and in the right places for the transition to be both feasible and fair.

9 Conclusion

This chapter answers the research questions posed in Chapter 1 by summarizing the findings on the implementation of the proactive versus reactive hydrogen infrastructure. Then it discusses implications for DSOs, industrial firms, and policymakers and reflects on key limitations. Finally, it outlines directions for future research.

9.1. Answering the Research Questions

The thesis was guided by several specific research questions. The following sections summarize the key findings in relation to each.

1. What are the conceptual trade-offs between proactive and reactive HDNO rollout strategies for regional hydrogen infrastructure in the short and long term?

The conceptual trade-offs between proactive and reactive HDNO roll-out strategies focus on how system operators address uncertainty, coordination failures, and long-term system development.

Proactive strategies assume that infrastructure can stimulate demand. By building ahead of need, they aim to break coordination deadlocks, signal commitment, and enable early adoption. In the short term, this can accelerate the formation of the system and attract stakeholders. However, it carries the long-term risk of misalignment: if technological pathways or policy priorities shift, early infrastructure may become obsolete or inefficiently used. Moreover, the more people are drawn to a common infrastructure, the greater the systemic exposure if it turns out to be suboptimal.

Reactive strategies, in contrast, wait for confirmed demand before investing. This reduces financial and political risks and aligns with current regulatory frameworks. In the short term, it ensures that infrastructure is more likely to match actual needs. But the downside is inertia: without visible infrastructure, potential users may delay or forgo action, reinforcing the very coordination problems that proactive approaches try to solve. In the long term, reactive implementation may protect against misalignment, but risks fragmentation, slower progress, and missed decarbonization targets.

Ultimately, the trade-off is this: proactive rollout drives change but risks locking in suboptimal pathways; reactive rollout avoids premature commitment but risks falling behind. These are not binary options; effective HDNO strategies will likely combine both approaches, pursuing early rollout in high-potential regions while maintaining flexibility elsewhere.

In conclusion, proactive rollout treats infrastructure as a catalyst, reactive rollout as a consequence. Each exposes the system to different short- and long-term risks, and successful strategies will need to balance leadership with adaptability.

2. How can the societal costs and benefits of these rollout strategies be defined and evaluated in a regional industrial context?

This thesis evaluates the societal impact of rollout strategies using a Societal Net Present Value (SNPV) metric. The SNPV framework accounts for direct and indirect societal effects over time, including infrastructure investment, retrofit costs, avoided CO_2 and NO_x, and greater system-wide savings, such as delayed grid reinforcements and reduced dependence on gas distribution networks.

Each cost and benefit stream is modeled on an annual basis and discounted using a consistent societal discount rate, allowing clear comparison across scenarios. This method captures both upfront expenditures and the enduring societal gains of early coordinated transitions.

Although SNPV does not cover all possible externalities or behavioral nuances, it provides a transparent, structured approach that goes beyond traditional cost-benefit or business-case analyses. It highlights the critical roles of timing and coordination in unlocking system-wide value, offering a practical benchmark for assessing how infrastructure deployment supports broader societal goals.

3. How can HDNO decision making be modeled in the context of regionally distributed industrial demand?

HDNO decision-making in the model is grounded in the core coordination failure between industrial firms and infrastructure providers at the regional level. Industrial users are only willing to adopt hydrogen if they can reasonably expect timely and affordable access to infrastructure. At the same time, the Hydrogen Distribution Network Operator (HDNO) -represented in the model as a prospective mandate embedded within the Regional Distribution System Operator (DSO) - can only justify infrastructure rollout if there are credible aggregated demand signals across space and time. However, these signals are themselves shaped by the expectations of firms of infrastructure availability. This mutual dependency creates a strategic coordination impasse: neither actor can act decisively without expecting the other to move first. The resulting chicken-and-egg dynamic is not just a matter of sequencing, but a structurally coupled loop of expectations that drives the persistent regional investment inertia analyzed in this model.

To capture this interaction, the model represents both the DSO and industrial companies as decentralized agents making decisions under uncertainty. Industrial firms conduct cost-benefit assessments each year, based on technical feasibility, capital replacement cycles, energy prices, and availability of local infrastructure. If conditions are favorable, they submit a letter of intent, indicating a commitment to switch to hydrogen if infrastructure becomes available.

The DSO then evaluates whether these demand signals, both confirmed and potential, are sufficient to justify the building of infrastructure in a given area. This is operationalized through a threshold rule that aggregates letters of intent and partially weights potential future users approaching asset end-of-life. The level of this weighting reflects the willingness of the DSO to anticipate demand, rather than respond only to confirmed commitments.

To explore how different planning approaches affect this coordination problem, the model includes three stylized strategies. In the reactive strategy, the DSO waits for sufficient confirmed demand before initiating a project, in line with the legal connection obligation used for electricity. In the proactive strategy, hydrogen infrastructure is built in anticipation of demand, even without firm commitments, assuming that nearby firms will follow. In the delay strategy, the DSO does not make any hydrogen investments, reflecting the current regulatory vacuum.

Through these interacting decision routines, infrastructure and demand co-evolve over time. The model simulates how different HDNO strategies shape the speed, scale, and spatial pattern of regional hydrogen adoption, highlighting the critical role of timing and credibility in resolving coordination failures.

4. How do variations in the timing and scale of the HDNO rollout strategies influence the societal outcomes of the development of regional hydrogen infrastructure?

The results show that both the timing and scale of hydrogen infrastructure rollout significantly affect societal outcomes, not through their absolute values, but through the trajectories they enable. What matters most is not how early infrastructure is built or how expansive it is, but whether it becomes available when firms are under pressure to make decarbonization decisions. When infrastructure is present at this moment, it allows multiple firms to switch in a coordinated way, improving infrastructure utilization, accelerating emission reductions, and reducing overall system costs.

Proactive strategies that act ahead of confirmed demand tend to enable this alignment. Even a moderate degree of anticipation, targeted toward visible industrial potential, can help trigger synchronized adoption patterns. This early cluster effect leads to more efficient infrastructure use, earlier returns on investment, and stronger societal value. Crucially, the results also show that pushing proactivity too far, investing heavily in the absence of clear signals, yields diminishing returns. Once the main window for coordinated adoption is opened, further speculation adds little value and increases the risk of underused assets.

In contrast, reactive or delayed rollouts often fail to meet the needs of firms at the right time. When infrastructure lags behind industrial decision cycles, adoption becomes scattered, leading to fragmented networks, higher per-connection costs, and prolonged reliance on fallback technologies. In many of these scenarios, the infrastructure never reaches sufficient utilization to offset its societal cost, and hydrogen fails to establish itself as a viable decarbonization route.

The overarching conclusion is that timing and scale influence outcomes primarily by shaping the extent to which rollout can be aligned with firm-level decision making. Strategies that establish infrastructure at the right moment and at sufficient scale can move the system toward coordinated, high-value pathways. Once this opportunity is missed, the region risks becoming locked into less efficient and more costly transition trajectories.

5. How do proactive policy instruments affect HDNO rollout strategies in regional hydrogen systems?

The findings show that policy instruments can meaningfully shape both the adoption dynamics of hydrogen and the societal value of infrastructure rollout, but their effectiveness strongly depends on the presence and timing of infrastructure. Price-based incentives, such as hydrogen consumption subsidies, can steer firm behavior and improve network utilization, but only when the infrastructure is available early enough to support adoption at the right moment.

In reactive rollout scenarios, even generous subsidies struggle to overcome the timing mismatch between infrastructure availability and firm decision points. As a result, firms switch technologies in a staggered and inefficient way, leading to fragmented networks and a lower system-wide value. Electricity subsidies, in particular, tend to reduce the coherence of hydrogen deployment by pushing firms toward electrification and undermining clustering effects. This increases infrastructure costs and reduces the ability to coordinate transitions between firms.

The simulations also show that carbon pricing, while helpful in discouraging fossil fuel use, does little to resolve the infrastructure coordination dilemma. Without a clear mechanism for aligning firm decisions and infrastructure provision, carbon prices alone are insufficient to generate large-scale adoption.

The most significant insight is that proactive infrastructure rollout amplifies the effectiveness of policy instruments. A short anticipatory build phase enables the system to benefit from clustering and network effects, reducing the need for ongoing subsidies and improving overall efficiency. In this setting, targeted policy support can help initiate adoption, but the core enabler is timely infrastructure.

In summary, proactive policy instruments can support hydrogen transitions, but they cannot compensate for delayed or fragmented infrastructure rollout. Their value is maximised when aligned with early, strategic investment by HDNOs, suggesting that coordination between infrastructure planning and policy design is essential for unlocking societal value.

6. What role can existing DSOs play in enabling the regional rollout of hydrogen infrastructure?

In the model developed in this thesis, the future role of a Hydrogen Distribution Network Operator (HDNO) is operationalised through the existing regional Distribution System Operator (DSO). This modeling choice reflects the reality that while HDNOs are likely to become key actors in future hydrogen systems, their institutional form remains undefined. It is not yet clear whether current DSOs will assume this role or whether new entities will emerge. However, the model uses DSO as a proxy to explore how different rollout strategies influence the dynamics of adoption, coordination, and societal value, particularly given that DSOs will play a central role in determining which energy carriers (hydrogen, electricity, or gas) are made available to industrial users at the regional level.

The results show that early decisions about infrastructure provision have long-lasting effects. When hydrogen infrastructure is delivered too late, after firms have already locked into electrification or other alternatives, its relevance as a decarbonization pathway diminishes. This leads to fragmented outcomes, underutilised assets, and reduced societal returns. Conversely, when infrastructure is made available just ahead of firm-level decision points, even in a limited and targeted way, it creates a window for coordinated adoption and more efficient system development.

This highlights the importance of DSOs not merely as service providers, but as system architects. As energy transitions become multi-carrier in nature, DSOs will increasingly shape which energy carriers are viable in which regions. Although the right to energy remains universal, the form that energy takes, be it hydrogen, electricity, or otherwise, is shaped by infrastructure decisions. DSOs are thus positioned to influence not only the rollout of networks but the direction of decarbonisation pathways themselves.

However, the findings also show that DSOs cannot adopt this enabling role under current institutional conditions. Currently, they lack the legal mandate, financial tools, and regulatory clarity to act in advance of an unconfirmed market. This constrains their behavior to reactive provision, even when more strategic action would improve long-term outcomes. The results indicate that a well-timed and spatially selective proactive rollout delivers the greatest societal value, but this requires clear rules and shared risk frameworks that do not yet exist.

So, while DSOs may or may not ultimately become HDNOs and while they cannot act unilaterally under current constraints, they are central to whether the early stages of the hydrogen transition are coordinated or fragmented. If empowered through institutional reform, DSOs can begin to design infrastructure that anticipates regional demand trajectories, supports clustering, and signals credibility to potential adopters. Their role would shift from passive implementer to active orchestrator, making hydrogen not just available but viable where and when it matters most.

In sum, DSOs will not decide the future of hydrogen alone, but without their involvement, its regional success is unlikely. Their proximity to industrial users, technical planning capacity, and coordinating position across carriers make them uniquely suited to unlock the first steps of rollout, provided the mandate to do so is established.

9.2. Main Research Question

How do proactive versus reactive rollout strategies by Hydrogen Distribution Network Operators (HDNOs) shape the societal costs and benefits of regional hydrogen infrastructure for medium-sized industrial users?

Proactive and reactive rollout strategies fundamentally shape the societal value of hydrogen infrastructure by determining whether it is available when firms face key decarbonization decisions. The model results show that timing is the most critical factor: When infrastructure is proactively in place as companies approach decision points, adoption follows, even without confirmed commitments. In contrast, if rollout waits for sufficient confirmed demand, it delays deployment until many firms have already acted independently. This not only fragments adoption and undermines coordination, but also prolongs fossil fuel use and drives up cumulative societal costs. By arriving too late, reactive strategies lose both infrastructure efficiency and climate impact.

Proactive strategies anticipate future demand by investing based on visible industrial potential rather than waiting for formal commitments. Although this approach involves a higher upfront investment, it enables firms to adopt in a more clustered and synchronized fashion. This reduces per-firm connection costs, increases infrastructure utilization, and accelerates emission reductions. Crucially, even if proactive rollout does not achieve full adoption, it still outperforms delayed strategies in terms of societal value, because the benefits of early transitions outweigh the risks of partial uptake.

Reactive strategies, in contrast, are guided by confirmed firm-level demand. But this 'wait and see' logic can backfire: If time commitments are sufficient to justify investment, many firms may already have chosen alternative paths, such as electrification. This results in piecemeal adoption, higher per-connection costs, and a weakened role for hydrogen in the transition. Even strong policy incentives have limited effect in these scenarios, as the infrastructure often arrives too late to be credible or relevant.

Importantly, the results do not support a fully speculative rollout either. While some anticipation is needed to resolve the coordination failure, the marginal benefits of further speculation diminish. Relying exclusively on potential demand, without sufficiently credible signals of adoption, risks overbuilding infrastructure and generating systemic inefficiencies. The most effective approach is a calibrated one: proactive enough to enable coordination and early action, but restrained enough to avoid excessive overbuild.

Policy instruments such as hydrogen subsidies can reinforce hydrogen adoption, but their impact depends heavily on the timing of infrastructure availability. In proactive rollout scenarios, these instruments accelerate and amplify coordinated switching. However, in reactive scenarios, even strong subsidies are insufficient to reverse fragmented adoption patterns. Electricity subsidies, meanwhile, tend to steer firms toward dispersed choices, which undermines network effects. This highlights that incentives alone are not enough—they must be aligned with timely infrastructure deployment to be effective.

In sum, HDNO rollout strategies influence societal outcomes not just through speed or scale, but through their timing, coordination, and credibility. A proactive approach - if applied moderately and in the right locations - can generate greater societal value by enabling earlier and more efficient transitions, even if it requires a higher upfront investment. In contrast, reactive rollout risks coming too late to support meaningful change. With many firms in Cluster 6 nearing critical and potentially path-dependent investment decisions, the opportunity to align infrastructure with industrial decarbonization is narrowing. Hence, a coordinated and timely action is not just beneficial; it is increasingly essential to steer the transition while the window remains open.

9.3. Implications for Stakeholders

This section translates the model's findings into concrete insights for key stakeholders, highlighting how each can act to overcome coordination barriers and accelerate the regional rollout of hydrogen infrastructure.

9.3.1. Hydrogen Distribution Network Operators

For Hydrogen Distribution Network Operators (HDNOs), the central insight from this research is clear: timing is decisive. The model demonstrates that when the infrastructure is already in place as firms approach key decarbonization decisions, coordinated hydrogen adoption follows, often even without formal commitments. In contrast, if rollout is delayed until sufficient demand is confirmed, the opportunity is often missed: firms will have already locked into alternatives like electrification, and network value diminishes as adoption fragments.

To avoid this, HDNOs should take a targeted and anticipatory approach. This means actively identifying high-potential industrial regions and initiating a limited rollout prior to formal commitments. Building infrastructure early sends a credible signal to firms, helping to break the chicken-and-egg cycle and triggering a wave of adoption. Crucially, this does not require full coverage or speculative build-out: limited, well-placed early investment is often sufficient to trigger broader system transformation.

HDNOs should not base their actions solely on long-term projections but rather on a clear sense of when a region is institutionally, economically, and technically ready for transition. Being slightly ahead of this tipping point, rather than waiting for ex post certainty, yields significantly higher societal value, as the results in this thesis confirm. Even if full network utilization takes time, early rollout avoids missed windows and prevents irreversible lock-in.

These findings reinforce recent public reports, which call for well-timed regionally tailored hydrogen infrastructure plans based on visible potential rather than firm contracts [100]. This research provides quantitative support for this recommendation: the modestly proactive rollout consistently outperforms reactive strategies, both in terms of adoption and societal benefit. For HDNOs, the path forward is clear: move early, move selectively, and move with conviction.

9.3.2. Distribution System Operators

Distribution System Operators (DSOs) have a pivotal role in enabling regional hydrogen infrastructure for medium-sized industry. As decarbonization pressures increase, many industrial clusters are urgently seeking alternatives to fossil fuels. DSOs are uniquely positioned to support this transition by helping to develop low-pressure hydrogen networks tailored to local demand and spatial conditions.

Unlike commercial market players, DSOs operate with a public mandate. Their role is not to maximize profit but to ensure reliable, efficient, and socially beneficial infrastructure. This makes them well-suited for use in the early phases of hydrogen deployment, where long-term public value may outweigh short-term returns.

To unlock this potential, DSOs should advocate for a formal mandate as HDNOs and begin transitioning from passive infrastructure providers to active energy system architects. This requires building internal capacity in spatial analysis, scenario planning, stakeholder engagement, and hydrogen-specific network design. Lessons from pilot projects and early initiatives can inform this development, helping DSOs anticipate regional needs and design infrastructure that is fit for purpose.

This approach is strongly supported by the findings of the Netbeheer Nederland [100] report, which emphasizes the need for regionally tailored rollout strategies that respond to industrial dynamics rather than await full demand certainty. Like this thesis, the report concludes that early and credible infrastructure planning - timed with firms' decision cycles - is key to breaking the current coordination deadlock.

Although the formal market framework for hydrogen distribution is still evolving, this should not delay action. DSOs can already begin working with local industry and governments to identify high-potential zones, initiate joint planning processes, and de-risk early investment through collaborative governance models. These bottom-up efforts are essential precursors to a functioning national rollout strategy.

Using their technical knowledge, institutional neutrality, and regional networks, DSOs can play a leading role in shaping the hydrogen transition. Their anticipatory planning, grounded in the public interest, will be essential to make hydrogen a realistic and cost-effective decarbonization option for the medium-sized industry.

9.3.3. Medium-Sized Companies

For medium-sized industrial companies, the key message is to prepare for a timely and coordinated transition. The results of this thesis show that when hydrogen infrastructure is in place as firms approach critical decarbonization moments, adoption accelerates, and firms that are ready to act stand to benefit most.

To seize this opportunity, companies should begin assessing their internal readiness: evaluating technical retrofit options, estimating investment needs, and aligning decarbonization plans with expected infrastructure availability. Early preparation allows firms to move quickly when the window opens and avoid costly lock-ins to suboptimal alternatives.

In addition, companies should not act alone. Coordinating with other firms in the region, through informal networks, structured coalitions, or joint investment arrangements, can significantly strengthen the demand signal perceived by Distribution System Operators (DSOs), as supported by Ateş [9]. This collective visibility improves the chances of timely infrastructure rollout. Shared investments in connection infrastructure, compressors, or supply agreements not only lower individual costs but also help de-risk early adoption. A credible joint signal from multiple firms can be decisive in triggering proactive DSO action, ultimately benefiting all participants.

In short, medium-sized companies should act not only as future hydrogen users but as co-designers of the transition. By early preparation, regional collaboration, and sharing investment burdens, they can help create the conditions for a viable and cost-effective hydrogen future.

9.3.4. Dutch Government

The Dutch government plays a critical enabling role in the rollout of regional hydrogen infrastructure. First, a clear legal framework must be established that empowers Distribution System Operators (DSOs) to act as Hydrogen Distribution Network Operators (HDNOs). DSOs already possess the technical expertise, regional presence, and institutional neutrality needed to coordinate complex infrastructure planning. Unlike commercial developers, their role is not to pursue profit, but to serve the public good by ensuring reliable and equitable access to energy. As supported by the Netbeheer Nederland [100] report, the current lack of formal rights and cost recovery mechanisms prevents DSOs from fully acting on this capacity. The forthcoming revision of *Energiewet* should address this gap by clearly defining connection rights, tariff structures, and depreciation rules: placing hydrogen on the same regulatory footing as gas and electricity and allowing DSOs to advance the public interest across all carriers.

Second, policy instruments must emphasize timing over scale. The results of this thesis show that moderate early rollout, targeted at high-potential areas and undertaken before full demand certainty, delivers the greatest societal value. Subsidies, guarantees, and carbon pricing mechanisms should therefore prioritize early movers over large-scale but delayed projects.

Third, the government must proactively mitigate rollout bottlenecks. This includes co-investing in workforce training, securing long-lead-time components like pipelines and pressure systems, and coordinating spatial planning between hydrogen networks, electricity infrastructure, and industrial development zones.

By enabling HDNOs to act ahead of confirmed demand and by supporting regions where hydrogen is already a credible option, government policy can unlock early adoption, lower long-term system costs, and accelerate the decarbonization of Dutch industry—particularly in mid-sized clusters like Cluster 6.

9.4. Limitations of the Research

While this thesis provides a structured and policy-relevant analysis of hydrogen infrastructure rollout strategies, its findings should be interpreted in light of several limitations.

First, the model is built to explore coordination dynamics under uncertainty, not to predict real-world outcomes with precision. Simplifications were made to keep the model tractable: technical systems are assumed to function without failure, regulatory conditions remain static, and firms are modeled as economically rational agents. These assumptions help isolate the strategic interaction between firms and infrastructure providers, but abstract from many complexities of actual deployment, such as financing constraints, political delays, or societal acceptance issues. As such, the results are best viewed as indicative of systemic tendencies rather than precise forecasts.

Second, the analysis is situated in a specific regional and institutional context: Cluster 6 in The Netherlands. This focus strengthens empirical relevance and ties the results to concrete planning realities. However, it also limits generalizability. Industrial structure, governance capacity, spatial fragmentation, and market maturity vary widely between regions, and results may differ under alternative conditions. However, the central insight, that infrastructure timing and credibility matter more than scale alone, is likely to hold in many industrial decarbonization contexts where adoption and infrastructure are mutually dependent.

Third, although the model captures the core strategic interdependence between DSOs and firms, it does not explore the full range of possible governance arrangements. It assumes that existing DSOs could evolve into Hydrogen Distribution Network Operators (HDNOs), but in practice, the institutional form of HDNOs remains unsettled. Future actors could include new public-private entities or regulated asset base companies, each with different incentives, mandates, and restrictions. These variations may significantly affect the feasibility and risks of proactive rollout strategies.

Lastly, the analysis is shaped by fundamental uncertainties about hydrogen as an emerging energy carrier. Key factors such as long-term cost competitiveness, supply chain maturity, interoperability of the infrastructure, regulatory evolution, and public acceptance remain unresolved. In particular, the future availability of green hydrogen, its distribution costs, and the development of safety and quality standards will strongly influence industrial adoption but are currently difficult to forecast. These unknowns introduce structural ambiguity into any modeling effort. While this thesis captures how rollout strategies interact with firm behavior under uncertainty, it does so in a context where the underlying viability of hydrogen itself is still in flux. As such, the findings should be understood as exploratory insights into coordination dynamics under emerging conditions, rather than as firm predictions about the future of hydrogen in industry.

In summary, although the quantitative results are shaped by modeling assumptions, regional scope, and data constraints, the core insights are robust. By focusing on the interaction of timing, coordination, and credibility, this thesis identifies key levers for unlocking societal valuable hydrogen transitions. The results highlight the value of moderate, well-targeted anticipatory action, not as speculative overreach but as a strategic tool to break coordination barriers in time-sensitive industrial contexts.

9.5. Directions for Future Research

This thesis has shown that a proactive and well-timed deployment of hydrogen infrastructure by HDNOs can create significant societal value in regions such as Cluster 6. However, several areas remain where further research is needed to deepen the understanding and expand the applicability of the model.

A key next step is to explore how the findings translate to other industrial regions. While the model was calibrated to Cluster 6, different clusters vary widely in spatial structure, industrial composition, and institutional support. As emphasized in the HyRegions study [100], no one-size-fits-all strategy exists. Future research could apply the model to other contexts, both within and outside of the Netherlands, to assess whether the anticipatory approach holds under varying conditions of fragmentation, coordination potential and demand density.

Second, the model could be enriched by better capturing the organizational and institutional complexities that shape firm-level decision-making. As shown by Ateş [9], firms do not respond to infrastructure signals solely based on economic optimization. Instead, their decisions are shaped by internal routines, limited foresight, and uncertainty about future technologies, policies, and market developments. Many firms lack the strategic capacity or coordination mechanisms needed to act collectively, especially in fragmented industrial settings. Rather than assuming fully rational actors, future models should incorporate behavioral realism, such as bounded rationality, internal organizational constraints, and interfirm dynamics. This would allow a more accurate simulation of how hydrogen adoption unfolds in practice, particularly under conditions of institutional ambiguity and evolving expectations.

Third, this thesis assumes a stylized system operator with decision authority, but in practice, Dutch hydrogen rollout is hindered by regulatory uncertainty about who bears the costs of connecting end users to the hydrogen grid. As shown by Keur [78], the absence of clear rules on connection financing—such as whether connection infrastructure should be paid by the user, the system operator, or socialized across the network—creates major hesitation among stakeholders. This ambiguity undermines investment planning and stalls proactive rollout, as DSOs are reluctant to act without clarity on cost recovery, and firms hesitate to commit without knowing their financial responsibility. Future research should explore how different regulatory approaches to connection cost allocation influence the willingness and ability of infrastructure actors to move ahead under uncertainty.

Finally, future modeling efforts should reflect the evolving nature of hydrogen policy and market conditions. Static assumptions on prices, subsidies, and regulations limit the capacity to anticipate policy feedbacks or market responses. Incorporating adaptive instruments, such as dynamic subsidies, evolving CO_2 prices, or learning curves for hydrogen supply, would allow for a more robust scenario analysis. In parallel, exploring how EU-level developments in hydrogen regulation, certification, and cross-border infrastructure planning influence regional rollout strategies would strengthen the relevance of the model's policy.

Together, these avenues offer a pathway for extending this thesis toward greater empirical depth, behavioral realism, and institutional applicability. By refining the model and testing it in new contexts, future research can provide more grounded guidance for policy and infrastructure planning, helping to accelerate hydrogen adoption where it matters most.

9.6. Use of Artificial Intelligence in the Research

Artificial intelligence tools, particularly ChatGPT, supported this thesis by improving the clarity, structure, and efficiency of both writing and technical tasks. AI was used to refine academic phrasing, suggest clearer formulations, and help to rewrite complex ideas while preserving meaning. This enhanced the coherence and readability of the final document. In addition to writing support, ChatGPT assisted in coding and document preparation. Provided Matlab snippets for data analysis and helped resolve LaTeX formatting issues, speeding up the development of figures, tables, and technical sections. It also served as a useful knowledge tool, offering quick explanations of unfamiliar concepts and methods during the research process.

While AI did not shape the core research methodology of agent-based modeling, it contributed meaningfully to the clear and effective communication of results. Used responsibly, it complemented conventional academic methods without compromising rigor.

References

[1] L. Abspoel-Bukman et al. “Monitoring and data - informed assessment of steel bridges - lessons learned from a case study”. In: *Ce/Papers* 6.5 (2023), pp. 553–560. DOI: 10.1002/cepa.2200.

[2] Agency for the Cooperation of Energy Regulators (ACER). *Consistency of Cost–Benefit Analysis Methodologies*. Position Paper. Ljubljana, Slovenia: ACER, 2014. URL: https://www.acer.europa.eu/sites/default/files/documents/Position%20Papers/ACER_Consistency%20of%20CBA%20methodologies.pdf.

[3] K. Agrawal et al. “Hydrogen an environmental revolution toward clean energy transition: a green concept for current and future perspectives”. In: *Clean Technologies and Environmental Policy* (2024). DOI: 10.1007/s10098-024-03015-6.

[4] S. O. Akpasi et al. “Hydrogen as a Clean Energy Carrier: Advancements, Challenges, and its Role in a Sustainable Energy Future”. In: *Clean Energy* 9.1 (Jan. 2025), pp. 52–74. DOI: 10.1093/ce/zkae112.

[5] M. Amjath, F. Eljack, and M. Haouari. “Strategic optimization and design of cost-effective and sustainable hydrogen supply chain networks – Qatar case study”. In: *Energy Conversion and Management* 327 (2025), p. 119543. DOI: 10.1016/j.enconman.2025.119543.

[6] B. W. Arthur. “Competing Technologies, Increasing Returns, and Lock-In by Historical Events”. In: *The Economic Journal* 99.394 (1987), pp. 116–131. DOI: 10.2307/2234208.

[7] P. Artikis and C. Artikis. “Proactive decision making by incorporation of discrete random sums”. In: *Intelligent Decision Technologies* 17.4 (2023), pp. 1199–1206. DOI: 10.3233/idt-230268.

[8] S. Asgarpour et al. “Scenario-Based Strategic Modeling of Road Transport Demand and Performance”. In: *Transportation Research Record* 2677.5 (2023), pp. 1415–1440. DOI: 10.1177/03611981221143377.

[9] E. Ateş. “Agent-Based Simulation of Industrial Collaboration for Regional Hydrogen Off-take”. Master’s thesis. Delft University of Technology, Aug. 2024. URL: http://repository.tudelft.nl/.

[10] Autoriteit Consument en Markt. *Gewijzigd Methodebesluit Regionale Netbeheerders Gas 2022–2026*. Zaaknummer: ACM/23/184726, Documentnummer: ACM/UIT/600687. Dec. 2023. URL: https://www.acm.nl.

[11] Autoriteit Consument en Markt. *Ontwikkeling en Regulering van Waterstofinfrastructuur*. Zaaknr. ACM/20/042263, Documentnr. ACM/INT/428825. 2021. URL: https://www.acm.nl/nl/publicaties/acm-signaal-2021-afspraken-over-voorwaarden-bij-waterstofexperimenten-noodzakelijk.

[12] Autoriteit Consument en Markt. *Tijdelijk Kader voor Waterstofpilots: Gedoogbeleid voor Betrokkenheid van Netbeheerders bij Pilots met Waterstof in de Gebouwde Omgeving*. Zaaknr. ACM/21/052956, Documentnr. ACM/UIT/579844. July 2022. URL: https://www.acm.nl/nl/publicaties/tijdelijk-kader-voor-waterstofpilots.

[13] R. Bhandari and N. Adhikari. “A comprehensive review on the role of hydrogen in renewable energy systems”. In: *International Journal of Hydrogen Energy* 49.54 (2024), pp. 791–816. DOI: 10.1016/j.ijhydene.2023.08.044.

[14] E. Bonabeau. “Agent-based modeling: Methods and techniques for simulating human systems”. In: *Proceedings of the National Academy of Sciences* 99.3 (2002), pp. 7280–7287. DOI: 10.1073/pnas.082080899.

[15] E. Borgonovo et al. “Sensitivity analysis of agent-based models: a new protocol”. In: *Computational and Mathematical Organization Theory* 28.1 (2022), pp. 52–94. DOI: 10.1007/s10588-021-09358-5.

[16] H. Bouwmeester. *Pilotprojecten waterstof in de gebouwde omgeving: Leerervaringen*. Tech. rep. Ministerie van Economische Zaken en Klimaat (EZK), 2024. URL: https://www.rvo.nl/sites/default/files/2024-04/Pilotprojecten_waterstof_in_de_gebouwde_omgeving.pdf.

[17] G. ten Broeke, G. van Voorn, and A. Ligtenberg. "Which Sensitivity Analysis Method Should I Use for My Agent-Based Model?" In: *Journal of Artificial Societies and Social Simulation* 19.1 (2016), p. 5. DOI: 10.18564/jasss.2857.

[18] M. T. Brozynski and B. D. Leibowicz. "A multi-level optimization model of infrastructure-dependent technology adoption: Overcoming the chicken-and-egg problem". In: *European Journal of Operational Research* 300.2 (2022), pp. 755–770. DOI: 10.1016/j.ejor.2021.10.026.

[19] J. Burchardt et al. *Turning the European Green Hydrogen Dream into Reality: A Call to Action*. Report. Boston Consulting Group, 2023. URL: https://media-publications.bcg.com/Turning-the-European-Green-H2-Dream-into-Reality.pdf.

[20] E. H. Caoui and A. Steck. "Content Providers and the Deployment of Internet Infrastructure". In: *Information Economics and Policy* (2025), p. 101134. DOI: 10.1016/j.infoecopol.2025.101134.

[21] J. Castro et al. "A review of agent□based modeling of climate□energy policy". In: *Wiley Interdisciplinary Reviews: Climate Change* 11.4 (2020), e647. DOI: 10.1002/wcc.647.

[22] CE Delft. *Afnameverplichting Groene Waterstof*. nl. In Dutch. Dec. 2023. URL: https://ce.nl/publicaties/afnameverplichting-groene-waterstof/.

[23] E. J. L. Chappin and G. P. J. Dijkema. "Agent-Based Modeling of Energy Infrastructure Transitions". In: *International Conference on Infrastructure Systems and Services*. 2008. URL: https://chappin.com/emile/docs/Chappin08a.pdf.

[24] B. Cohen et al. "Co-benefits and trade-offs of climate change mitigation actions and the Sustainable Development Goals". In: *Sustainable Production and Consumption* 26 (2021), pp. 805–813. DOI: 10.1016/j.spc.2020.12.034.

[25] A. Collins, M. Koehler, and C. Lynch. "Methods that Support the Validation of Agent-Based Models: An Overview and Discussion". In: *Journal of Artificial Societies and Social Simulation* 27.1 (2024). DOI: 10.18564/jasss.5258. URL: https://www.jasss.org/27/1/11.html.

[26] A. Čučuk. *Evonik and VoltH2 to Advance Hydrogen Production in the Netherlands*. Accessed: 2025-02-19. 2025. URL: https://www.offshore-energy.biz/evonik-and-volth2-to-advance-hydrogen-production-in-the-netherlands/.

[27] P. A. David. "Clio and the Economics of QWERTY". In: *The American Economic Review* 75.2 (1985), pp. 332–337. URL: https://www.jstor.org/stable/1805621.

[28] J. Gorenstein Dedecca et al. *Energy costs, taxes and the impact of government interventions on investments: Final Report – Network Costs*. Tech. rep. European Commission, Directorate-General for Energy, Unit A.4, 2020. URL: https://op.europa.eu/en/publication-detail/-/publication/76c57f2f-174c-11eb-b57e-01aa75ed71a1/language-en.

[29] S. Deetman et al. "Projected material requirements for the global electricity infrastructure – generation, transmission and storage". In: *Resources, Conservation and Recycling* 164 (2020), p. 105200. DOI: 10.1016/j.resconrec.2020.105200.

[30] V. Delapedra-Silva et al. "Methods for Financial Assessment of Renewable Energy Projects: A Review". In: *Processes* 10.2 (2022), p. 184. DOI: 10.3390/pr10020184.

[31] A. K. Dixit and R. S. Pindyck. *Investment under Uncertainty*. Princeton, NJ: Princeton University Press, 1994.

[32] DNV. *Maakbaarheidsgat Nederlandse elektriciteitsnet per 2030*. Tech. rep. Gepubliceerd op 20 februari 2024. Arnhem, The Netherlands: DNV, 2024. URL: https://energeia.nl/energeie-artikel/40112335/plannen-netbeheerders-tonen-8216-maakbaarheidsgat-8217-tot-25.

[33] DNV. *Repurposing Onshore Pipelines for Hydrogen: Guiding Operators Through the Re-evaluation Process*. Tech. rep. Accessed: 2025-05-20. Amsterdam: DNV, 2024. URL: https://www.dnv.com/focus-areas/hydrogen/repurposing-pipelines-for-hydrogen-guiding-operators-through-the-re-evaluation-process/.

[34] D. Duma et al. "Defining and measuring active distribution system operators for the electricity and natural gas sectors". In: *Utilities Policy* 87 (2024), p. 101708. DOI: 10.1016/j.jup.2024.101708.

[35] N. Economides. "The Economics of Networks". In: *International Journal of Industrial Organization* 14.6 (1996), pp. 673–699. DOI: 10.1016/0167-7187(96)01015-6.

[36] Enexis Netbeheer. *Eenmalige Aansluittarieven Gas Grootverbruik per 1 Januari 2025*. Accessed: May 2025. 2024. URL: https://www.enexis.nl/zakelijk/aansluitingen/tarieven.

[37] EU Energy Live. *Electricity Prices in Netherlands*. https://euenergy.live/country.php?a2=NL. Accessed: 2025-05-06. 2025.

[38] European Central Bank. "ECB staff macroeconomic projections for the euro area, March 2025". In: *European Central Bank* (2025). DOI: 10.2866/4153746. URL: https://www.ecb.europa.eu/press/projections/html/ecb.projections202503_ecbstaff~106050a4fa.en.html.

[39] European Commission and CLIMA C.2 – Low Carbon Solutions (II): Research & Low Carbon Technology Deployment. *Innovation Fund IF24 Auction Terms and Conditions*. https://climate.ec.europa.eu/document/download/b996825e-cd36-44c1-895d-a780062f626d_en?filename=policy_funding_innovation_fund_if24_auction_tc_en.pdf. Directorate C – Innovation for a Low Carbon, Resilient Economy. 2024.

[40] European Environment Agency. *Technical note—Estimating the external costs of industrial air pollution: Trends 2012–2021*. Tech. rep. European Environment Agency, 2024. URL: https://www.eea.europa.eu/publications/the-cost-to-health-and-the/technical-note_estimating-the-external-costs/view.

[41] European Parliament and Council of the European Union. "Directive (EU) 2024/1788 of 13 June 2024 on common rules for the internal markets in renewable and natural gases and in hydrogen and amending Directive (EU) 2023/1791 and repealing Directive 2009/73/EC". In: *Official Journal of the European Union* L 178 (2024), pp. 1–116. URL: https://eur-lex.europa.eu/eli/dir/2024/1788/oj.

[42] Evida and CE Delft. *Cost-benefit analysis of a Danish hydrogen infrastructure*. Background Report. Accessed June 2025. Evida, 2022. URL: https://evida.dk/media/vx4emhu5/221011-backgroud-report-hydrogen-cba.pdf.

[43] R. Faia et al. "Distribution Network Expansion Planning Considering the Flexibility Value for Distribution System Operator". In: *2019 International Conference on Smart Energy Systems and Technologies (SEST)*. IEEE. 2019, pp. 1–6. DOI: 10.1109/SEST.2019.8849043.

[44] FME and VEMW. *Project 6-25: Hoe de industrie tussen nu en 2025 6 miljoen ton CO_2-uitstoot kan verminderen*. Brochure over energiebesparende technologieën voor industriële CO_2-reductie in Nederland. Zoetermeer, Netherlands: FME and VEMW, 2019. URL: https://www.kicmpi.com/sites/default/files/2019-10/19280801_fme_brochure_project_6-25_2019_nl_web_1_0.pdf.

[45] F. W. Geels. "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study". In: *Research Policy* 31.8-9 (2002), pp. 1257–1274. DOI: 10.1016/S0048-7333(02)00062-8.

[46] M. Genovese et al. "Power-to-hydrogen and hydrogen-to-X energy systems for the industry of the future in Europe". In: *International Journal of Hydrogen Energy* 48.44 (2023), pp. 16545–16568. DOI: 10.1016/j.ijhydene.2023.01.194.

[47] S. Gersen, M. van Essen, and P. Wolff. *D9.1 & D9.2 Literature research on low NOx hydrogen burners and developing design rules for low NOx burners*. Report v1. This project is co-financed by TKI Nieuw Gas | Topsector Energie (TKI2022-HyDelta). HyDelta 2.0, 2023. DOI: 10.5281/zenodo.7956519. URL: https://doi.org/10.5281/zenodo.7956519.

[48] I.-C. Gonzalez-Romero, S. Wogrin, and T. Gomez. "Proactive transmission expansion planning with storage considerations". In: *Energy Strategy Reviews* 24 (2019), pp. 154–165. DOI: 10.1016/j.esr.2019.02.006.

[49] Y. Goto and S. Takahashi. “Agent-Based Modeling and Simulation Validation by Scenario Analysis”. In: *Agent-Based Social Systems*. Springer, 2013, pp. 3–16. DOI: 10.1007/978-4-431-54279-7_1. URL: https://doi.org/10.1007/978-4-431-54279-7_1.

[50] M. Grajek and T. Kretschmer. “Identifying critical mass in the global cellular telephony market”. In: *International Journal of Industrial Organization* 30.6 (2012), pp. 496–507. DOI: 10.1016/j.ijindorg.2012.06.003.

[51] F. Greer. “Leveraging environmental assessment and environmental justice to deliver equitable, decarbonized built infrastructure”. In: *Environmental Research Infrastructure and Sustainability* 3.4 (2023), p. 040401. DOI: 10.1088/2634-4505/ad084b.

[52] V. Grimm et al. “The ODD protocol: A review and first update”. In: *Ecological Modelling* 221.23 (2010), pp. 2760–2768. DOI: 10.1016/j.ecolmodel.2010.08.019.

[53] Stedin Groep. *Jaarverslag 2024: Balanceren in een Stroomversnelling*. Rotterdam, Nederland: Stedin Groep, 2024. URL: https://www.stedin.net.

[54] P. Hansen, X. Liu, and G. M. Morrison. “Agent-based modelling and socio-technical energy transitions: A systematic literature review”. In: *Energy Research & Social Science* 49 (2018), pp. 41–52. DOI: 10.1016/j.erss.2018.10.021.

[55] S. Hardman, E. Shiu, and R. Steinberger-Wilckens. “A Review of Consumer Preferences of and Interactions with Electric Vehicle Charging Infrastructure”. In: *Transportation Research Part D: Transport and Environment* 62 (2018), pp. 508–523.

[56] M. Hasankhani et al. “Coordinating social dynamics for integrating hydrogen in the Netherlands”. In: *Renewable and Sustainable Energy Reviews* 212 (2025), p. 115372. DOI: 10.1016/j.rser.2025.115372.

[57] Q. Hassan et al. “Green hydrogen: A pathway to a sustainable energy future”. In: *International Journal of Hydrogen Energy* 50 (2024), pp. 310–333. DOI: 10.1016/j.ijhydene.2023.08.321.

[58] Q. Hassan et al. “Hydrogen as an energy carrier: properties, storage methods, challenges, and future implications”. In: *Environment Systems and Decisions* 44.2 (2023), pp. 327–350. DOI: 10.1007/s10669-023-09932-z.

[59] Sophie Hermans. *Voortgang Waterstofbeleid*. Brief aan de Voorzitter van de Tweede Kamer der Staten-Generaal. Den Haag, Nederland, 2024. URL: https://www.rijksoverheid.nl/kgg.

[60] W. W. Hogan. “Contract Networks for Electric Power Transmission”. In: *Journal of Regulatory Economics* 4.3 (1992), pp. 211–242. DOI: 10.1007/BF00133621.

[61] A. van Huisseling, M. Altaghlibi, and C. Burgering. *ESG Economist – The Role and Effectiveness of Dutch Transition Subsidies*. Published: 2023-11-16. ABN AMRO Bank. 2023. URL: https://www.abnamro.com/research/en/our-research/esg-economist-the-role-and-effectiveness-of-dutch-transition-subsidies (visited on 05/07/2025).

[62] J. Van Huyck, R. C. Battalio, and R. Beil. “Tacit Coordination Games, Strategic Uncertainty, and Coordination Failure”. In: *The American Economic Review* 80.1 (1990), pp. 234–248.

[63] Hydrogen Europe. *Hydrogen Infrastructure Report*. Hydrogen Europe, 2024. URL: https://hydrogeneurope.eu/wp-content/uploads/2024/10/2024.10_HE_Hydrogen-Infrastructure-Report.pdf.

[64] Hydrogen Europe. *Mitsubishi Eyes Massive Green H2 Plant in Netherlands*. Published: 2024-01-15. 2024. URL: https://hydrogeneurope.eu/mitsubishi-eyes-massive-green-h2-plant-in-netherlands/ (visited on 02/19/2025).

[65] HyNetwork Services. *Conceptvoorstel Aanpassing Uitrolplan Waterstofnetwerk Nederland*. Consultatiedocument over de aangepaste fasering en planning van het landelijke waterstofnetwerk in Nederland. HyNetwork Services, 2024. URL: https://www.hynetwork.nl/kennisbank/artikel/update-actualisatieronde-waterstofnetwerk.

[66] HyRegions. *Onderzoek naar aanpak voor mogelijke uitrol regionale waterstofinfrastructuur*. Research Report. Accessed: 2025-02-20. Rotterdam, The Netherlands: Trinomics B.V., BlueTerra, for the Ministry of Economic Affairs, and Climate Policy, 2024. URL: https://open.overheid.nl/documenten/71de0f0e-9195-4eac-ba05-8b6d428e36f3/file.

[67] Intergovernmental Panel on Climate Change. *Emission Factor Database (EFDB)*. Dataset by Our World in Data, processed for IPCC EFDB. 2023. URL: https://ourworldindata.org/grapher/carbon-dioxide-emissions-factor (visited on 10/24/2023).

[68] Intergovernmental Panel on Climate Change. "Summary for Policymakers". In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by Core Writing Team, H. Lee, and J. Romero. Geneva, Switzerland: IPCC, 2023, pp. 1–34. DOI: 10.59327/IPCC/AR6-9789291691647.001.

[69] International Energy Agency. *Energy Policy Review: The Netherlands 2024*. Revised version, January 2025. Paris, France: International Energy Agency, 2024. URL: https://www.iea.org/reports/energy-policy-review-the-netherlands-2024.

[70] Investing.com. *Dutch TTF Natural Gas Futures Historical Prices*. https://www.investing.com/commodities/dutch-ttf-gas-c1-futures-historical-data. Accessed: 2025-05-06. 2025.

[71] R.A.A. Jetten. *Ontwikkeling Transportnet voor Waterstof*. Kamerbrief, Tweede Kamer der Staten-Generaal. 2022. URL: https://www.rijksoverheid.nl/ezk.

[72] R.A.A. Jetten and M.A.M. Adriaansens. *Voortgang Waterstofbeleid*. Brief aan de Voorzitter van de Tweede Kamer der Staten-Generaal. Den Haag, Nederland, 2024. URL: https://www.rijksoverheid.nl/ezk.

[73] P. L. Joskow. "Restructuring, Competition and Regulatory Reform in the U.S. Electricity Sector". In: *Journal of Economic Perspectives* 11.3 (1997), pp. 119–138. DOI: 10.1257/jep.11.3.119.

[74] B. Junquera, B. Moreno, and R. Álvarez. "Analyzing consumer attitudes towards electric vehicle purchasing intentions in Spain: Technological limitations and vehicle confidence". In: *Technological Forecasting and Social Change* 109 (2016), pp. 6–14. DOI: 10.1016/j.techfore.2016.05.006.

[75] Y. Kabiri-Renani et al. "Coordinated Power System Expansion Planning Considering the DSO's Market Operations". In: *IET Generation, Transmission & Distribution* 13.23 (2019), pp. 5462–5473. DOI: 10.1049/iet-gtd.2019.0927.

[76] D. Kamissoko et al. "Resilience of Interconnected Infrastructures and Systems: The RESIIST Project". In: *Applied Technologies*. Springer, 2020, pp. 257–270. DOI: 10.1007/978-3-030-42517-3_20.

[77] J. Kee, R. Van Zoelen, and M. van Schot. *HyDelta WP7A – Value Chain Analysis: Hydrogen value chain literature review*. Dit project is medegefinancierd door TKI Energie uit de Toeslag voor Topconsortia voor Kennis en Innovatie (TKI's) van het ministerie van Economische Zaken, onder referentie nummer TKI2020-HyDelta. Netherlands: New Energy Coalition (NEC), 2021. URL: https://www.newenergycoalition.org.

[78] D. van der Keur. "Hydrogen Infrastructure Development under Different Third-Party Access Regimes: Exploring Implications for Coordination and Investment". Master's thesis. Delft University of Technology, 2023. URL: https://repository.tudelft.nl/islandora/object/uuid%3A597bc680-e3eb-455d-ade1-61033534b78d.

[79] T. Klatzer et al. "Ramping up the hydrogen sector: An energy system modeling framework". In: *Applied Energy* 355 (2024), p. 122264. DOI: 10.1016/j.apenergy.2023.122264.

[80] David M. Kreps. *Game Theory and Economic Modelling*. Oxford: Clarendon Press, 1990. ISBN: 978-0198283812. DOI: 10.1093/0198283814.001.

[81] Landelijke Regieorganisatie Lokale Energiestrategieën (NP RES). *Landelijke Cluster Energie Strategie: Cluster 6 - Final*. Accessed: 2025-04-29. Landelijke Regieorganisatie Lokale Energiestrategieën (NP RES), 2022. URL: https://files.enflow.nl/26b93bd8-4832-473a-bb56-a58f7d707680/4b3523bb-d6a0-46ba-81d4-74c07242b9b7/publications/landelijke-cluster-energie-strategie-cluster-6-final.pdf.

[82] R. Li et al. “Petri Net-Based Model for 5G and Beyond Networks Resilience Evaluation”. In: *2022 25th Conference on Innovation in Clouds, Internet and Networks (ICIN)*. 2022, pp. 131–135. DOI: 10.1109/ICIN53892.2022.9758134. URL: https://ieeexplore.ieee.org/document/9758134.

[83] Y. Li, C. Kool, and P.-J. Engelen. “Analyzing the Business Case for Hydrogen-Fuel Infrastructure Investments with Endogenous Demand in The Netherlands: A Real Options Approach”. In: *Sustainability* 12.13 (2020), p. 5424. DOI: 10.3390/su12135424.

[84] R. Linden et al. “Security of supply in gas and hybrid energy networks”. In: *Energies* 14.4 (2021), p. 792. DOI: 10.3390/en14040792.

[85] D. Loorbach. “Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework”. In: *Governance* 23.1 (2009), pp. 161–183. DOI: 10.1111/j.1468-0491.2009.01471.x.

[86] S. Luo et al. “Decision-making based on network analyses of new infrastructure layouts”. In: *Buildings* 12.7 (2022), p. 937. DOI: 10.3390/buildings12070937.

[87] C. M. Macal. “Everything you need to know about agent-based modelling and simulation”. In: *Journal of Simulation* 10.2 (2016), pp. 144–156. DOI: 10.1057/jos.2016.7.

[88] G. Madigan et al. *Cost and Economic Aspects: Comparing High Voltage Overhead and Underground Transmission Infrastructure (up to 500 kV)*. IEA Hydrogen TCP, Report 04. University of Queensland, 2023. URL: https://s37430.pcdn.co/ciet/wp-content/uploads/sites/16/2023/11/04_Cost_Economics_Aspects.pdf.

[89] E. S. Maskin. “Mechanism Design: How to Implement Social Goals”. In: *American Economic Review* 98.3 (2008), pp. 567–576. DOI: 10.1257/aer.98.3.567.

[90] R. Messias, P. M. S. Carvalho, and J. Sousa. “Hybrid Distribution Network Planning to Incorporate Virtual Capacity from Distributed Flexibility Resources”. In: *Utilities Policy* 93 (2025), p. 101892. DOI: 10.1016/j.jup.2025.101892.

[91] Ministerie van Economische Zaken en Klimaat. *Elektriciteitswet 1998*. Wetgeving, bijgewerkt op 1 januari 2024. 2024. URL: https://wetten.overheid.nl/BWBR0009755/2024-01-01.

[92] Ministerie van Economische Zaken en Klimaat. *Gaswet*. Wetgeving, bijgewerkt op 1 mei 2024. 2024. URL: https://wetten.overheid.nl/BWBR0011440/2024-05-01.

[93] Ministerie van Economische Zaken en Klimaat. *Samenvatting openbare consultatie marktordening waterstof*. Accessed: 2025-02-20. Ministerie van Economische Zaken en Klimaat (EZK), 2022. URL: https://open.overheid.nl/documenten/ronl-35ee832d2f7534a06696262948fd89cf45e22995/pdf.

[94] Ministerie van Klimaat en Groene Groei. *Subsidieregeling Grootschalige Productie Volledig Hernieuwbare Waterstof via Elektrolyse*. Staatscourant 2024, nr. 27564, 19 augustus 2024. 2024. URL: https://zoek.officielebekendmakingen.nl/stcrt-2024-27564.html.

[95] Ministry of Economic Affairs and Climate. *National Climate Agreement - The Netherlands*. The Hague, Netherlands: Government of the Netherlands, 2019. URL: https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands.

[96] J. Moerenhout et al. *Assessment of Policy Instruments for Hydrogen in the Netherlands*. Tech. rep. Commissioned by the Ministry of Economic Affairs and Climate Policy (EZK). NL Ministry of Economic Affairs and Climate Policy; Trinomics; Quo Mare, 2023. URL: https://open.overheid.nl/documenten/8603ad17-11c0-4720-92fd-e27b8a09792d/file.

[97] N. Namazifard, P. Vingerhoets, and E. Delarue. “Long-term cost optimization of a national low-carbon hydrogen infrastructure for industrial decarbonization”. In: *International Journal of Hydrogen Energy* 64 (2024), pp. 583–598. DOI: 10.1016/j.ijhydene.2024.02.324.

[98] Netbeheer Nederland. *Betrouwbaarheid van elektriciteitsnetten in Nederland – Resultaten 2024*. Technical Report KR-2025-03007. Version 1.0. Accessed: 2025-06-07. Netbeheer Nederland, 2025. URL: https://www.netbeheernederland.nl/sites/default/files/2025-04/03.02._betrouwbaarheid_van_elektriciteitsnetten_in_nederland_-_resultaten_2024.pdf.

[99] Netbeheer Nederland. *Feiten en Cijfers*. Geraadpleegd op 20 mei 2025. 2025. URL: https://www.netbeheernederland.nl/feiten-en-cijfers.

[100] Netbeheer Nederland. *HyRegions 2 Eindrapport*. Geraadpleegd op 19 mei 2025. 2025. URL: https://www.netbeheernederland.nl/hyregions-2-eindrapport.

[101] Netbeheer Nederland. *Rapport II3050 Scenario's*. Netbeheer Nederland, 2023. URL: https://www.netbeheernederland.nl/publicatie/rapport-ii3050-scenarios.

[102] Netbeheer Nederland. *Recommendations from II3050 – Second Edition*. Netbeheer Nederland, 2024. URL: https://www.netbeheernederland.nl/publicatie/recommendations-ii3050.

[103] Netherlands Enterprise Agency (RVO). *Subsidy Scheme for Large-Scale Hydrogen Production Using an Electrolyser (OWE)*. https://english.rvo.nl/subsidies-financing/owe. Accessed: 2025-05-06. 2024.

[104] I. Nikolic and A. Ghorbani. "A Method for Developing Agent-Based Models of Socio-Technical Systems". In: *International Journal of Social Research Methodology* 14.3 (2011), pp. 1–19. DOI: 10.1080/13645579.2011.572673.

[105] I. Nikolic et al. "On the Development of Agent-Based Models for Infrastructure Evolution". In: *2008 First International Conference on Infrastructure Systems and Services: Building Networks for a Brighter Future (INFRA)*. Rotterdam, Netherlands, 2008, pp. 1–6. DOI: 10.1109/INFRA.2008.5439640.

[106] OECD. *Effective Carbon Rates 2021: Pricing Carbon Emissions Through Taxes and Emissions Trading*. Brochure, OECD Publishing. 2021. URL: https://www.oecd.org/content/dam/oecd/en/topics/policy-sub-issues/carbon-pricing-and-energy-taxes/effective-carbon-rates-2021-brochure.pdf.

[107] Parlementaire enquêtecommissie aardgaswinning Groningen. *Groningers boven gas. Rapport parlementaire enquêtecommissie aardgaswinning Groningen. Boek 2: Feitenreconstructie 1959–2012*. Den Haag: Tweede Kamer der Staten-Generaal, 2023. URL: https://www.tweedekamer.nl/sites/default/files/2023-02/Groningers-boven-gas_boek2-1959-2012_0.pdf.

[108] Andover Technology Partners. *CO2 and NOx Emissions from Natural Gas Combined Cycle and Natural Gas Combustion Turbine Power Plants*. Technical Report. Andover Technology Partners, 2023. URL: https://www.andovertechnology.com/wp-content/uploads/2023/09/CO2-and-NOx-from-NG-plants.pdf.

[109] PBL Netherlands Environmental Assessment Agency. *Netherlands Climate and Energy Outlook 2021 - Summary*. Tech. rep. Accessed: 2025-05-19. PBL Netherlands Environmental Assessment Agency, 2021. URL: https://www.pbl.nl/uploads/default/downloads/pbl-2021-netherlands-climate-and-energy-outlook_2021-summary-4709.pdf.

[110] P. Perez, A. Banos, and C. Pettit. "Agent-Based Modelling for Urban Planning: Current Limitations and Future Trends". In: *Agent Based Modelling of Urban Systems*. Ed. by M.-R. Namazi-Rad et al. Vol. 10051. Lecture Notes in Computer Science. Springer, 2017, pp. 60–69. DOI: 10.1007/978-3-319-51957-9_4. URL: https://doi.org/10.1007/978-3-319-51957-9_4.

[111] A. Piazza. "Collective responsibility in the cooperative governance of climate change". In: *Sustainability* 13.8 (2021), p. 4363. DOI: 10.3390/su13084363.

[112] S. Poledna et al. "Economic forecasting with an agent-based model". In: *European Economic Review* 151 (2022), p. 104306. DOI: 10.1016/j.euroecorev.2022.104306.

[113] M. Pollitt et al. *The Active Distribution System Operator (DSO) – An International Study*. CERRE report supported by ARERA, E.ON, GRDF, Ofgem, and UREGNI. Brussels, Belgium: Centre on Regulation in Europe (CERRE), 2022. URL: https://www.cerre.eu.

[114] Port of Rotterdam. *First Large-Scale Hydrogen Plant on the High-Voltage Grid*. Published: 2024-09-24. 2024. URL: https://www.portofrotterdam.com/en/news-and-press-releases/first-large-scale-hydrogen-plant-high-voltage-grid (visited on 02/19/2025).

[115] K. Prebanić and M. Vukomanović. "Exploring stakeholder engagement process as the success factor for infrastructure projects". In: *Buildings* 13.7 (2023), p. 1785. DOI: 10.3390/buildings13071785.

[116] PricewaterhouseCoopers (PwC). *Unit Investment Cost Indicators – Project Support to ACER*. Final Report. European Union Agency for the Cooperation of Energy Regulators (ACER), 2023. URL: https://www.acer.europa.eu/sites/default/files/documents/Publications/UIC_report_2023_corrigendum.pdf.

[117] U. Y. Qazi. "Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications: Challenges and Expected Opportunities". In: *Energies* 15.13 (2022), p. 4741. DOI: 10.3390/en15134741.

[118] A. Revez et al. "Mapping emergent public engagement in societal transitions: a scoping review". In: *Energy Sustainability and Society* 12.1 (2022). DOI: 10.1186/s13705-021-00330-4.

[119] S. Revinova et al. "Hydrogen in energy transition: The problem of economic efficiency, environmental safety, and technological readiness of transportation and storage". In: *Resources* 13.7 (2024), p. 92. DOI: 10.3390/resources13070092.

[120] Rijksdienst voor Ondernemend Nederland. *Richtsnoeren voor Veilig Omgaan met Waterstof*. Laatst gecontroleerd op: 19 juni 2024. 2022. URL: https://www.rvo.nl.

[121] Rijksoverheid Nederland. *Energiewet 2025*. Geraadpleegd op 27 februari 2025. 2025. URL: https://www.eerstekamer.nl/wetsvoorstel/36378_energiewet.

[122] S. Robinson. *Simulation: The Practice of Model Development and Use*. John Wiley & Sons Ltd, 2004. URL: https://lmsspada.kemdiktisaintek.go.id/pluginfile.php/123916/mod_label/intro/simulation-the-practice-of-model-development-and-use.9780470847725.21800.pdf.

[123] A. Roumboutsos, A. Temeljotov-Salaj, and I. Karousos. "Indicators for Sustainable Demand Risk Allocation in Transport Infrastructure Projects". In: *Sustainability* 12.22 (2020), p. 9650. DOI: 10.3390/su12229650.

[124] L. Rutten. *TECHNOLOGY FACTSHEET*. Energy Academy Europe; accessed 2025-06-14. 2019. URL: https://energy.nl/wp-content/uploads/technology-factsheets-natural-gas-boiler-industry-7.pdf.

[125] L. Rutten. *TECHNOLOGY FACTSHEET*. Energy Academy Europe; accessed 2025-06-14. 2020. URL: https://energy.nl/wp-content/uploads/h2industrialboiler_28092020_upd-7.pdf.

[126] RWE AG. *NorthH$_2$ | Hydrogen Project of RWE*. Accessed: 2025-02-19. 2025. URL: https://www.rwe.com/en/research-and-development/hydrogen-projects/north2/.

[127] S. Sachan, S. Deb, and S. Singh. "Different charging infrastructures along with smart charging strategies for electric vehicles". In: *Sustainable Cities and Society* 60 (2020), p. 102238. DOI: 10.1016/j.scs.2020.102238.

[128] K. Schoots et al. "Learning curves for hydrogen production technology: An assessment of observed cost reductions". In: *International Journal of Hydrogen Energy* 33.11 (2008), pp. 2630–2645. DOI: 10.1016/j.ijhydene.2008.03.011.

[129] L. Shi et al. "A comprehensive charging network planning scheme for promoting EV charging infrastructure considering the Chicken-Eggs dilemma". In: *Research in Transportation Economics* 88 (2021), p. 100837. DOI: 10.1016/j.retrec.2020.100837.

[130] Jaime S. Sichman, Rosaria Conte, and Nigel Gilbert, eds. *Multi-Agent Systems and Agent-Based Simulation: First International Workshop, MABS '98, Paris, France, July 4–6, 1998, Proceedings*. Vol. 1534. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 1998. ISBN: 978-3-540-65476-6. DOI: 10.1007/b71639. URL: https://link.springer.com/book/10.1007/b71639.

[131] W. Sierzchula et al. "The influence of financial incentives and other socio-economic factors on electric vehicle adoption". In: *Energy Policy* 68 (2014), pp. 183–194. DOI: 10.1016/j.enpol.2014.01.043.

[132] G. N. da Silva et al. "Developing and applying the Hydrogen Economics and infRAstructure optimization model (HERA)". In: *International Journal of Hydrogen Energy* 61 (2024), pp. 1170–1186. DOI: 10.1016/j.ijhydene.2024.02.015.

[133] Brian Skyrms. *The Stag Hunt and the Evolution of Social Structure*. Cambridge, UK: Cambridge University Press, 2004. ISBN: 9780521533928. URL: https://www.cambridge.org/core/books/stag-hunt-and-the-evolution-of-social-structure/AB3181FA469D6EA411E05D6CBF644507.

[134] John D. Sterman. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston, MA: McGraw-Hill Education, 2000. ISBN: 978-0072389159.

[135] Strategy&. *HyWay27 Final Report (UK)*. Tech. rep. Accessed: 2025-06-10. Strategy& (part of the PwC network), 2021. URL: https://www.entsog.eu/sites/default/files/2021-11/1.2.%20HyWay27%20Final%20report%20%28UK%29.pdf.

[136] Stuurgroep NPVI. *Actieplan Cluster 6 Gericht op Oplossingen*. Netherlands: Stuurgroep NPVI, 2025. URL: https://open.overheid.nl/documenten/57c1c678-62ea-4983-addf-13891aa95c5a/file.

[137] M. Teng et al. *Het effect van het stagneren van de groei van warmtenetten*. CE Delft, 2024. URL: https://ce.nl/wp-content/uploads/2025/01/CE_Delft_240411_Het_effect_van_het_stagneren_van_de_groei_van_warmtenetten_Def.pdf.

[138] D. Then et al. "Analysis of dependencies between gas and electricity distribution grid planning and building energy retrofit decisions". In: *Sustainability* 12.13 (2020), p. 5315. DOI: 10.3390/su12135315.

[139] H. Thomas et al. "Models and Methods for Transport Demand and Decarbonisation: A Review". In: *Environmental Research Letters* 19.9 (2024), p. 093005. DOI: 10.1088/1748-9326/ad6b3a.

[140] TotalEnergies and Air Liquide. *TotalEnergies Joins Forces with Air Liquide to Decarbonize its Refineries in Northern Europe with Green Hydrogen*. Accessed: February 18, 2025. 2025. URL: https://totalenergies.com/fr/actualites/communiques-de-presse/pays-bas-totalenergies-acquiert-une-participation-dans-le-parc.

[141] T. Veith. "The national regulatory structure against the background of the European regulatory system". In: *SSRN Electronic Journal* (2010). DOI: 10.2139/ssrn.1727452.

[142] E. Van Der Walle. *Stedin Wil Vers Kapitaal van Provincies voor Verzwaring Elektriciteitsnetwerk*. 2023. URL: https://www.nrc.nl/nieuws/2023/05/09/stedin-wil-vers-kapitaal-van-provincies-voor-verzwaring-elektriciteitsnetwerk-a4164208 (visited on 05/27/2025).

[143] P. van der Werff and S. Groenendijk. "Een fabriek van 1 miljard die misschien niet eens opent: de transitie van de Rotterdamse haven hapert". In: *AD.nl* (2025). URL: https://www.ad.nl/binnenland/een-fabriek-van-1-miljard-die-misschien-niet-eens-opent-de-transitie-van-de-rotterdamse-haven-haperta4f74980/.

[144] S. van der Werff. "Rotterdam loopt deuk op door 'onbegrijpelijk' uitstel belangrijke pijpleiding: 'Willen betrouwbaar blijven'". In: *Algemeen Dagblad* (2024). URL: https://www.ad.nl/rotterdam/rotterdam-loopt-deuk-op-door-onbegrijpelijk-uitstel-belangrijke-pijpleiding-willen-betrouwbaar-blijven~a0c94385c/.

[145] U. Wilensky. *NetLogo*. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. 1999.

[146] S. Wogrin et al. "LEGO: The open-source Low-carbon Expansion Generation Optimization model". In: *SoftwareX* 19 (2022), p. 101141. DOI: 10.1016/j.softx.2022.101141.

[147] World Business Council for Sustainable Development. *Catalogue of Key Decarbonization Actions (Phase II Forest Sector Net-Zero Roadmap)*. en-US. Accessed: 2025-06-14. WBCSD, 2024. URL: https://www.wbcsd.org/resources/catalogue-of-key-decarbonization-actions-phase-ii-forest-sector-net-zero-roadmap/.

A

Variable Table

Parameter Name	Model Variable	Unit	Behaviour	Value / Range	Source / Note
Simulation & Time Control					
Current simulation year	`year`	year	Dynamic	[2025;2050]	Model logic
Patch length scale	`km-per-patch`	km/patch	Fixed	0.05	Case Study
Case-study data-	`case-data`	list	Dynamic	–	Case Study
Data loaded flag	`data-loaded?`	Boolean	Dynamic	–	Model logic
Baseline Emission Benchmarks					
Baseline CO_2 cost	`baseline-co2-cost`	€/yr	Dynamic	–	Model logic
Baseline NO_x cost	`baseline-nox-cost`	€/yr	Dynamic	–	Model logic
Policy & Permitting					
Payback threshold	`payback-period-threshold`	yr	Fixed	7	[44]
ROI threshold	`roi-threshold`	–	Fixed	0.15	[44]
Probability of subsidy	`probability-of-subsidy`	–	Fixed	0.75	[61]
CO_2 tax	`co2-tax`	€/t CO_2	Dynamic	-	Section 5.2.3
Permit time range	`permit-time-range`	yr	Fixed	1	[53]
Market Prices & Macro Drivers					
Inflation rate	`inflation`	1/yr	Fixed	0.02	[38]
Industrial natural-gas price	`natural-gas-price`	€/MWh	Dynamic	–	[70]
Industrial electricity price	`electricity-price`	€/MWh	Dynamic	–	[37]
Spot hydrogen price	`hydrogen-price`	€/MWh	Dynamic	–	Section 5.2.1
Hydrogen minimum price	`hydrogen-minimum-price`	€/kg	Fixed	1.18	[66]
Hydrogen learning rate	`hydrogen-learning-rate`	–	Fixed	0.15	[128]
H_2 cumulative production	`hydrogen-cumulative-production`	MWh	Dynamic	–	Model logic
Initial cumulative H_2	`hydrogen-initial-cumulative`	MWh	Fixed	-	Model logic
H_2 Scenario Tables					
H_2 price forecast table	`h2-price-forecast`	table	Fixed	–	Section 5.2.1
H_2 demand forecast table	`h2-demand-forecast`	table	Fixed	–	Section 5.2.1
H_2 price scenarios	`h2-scenario`	enum	Interface	[low,medium,high]	Interface
Company-Side Cost & Flow Tracking					
CO_2 emission factor	`co2-emission-factor`	t/MWh	Fixed	0.202	[67]
NO_x emission factor	`nox-emission-factor`	t/MWh	Fixed	0.00046	[108]
Hydrogen retrofit CAPEX	`installation-replacement-cost-h2`	€/MWh	Fixed	31.25	[125]
Electric switch CAPEX	`installation-replacement-cost-elec`	€/MWh	Fixed	56.25	[147]
New gas boiler CAPEX	`installation-replacement-cost-gas`	€/MWh	Fixed	1.88	[124]
Company H_2 CAPEX	`cost_company_capex_h2`	€/yr	Dynamic	–	Model logic
Company H_2 OPEX	`cost_company_opex_h2`	€/yr	Dynamic	–	Model logic
Company Elec CAPEX	`cost_company_capex_elec`	€/yr	Dynamic	–	Model logic
Company Elec OPEX	`cost_company_opex_elec`	€/yr	Dynamic	–	Model logic
Replacement gas CAPEX	`cost_company_capex_gas`	€/yr	Dynamic	–	Model logic
Δ OPEX vs gas (H_2)	`cost_company_delta_opex_h2`	€/yr	Dynamic	–	Model logic
Δ OPEX vs gas (Elec)	`cost_company_delta_opex_elec`	€/yr	Dynamic	–	Model logic
Hydrogen Infrastructure Parameters					
HP pipeline cost	`hp-pipeline-cost`	€/km	Fixed	3,200,000	Section 5.2.4
LP pipeline cost	`lp-pipeline-cost`	€/km	Fixed	500,000	Section 5.2.4
HP pipeline OPEX rate	`hp-opex-rate`	–/yr	Fixed	0.0025	Section 5.2.4
LP pipeline OPEX rate	`lp-opex-rate`	–/yr	Fixed	0.0333	Section 5.2.4
HP build speed	`hp-pipeline-build-speed`	km/yr	Fixed	80	Section 5.2.4
LP build speed	`lp-pipeline-build-speed`	km/yr	Fixed	240	Section 5.2.4
HP workforce per km	`hp-workforce-per-km`	FTE/km	Fixed	0.375	Section 5.2.4
LP workforce per km	`lp-workforce-per-km`	FTE/km	Fixed	0.125	Section 5.2.4
HP materials per km	`hp-materials-per-km`	t/km	Fixed	50	Section 5.2.4
LP materials per km	`lp-materials-per-km`	t/km	Fixed	30	Section 5.2.4
Electric Infrastructure Parameters					
Cable cost	`wire-cost-per-km`	€/km	Fixed	831,000	Section 5.2.5
Cable build speed	`wire-build-speed`	km/yr	Fixed	80	Section 5.2.5
Cable workforce per km	`wire-workforce`	FTE/km	Fixed	1.5	Section 5.2.5
Cable materials per km	`wire-materials`	t/km	Fixed	20	Section 5.2.5

Table A.1: Global input parameters (Part 1)

Parameter Name	Model Variable	Unit	Behaviour	Value / Range	Source / Note
Connection & Pressure Reduction					
Direct-HP demand threshold	`direct-hp-threshold`	MWh/yr	Fixed	10,000	[81]
PRS CAPEX	`prs-cost`	€	Fixed	234,000	Section 5.2.4
Infrastructure State (Patch Sets)					
PRS patch -	`prs-patches`	-	Dynamic	–	Model logic
Active LP pipeline patches	`active-lp-patches`	-	Dynamic	–	Model logic
Approved LP patches	`approved-lp-patches`	-	Dynamic	–	Model logic
Approved HP patches	`approved-hp-patches`	-	Dynamic	–	Model logic
Candidate anchor patches	`candidate-patches`	-	Dynamic	–	Model logic
Proposed LP patches	`proposed-lp-patches`	-	Dynamic	–	Model logic
Completed pipeline count	`cumulative-completed`	-	Dynamic	–	Model logic
Under-construction count	`cumulative-construction`	-	Dynamic	–	Model logic
Project & Link Trackers					
Pipeline project list	`pipelines`	-	Dynamic	–	Model logic
Electric anchor states list	`electric-anchor-states`	-	Dynamic	-	Model logic
Adoption & Emissions					
Total hydrogen adopters	`total-h2-adopters`	-	Dynamic	–	Model logic
Total electricity adopters	`total-elec-adopters`	-	Dynamic	–	Model logic
Annual H_2 applicants	`annual-h2-applicants`	-	Dynamic	–	Model logic
System-wide CO_2	`total-co2`	t/yr	Dynamic	–	Model logic
Government Cash Flows					
Annual H_2 subsidy	`annual-subsidy-h2`	€/yr	Dynamic	–	Model logic
Annual electricity subsidy	`annual-subsidy-elec`	€/yr	Dynamic	–	Model logic
Annual CO_2 tax rev.	`annual-co2-tax`	€/yr	Dynamic	–	Model logic
Cumulative H_2 subsidies	`cost_subsidy_h2`	€	Dynamic	–	Model logic
Cumulative electricity subsidies	`cost_subsidy_elec`	€	Dynamic	–	Model logic
Infrastructure Cash Flows					
Cumulative infra CAPEX	`cost_infra_capex`	€	Dynamic	–	Model logic
Cumulative infra OPEX	`opex-infra`	€	Dynamic	–	Model logic
Yearly H_2 infra CAPEX	`cost_infra_capex_h2`	€/yr	Dynamic	–	Model logic
Yearly H_2 infra OPEX	`opex_infra_h2`	€/yr	Dynamic	–	Model logic
Yearly electric infra CAPEX	`cost_infra_capex_elec`	€/yr	Dynamic	–	Model logic
Yearly electric infra OPEX	`opex_infra_elec`	€/yr	Dynamic	–	Model logic
Societal Costs & Benefits					
Shadow price of CO_2	`societal-cost-co2`	€/t	Fixed	120	[106]
Shadow price of NO_x	`societal-cost-nox`	€/t	Fixed	15,353	[40]
Grid-upgrade cost avoided	`grid-upgrade-cost-per-mw`	€/MW	Fixed	501,000	[137]
Gas-grid OPEX per MWh	`gasinfra-opex-per-unit-gas`	€/MWh	Fixed	2.3	[28]
Generic infra O&M rate	`infra-maintenance-rate`	–/yr	Fixed	0.0015	Section 5.2.5
Avoided grid upgrade benefit	`benefit_grid_avoided_upgrade`	€/yr	Dynamic	–	Model Logic
Annual avoided gas-grid OPEX	`benefit_gasnet_avoided_opex`	€/yr	Dynamic	–	Model Logic
Annual CO_2 cost (post-switch)	`cost_co2`	€/yr	Dynamic	–	Model Logic
Annual NO_x cost (post-switch)	`cost_nox`	€/yr	Dynamic	–	Model Logic
Discounted Societal Account					
Cumulative societal NPV	`cumulative-societal-npv`	€	Dynamic	–	Model Logic

Table A.2: Global input parameters (Part 2)

Parameter Name	Model Variable	Unit	Behaviour	Value / Range	Source / Note
Static Attributes					
Annual energy demand	`energy-consumption`	MWh/yr	Fixed	-	Case Study
Installation lifetime	`installation-lifetime`	yr	Dynamic	[9;15]	[81]
Installation age	`installation-age`	yr	Dynamic	[0;15]	[81]
Replacement look-ahead	`replacement-lookahead`	yr	Dynamic	[2;4]	[81]
Dynamic State					
Current fuel type	`fuel-type`	-	Dynamic	[Gas, H_2, Electricity]	Model logic
Connected to H_2?	`h2-connected?`	-	Dynamic	–	Model logic
Distance to pipeline	`distance-to-pipeline`	patches	Dynamic	–	Model logic
Needs PRS?	`company-needs-prs?`	-	Dynamic	–	Model logic
Distance to elec. anchor	`elec-distance`	patches	Dynamic	–	Model logic
Application State					
Requested fuel type	`application-fuel-type`	-	Dynamic	–	Model logic
Application status	`application-status`	-	Dynamic	–	Model logic
Proposal distance score	`proposal-distance`	–	Dynamic	–	Model logic
Hydrogen Investment Metrics					
H_2 net benefit	`h2-net-benefit`	€	Dynamic	–	Model calc.
H_2 ROI	`h2-roi`	–	Dynamic	–	Model calc.
H_2 payback	`h2-payback`	yr	Dynamic	–	Model calc.
H_2 viable?	`h2-viable?`	-	Dynamic	–	Decision rule
Electricity Investment Metrics					
Electric net benefit	`elec-net-benefit`	€	Dynamic	–	Model calc.
Electric ROI	`elec-roi`	–	Dynamic	–	Model calc.
Electric payback	`elec-payback`	yr	Dynamic	–	Model calc.
Electric viable?	`elec-viable?`	-	Dynamic	–	Decision rule

Table A.3: Company-level variables aligned with the current NetLogo implementation.

Parameter Name	Model Variable	Unit	Behaviour	Value / Range	Source / Note
DSO Strategy & Resources					
Investment approach	`dso-investment-approach`	–	Dynamic	[Delay, Proactive, Reactive]	Model logic
H_2 demand	`dso-h2-demand`	MWh	Dynamic	–	Model logic
DSO materials	`dso-materials`	tonne	Dynamic	470,000	Sensitivity Analysis
DSO workforce	`dso-workforce`	FTE	Dynamic	16	Sensitivity Analysis
Reactive threshold	`dso-reactive-threshold`	–	Fixed	0.4	Sensitivity Analysis
Potential hydrogen demand	`D_pot`	–	Dynamic	–	Model logic
Weighted potential demand	`D_eff`	–	Dynamic	–	Model logic
Investment Strategy Windows					
Proactive window	`proactive-window`	yr	Interface	[0;25]	Interface
Delay window	`delay-window`	yr	Interface	[0;25]	Interface
Proactiveness factor β	`dso-proactiveness-beta`	–	Interface	[0;1]	Interface

Table A.4: DSO variables used in the model after typo fixes and name harmonisation.

A dash (–) indicates that the parameter is an internal model variable, not directly sourced from literature. Where a source is provided, the value is either taken directly from the cited work or approximated based on it. Some values have been adapted to fit the simulation context while remaining consistent with literature, expert judgment, or policy expectations, as discussed in Chapter 5

B

Model Data and Outputs

Figure B.1: Conceptual model overview: agent-based structure, company, DSO, and global-level input/output variables.

C

Experiment Scenarios

This appendix visualizes illustrative rollout sequences used in the experiments. Each scenario follows the same phase order: delay, proactive, then reactive, but the durations of the delay and proactive windows vary, including cases where they are set to zero. The window lengths are fixed in the figures for clarity; actual durations are systematically varied when mentioned (see Chapter 7).

Window Type	Simulation Logic
Delay	No planning occurs. Firm requests are ignored. Models institutional inertia.
Proactive	Infrastructure is built in anticipation of clustered demand, without confirmed requests.
Reactive	Infrastructure is planned once effective demand exceeds a threshold: $$D_{\text{eff}} = D_{\text{conf}} + \beta \cdot \min(D_{\text{pot}}, D_{\text{thresh}})$$ β captures the DSO's responsiveness to unconfirmed demand (higher β = more anticipatory).

Table C.1: Rollout window types and their functional role in the simulation.

Experiment 1: Impact of the Scale of Proactiveness

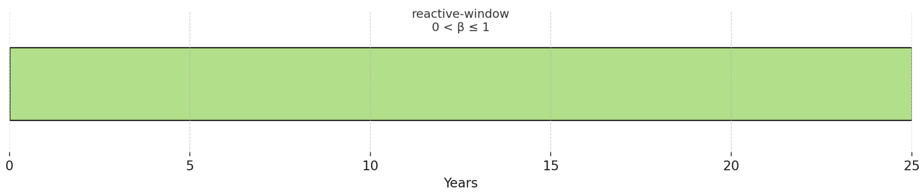

Figure C.1: Fully reactive rollout strategy. Used in Experiment 1 (Section 7.1) with varying proactivity levels ($\beta \in [0, 1]$). No proactive or delay window.

Experiment 2: Investment Timing

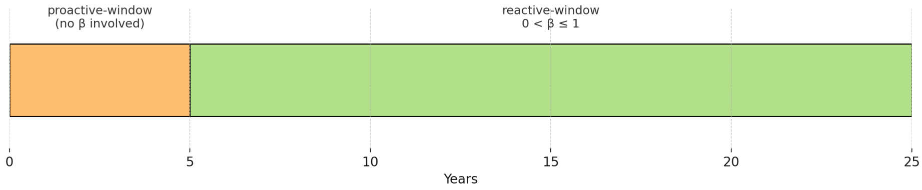

Figure C.2: Proactive-then-reactive strategy (illustrative: 5-year proactive window). Used in Experiment 2 (Section 7.2) to examine isolated anticipatory planning effects.

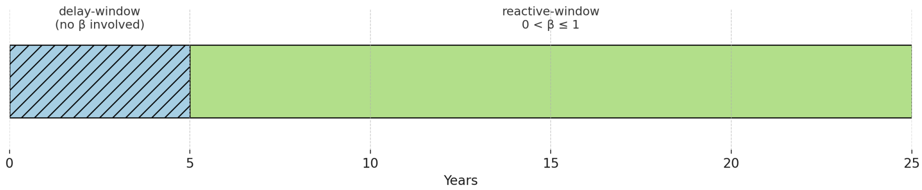

Figure C.3: Delayed-reactive strategy (illustrative: 5-year delay). Used in Experiment 2 (Section 7.2) to assess the isolated impact of delaying infrastructure rollout.

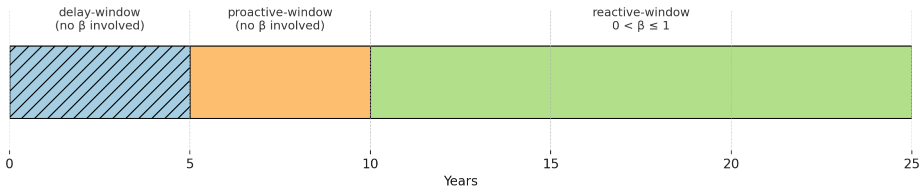

Figure C.4: Combined rollout strategy: delay, then proactive rollout, then reactive completion. Used in Experiment 2 (Section 7.2.3).

Experiment 3: The Role of Proactive Policy Instruments

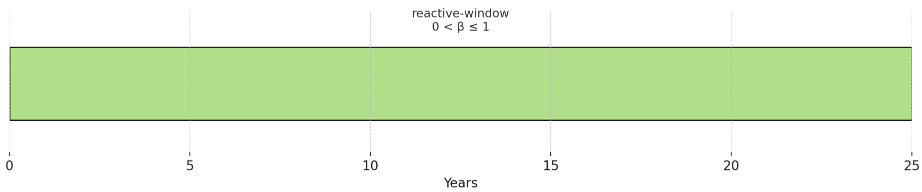

Figure C.5: Fully reactive rollout strategy. Used in Experiment 3 (Section 7.3) to assess the effect of policy instruments without anticipatory planning.

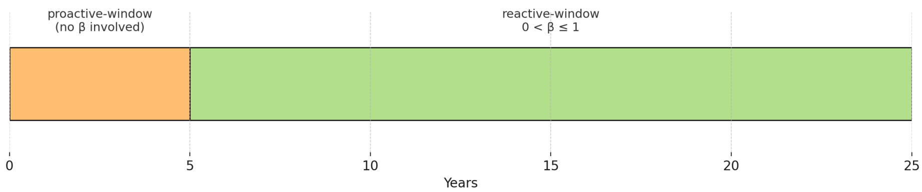

Figure C.6: Partially proactive strategy (5-year proactive window), followed by reactive behavior. Used in Experiment 3 (Section 7.3) to assess coordination with policy instruments.