Third-Party Access Regimes in Cluster 6
An Agent-Based Simulation of the Dutch Regional Industrial Hydrogen Market

EPA Master Thesis

Diane van der Keur

TU Delft

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An Agent-Based Simulation of the Dutch Regional Industrial Hydrogen Market

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Diane van der Keur

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Thesis Comittee:	Zofia Lukszo	TU Delft (Chair and Second Supervisor)
	Amineh Ghorbani	TU Delft (First Supervisor)
	Renske van 't Veer	TU Delft (Assistant Supervisor)
	Iman Pishbin	Stedin (External Supervisor)
	Tayebeh Solat Pour	Stedin (External Supervisor)
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TU Delft

Preface

Before you lies the master thesis *"Third-Party Access Regimes in Cluster 6: An Agent-Based Simulation of the Dutch Regional Industrial Hydrogen Market"*. It has been written to fulfil the graduation requirements for the MSc Engineering and Policy Analysis at Delft University of Technology.

During my studies, I have always had an interest in sustainability and energy transition, which attracted me to this topic of hydrogen transition in the Netherlands. Of course, I wanted to finish my studies with a bang, which is why I wanted to personally challenge myself to gain more skills in modelling, using the difficult (and honestly: a bit scary) approach of agent-based modelling. This thesis has made me a more skilled and experienced modeller. In addition, I have learned that struggling is part of the process. Therefore, this thesis has taught me valuable lessons both professionally and personally.

Additionally, I had the inspiring opportunity to conduct my research at Stedin. I wanted to challenge myself by doing my thesis at an external company. This way, I got a taste of the working life and got the chance to see energy transition happen from up close. I am very grateful for the opportunity and experience provided by Stedin. A special thanks goes to my company supervisors Iman Pishbin and Tayebeh Solat Pour, for their time, support and interest in my work. The willingness of people within Stedin to help me out with both a small question or an in-depth meeting has been incredible.

I would like to extend my gratitude to my academic supervisors as well. Firstly, I want to thank Dr. Amineh Ghorbani, for sharing her expertise and critical insights. I want to thank Renske van 't Veer, for her readiness to support me, the consistent feedback, and brainstorm sessions to help me out when I got stuck. And last but not least, I want to thank Prof. Dr. Zofia Lukszo for sharing her expertise and experiences and for her encouraging and calming words when I was nervous or stressed.

I am very grateful for my committee members and their guidance and support, you have been a great source of inspiration for me throughout the thesis process. Additionally, I want to thank everyone else who aided in my thesis process through e.g. interviews and sharing expertise.

Finally, I want to thank my family and friends for being there for me, being my rubber ducky, believing in me and supporting me (mentally) throughout this process.

I wish you a pleasant reading experience.

Diane van der Keur
Delft, May 2025

Summary

Urged by international accords such as the Paris Agreement and the Intergovernmental Panel on Climate Change's global warming report, the Dutch government is in the process of initial development of the national industrial Dutch hydrogen market in the five main Dutch industry clusters. Alongside the national hydrogen demand, potential regional demand is researched to complement the national hydrogen backbone, by connecting decentralized customers outside the five main industry clusters through regional distribution networks. This Dutch potential regional industrial hydrogen market is collectively referred to as Cluster 6.

In this regional transition, hydrogen distribution network operators (HDNOs) will play a key role due to their role as neutral market facilitators at the regional level. However, HDNOs are heavily regulated infrastructure entities dependent on the right frameworks to deliver and face challenges due to uncertain regulation. The European Union's Hydrogen and Gas Decarbonisation Package introduces a regulatory framework for network operators with various implementation options for third-party access (TPA) regimes by Member States. These range from negotiated (nTPA) and regulated (rTPA) to hybrid forms (hnTPA). In the Dutch context, TPA regulations are still under development and have yet to be applied at the regional distribution level. However, the impact of these TPA regimes and their implications for HDNOs remain unclear. The regulatory framework chosen for TPA could significantly impact how regional hydrogen markets evolve.

This research addresses the knowledge gap surrounding the influence of TPA regimes and how this affects the hydrogen transition within the regional industrial area. The study employs a Cluster 6 case study to evaluate how TPA regimes shape stakeholder decision-making and hydrogen network development. The study combines literature review, semi-structured expert interviews, and an agent-based modelling (ABM) approach to analyse system behaviour under different regulatory TPA scenarios.

Expert interviews are conducted with system operators, a Cluster 6 representative and the case study's municipality and industries. They reveal regulatory challenges due to uncertainty regarding stakeholder roles and financial responsibility. Industries show interest in hydrogen, mainly driven by forward-thinking entrepreneurs who strongly believe hydrogen is a necessity for the future. However, industries take a hesitant and awaiting stance and are dependent on the decisions of other industries for success of the regional hydrogen network. In addition, they favour partial transition to avoid dependency on a single energy source and emphasize the high cost and uncertainty in hydrogen price development is a great issue. Network operators discuss negotiated terms of interest for the nTPA regime included the prioritization order of connection (e.g. priority for largest volumes over minimal grid investment) and division of investment costs.

These insights and negotiation aspects are input for the agent-based model to simulate a regional hydrogen market. Scenarios in the model are defined by the different TPA mechanisms and the associated rules, such as a first-come-first-served prioritization in the rTPA regime, and negotiation terms for alternative prioritization and a division of investment costs in the nTPA regime. Key behavioural inputs for industrial agents include peer influence, cost-benefit analysis outcomes, and waiting list effects due to the prioritization mechanism.

Experimentation with the model shows the third-party access regime plays a central role in shaping both the speed and scale of hydrogen deployment in Cluster 6. Industries' ability to successfully join the hydrogen network and the pace at which they do so is shaped by both institutional rules and behavioural dynamics.

Across all regimes, nTPA yields the most favourable outcomes for hydrogen off-take and CO_2 reduction, driven by the negotiated prioritization mechanism. The prioritization mechanism of nTPA, or the initial negotiation window in hnTPA, rewards larger, cost-efficient projects with prioritized access. This incentivizes more ambitious transition strategies among industries. However, it does not speed up the hydrogen transition, as this mechanism only influences the individual pace of transition for industries. The incentive does not affect average waiting times for connection or the final year of transition. Although nTPA yields the most favourable results in hydrogen off-take and CO_2 reduction, its effectiveness depends on supportive economic conditions and clear transition signals to stimulate peer pressure in the region to drive early hydrogen adoption. This highlights that institutional flexibility alone in the first few years of hydrogen transition is insufficient. Here, the cost division negotiation term complements the prioritization negotiation term.

The pace of the hydrogen off-take is mainly driven by the investment cost division. Under the cost negotiation terms, industries are partially relieved of investment costs, resulting in lower average waiting times for a connection and an earlier final year of transition of the region on average. The similar performance of nTPA and hnTPA on pace indicate that the short negotiation window from hnTPA is effective. Although the rTPA period in hnTPA lacks prioritization negotiation, its queue is processed based on earlier decisions. Combined with the cost division, this leads to stronger CBA outcomes and peer pressure effects early on, enabling solid pace results even after switching to rTPA.

Based on the study, recommendations are given for improvements of the TPA framework to optimize the development of the regional hydrogen markets. Policymakers should resolve stakeholder role and financial uncertainties by assigning an HNDO and e.g. implementing scenario-based price guarantees to encourage early hydrogen adoption. HDNOs should use negotiation terms to incentivize ambitious transition strategies, such as prioritizing cost-efficient projects. Social responsibility could be taken by introducing cost division models as tested to take away financial uncertainty. Both parties should integrate behavioural incentives into the TPA framework, such as increasing visibility of hydrogen transition plans and supporting flexible prioritization rules in early-phase access regimes to enhance the motivational impact of TPA regimes.

In conclusion, the study demonstrates that third-party access mechanisms play a key role in the transition of regional hydrogen markets. The study reveals that negotiated TPA supports faster and more ambitious transitions through flexible prioritization and cost-sharing, while regulated TPA leads to delays and has less hydrogen off-take due to its first-come-first-serve structure and lack of financial incentives. Hybrid negotiated TPA offers limited improvements on size of hydrogen off-take hindered by high hydrogen prices and low early motivation, but aids in the pace of hydrogen transition.

This research faces several limitations, primarily due to the relative newness of the hydrogen sector in the Netherlands, resulting in scarce literature and reliance on evolving EU legislation which has yet to clarify distinctions between transmission and distribution networks. The case study used, though appropriate, involved little diversity in sectors and natural gas consumption patterns, limiting generalizability. Future research should include multiple, more diverse case studies, richer stakeholder recruitment for interviews, and enhanced agent complexity by accounting for varied decarbonization strategies, energy alternatives besides hydrogen, and further transition beyond initial transition of agents. Additionally, a broader exploration of possible negotiation terms under nTPA regimes can be considered to create a wider view on how various negotiation terms can impact the development of the hydrogen network.

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List of abbreviations

Abbreviation	**Explanation**
ABM	Agent-based model(ling)
ACM	Authority Consumer and Markets
AI	Artificial intelligence
CapEx	Capital expenditure
CCS	Carbon capture storage
$\mathbf{CO_2}$	Carbondioxide
CPH	Combined heat and power
DSO	Distribution system operator
EU	European Union
EU ETS	European Union Emissions Trading System
EPA	Engineering and Policy Analysis
FCFS	First come first served
$\mathbf{H_2}$	Hydrogen
HDNO	Hydrogen distribution network operator
HNO	Hydrogen network operator
hnTPA	Hybrid negotiated third-party access
HTNO	Hydrogen transmission network operator
KPI	Key performance indicator
LCOH	Levelized cost of hydrogen
LOHC	Liquid organic hydrogen carriers
MD	Motivation degree
NPV	Net present value
nTPA	Negotiated third-party agreement
OFAT	One-factor-at-a-time
OpEx	Operational expenditures
PP	Peer pressure
ROI	Return on investment
TPA	Third-party access
TSO	Transmission system operator
rTPA	Regulated third-party access
WL	Waiting list

1 Introduction

This introductory chapter begins with providing background information in 1.1, followed by a literature review in 1.2. The knowledge gap in literature and associated research questions are defined in 1.3. The research approach can be found in 1.4. Then, the relevance of the research to the study programme is explained in 1.5. Lastly, the outline of the report is presented in 1.6.

1.1 Background

Many scientists believe hydrogen will be the key strategy in the sustainable energy transition and our joint effort to protect our planet's future [1], [2]. Urged by international accords such as the Paris Agreement and the Intergovernmental Panel on Climate Change's global warming report [3], the Dutch government is the process of initial development of the national industrial Dutch hydrogen network connecting the five largest Dutc industrial clusters [4]. This shows the phenomenon of energy systems changing to conform to the net zero objectives committed to by countries such as the Netherlands [5], [6]. Hydrogen has great potential to function as energy storage technology, heating and transportation fuel. Integrated with renewable electricity, it could lead to a 100% renewable future [1].

Research project HyRegions conducted research for the Ministry of Economic Affairs and Climate on regional hydrogen networks in the Netherlands to meet additional industrial demand in addition to the national network. This regional hydrogen market consists of the collection of potential customers and producers with possible interest for a connection to the Dutch hydrogen infrastructure located regional outside the five large-scale industry clusters and is called Cluster 6 [7]. The development of Cluster 6 into a regional industrial hydrogen market with the required distribution grid in the Netherlands is progressing rapidly. At present, the Netherlands is in a crucial phase of its hydrogen transition as most Dutch initiatives are in the planning or early development stages, specifically in the feasibility studies and conceptual phases [8]. Distribution system operators (DSOs) are likely to play a crucial role in this transition to net zero [5] due to their role as neutral market facilitator and network operator on regional level. A key challenge here is that network operators such as DSOs remaining foundational infrastructure actors and regulated entities that are dependent on the right framework conditions to deliver [9]. This highlights the European-wide need for strong regulation and appropriate market design to direct future hydrogen distribution network operators (HDNOs) to develop and operate the system needed [10].

To provide strong regulation and appropriate market design, the European Union has worked on a design enabling market rules for the deployment of hydrogen, including removing barriers for efficient hydrogen infrastructure development and to ensure access to liquid markets for hydrogen producers and customers [11]. In 2024, a directive has been published on the hydrogen market and network development among other subjects, which needs to be transposed into national law before being applicable [12]. One of the options Member States have is to implement a *regulated* third-party access regime, whereby the national regulator sets tariffs and access conditions, or a *hybrid negotiated* third-party access. Here, prior to regulated third-party access, a *negotiated* third-party access regime holds, whereby the hydrogen distribution network operator and its customers are free to determine tariff and access conditions by negotiations [12], [13].

In previous research, due to the unclear regulation and legislative frameworks of the hydrogen market, there are still interaction uncertainties between stakeholders. There are also behavioural uncertainties related to e.g. uncertain regional hydrogen demand due to dependency on big consumers. Research into these regional areas still needs to further assess the role and activities of hydrogen distribution network operators and the conditions under which they are allowed to operate and interact with the consumers and producers in the regional hydrogen market [7], [14]. By researching the effects of regulative frameworks such as the third-party access (TPA) on behaviour and interaction between stakeholders, insight can be generated into this and how it affects the development of a regional industrial hydrogen market such as Cluster 6, using agent-based modelling and expert interviews as an approach.

1.2 Literature review

In previous literature, the hydrogen value chain has been mapped using mainly optimization modelling as a method [15]–[19], confirmed by [20], [21]. A complete overview of the methods of the selected literature can be found in appendix A. Noticeable from previous research is the one-sided techno-economic view of the researches. [15], [18], [19] and [17] focus on the technical and economical context and aim to analyse economic feasibility of hydrogen technologies, rather than socio-technical aspects such as stakeholder interaction and the influences of hydrogen distribution network operator coordination on the regional networks. [20] confirms a great quantity of techno-economic analysis on operating hydrogen facilities has been performed, in which cost, efficiency and durability are the main critical aspects. Similarly, [16] focuses on the economic and environmental viability of hydrogen value chains and is focused on advising developers on solely costs-related performance criteria. [19] does include market dynamics due to the varying grid prices, however with the goal of assessing economic feasibility for solving congestion with electrolyser usage, not to gain insight into stakeholder behaviour inside the market.

Based on the above, literature does not account for the market dynamics and behaviour of key stakeholders under hydrogen distribution network operator regimes. This is confirmed by [21], who states that behavioural, institutional and political barriers have been largely ignored in literature pertaining to hydrogen. This overall lack of focus on interaction and behaviour under regulatory frameworks in previous research leads to an incomplete system-understanding of the regional industrial hydrogen markets.

In current research, the behaviour of stakeholders is simplified mainly using production and consumption profiles. Scenarios are primarily created based on different technical specifications and configurations of technology. In [16] consumers are reduced to end-use nodes with a demand and producers are modelled as production nodes with energy inputs. The scenarios are created with different technology configurations. [17] uses current demand profiles and electricity supply sources as representation for consumers and producers. The scenarios are based on different groups of technologies. In [15] the consumers and producers of hydrogen are modelled using respectively energy consumption patterns and production profiles based on forecasts. The scenario structure differs in the different studies, as some scenarios include the network support of the network operator in a regional energy community.

[18] and [19] give a more realistic representation of stakeholder interaction. [18] represents stakeholders through investors, based on technology, geographic location and position in the hydrogen value chain. Depending on the cooperation of independent players, financial rewards are divided. Scenarios are based on expected demand, different economic assumptions and market conditions. [19] allows consumers and producers to adjust their output and consumption based on price incentives, which differ per scenario.

The uncertainty of production [21] and demand [15] over time and space is one of the main risks in the regional energy community. This emphasizes the need for a more complex representation of stakeholders in hydrogen modelling to gain insight of incentives and constraints. In the model of [18] with more complex stakeholder definitions, a complicated system of interdependencies between all elements of the hydrogen infrastructure emerges, which needs future research. [19]

has more complex stakeholder definitions as well. However, it contributes to insights regarding the potential role of grid incentives. For deeper insights in the influence of network operator regimes on stakeholders besides financial incentives, future research is needed.

What is striking in the selected literature (see appendix A) is the absence of the role of the network operators in research up to this point [16]–[18], [20]. In [15]'s approach, the hydrogen distribution network operator is included in the scenarios with the goal of financial optimization. [19] models network operators with the ability to adjust prices for consumers, in order to calculate the economic value of electrolysis as provider of grid flexibility. This does not comprehend knowledge on the coordination of hydrogen into regional industrial areas. As network operators operate under public regulation, their goal is more complex than cost minimization [9] which should be reflected in future research.

The availability of literature on hydrogen distribution network operator regulation in hydrogen networks is limited, as it is new. For that reason, this literature review can be enriched by providing a broader perspective on network operator regulation by looking at DSO (distribution system operator) regulation and behaviour on regular electricity networks.

In previous literature, ABMs regarding changes in DSO regulation due to energy transition have been made to see how it affects behaviour. These studies do however focus on residential behaviour [22], [23] and prosumption [24], the issue arising with consumers also producing electricity due to e.g. solar panels, which is not yet applicable for the hydrogen networks which are now mainly for industrial use. The papers do emphasize the importance of realistic behaviour models for stakeholders and offer examples on how these can be implemented [22]–[24]. [24] for example applies a more realistic way of modelling stakeholder behaviour than previous papers by implementing the goal to aim for maximum social welfare on the market, but does not research different regulatory frameworks.

1.3 Knowledge gap and research questions

Despite growing attention to hydrogen in the academic and political world, research into the regulation of regional industrial hydrogen distribution networks remains underdeveloped. Existing studies adopt a techno-economic perspective, focusing on cost optimisation with simplified stakeholder behaviour. This literature largely overlooks how regulatory frameworks, particularly third-party access regimes, shape stakeholder decision-making and regional hydrogen deployment. Moreover, the role of the network operator is either not taken into account or remains highly limited in scope.

This results in an incomplete understanding of how regulatory frameworks, network operator roles and industrial decision-making collectively influence the development of the hydrogen value chain. Although the EU's 2024 Hydrogen and Gas Decarbonisation Package offers Member States a choice between regulated and hybrid negotiated TPA regimes, their practical implications for e.g. connection prioritisation, cost-sharing, and stakeholder behaviour in Cluster 6 are unknown.

This thesis therefore explores how TPA regimes influence the Cluster 6 distribution network and its emerging hydrogen market. The central research question is:

To what extent do third-party access regimes of hydrogen distribution network operators affect the hydrogen transition of Cluster 6?

By addressing this research question, the study aims to contribute to a deeper system understanding of regional hydrogen market development under different TPA regimes. As hydrogen evolves into a major energy carrier, clear frameworks for third-party access become essential for guiding stakeholder interactions and ensuring timely infrastructure deployment [8].

To structure the research, the following sub-questions are formulated:

1. *What different institutional mechanisms regarding third-party access applicable to Cluster 6 can be identified?*
2. *How do third-party access regimes shape the rights, constraints, stakeholder interactions and strategic decision-making of key stakeholders in Cluster 6's hydrogen market?*
3. *How can the key system components of the regional hydrogen market system Cluster 6 be modelled?*
4. *How do different third-party access regimes affect hydrogen deployment in the Cluster 6 case study?*
5. *What are possible additions to the regulatory framework of third-party access that will support the hydrogen transition of Cluster 6?*

1.4 Research approach

To answer the research questions, a modelling approach is adopted to analyse the impact of different TPA regimes on the distribution network and to develop a better system understanding of regional hydrogen market dynamics. This approach also provides insights for stakeholders into how different TPA mechanisms could influence behaviour and infrastructure development, considering technical, economic, and institutional constraints.

The research first applies secondary methods, including a literature review and expert interviews, to deepen understanding of TPA regimes, stakeholder behaviour, market rights and constraints, and to identify key system components. This supports the conceptualisation of the system and answers the first three sub-questions. Subsequently, agent-based modelling (ABM) is used to simulate the effects of different TPA regimes using a Cluster 6 case study, addressing the final two sub-questions. The last sub-question allows to reflect on the TPA regimes and aids HDNOs and policy makers in shaping the regulatory frameworks.

1.5 Link to study programme

The main purpose of this research is to gain insight into the behaviour of and interaction between stakeholders on regional hydrogen networks under different types of regulation and how this affects hydrogen development. This research integrates policy and politics, system understanding and modelling, the core foundations of the MSc Engineering and Policy Analysis (EPA). It will analyse the impact of policy decisions regarding third-party access regimes on technical systems as the regional hydrogen network, using agent-based modelling to simulate system behaviour. This is an EPA engineering approach to solve today's International Grand Challenges, such as climate change.

1.6 Thesis outline

In this thesis, firstly grey and academic literature is reviewed for background information in chapter 2. Next, the methodology of this research is explained in 3. The report continues with the interview results in 4. Then, chapter 5 explains the model. The results of the experiments and sensitivity analysis will be presented in chapter 6 and 7. A discussion and reflection is presented in chapter 8 and lastly, the conclusions from the thesis are given in chapter 9.

2 Background information

In this chapter, an introduction into the Dutch regional industrial hydrogen markets is given in section 2.1. The hydrogen value chain and its stages are described in section 2.2. Next, the theoretical background regarding stakeholders in regional industrial hydrogen markets and third-party agreement regimes is analysed in respectively section 2.3 and section 2.4.

2.1 Background information on Cluster 6

In the Netherlands, hydrogen development is currently progressing along two pathways: large-scale centralized systems and decentralized local systems [8]. HyNetwork Services (HNS), subsidiary company of the Dutch infrastructure company Gasunie, is tasked with developing and operating a national hydrogen infrastructure as TSO [25]. This large-scale centralized system connects five geographic industry clusters in Rotterdam/Rijnmond, Noordzeekanaalgebied, Chemelot, Zeeland and Noord-Nederland to a hydrogen network with roughly 12.000 kilometers of pipelines, scheduled to be completed in 2030 [26], see figure 1.

Figure 1: National hydrogen infrastructure with the five industry clusters [27]

Alongside the five main industry clusters, research project HyRegions identified a sixth cluster (Cluster 6) for possible roll-out of decentralized regional systems [7]. Decentralized regional systems involve community-driven, smaller initiatives aimed at catering to the needs of local areas and involve sectors such as local industries [8]. Cluster 6 is the collection of potential customers and producers with possible interest for a connection to the Dutch hydrogen infrastructure located outside the five large-scale industry clusters [7], [14]. These decentralized regional systems where local industries express the need for a hydrogen connection can be called *regional industrial hydrogen markets.*

The development of the regional industrial hydrogen market and required distribution grid in the Netherlands is progressing rapidly. At present, the Netherlands is in a crucial phase of its hydrogen transition as most Dutch initiatives are in the planning or early development stages, specifically in the feasibility studies and conceptual phases [8]. The planning of regional hydrogen infrastructure development has begun, aiming to scale up renewable hydrogen production and demand, and to connect smaller industrial players in cluster 6, that are currently linked to the regional gas network, to the national hydrogen network [28].

2.2 Background information on the hydrogen value chain

The hydrogen value chain can be divided into four stages: the feedstock and production, distribution, storage and end-use, as illustrated in figure 2.

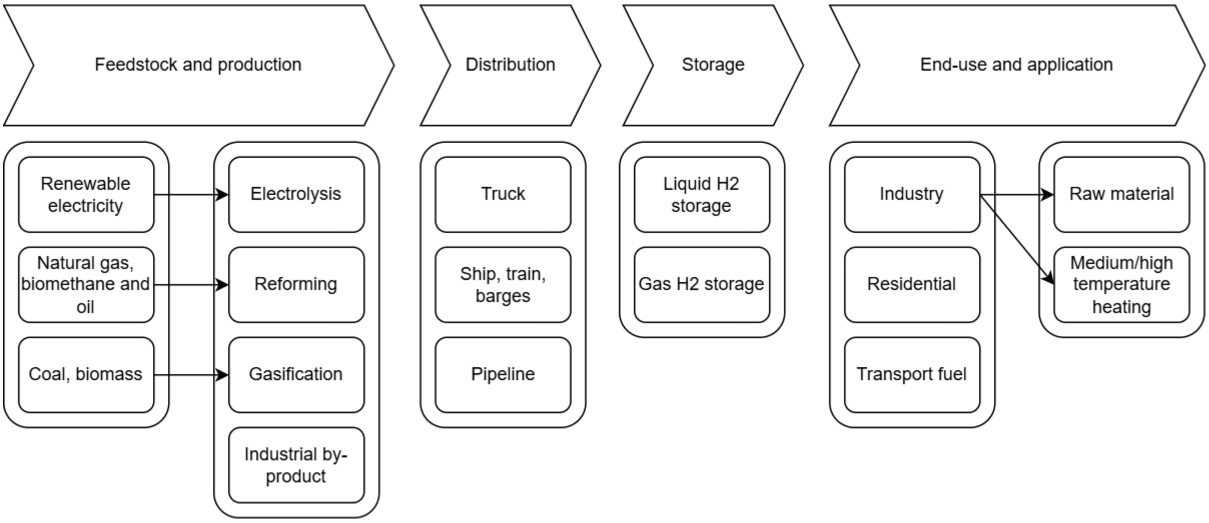


Figure 2: Hydrogen value chain, adapted from [29], [30]

2.2.1 Feedstock and production

There are several methods for producing hydrogen, using different feedstocks. The methods are primarily categorized as reforming, gasification and electrolysis.

The amount of greenhouse gas emissions generated during the production depends on the cleanliness of the feedstock used during the production process. In literature, colour labels 'grey', 'blue' and 'green' hydrogen are used to categorize the cleanliness of the hydrogen, based on the emissions related to hydrogen generation. Grey hydrogen involves production methods that emit CO_2. Blue hydrogen uses the same production methods as grey, but adopts carbon capture storage (CCS) technologies to account for the CO_2 emissions. Green hydrogen is hydrogen produced from water through an electrolysis process using renewable energy, which makes it carbon neutral [31].

Currently, mainly grey hydrogen using steam reforming of natural gas is the most composed type of hydrogen, using 6% of the global natural gas use, producing three-quarters of the global hydrogen production. Grey hydrogen from coal gasification (but also biomass) is the second production technology, using 2% of the global coal use, producing 23% of the global hydrogen production. Both reforming and gasification can be combined with CCS, become grey and lead to negative emissions.

Electrolysis splits water molecules into hydrogen and oxygen using electricity. The levelized cost of hydrogen (LCOH), which is the total cost per produced unit of hydrogen over the whole lifetime of a producing asset, is highly impacted by the electricity price. Additionally, efficiency, capital expenditure (CapEx), amount of load hours and scale also play a considerable role in the LCOH. Lastly, the availability of renewables and thus renewable electricity highly impacts the price [29].

2.2.2 Distribution

Distribution is another important step in the hydrogen value chain and can be done via various routes: in pure form via pipelines, trucks, ships, trains, barges, or by converting it into other carriers such as methanol, ammonia or liquid organic hydrogen carriers (LOHC) [7]. The different transportation methods have different infrastructures, costs, flexibility, pressure and form. Methods such as transportation by trucks do have low investment costs, however the transport costs increase significantly when volume and distance increase, which makes pipelines more interesting for industrial companies. Mostly pipelines can be effective for delivering hydrogen to a large number of high capacity users [32].

2.2.3 Storage

Hydrogen can be stored in both a liquid and gas form in tanks and underground storage [29]. Hydrogen can be seen as both a final product and an energy carrier to store electricity, both in terms of time and space. Hydrogen storage can be used strategically to shift demand and supply across seasons and to buffer short-term supply and demand shortages [30]. Due to the intermittent renewable energy sources, storage plays a big role to bridge the lack of continuous supply [33].

2.2.4 End-use and application

The last step in the hydrogen value chain is end-use and application. Hydrogen can be used in an industry, as a transport fuel or for heating in the residential environment. Given the focus of the report, industrial end-users are further discussed. These have different applications of hydrogen. The three main usage types identified by and considered relevant by [7] are hydrogen as a raw material, for power generation or for thermal applications as replacement for natural gas. The extend to which hydrogen can be an interesting sustainability route varies by process, sector and thus the usage type. The three options are explained below.

Firstly, hydrogen can be used as a *raw material* for industrial products. Companies using hydrogen as a raw material tend to have a higher willingness to pay compared to companies using hydrogen for heat generation. The future demand for hydrogen as raw material in the industry can rise, depending on the developments in the biochemical industries. In addition, if the industries adapt their production processes to use hydrogen as a raw material for production, the value of hydrogen rises in the industries and will thus lead to a higher willingness to pay.

Secondly, hydrogen can also be used for *power generation*. Due to the energy transition, the share of power generation using natural gas is decreasing. Hydrogen, or green gas and biomass, can provide a flexible CO_2-free power generation by converting natural gas power plants and power generation units from co-generation in industries like greenhouse farming. The willingness to pay for hydrogen for power generation is largely dependent on the regulation around flexible CO_2-free power generation capacity.

Lastly, hydrogen can be used for *thermal applications* as a replacement for natural gas. From a practical point of view, hydrogen as fuel for direct combustion for heat generation is an appealing alternative for heat generation with natural gas. The potential replacement of natural gas for hydrogen for thermal application is a crucial factor in the development of regional hydrogen infrastructure, as it could lead to a hydrogen demand far above 10 tonnes per day for large-scale consumers. Large-scale consumers of natural gas are widely distributed throughout the Netherlands and tied to their current location. However, the likelihood of hydrogen replacing natural gas for heating applications is largely dependent on the specific industry process, and on the suitability of alternatives to fill this demand.

For large-scale development of regional application of hydrogen and thus the demand for regional hydrogen infrastructure, the different demand types are dependent on each other.

2.3 Stakeholders in the regional industrial hydrogen market

Stakeholder identification in the emerging hydrogen value chain in the Netherlands is typically divided into the following seven categories which are all interconnected: "primary producers and suppliers", "infrastructure, storage, and distribution entities", "intermediaries", "technology and service providers", "end-users", "policymakers and regulators" and "research and education institutions" [8], [34]. According to [34], stakeholder dynamics within the Dutch context, involving the seven categories, have been insufficiently explored in existing literature.

Previous research analysing the HVC and stakeholder interactions in the Dutch hydrogen sector revealed insights for regions interested in integrating hydrogen technologies into their energy frameworks, emphasizing the need for stakeholder coordination to navigate technical, operational, and regulatory hurdles [8]. According to [8], unclear or inconsistent regulations are negatively impacting efforts to maintain a unified market and promote fair competition. Distribution tariffs, which presently mirror that of natural gas, fail to adequately account for the distinct properties of hydrogen or the dynamic state of its market. Stakeholders are hesitant to commit to big investments without clear regulatory frameworks and guaranteed returns. This situation highlights the critical role of government intervention in providing a stable and supportive policy environment that encourages investment, mitigates financial risks and facilitates the transition from planning to operational stages. [34] says in agreement that incomplete hydrogen policies throughout the whole value chain obstruct growth. Definitive government guidelines are crucial for rapid development in the hydrogen sector.

[35] found that DSOs are fundamental forces, shaping the network infrastructure, storage applications and even influencing regulatory frameworks. The absence of a clearly defined role for the DSO however might cause further setbacks. This issue is especially critical for Cluster 6, which includes regional industries and business parks dependent for a connection to Gasunie's "Hydrogen Backbone." Such centralized planning could overlook the needs of local stakeholders, limiting their engagement in the hydrogen economy and restricting broader economic integration [8].

The current perspective of stakeholders on the hydrogen value chain reach from minimal utilisation, for instance, only in sectors where electrification is technically infeasible, to large utilisation scenarios in all end-use appliances [36]. [34] identified five challenge areas: technical, infrastructural, socioeconomic, environmental and institutional challenges, where infrastructure and financial challenges were most apparent. The financial challenges posed by steep initial costs and scalability issues, suggesting that the current Capital Expenditure (CapEx) subsidies might not be sufficient to both offset operational costs and attract private investments. Here, feed-in tariffs and tax incentives might emerge as possible motivators for industries.

[37] conducted a stakeholder analysis for the perspectives on green hydrogen and electrolyzers and found hydrogen consumers, producers, electrolyzer manufacturers, electricity producers and the government to be the most important stakeholders. [35] identified five stakeholder groups: "network operators", "technology and infrastructure providers", "energy and utility companies", "end-users" and "supporting entities, including government bodies". [36] conducted a stakeholder analysis for Germany, resulting in 49 stakeholder (sub)categories. [34] conducted a

stakeholder analysis and adapted [36]'s framework for stakeholder identification in the Netherlands.

2.4 Institutional mechanisms of third-party access

Due to the relative infancy of hydrogen in the energy market, regulation surrounding the development of regional hydrogen infrastructure was not available yet for a long time [38]. As no regulation was available for hydrogen networks, resulting in unclarity and uncertainty for stakeholders, the European Union has worked on a design enabling market rules for the deployment of hydrogen [11]. The EU has published a Hydrogen and Gas Decarbonisation package, with a regulation [13] and directive [12], of which the first one is directly applicable in Dutch law, and the second one has to be transposed into Dutch law. Based on an extensive analysis of these articles (see appendix B), seven topics of legislation are identified: general, network development, cooperation, unbundling, third-party access, customer rights and tariffs.

The regulatory framework for hydrogen infrastructure in general and the rules on third-party access in particular are in full development [39]. In the directive, the Member States are given some liberty regarding the implementation third-party access by allowing them to implement different forms. The regulations regarding third-party access will greatly influence the regional industrial hydrogen market as described in 2.1, as it dictates how flexibility regarding market development is shaped and how it can accelerate or delay hydrogen market development. Gaining insight in the different TPA mechanisms can guide effective hydrogen regulation.

The term third-party access (TPA) refers to access to (hydrogen) infrastructure by parties who do not control the concerning infrastructure. The EU regulation distinguishes several forms of TPA regimes for hydrogen, ranging from *regulated* third-party access (rTPA), whereby the national regulator sets tariffs and access conditions, to *negotiated* third-party access (nTPA), whereby the hydrogen network operator and its customers are free to determine tariff and access conditions by negotiations. The middle form is *hybrid negotiated* third-party access (hnTPA), where nTPA is applicable until the predetermined year 2033. Then, rTPA shall be applicable. It seems however that permanently ongoing nTPA is not an option [12], [13], [39], [40].

With rTPA, Member States are to ensure that access to transport infrastructure is granted to hydrogen suppliers based on an objective and non-discriminatory TPA tariff system, as is currently the case with electricity and gas. In this regime, the government determines the tariff system. This ensures clarity and objective and non-discriminatory tariffs and access for all hydrogen network users [12], [13], [40].

In addition to the rTPA, Member States are allowed to temporarily implement a system of nTPA to hydrogen networks, which means that the tariffs can be negotiated, in good faith, bilaterally between the hydrogen network operator and the user [12], [40]. This ensures flexibility for the market that is yet to develop and possibly more favourable tariffs for hydrogen network users.

In the Netherlands, the Minister of Climate and Energy Policy had indicated his intention to make use of the option to introduce a nTPA on transmission level, and to determine the framework within which the conditions and tariffs for access and services are setup and HyNetwork Services has to negotiate with parties [41]. The parliamentary letter from December 2024 updates that the transport and storage infrastructure will switch to rTPA and be regulated from 1 January 2033. Until then, a regime of nTPA applies [42]. This is called a *hybrid* negotiated third-party access (hnTPA) regime, which is a third-party access regime that will be somewhere in between a true negotiated third-party access regime and fully regulated third-party access:

some of the terms and conditions set under a regulated third-party access regime are set by the Minister, but not all. The hybrid negotiated third-party access will be gradually transformed into a regulated third-party access regime with an advisory role for the Dutch Authority for Consumers and Markets (ACM) [39]. Figure 3 below shows the timelines of the different TPA regime options for Member States.

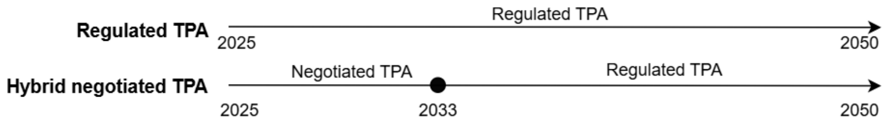


Figure 3: Timelines of different TPA regime options for Member States

It is important to note that the directive does not distinguish TPA between transmission and distribution levels within hydrogen networks. In literature, it is argued that nTPA should be available for the distribution level as well, in order to provide for further flexibility for the accommodation of different regional circumstances [43]. According to [44], a distinction between transmission and distribution level within hydrogen networks should be introduced, where rTPA with tariffs after the threshold date of 1 January 2033 should be applied to transmission, while the choice between rTPA and nTPA should be left to the Member States for the distribution level.

The allowance for nTPA makes sense, as the hydrogen transport markets are yet to develop or have only just started to develop. Too deep regulation on the too immature market could slow or even hinder the development of the hydrogen market. The choice for a hnTPA regime on the other hand is due to the risk of nTPA. The complete freedom in agreeing on tariff and access condition could result in (long-term) agreements greatly differing with the requirements of the later introduced rTPA regime. The hnTPA regime gives a more gradual transition to the fully regulated third-party access [39].

There is no further literature available on specifics of what precisely can be negotiated with nTPA on the hydrogen market for example, or how nTPA will be defined in the Netherlands or other European countries.

3 Research approach

This research followed a modelling approach to simulate the impact of different TPA mechanisms on the development of the distribution grid, in order to obtain a better system understanding of the Dutch regional industrial hydrogen market called Cluster 6. The diagram in figure 4 gives an overview of the research flow with the methods and research sub-questions it answers.

The first method of desk research surveyed EU regulation and hydrogen literature, which answers the first two research sub-questions and forms a foundation of background information to answer the third research question. The desk research method will be explained in section 3.1. The second method of expert interviews (section 3.2) grounds stakeholder rights, constraints and decision-making and interaction in practise and deepens sub-question two and shapes sub-question three. The method of agent based modelling uses inputs from the other two methods to design the model and answer sub-question three. Next, it runs experiments and sensitivity analyses to resolve sub-question four and five. This method and modelling methodology are described in 3.3 and 3.4.

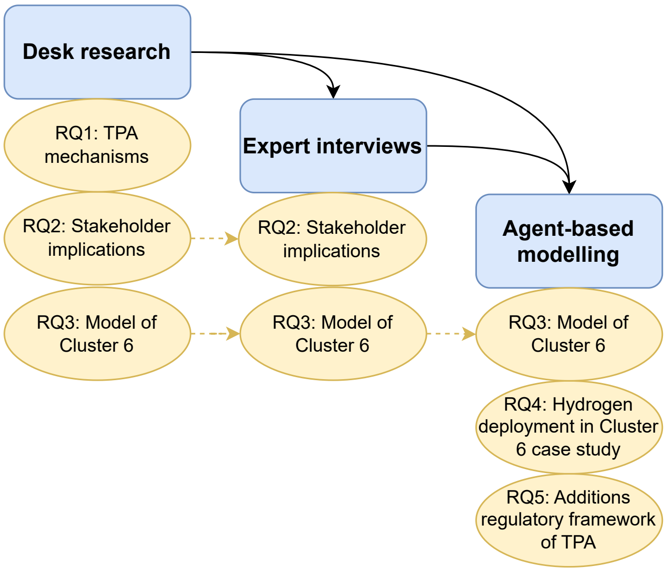


Figure 4: Research flow diagram with a keyword description of the research sub-questions

The study was applied to a case study of a potential regional hydrogen network in the Netherlands within Cluster 6, within Stedin's service area. The use of a case study makes the model more realistic by using real world data, such as case specific data of natural gas consumption patterns, which can be obtained through Stedin's data bases. A real-world example provides a richer understanding of the factors that drive system behaviour, due to specific circumstances and decisions that affect the system.

The case study region is interested in developing a hydrogen network for the current industries, and to attract new industries in the near future by creating a sustainable industrial zone. This case study presents unique case-specific circumstances, which make it particularly favourable to transition to hydrogen. Due to closeness to the backbone, a system connection for a branch off the national hydrogen network is likely. In addition, there appears to be industry support within this case study for breaking the "chicken-and-egg" problem, as some companies expressed willingness to invest in the branching off the backbone in advance, anticipating a future mature market.

3.1 Desk research

The desk research providing background information on various topics has taken place in chapter 2 and aids in answering the first three research sub-questions. For answering the first sub-question, *"What different institutional mechanisms regarding third-party access applicable to Cluster 6 can be identified?"*, literature on the institutional mechanisms of TPA has provided the groundwork for the regulatory framework. In addition, it aided in answering sub-question two, *"How do third-party access regimes shape the rights, constraints, stakeholder interactions and strategic decision-making of key stakeholders in Cluster 6's hydrogen market?"*, regarding what rights and constraints the stakeholders have based on this regulatory TPA framework. Further academic literature on stakeholders has provided insight in the current stakeholders identified in the Dutch regional industrial hydrogen market. For general background information of this research and and for the model in sub-question 3, grey literature on Cluster 6 has provided insight in the Dutch regional industrial hydrogen market of Cluster 6. Thereby, literature on the hydrogen value chain has provided insight in the stages and routes of the HVC and has contributed to science-based assumptions.

With regard to the grey literature regarding institutional mechanisms of TPA, only upcoming regulations specifically defined for hydrogen were taken into account the scope of this thesis. These documents are the regulation and directive from the EU Hydrogen and Gas Decarbonisation Package. The articles selected from the EU documents were considered relevant if they fit the level of demarcation (a regional, industrial hydrogen market), indicate how the system is shaped and regulated and if it indicates what rights or obligations a stakeholder (like an industrial customer or hydrogen distribution system operator) has. Additional literature on regulation was analysed as well.

3.2 Expert interviews

To gain a more comprehensive understanding of the stakeholders and the factors driving their behaviour and decisions, it is suitable to conduct semi-structured expert interviews with diverse experts from the Dutch hydrogen market and stakeholders from the case study. This supplements and grounds the previous findings from literature in practice and deepens the answers to sub-question two and three. The semi-structured format is both versatile and flexible and allows for some improvisation for follow-up questions based on participant's responses.

Following the Human Research Ethics guidelines from TU Delft [45] throughout the whole process and [46]'s method for semi-structured interviews, firstly selection of stakeholders and participant recruitment takes place. For selection of stakeholders fit for recruitment, [36]'s scoping method was adopted. Within the demarcation of this research, the geographical scope (i) is regional hydrogen industrial markets within Cluster 6 of the Netherlands. The temporal scope (ii) was set to the period of hydrogen market development, so from now until 2050. The stakeholders considered (iii) were mainly in the categories of "infrastructure, storage, and distribution entities", "end-users" and "policymakers and regulators", as these affect the regional industrial hydrogen market the most.

The "infrastructure, storage and distribution entities" are the project developers, network operators et cetera involved. The "end-users" are the industries who will employ hydrogen as a feedstock or energy source in their process and the "policy-makers and regulators" are the parties who shape the hydrogen industry through policies, regulations and incentives. An overview of the stakeholders of interest in this research is given in table 1.

Using the network of Stedin, experts and stakeholders were contacted. Data was collected using

Table 1: Stakeholders per stakeholder category and description

Stakeholder Category	**Stakeholder Name**	**Stakeholder Description**
Infrastructure, Storage and Distribution Entities	Hydrogen Network Operator	Hydrogen network operator (HNO) is a more general term for the legal person that carries out tasks related to hydrogen transport and operation, maintenance, network development and long-term availability of the system to meet reasonable demands for hydrogen transport in a hydrogen network in a given area [12].
	Hydrogen Distribution Network Operators	The definition of the hydrogen distribution network operator (HDNO) is similar to the HNO, but more specific for a hydrogen distribution network in a given area [12].
	Hydrogen Transmission Network Operator	The definition of the hydrogen transmission network operator (HTNO) is similar to the HNO, but more specific for the hydrogen transmission network in a given area [12]. The HDNO and HTNO, both HNO's, work in cooperation together with the HTNO on a national level and the HDNO on a regional level.
End-users	Consumers	Consumers, or customers, in this report are the industries with a potential hydrogen demand and desire to connect to the regional distribution grid.
Policy-makers and regulators	Ministry of Climate and Energy Policy	This actor has the regulatory authority in the Netherlands. Representing the Netherlands and as EU Member State, the ministry is responsible for the decisions regarding the national regulation on hydrogen markets, infrastructures and network operators.
	Dutch Authority for Consumers and Markets	This stakeholder is the prospective regulator of hydrogen infrastructure in the Netherlands. ACM has the authority to oversee the market and has an advisory role to the government and ministry of climate and policy regarding regulation.
	City council of the relevant municipality.	This stakeholder is the authority in the municipality and can act as project developer for the regional hydrogen transition.

a semi-structured interview guide. The interviews have taken place via Microsoft Teams and was recorded and transcribed. The data analysis of the interviews took place using thematic coding focusing on challenges related to policy, sources, view on TPA mechanisms, interaction with other stakeholders and key components in the Dutch regional hydrogen market. The results were reported in anonymous summaries and used as an input for the conceptual model and to underpin knowledge of stakeholders and the hydrogen market.

Limitations of this method is the time intensity and bias of the interviewee, which is why time should be taken for this, different stakeholders should be interviewed and bias should be prevented as much as possible.

3.3 Agent-based modelling

ABM models real-world systems by representing individual entities (agents) that interact with each other and their environment [47], [48]. In ABMs, all "things" interact, such as technical objects like hydrogen pipelines or social entities such as consumers, producers, or organizations. The key is to capture relevant behaviours and interactions and code them into a simulation model [49]. ABM is particularly suited for socio-technical systems, which combine physical networks of technical artifacts (e.g., machines, pipelines) with social networks of actors (e.g., individuals, companies, governments) [49]. It enables modelling complex structures and dynamics, helping us understand and interact with such systems more effectively [49], [50].

This research examines how third-party access regimes influence the development of the regional hydrogen market in the Netherlands. The research can be compared to the three conditions from [51] to see if ABM is a fit method. The first condition of distributed problems with autonomous actors is met, as the system involves multiple independent stakeholders such as hydrogen consumers, infrastructure operators, and regulatory bodies. The second condition of a highly dynamic environment is reflected in uncertainties around infrastructure development, coordination challenges, and evolving regulations. The third condition, flexible agent behaviour, is key to this study, as social interaction, strategic decision-making and dependency among actors play a central role. Existing literature, as discussed in 1.2, often relies on equation-based models that reduce stakeholders to average behaviours or representative agents [47], whereas ABM allows for more detailed representations.

However, limitations exist in applying ABM to specific case studies. This research focuses on a case study within Cluster 6, which may not be representative of national conditions due to local infrastructure and socio-economic differences. The model builds on case-specific literature and interviews, which may oversimplify the real-world complexity. While such assumptions can introduce bias, the value of ABM lies in its ability to enhance our understanding of complex systems rather than purely predict outcomes. Therefore, validation, sensitivity analyses, and transparent reporting of assumptions, such as infrastructure timelines or regulatory uncertainties, are essential to ensure robustness and credibility.

3.4 Modelling methodology

Model conceptualization
In the conceptual model, a description of the relationships, external factors and their influences, policy levers and metrics was determined [52]. The design of the model aids in answering subquestion three: *"How can the key system components of the regional hydrogen market system Cluster 6 be modelled?"*. For determining the relevant concepts involved in regional industrial hydrogen markets, the previous desk research and expert interviews were utilized.

Formalization
Following the conceptualization, the model was formalized by making a mathematically defined representation of the system by specifying the rules and equations governing the behaviour of the system using pseudo-code. In addition, the agent parameters and variables were formalized. In this modelling step, a selection of the key performance indicators (KPIs) is made as well to measure the performance of the system.

Data collection
The conceptualized and formalized model was based on quantitative data from various sources. This data was used as an input in the actual agent-based model and was used to create proxies for concepts such as a motivation degree. The following categories of data will be used in the research.

- *Industry specific data*: industries will be the agents in the model. Per industry, data related to their demand, gas consumption and sector in which they operate will be collected from Stedin's gas consumer databases. Other qualitative demand about companies such as behaviour or company characteristics can be derived from the interviews executed.

- *Environmental data*: this data concerns all data which is the same for all industries and sectors. This data can include price forecasts of gas and hydrogen, as well as forecasts of CO_2 tax and EU ETS emission allowance prices. Additionally, data regarding the prices of retrofitting industry equipment for hydrogen use and access costs can be used.

Important to note is that certain model parameters and proxies are estimations, as data may not be available yet or derivable from existing sources due to the newness of the topic.

Software implementation
The formalized model was implemented using NetLogo NetLogo is a programmable environment specifically designed for multi-agent models. Due to past experience with NetLogo, it was used in the study.

Model verification
Model verification has taken place after implementation of the conceptualized model in NetLogo to ensure if the modeller *"built the thing right"*. It was checked if the conceptualized agent interactions and behaviour are accurately translated into the software implementation. Verification was done by debugging and unit testing while implementing [52] and recording and tracking agent behaviour, single agent testing, interaction testing in a minimal model and using multi-agent testing techniques [53].

Model validation
Next, model validation takes place to address whether the modeller *"built the right thing"* to answer the research questions and produce convincing outcomes. Traditional validation methods to see if the model accurately represents the real world-system, such as comparison of experimental results with real-world data, are not always applicable to ABM [54]. Validation cannot simply compare computed behaviour to real system behaviour if there is no real system available for comparison [53].

As this model is exploring possible future states in a relatively new topic, validation should focus on whether the model is useful and convincing in its explanation of how the system of regional industrial hydrogen market development works and if it an provides an increased insight and knowledge. There are several methods identified by [53] to perform validation for ABMs. For this study, literature comparison was performed, by comparing the observed system behaviour with the expectations or predictions of academic literature. Validation through experts has been partly done throughout the whole process by basing assumptions on interviews and expert insights and recommendations.

Model Experimentation
To explore the effects of TPA regimes on the regional hydrogen transition, three experiments were conducted using the agent-based model. These experiments aim to answer sub-questions 4: *"How do different third-party access regimes affect hydrogen deployment in the Cluster 6 case study?"*. Answering the fourth sub-question and all sub-questions prior will finally give a full system understanding and allows to answer sub-question 5: *"What are possible additions to the regulatory framework of third-party access that will support the hydrogen transition of Cluster 6?"*

Experiment 1: the impact of the prioritization order of TPA regimes
This experiment explores how the prioritization order of the TPA regimes, in combination with varying behavioural strategies of the industries corresponding to the TPA regime in place, influences transition dynamics in the region.

Experiment 2: the impact of the investment cost division of TPA regimes
This experiment investigates how the allocation of investment costs between HDNOs and industries affects industry participation and overall transition speed, providing insight into financial incentives embedded in TPA regimes.

Together, these experiments provide comparative insights into how the two negotiation terms implemented in the TPA regimes influence system-level outcomes in regional hydrogen market development, which can provide insight in what possible additions to the regulatory framework can be made.

Sensitivity analysis

To access robustness and impact, the six-step plan for sensitivity analysis in ABMs from [55] was used. Firstly, based on the KPIs defined in the conceptualization, the output of interest was determined. Next, the goal of the sensitivity analysis was set. The goal was to show robustness of the model and to reveal which elements or combinations of elements have the greatest impacts on the results [55]. As there is limited information on the starting conditions in this new topic of Dutch regional industrial hydrogen markets, the exact state of the modelled system cannot be predicted with certainty, and the uncertainty grows with the distance of the forecast [49]. The goal of this model is not to predict the future of regional industrial hydrogen markets but to gain insight in the possible development of them.

The third step was to decide which elements will be varied in the sensitivity analysis, which requires a critical review of the model, its main principles, assumptions, parameters, and procedures. The fourth and fifth step include the design of the sensitivity method and the selection of numerical values for the parameters. The method used is a deterministic scenario analysis, as the key parameter combinations must be explored together, especially since the interactions between these parameters are critical to the models behaviour. In addition, (OFAT) sensitivity analysis is used, which consists of selecting a base parameter setting and varying one parameter at a time while keeping all other parameters fixed, to show the form of the relationship between the varied parameter and the output of interest [56]. Lastly, visualization of the analysis through various plots was created.

4 Case study of a regional industrial hydrogen market within Cluster 6

This chapter describes the case study on which the model was applied, using the semi-structured expert interviews. Five interviews were conducted in total, among which two employees of a DSO and a Cluster 6 employee. In addition, parties interested in developing a regional hydrogen distribution network and the city council involved in the municipality of the selected case study were interviewed. The extensive results and anonymized summaries of the interviews can be found in appendix C.

Firstly, a description of the case study plans and ambitions is given in section 4.1. Next, the empirical findings of interviews within the case study are described in section 4.2. Following research sub-question 2 *"How do third-party access regimes shape the rights, constraints, stakeholder interactions and strategic decision-making of key stakeholders in Cluster 6's hydrogen market?"*, an overview is made in section 4.3 based on the analysis of regulations and stakeholders identified in chapter 2 and the findings of this chapter.

4.1 Case study description and plans

This study was applied to a case study of a potential regional hydrogen distribution network in the Netherlands within Cluster 6, within Stedin's service area. The selected case study presents unique case-specific circumstances, which make it particularly favourable to transition to hydrogen. The industries in the area are mainly food industries, which have a high temperature process fit for hydrogen. In addition, the area has an advantageous location in relation to the hydrogen backbone, which makes a system connection interesting.

Within this case study, there appears to be industry support for breaking the "chicken-and-egg" problem, as some companies expressed willingness to invest in the branching off the backbone in advance, anticipating a future mature market. The industries however favour a partial transition to hydrogen where 20% volume of hydrogen is mixed with natural gas above retrofitting due to cost considerations. In addition to that, they prefer a hybrid energy solution to avoid dependency on a single energy source, which makes a 100% transition to hydrogen unlikely. The interview with Cluster 6 confirms this, stating the most likely scenarios for hydrogen adoption currently are no hydrogen use at all, partial transition to hydrogen or hydrogen as a backup energy source (see C.3).

In the interview with the city council, it became apparent the success of the project can depend on the decisions of individual industries, showing the dependence and anticipation the industries are experiencing.

The city council aims to create a sustainable industrial zone by developing the hydrogen network. Their next step is to expand the industrial area by 2030 by attracting industries meeting the requirements of environmental category four or higher and industries in the agrifood sector. Industries in the agrifood sector resonate with the profile and businesses of the rest of the area. The intention is to attract around 10 industries with a total capacity of 200 MW.

4.2 Findings of interviews with case study stakeholders

Regulatory challenges

One of the regulatory challenges identified is the uncertainty regarding the role of key stakeholders, mentioned by all interviewees (see appendix C). There is no definition of roles, responsibilities and criteria for being designated as a hydrogen network operator (C.1). In addition, present regulations focus primarily on hydrogen TSOs, but HDNOs have distinct structures and requirements (C.2). Until these details are clarified, the grid operators are organizing themselves based on their expectations of the final legislation (C.1). However, the lack of policy raises uncertainty by industries about their decision-making regarding hydrogen and sustainability (C.3), making it difficult to commit to hydrogen-related investments (C.4, C.5).

The second regulatory uncertainty is regarding financial responsibilities, which is particularly important for industries. In interview C.4, industries stressed they cannot bear all investment costs alone. Industries in Cluster 6 wonder who will cover the expensive connection costs and network development costs (C.3). Interviewee C.2 explained energy transition entails long-term costs. Given that hydrogen adoption is unlikely to be financially attractive, governmental strategy here is critical. Defining how costs are distributed among customers, HDNOs, and the government is essential for moving forward with the regional hydrogen network. An additional challenge regarding costs for industries is the uncertainty of the hydrogen price (C.3). Hydrogen remains significantly more expensive than other energy sources. As it remains unclear how the hydrogen market will develop, it is difficult to predict investment payback periods. This uncertainty reduces the attractiveness of hydrogen adoption (C.4).

Industry perspective

Despite a growing interest in hydrogen among Cluster 6 industries, its large-scale adoption remains a distant prospect. Currently, most companies within Cluster 6 are exploring electrification as the first option, as hydrogen is financially out of reach (C.3). However, electrification is often unfeasible due to grid congestion (C.4). A study by Cluster 6 found that 73% of all industrial sustainability plans cannot proceed before 2030 due to the lack of necessary energy infrastructure. While electricity infrastructure is already a bottleneck, hydrogen infrastructure is even further behind, creating a major dilemma for companies.

Interest in hydrogen is currently mainly driven by a small group of forward-thinking entrepreneurs within Cluster 6 who strongly believe hydrogen is a necessity for the future. These companies are willing to invest early despite the high costs, hoping to accelerate market development. However, the majority of industries view hydrogen as a secondary option. They would only consider using it if it becomes affordable.

DSO perspective

For DSOs (see C.1 and C.2), it is an interesting question how they can facilitate hydrogen distribution while managing the existing gas network. As described in the challenges, the DSOs are in a grey area as hydrogen does not fall under their official scope yet. If DSOs are designated as hydrogen distribution network operator (HDNO) (see EUD12 in appendix B), this will resolve the regulatory challenge of stakeholder definitions mentioned.

DSOs are now exploring hydrogen opportunities from two rationales: a systemic and financial motivation. Firstly, hydrogen is needed to support the energy system and by alleviating pressure on the electricity grid. Secondly, a viable business case is required with sufficient contracts and a minimum return on investment. As came to light by interview C.4, despite the high investment costs for hydrogen infrastructure for the system operator, these costs are still lower than the cost of reinforcing the electricity grid. A third motivation for social responsibility is also voiced, as DSOs have a social responsibility to facilitate energy transition and help achieve climate goals.

Negotiated third-party access

When asked how negotiation could take place, several aspects came to light which can be used as an input in this research on how to form nTPA in the model (see appendix C.1 and C.2). It is not expected negotiation will take place on fundamental contractual terms like for example tariffs, as drastic changes once rTPA applies are undesirable.

One of the aspects on which can be negotiated is the prioritization order which defines in what order customers will be connected. Under regulated third-party access, a *first come, first served* (FCFS) system is most likely to be applied. This means that customers who apply first will receive their connection first. However, with nTPA, the connection order might differ. Here, alternative prioritization methods can be applied of which several examples were given, such as development based on most efficient grid architecture. Here, the network is developed in the most cost-effective way. Another option is the prioritization based on volume and grid investment, where priority is given to projects that require minimal grid investment while delivering large volumes.

The second aspect which can be negotiated might be on additional aspects in the contract, such as the division of investment costs, discounts for constant off-take, spread of development costs over time or contract durations to ensure long-term customer commitments. The division of investment costs is closely related to the unclear roles of stakeholders, which makes it difficult to determine who is responsible for which costs. It was mentioned by respondent C.2 that this division might also include the government, as it is their policy to decarbonize and responsibility to aid in this. A spread of development costs ensures first-movers do not carry all costs and risk.

4.3 Rights, constraints and strategic behaviour of stakeholders

Table 2 presents an overview of the influence of the regulation on each of the stakeholders on their rights, constraints and possible strategic behaviour they can have based on these regulations and the interview results from the previous section. For an overview of the institutional mechanisms and their explanation, see appendix B. Important to note is that the city council has no institutional mechanisms applicable. This is because of the lack of focus of the current regulations on regional level and distribution networks, as explained in section 2.4. No clear role distribution is here is available yet, see section 4.2.

Table 2: Institutional mechanisms, rights, constraints and strategic behaviour per stakeholder identified

Stakeholder	**Institutional Mechanisms**	**Rights**	**Constraints**	**Stakeholder interactions and strategic decision-making**
Ministry of Climate and Energy Policy	EUR1/EUR9 (Spread of network development costs), EUR2 (Tariff setting),EUR3 (Cooperation), EUR7 (General principles), EUD5/EUD10 (Third-party access), EUD12 (Designation of HDNO's)	Right to establish national hydrogen policy; right to oversee compliance with EU principles.	Must align with EU policies; must set tariffs, ensure cooperation and transparency.	Encourage alignment with decarbonisation goals; promotion of regional cooperation for fair market operation and transparency; aid in startup of hydrogen by making financially attractive (C); provide regulatory clarity on stakeholder roles and financial responsibilities (C.1).
Dutch Authority for Consumers and Markets	EUR7 (General principles), EUR11 (Tariffs), EUD13 (Unbundling)	Authority to regulate tariffs, ensure non-discriminatory market access, oversee and monitor third-party access and unbundling.	Must enforce EU regulations and national regulations.	Ensures tariff transparency; monitors market behaviour; facilitates a level playing field in hydrogen markets.
City council of respective municipality	-	Right to facilitate projects within municipality; right to issue permits; right to manage land ownership (C.5).	Must ensure all stakeholders' interests within the municipality are considered. (C.5).	Lobby to address legal and regulatory barriers; coordinate working groups for hydrogen project; securing and managing subsidies; create sustainable industrial zone; attracting food industries to the agrifood municipality (C.5).
Hydrogen Network Operators	EUR1 (Spread of network development costs), EUR7 (General principles), EUR8 (Separation regulatory assets), EUR6 (Early access), EUR10 (Third-party access), EUD2 (Vertical unbundling), EUD5 (Co-location), EUD11 (Refusal of access and connection), EUD14 (Tasks), EUD15 (Confidentiality), EUD18 (Unbundling)	Right to operate, maintain, and develop hydrogen networks; if implemented: right to spread network development costs; if implemented: receives flexibility with TPA.	Are subject to regulatory authority for tariff setting; must separate regulatory assets and follow unbundling requirements; subject to strict transparency, efficiency and non-discrimination rules.	Invests in infrastructure development; collaborates with stakeholders to optimize network planning and efficiency; engage in selective infrastructure expansion, prioritizing projects with the highest economic return (C.1), negotiate cost-sharing agreements strategically to shift risks to other stakeholders (C.2).
Hydrogen Distribution Network Operators	EUR12 (Cooperation), EUD13 (Unbundling), EUD17 (Hydrogen distribution network development)	Right to develop regional distribution networks.	Constrained by cost efficiency and stakeholder input.	Engages in stakeholder consultations; explores possibility and feasibility of hydrogen from systemic motivation to relieve pressure on electricity grid; take financial responsibility (C).
Hydrogen Transmission Network Operator	EUR5 (Regional structures), EUD16 (Hydrogen network development)	Right to manage and develop national-level transmission networks.	Must oversee cooperation at regional level; must cooperate with HDNO's and other HTNO's.	Focuses on strategic investments in transmission infrastructure; engages in coordinated regional planning to align investments with expected market developments (C.4).
Consumers	EUR7 (General principles), EUD1 (Customer protection), EUD3 (supplier choice), EUD8 (Contractual rights), EUD9 (Protection of remote customers)	Right to receive clear contractual conditions; Right to be protected and empowered to make best choices.	Limited by network development status and market conditions; subject to network access tariffs.	Advocates for better network access; engages in demand forecasting; optimize energy source and decarbonization decisions; engage in partial transition to hydrogen; avoid dependency on single energy source; delay adoption of hydrogen until cost certainty improves; using market uncertainty as leverage; anticipate actions of other industries/stakeholders; relocate to countries with lower energy prices(C.3, C.4, C.5).

5 ABM of a regional industrial hydrogen market

This chapter describes the modelling steps applied in building the simulation model, which ultimately answers sub-question 3: *How can the key system components of the regional hydrogen market system Cluster 6 be modelled?*. This model will then be used to answer the remaining sub-questions.

5.1 Conceptualization

In the model, there is a focus on understanding the implications of individual decisions and their macro-scale implications. Individual decisions here can be the policies by which the HDNO acts or individual investment decisions of an industry. Their macro-scale implications are how these decisions impact the whole system. Before diving into the conceptual model, the focus of the simulation and what insights want to be extracted from it are clarified with the modelling question below.

How do the actions of HDNOs in different TPA mechanisms impact hydrogen deployment in a Cluster 6 case study?

An overview of all assumptions made in the conceptualisation can be found in appendix D and are referred to in text as e.g. A1.

5.1.1 Scope of the hydrogen value chain

The hydrogen value chain, as explained in 2.2, is here adapted to the scope of this research. The components of the value chain highlighted in blue in figure 5 fall within the scope of this study.

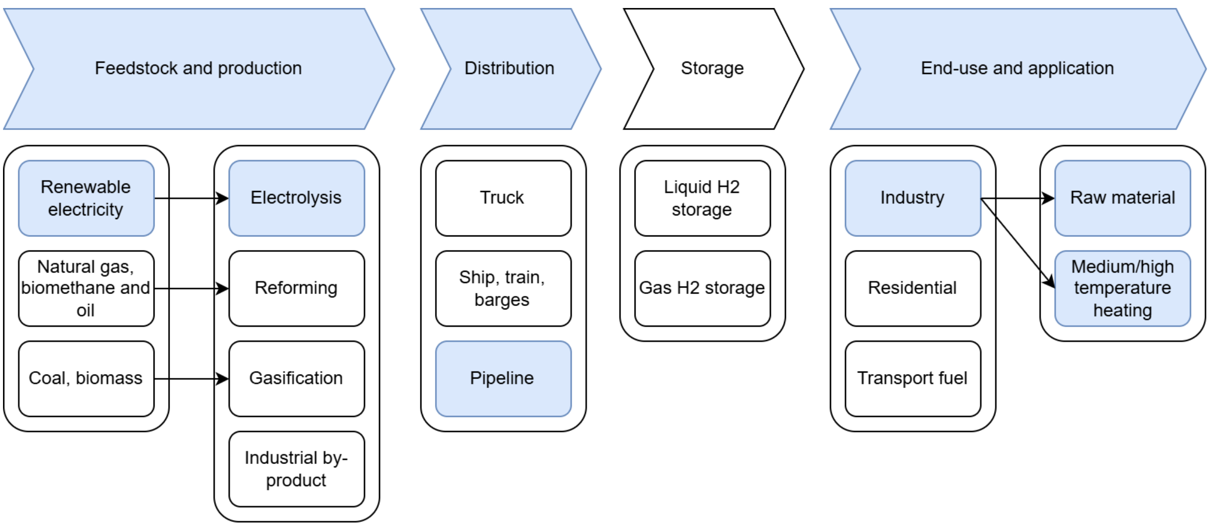


Figure 5: Scope of the hydrogen value chain, adapted from [29], [30]

Feedstock and production

In this study, the hydrogen colour considered is green hydrogen, produced with electrolysis which consumes electricity directly from a renewable energy source and electricity grid. This is because of the main driving factor in Cluster 6 for the potential rollout of regional grid infrastructure: to replace natural gas for heat production to decarbonize [7], which eliminates the demand for grey hydrogen. Currently grey hydrogen is predominant and cheaper, while green hydrogen is less available and prices are higher. This marks the important assumption A10 that green hydrogen is available in the model. However, the current rise in natural gas prices, along with growing CO_2 prices, may also make green hydrogen a more affordable and available alternative [31]. In addition, the scarcity of green hydrogen will also be reflected in is price.

According to [7] regional production (and supply) of hydrogen is less defining for the initial development of regional hydrogen infrastructure than potential demand. Considering the economic perspective, it is more logical that hydrogen production follows the hydrogen demand, because the demand comes from existing companies and production projects start from scratch. Important to note is that small-scale regional production projects are probably less competitive than bigger hydrogen production projects with a connection to the national hydrogen network. It is hard to predict the location of regional production supply and it is expected (in 2035) to be relatively small outside the five Clusters. For that reason, the emergence of suppliers is not taken into account in this model as a connection to the backbone is assumed (A5).

Distribution
Given the demarcation of a regional industrial area, mostly pipelines can be effective for delivering hydrogen to a large number of high capacity users [32]. Methods such as transportation by trucks do have low investment costs. However, the transport costs increase significantly when volume and distance increase, which makes pipelines more interesting for industrial companies. This marks assumption A1: in the model, pipelines are the only method of transport.

Based on the assumption of pipelines being the only form of transport (A1), other assumptions can be made regarding pipelines. It can be assumed that the purchase of hydrogen only occurs if an industry is connected via pipeline support (A2), as no other form of transport is available. The focus in this study is on newly constructed pipelines, no repurposing of existing pipelines (A3), and no renewal of pipelines is needed (A4). See appendix D for further explanation and grounding for these assumptions.

Storage
In this study, storage is not taken into account (A7). This study focusses on the influence of regulatory frameworks on the development of the industrial hydrogen distribution grid. In other words, the study examines how regulatory conditions can influence the conditions for the development of a market over the scope of 25 years, and does not aim to match hydrogen supply and demand. This sets the time step of the model to years, which does not take into account hourly demand fluctuations.

End-use and application
The last step in the hydrogen value chain is end-use and application. As described in section 4.1, the industrial area of the case study consists of food processing industries with high-temperature energy demands and one greenhouse farming with lower temperature needs. These stakeholders are the end-users considered for the scope within the industrial area in this study. The case study however excludes other sectors outside agrifood and agriculture from the end-use. Due to the little diversity in sectors, it is assumed the sector has no impact on the decision-making of agents (A38). In addition, thermal applications only are assumed, as the majority of industries in the case study are food processing industries. This excludes application as raw material or for power generation (A39).

Important to highlight is that the strategic behaviour of industries to relocate their industries abroad where energy prices are cheaper (see section 4.3) has been excluded from the scope, as the model focusses on regional hydrogen development and not international strategies (see A36). Additionally, in the report it is assumed that current DSOs are most likely to become the HDNO (see A40) due to their strategic behaviour to explore the possibility and feasibility of hydrogen while not being HDNO yet, as described in 4.3. The terms of DSO and HDNO can be used interchangeably.

Initial overview of the conceptual model based on the scope
Based on the demarcation of the scope as described above, an initial overview of the conceptual model can be made, see figure 6.

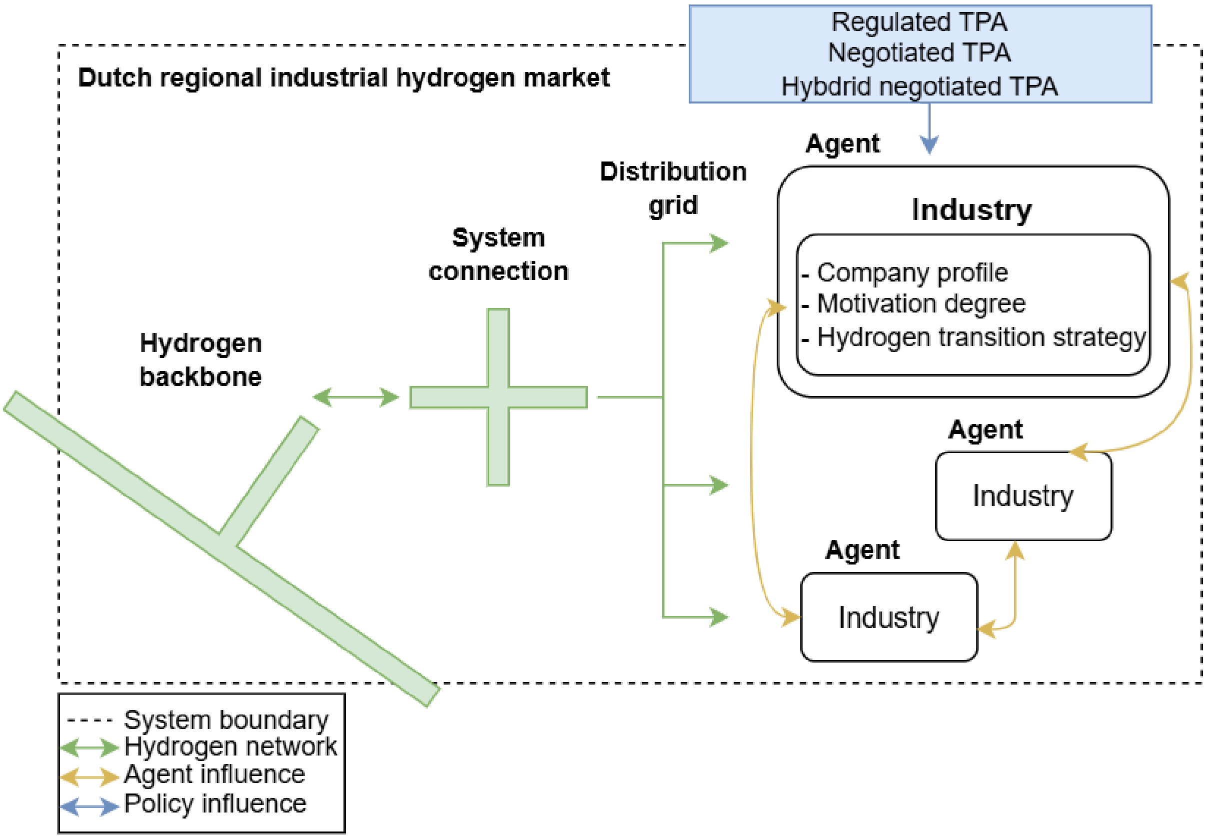


Figure 6: Conceptual model: overview

In this model, the system boundary is the Dutch regional industrial hydrogen market as described in the case study description in section 4.1. The industries are modelled as the agents, which have several properties, such as the company profile containing sector they operate in and their natural gas consumption pattern. Other states are their motivation degree to switch to hydrogen and the strategy they adopt to transition to hydrogen. The industries are influenced by the policy in place indicated in blue, which are set and implemented by the observer on behalf of the HDNO and ministry. The agents are influenced by each other as well, as their motivation degree to switch to hydrogen can change due to the developments in the regional hydrogen transition, indicated in yellow.

The physical system in the model consists of the hydrogen backbone, the distribution grid, and the system connection connecting them. Together, these form the regional hydrogen network, indicated in green. As explained in this section, this model assumes a system connection to the hydrogen backbone is possible and available. As the hydrogen backbone is developed on national level, not on regional level, the backbone falls partly out of the system boundary as can be seen in figure 6.

5.1.2 Agents and interactions

Going into detail on the internal process of an agent, the flow diagram in figure 7 can be made. Firstly in the set-up step from the ABM, the properties from the industries are assigned, such as the sector they operate in and their current gas consumption pattern. Each industry receives a random location (due to data privacy for the case study industries) and has a distance to the system connection at the centre of the model at patch 0 0 (see A6). Based on the industries location, their peers can be determined, which are industries within a defined distance. A motivation degree is set as well, starting with 0. In a previous study [33], the motivation degree to transition to hydrogen was initially assigned based on the sector, since the motivation for hydrogen transition strongly depends on characteristics of the industrial process, the availability and applicability of other sustainability alternatives for this process and how easy they are to implement [7]. As this case study has a low variety in sectors, the industries start with a clean slate: their motivation degree starts with zero and will change based on different factors: the waiting list factor, the CBA factor and the peer pressure factor, explained below. In relation to their motivation degree, the transition strategy is determined, which will later determine what percentage of hydrogen energy (kWh) will be transitioned. Based on data available from Stedin's gas consumer databases, each industry receives their gas consumption pattern.

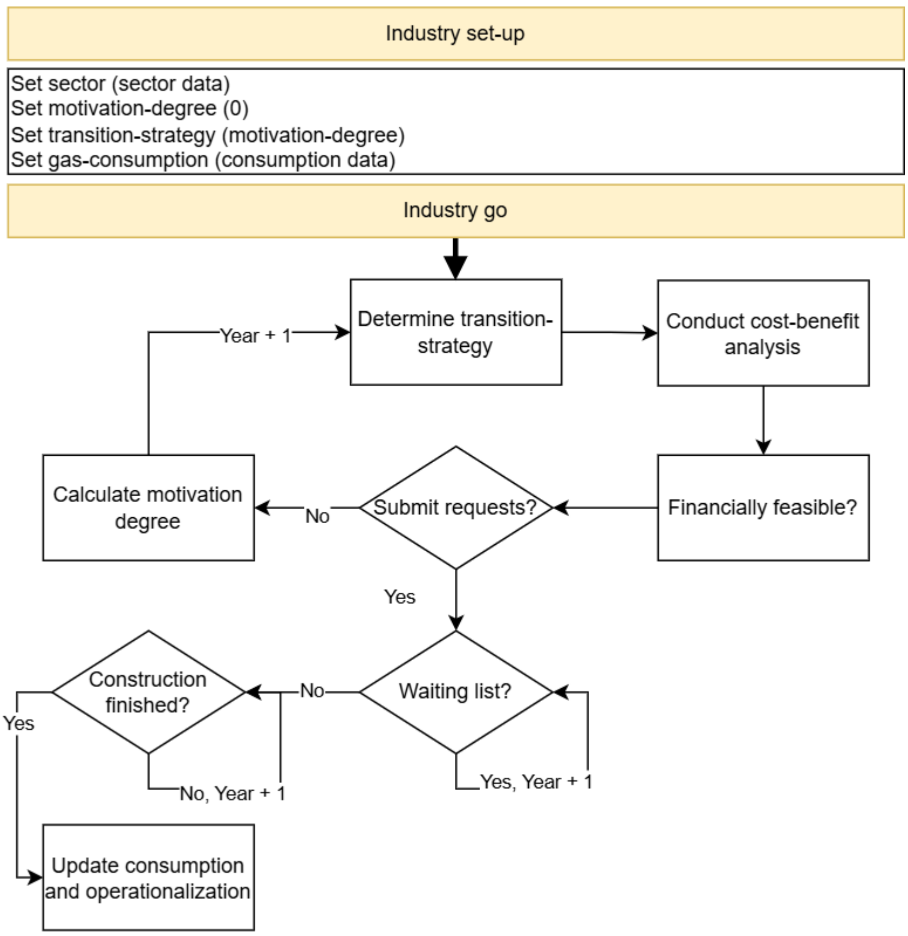


Figure 7: Conceptual model: flow chart of the agents

In the go step of the ABM, each year industries begin by determining their transition strategy. This strategy is based on the motivation-degree and consists of two components: the energy percentage the industry wants to convert to hydrogen and if the industry will mix hydrogen with natural gas, or retrofit their industrial process. If an industry is replacing 7% of hydrogen or below, it will mix hydrogen, which does not require retrofitting in the industrial process. Hydrogen can be seen as an easy sustainable replacement for natural gas without complex technical adaptations needed [7]. However, as only pure hydrogen is permitted in the Dutch hydrogen network (see A9), a mixing station is required to mix natural gas with hydrogen. To reflect hesitance and the need for security from industries (see 4), the threshold to choose a higher percentage than 7% hydrogen choose retrofitting instead of mixing as transition-strategy is set quite high.

The next step is to yearly conduct a cost-benefit analysis for the transition to hydrogen, calculating 15 years [57] ahead. The amount of hydrogen energy is calculated using natural gas consumption patterns and convert the energy consumption of natural gas to the corresponding hydrogen consumption. Here, no further consideration is given to e.g. efficiency of hydrogen versus natural gas (A11).

After conducting the CBA, the industry determines if the industry is financially feasible or not. Then, based on the height of the motivation-degree, a request for connection will be submitted or not. If not, the motivation-degree is recalculated and all steps above happen again. If a request is submitted, the industry enters a waiting list. Once it is its turn to start constructing, the industry waits a few years and then it will update its consumption and start operating with the new consumption patterns. As the industries indicated in the interviews (4.2 and 4.1) a full hydrogen transition is not likely due to their desire for a hybrid energy solution and the high and uncertain costs for hydrogen. This is the motivation for the transition strategies of 7, 20 or 40 energy %, which can increase if the alternative strategy is adopted, but does not become much higher (A32). In addition, for simplification of the model the model only considers the first step of transition to hydrogen from the industry and does not allow for industries to grow in hydrogen demand after several years (see A29). While this limits the insights to a few years, the focus on the first transition is valuable given that this is where the focus for HDNOs and policymakers currently lies. In doing so, the model avoids 'predicting the future' because there is still so much uncertainty in hydrogen network development due to e.g. energy prices. However, in future research further transition to hydrogen once transitioned could be taken into account as well to bring the model closer to reality.

Motivation degree
Translation from potential hydrogen demand to actual demand depends on several economic factors, such as availability, price and alternative sustainable replacements [7]. But other factors such as the application of hydrogen, sustainability goals, local dependency and the regional hydrogen transition can also play a role here. Therefore, more factors aside from financial performance are included in this model with as goal to increase the complexity of the decision-making from the industries. To reflect the regional hydrogen transition and hesitance and dependency among industries to await the decisions of individual industries (see 4.1) the factor of peer pressure (PP) is added. In addition, the factor of waiting list (WL) is added to give industries the ability to respond to negotiation terms in the nTPA and hnTPA regimes. See appendix F.3 for validation of these factors.

As mentioned, all industries begin with a clean slate in the model and have a motivation degree of zero. Each year, the industries' motivations can grow based on the three factors of the waiting list, CBA and peer pressure. This can alter the transition strategy of an industry. All factors have a different weight, which will be implemented as sliders so they can be altered. The motivation degree is calculated as shown in the equation 1 below.

$$MD = w_1 \cdot PP_{\text{norm}} + w_2 \cdot WL_{\text{norm}} + w_3 CBA_{\text{norm}} \cdot CBA_{\text{norm}} \tag{1}$$

Where

- MD = Motivation degree of an industry.
- w_1, w_2, w_3 = Weights assigned to each factor, with $w_1 + w_2 + w_3 = 1$.
- PP_{norm} = Normalized peer pressure score.
- WL_{norm} = Normalized waiting list score.
- CBA_{norm} = Normalized Cost-benefit analysis score (financial feasibility).

MD1 Peer pressure factor
The peer pressure factor is determined based on the financial feasibility and phase of peers. The peers are the industries that are near. It is assumed that industries near you can influence you to transition as well. If more peers around an industry are considering the option of transitioning to hydrogen because they are financially feasible, or are already operating with hydrogen, the industry feels more incentive to transition as well. The peer pressure is calculated as shown below in equation 2:

$$PP_{\text{norm}} = \frac{Peers\ transitioned\ or financially\ feasible}{Total\ number\ of\ peers} \tag{2}$$

MD2 Waiting list factor
The waiting list factor is based on the position in the waiting list. As will be explained in section 5.1.3, industries will be put in a waiting list when they submit their request, following a prioritization mechanism different for the TPA regimes. In the case of nTPA, the order is based the ratio of hydrogen volume divided by the investment costs, based on the negotiation terms which came to light in the interviews (see 4.2). The higher this ratio, the higher the position in the waiting list. In this policy scenario, industries have an incentive (or motivation) to adapt their transition strategy and try to reach a higher place on the waiting list. This is calculated as shown in equation 3, where a lower position returns a higher WL_{norm}.

$$WL_{\text{norm}} = 1 - \frac{Waiting\ list\ position}{Length\ waiting\ list} \tag{3}$$

MD3 CBA factor
The last factor is the CBA factor, which determines the motivation based on the CBA outcomes. The NPV and ROI, explained below in **Cost benefit analysis**, are scaled and receive an absolute ranking to define a "good" ROI and NPV. By setting a bounded NPV and ROI, the CBA values are kept within a reasonable limit. By making the CBA values bounded, it is ensured the CBA is ranked within an allowed range. These values have to be set by trial and error. Next, the normalized values of the CBA and NPV are calculated. By computing the average of these two normalized values, the normalized CBA factor is reached.

$$\begin{aligned}
&\text{bounded_NPV} = \min(\text{NPV}_{\text{max}}, \max(\text{NPV}_{\text{min}}, \text{NPV}_{\text{t}}))\\
&\text{bounded_ROI} = \min(\text{ROI}_{\text{max}}, \max(\text{ROI}_{\text{min}}, \text{ROI}_{\text{t}}))\\
&\text{NPV}_{\text{norm}} = \frac{\text{bounded_NPV} - \text{NPV}_{\text{min}}}{\text{NPV}_{\text{max}} - \text{NPV}_{\text{min}}}\\
&\text{ROI}_{\text{norm}} = \frac{\text{bounded_ROI} - \text{ROI}_{\text{min}}}{\text{ROI}_{\text{max}} - \text{ROI}_{\text{min}}}\\
&\text{CBA}_{\text{norm}} = \frac{\text{NPV}_{\text{norm}} - \text{ROI}_{\text{norm}}}{2}
\end{aligned} \tag{4}$$

Where

- $\mathrm{NPV_t}$, $\mathrm{ROI_t}$ = NPV and ROI values from this time step.
- $\mathrm{NPV_{min}}, \mathrm{NPV_{max}}$ = Predefined minimum and maximum bounds for NPV.
- $\mathrm{ROI_{min}}, \mathrm{ROI_{max}}$ = Predefined minimum and maximum bounds for ROI.
- $\mathrm{bounded\_NPV}, \mathrm{bounded\_ROI}$ = NPV and ROI values bounded within the min and max range.
- $\mathrm{NPV_{norm}}, \mathrm{ROI_{norm}}, \mathrm{CBA_{norm}}$ = Normalized NPV, ROI and CBA in range [0,1].

Cost benefit analysis

For industries, it is important the transition to hydrogen is financially feasible. The economic feasibility plays a big role for the development of hydrogen demand. Uncertainty about for example future energy prices and the cost development of hydrogen and alternative sustainability options make investment calculations and decisions complex [58]. An effort is made by assessing economic feasibility of investments through cost-benefit analysis (CBA), which is widely used by industries to evaluate the financial gains of investment plans [59]. It is considered the most comprehensive and theoretically sound form of economic evaluation and it has been used as an aid to decision making in many different areas [60]. A project's feasibility can be calculated using the net present value (NPV) of the project, see equation 5. If the NPV exceeds 0, then the project is beneficial. In the model, each timestep (years) industries conduct the CBA for an investment time horizon of 15 years, which means industries calculate until 15 years ahead from the year they expect to be operational, whether their project is beneficial or not.

$$Net\ Present\ Value = \sum_{t=0}^{T} \frac{Total\ benefits_t - Total\ costs_t}{(1 + discount\ rate)^t} - CapitalExpenditure \tag{5}$$

NPV however does not tell how efficient the investment is relative to its cost. For that reason, the NPV can be scaled to show the percentage return on the initial investment. This is called the return on investment (ROI) of the project, see equation 6, and shows the share of project costs that is covered by the net return of the project.

$$Return\ on\ investment = \frac{Net\ Present\ Value}{Capital\ Expenditure} \times 100\% \tag{6}$$

The costs and benefits influencing these total benefits, total costs and capital expenditure are explained below.

CBA1 Costs in the cost-benefit analysis

Within the demarcation of this project, the costs included in the cost-benefit analysis include capital expenditures (CapEx) for the access costs and the cost of retrofitting or a mixing station. Operational expenditures (OpEx) include hydrogen costs and tariffs. Important to note is that an industry has either retrofitting or mixing station costs, based on the transition strategy. If the strategy is 7%, a mixing station is necessary. Above 7%, retrofitting is necessary and no mixing station costs are incurred.

Costs not included in the OpEx are for example labour and maintenance, as it is assumed these will not differ from the operations with natural gas (A12). However, additional necessary training or extra maintenance due to hydrogen safety requirements could increase the costs, but this is expected to be minor [61].

CBA1.1 Connection costs CapEx
As new infrastructure needs to be rolled out, costs for access and infrastructure needs to be incurred. Since no literature is available on this topic, it is assumed these costs are a bit higher compared to other gas infrastructures due to the many (safety) requirements. The connection fee from Stedin data is used as a proxy [62] to estimate a connection fee for connections up to 25 meters of €58.050 (A21). For each meter extra, a cost of €170 is incurred for the industry.

As stated in 5.1.1, in this study it is assumed only new pipelines will be used, which means there will be no repurposing of existing pipelines (A3).

CBA1.2 Retrofitting CaPex
Retrofitting is the phenomenon where existing equipment or systems are modified with new technologies, components or functions. Research on retrofitting combustion engines for hydrogen has shown that hydrogen can achieve increased engine efficiency and near-zero emissions [63].

[61] has assessed the technical requirements and challenges associated with industrial hydrogen conversion and estimate the associated costs and time frames. Following the development time frames, it is expected all technologies for industrial equipment can be ready at the end of 2025. Given this time frame, it is assumed all required technologies for retrofitting are available in the model (A17).

Using the estimated CapEx from [61], the cost of converting some typical pieces of equipment from natural gas to hydrogen is given below in table 3 for the food and agriculture industry, as these are the only sectors present in the model. In the model, the scale-up formula 7 can be used to calculate the cost of retrofitting, based on the size of the equipment. For the production capacity being conversed, if more equipment options are available in the model the choice for the most cheap option is. In table 3, the cost and size of reference equipment and the scale-up factor, calculated using the two known equipment retrofitting costs from [61], can be found.

$$Cost\ of\ desired\ equipment\ = Cost\ of\ reference\ equipment \times \left(\frac{Desired\ equipment\ size}{Reference\ equipment\ size}\right)^{scale-up\ factor} \tag{7}$$

Table 3: Equipment retrofitting cost per industry and scale-up factor

Industry sector	Typical equipment	Retrofitting cost (€'000s*)		Scale-up factor
		1 MW	10 MW	
Food	Steam boiler	191	776	0.608
	Oven	169	551	0.514
Agriculture	Heating boiler	191	766	0.608

* The costs are originally in GBP, but converted to € using the average 2020 conversion rate of 1.1248 [64].

Important to note is that the agricultural equipment data was not available. Here, an estimation is made. Typical equipment in the agricultural sector could be a combined heat and power (CPH) unit or a boiler. As the data for a food steam boiler are available, it is assumed the conversion challenges and costs are similar, which makes the food steam boiler a fitted proxy for an agricultural heating boiler (see A18). The CPH requires extra changes beyond those of a boiler due to its dual function, making estimations for this less certain.

CBA1.3 Mixing station CaPex
If the transition strategy includes mixing of natural gas with hydrogen, a mixing station is necessary. Given the unavailable data for the mixing station, an expert estimate was used which estimated the cost between €100.000 and €200.000 euro's. In the model, it is assumed mixing a capacity of 1 MW costs €100.000 and 10 MW €200.000 (A19). For that reason, we can follow the same formula as 7, where a scale-up factor of 0.301 can be assumed.

CBA1.4 Hydrogen cost OpEx
The purchase cost of hydrogen via the pipelines can be calculated for the entire investment time horizon of 15 years, using hydrogen price forecasts, see appendix H. The energy percentage of the hydrogen is decided during in the previous phase of the model, where the amount of hydrogen energy intake is calculated using natural gas consumption patterns and convert the energy consumption of natural gas to the corresponding hydrogen consumption.

Important to note is that hydrogen price forecasts vary widely. An average of these forecasts will be implemented in the model, see appendix H for an explanation. The sensitivity analysis will give more insights in how sensitive the model is to the price forecast.

CBA1.5 Hydrogen tariffs OpEx
Comparable to the current gas infrastructure, system users are expected to pay a tariff for using the distribution network and the service of operating, maintenance and development of the hydrogen distribution system operator [12].

Based on the interviews (see appendix C), hydrogen tariffs could be two to three times higher compared to current natural gas distribution tariffs. For that reason, the gas distribution tariffs from [62] are used and a slider is implemented in the interface which multiplies those tariffs by two to three times, so it can be seen how these changes in tariffs influence the model.

CBA2 Benefits in the cost-benefit analysis
Within the demarcation of this project, the benefits included are avoided natural gas cost, avoided CO_2 arising and avoided EU ETS costs from transitioning to hydrogen.

CBA2.1 Avoided natural gas cost
By substituting a certain amount of natural gas consumption for an energy-equivalent of hydrogen, natural gas costs are saved. The avoided natural gas costs can be calculated for the entire investment horizon of 15 years [57], using natural gas price forecasts, see appendix H.

CBA2.2 Avoided CO_2 cost
One of the measures to ensure that industries in the Netherlands meet the agreements from the Climate Agreement is the CO_2 tax. This tax is an amount of money that an industry with high CO_2 emissions must pay to the government per tonne of CO_2 emissions. In CO_2 tax rate predictions, the government has even increased the CO_2 tax rate on the industry in the upcoming years [65]. These predictions will be used in the model, see appendix H.

In the model, there are two different levels of CO_2-tax implemented, based on the amount of emissions. Industries emitting more than 50 Ktonne yearly pay more than industries below. Annual CO_2 emissions avoided due to hydrogen transition will be calculated using CO_2 emissions corresponding to the volume of natural gas avoided and the predicted CO_2 tax rate. Important to note is that only industries with an installation capacity above 20 MW have to pay CO_2 tax.

Additionally to CO_2 tax, companies in the Netherlands are obliged to pay energy tax for each cubic meter of natural gas and kilowatt hour of electricity used to the government [66]. Since the energy tax is part of the price paid for gas, the benefit of avoided natural gas consumption will already include this aspect in the modelling.

CBA2.3 Avoided EU ETS
The European Union Emissions Trading Scheme (EU ETS), created in 2005, is a carbon market for emission allowances within the EU which helps bring down EU emissions and generates revenue to finance the green transition. The number of emission allowances available is limited and the EU ETS cap of emission goes down every year. EU ETS-1 covers emissions from electricity and heat generation, industrial manufacturing, aviation and maritime sectors [67]. Based on the size of the plant, industries with a capacity above 20 MW have to pay for EU ETS emission allowances on top of the CO_2 tax. However, the price of the Dutch CO_2 tax can be deducted from the ETS price. EU ETS-2 requires fuel suppliers to monitor, report and hand in CO_2 emissions from their supplied fuels. If the fuel supplier delivers to sectors included in EU ETS-2, EU ETS will be charged on these fuels from 2027. The manufacturing sector with emissions from combustion of fuels in industry and combustion for the generation of electricity and heat for own use in these industries is included in EU ETS-2 [68]. In the model, it is assumed that the energy supplier charges the ETS to the customer (A16.

In short, EU ETS is a market for buying emission allowances. The quantity of available emission allowances is going to decrease over the years. Forecasts of the EU ETS price give an estimation of how the price will develop over time, see appendix H, to determine how much EU ETS an industry has to pay [69]. The EU ETS cap is simplified by assuming it is included in the allowance price (A15). The logic behind this is that there is a decreasing amount of allowances available due to the EU ETS cap of emissions, which as a result rises the price of the emission allowances due to scarcity.

5.1.3 Environment

The environment is the world outside the agents, containing all exogenous factors which cannot be influenced by the agents within the system, such as (government) policies [53]. Figure 8 shows the flow chart of the environment. In this model the stakeholders HDNO, HTNO, ministry of climate and energy policy and ACM are modelled as the environment. This means these stakeholders set the rules and policy options and assumes industry agents are not able to influence these policies (A27). The internal decision-making processes of stakeholders mentioned are not modelled in detail, as the primary interest of this research is in understanding how industries respond to different TPA regimes, rather than how for example the ministry decides on which regime to implement in national law, or how de HDNO decides by which rules they want to negotiate with industries. It reduces complexity in the model by focussing on how industry agents respond to these predetermined rules rather than also modelling the HDNO's internal process.

In the setup step of the environment, the setup of industries is called (create-region) and exogenous variables are set. In this model, several exogenous factors which are constant for all industries are set, such as the price forecasts, the time span of the model and conversion parameters for calculations.

In the go step of the model, the time is tracked. The model runs in time steps of one year. Furthermore, if there are any requests for connection of the industries, those are handled based on the policy in place, see 5.1.3. Firstly, it needs to be checked if the amount of industries meets the threshold set by the HDNO. As described in 4.2, network operators feel both a systemic motivation that hydrogen is needed to support the energy system by alleviating pressure on the electricity grid and social responsibility to facilitate energy transition. In addition, network operators have a financial motivation, which requires a viable business case with sufficient contracts and a minimum ROI. However, despite high investment costs for hydrogen infrastructure, these costs are still lower for network operators than the costs of reinforcing the electricity grid. Based on these insights, it is assumed the HDNO will establish the system connection and roll out the distribution network once three industries or more submit a request for a connection. Once the system connection is accessible, the threshold is set at one industry. No further financial threshold for the HDNO is considered (see A23).

If requests get accepted, construction is initialized. For simplification of the model, it is assumed nothing else happens if construction is happening (A22). Lastly, all KPIs are calculated and updated by the environment.

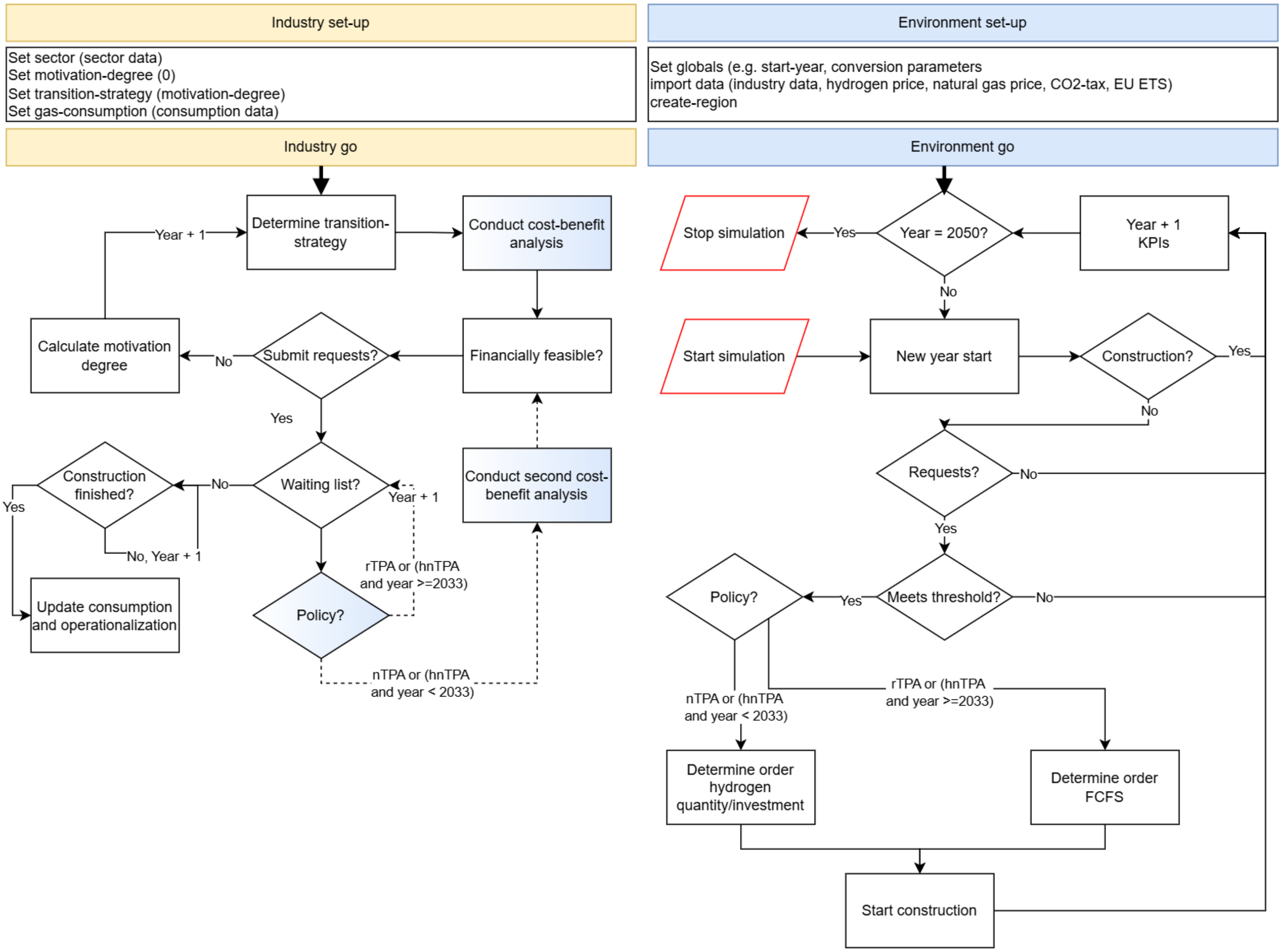


Figure 8: Conceptual model: flow chart of the agents and environment

Policies in the environment

The institutional mechanisms identified in section 2.4 regarding third-party access form three different scenarios for policy regimes in the model: regulated TPA, negotiated TPA and the form of hybrid negotiated TPA, indicated in blue in figure 6. Their corresponding timelines, which can be adapted from figure 3, are shown in figure 9.

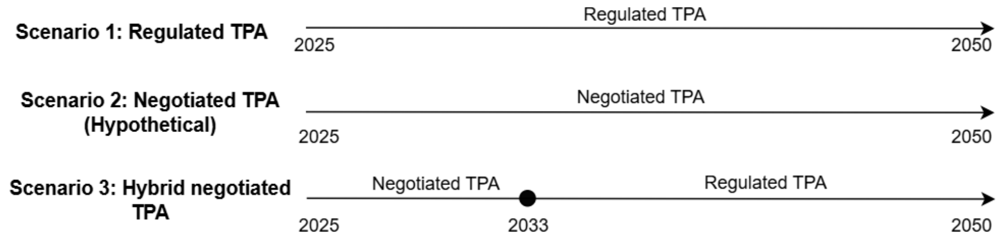


Figure 9: Third-party access timelines

Based on the interviews, different options to consider for HDNOs in the regime of nTPA or hnTPA have come to light, such as the prioritization order and additional contractual terms, see section 4.2, 4.3 and appendix C. Therefore, in this conceptual model, a selection of negotiation aspects will be simulated. Firstly, the connection order will be simulated. Where in rTPA the prioritization order is based on first-come-first-served, will nTPA be based on amount of hydrogen and grid investment. Here, priority is given to projects that require minimal grid investment while demanding larger quantities. Secondly, the investment cost division between HDNOs and customers will be simulated. Where customers pay the full cost of their own connection in rTPA, the costs will be spread between more evenly between HDNO and customer (see A37) in nTPA.

Important to note is that if too many industries request a connection at once, they are placed on a waiting list. This is where the second incentive comes into play. In rTPA, the prioritization of this waiting list follows a first-come-first-served approach. However, industries in nTPA can attempt to increase their hydrogen demand to move up the list or to avoid losing their place. They do this by setting an alternative transition strategy and assessing whether it is financially feasible through a revised CBA. The influences of the policies on the agent behaviour are indicated in the fading blue in figure 8.

At this point, one might question why industries do not always conduct two CBAs and choose retrofitting if it is financially feasible. The reason lies in the hesitation toward adopting new technologies and a general preference among Cluster 6 industries (as well as in the case study) to begin with a partial transition to hydrogen, blending it with natural gas (C.3, C.4). Therefore, it is assumed that industries only consider conducting an alternative CBA under nTPA if they are placed on the waiting list (A30).

It is important to note that the second scenario in figure 9, where nTPA is applicable for the whole simulation period, is hypothetical. As explained in section 2.4, the directive only gives the option of full rTPA (scenario 1 in figure 9) or hybrid negotiated TPA with the threshold date for switching from nTPA to rTPA (scenario 3 in figure 9). Nevertheless, as [44] noted, the directive does not distinguish between transmission and distribution level within hydrogen networks. This is however necessary, as more flexibility might be required at distribution level for accommodating different local situations. For that reason, it is valuable to see the influence of nTPA over a longer period and to see how the development of the distribution grid compares to the other scenarios.

Construction
The duration of construction is case-specific and depends on various factors, such as the capacity and budget of the HDNO. Based on EUD11 (see appendix B.3) from the EU directive, hydrogen network operators are allowed to refuse access to the hydrogen system based on the lack of

capacity or connection. Therefore, it is assumed industries will enter the waiting list until capacity is available (A24). To simulate construction, its capacity and the waiting list, it is assumed that constructing connections for four neighbouring industries takes two years, based on benchmarking of green gas fitters and an expert estimation. No more than four industries will be constructed at the same time. Constructing one industry or two industries near each other takes only a year. If three or more industries are more scattered, the construction takes three years. Lastly, if the system connection needs to be established, the construction takes an extra year (see A25).

5.2 Formalization

The conceptual model was translated to a formalisation by creating the model narrative: an informal description of the system under study, where the behaviour of each of the agents can be captured in a story which explains which agent does what with whom and when. This is necessary to ensure clear translation from concept to code [53]. The model narrative was developed using pseudo-code, which is provided in appendix E. In addition, the agent and model parameters and variables were formalized, of which a full overview including their types, values and descriptions is listed in appendix G.

As part of the formalization process, key performance indicators (KPIs) were selected and formalized to reflect both the system-level outcomes of the regional hydrogen market and the behavioural mechanisms embedded in the model (see table 4). These KPIs were designed to evaluate how different third-party access (TPA) regimes influence hydrogen uptake, industry decisions, and infrastructure outcomes in Cluster 6. They are derived directly from the conceptual model components and were used throughout the model experiments to compare the effects of TPA regimes and stakeholder behaviour in Cluster 6.

The KPIs can be grouped in four categories to clarify their relevance and link to the model's conceptual design:

- *Hydrogen off-take and CO_2 reduction*: this group captures the system's energy transition over time. These KPIs measure total hydrogen and natural gas consumption, the hydrogen-to-gas usage ratio, and cumulative CO_2 reductions. The indicators reflect the environmental objectives of the model and links directly to agent energy consumption profiles and emission parameters. Given the goal to measure the deployment of hydrogen, these KPIs are a fit measure to express the volume of natural gas, hydrogen and CO_2 reduction.

- *Pace of hydrogen transition*: this group reflects system-level dynamics, such as the number of transitioned industries, the year in which the final transition occurs, and the average waiting time between a connection request and actual connection. They are directly tied to TPA regime characteristics like prioritization order and system constraints such as annual construction capacity. Given the goal to measure the hydrogen deployment in a Cluster 6 case study under the different TPA mechanisms, these KPIs are a fit measure to measure the pace of the hydrogen transition and allow to compare how different TPA mechanisms score on this.

- *Transition choices of industries*: this group reflects individual decision-making strategies under the TPA regimes, such as the choice for retrofitting or mixing. It reflects how different behavioural inputs (such as motivation-degree, transition-strategy) combined with the policy in place shape strategic decision-making at the agent level. It allows to measure how the individual decisions from industries affect the hydrogen deployment in the region.

- *Cost for stakeholders*: these KPIs asses the economic implications of TPA regimes, especially of relevance for the HDNO. These KPIs track the allocation of infrastructure costs, both in absolute terms and as a share of total investment, as well as the cost-efficiency of hydrogen deployment (HDNO cost per kWh of hydrogen realized). These KPIs provide insight into how hydrogen off-take is reflected in invested costs. While this does not necessarily support a goal of the model, it does provide a more complete understanding of the system and its financial implications.

Table 4: Key performance indicators

`Variable`	**Type**	**Description**
Hydrogen off-take and CO_2 reduction		
`KPI-NG`	Float	Total amount of natural gas consumed in KWh.
`KPI-hydrogen`	Float	Total amount of hydrogen consumed in KWh.
`KPI-hydrogen-NG-ratio`	Float	Ratio of hydrogen used in the operationalization compared to natural gas.
`KPI-CO2-reduced`	Float	Amount of CO_2 reduced in the region.
Pace of hydrogen transition		
`KPI-#industries-transitioned`	Integer	Number of industries transitioned to hydrogen.
`KPI-final-transition-year`	Integer	Year all industries that are financially feasible are transitioned to hydrogen.
`KPI-average-waiting-time`	Float	Average time industries are in the waiting list, waiting for a connection to the network once a request is sent.
Transition choices of industries		
`KPI-#industries-mixing`	Integer	Number of industries transitioned to hydrogen with mixing as strategy.
`KPI-#industries-retrofitting`	Integer	Number of industries transitioned to hydrogen with retrofitting as strategy.
`KPI-avg-transition-strategy`	Float	Average strategy of industries to transition to hydrogen.
`KPI-avg-motivation`	Float	Average motivation degree of industries.
Costs for stakeholders		
`KPI-HDNO-costs`	Float	Total costs incurred by the HDNO for the network outroll.
`KPI-total-industry-connection-costs`	Float	Total costs for the connection incurred by industries.
`KPI-%-costs-borne-by-industries`	Float	Percentage of connection costs borne by industries (the total is the sum of connection costs for industries and the HDNO).
`KPI-HDNO-cost-per-kWh-hydrogen`	Float	Costs the HDNO has paid per kWh hydrogen realized.

5.3 Model implementation

After completing the conceptualization and formalization steps, the next step is to translate the model into the programming environment by coding. The programming environment used is Netlogo 6.4.0 software.

Figure 10 shows the NetLogo interface. On the left side, model inputs that are subject to change and candidate for experimenting are presented. On the right side, model outputs are depicted through monitors and graphs.

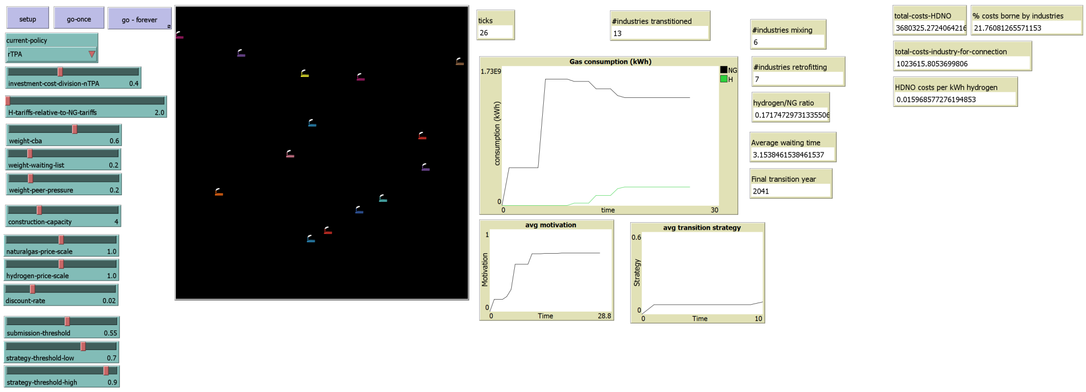


Figure 10: NetLogo Interface

The model is initialized by using the set-up button on the left. With the setup values from the input file are loaded, agents are created, parameters are assigned and other model variables are initialized as described in the conceptualization (5.1) and formalization (5.2).

5.4 Model verification

Verification was performed to verify whether the software implementation is completed correctly and the conceptualized and formalized concepts agent interactions and behaviours are accurately translated. From the verification it became clear the model behaves as intended. Several tests where conducted, such as the extreme condition of a hydrogen price of zero, where as a result the agents have a minimal OpEx, very high benefits and a positive, very high NPV. A full explanation of the verification results can be found in appendix F.1.

5.5 Model validation

Validation of model components was performed throughout the process by experts through close collaboration and after by literature, of which the complete results can be found in appendix F.3. The motivation degree factors can be compared to the core dimensions for sustainable decision-making by [70] of environmental/technical (CBA), economic (CBA, waiting list), and political/social factors (peer pressure, waiting list). The weight of CBA can be compared to the findings of [71], where CBA contributes significantly, but not exclusively to decision-making.

6 Experiments and results

The two experiments designed in section 3.4 are conducted with the model. The implication of the three TPA regimes and the effects of both negotiation terms implemented are explored. These negotiation terms are the different prioritization regimes, analysed in section 6.1, and the investment cost division in section 6.2.

6.1 Experiment 1: the impact of the prioritization order of TPA regimes

The first distinction between TPA regimes is the prioritization order. The nTPA regime follows a prioritization based on quantity and investment, while rTPA follows a prioritization based on first-come-first-served. The isolated impact of the prioritization order can be observed by setting the investment-cost-division-nTPA variable to zero.

The prioritization order under the different TPA regimes influences the energy consumption of industries. Figure 11 shows that a scenario where negotiation is allowed for the full timespan of the model (nTPA) results in higher hydrogen consumption among industries. This is due to the increased motivation due to the waiting list incentive, where industries aim for a higher position in the waiting list to transition quicker and to avoid high costs of e.g. EU ETS and CO_2 tax. Industries achieve this by increasing their hydrogen demand and switching from mixing to retrofitting, which means more CO_2 reduction can be achieved, as figure 12 indicates. From this, it can be concluded the negotiation policy has a desirable influence on the behaviour of industries.

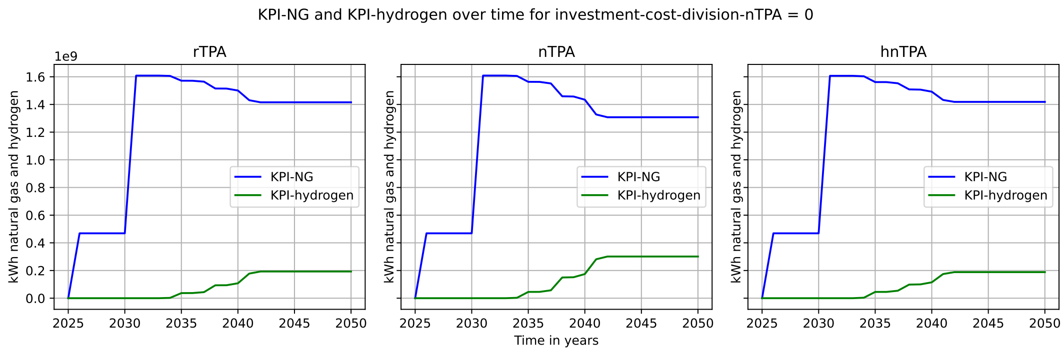


Figure 11: Experiment 1: impact of prioritization order on hydrogen and natural gas consumption of industries in kWh per TPA regime over time

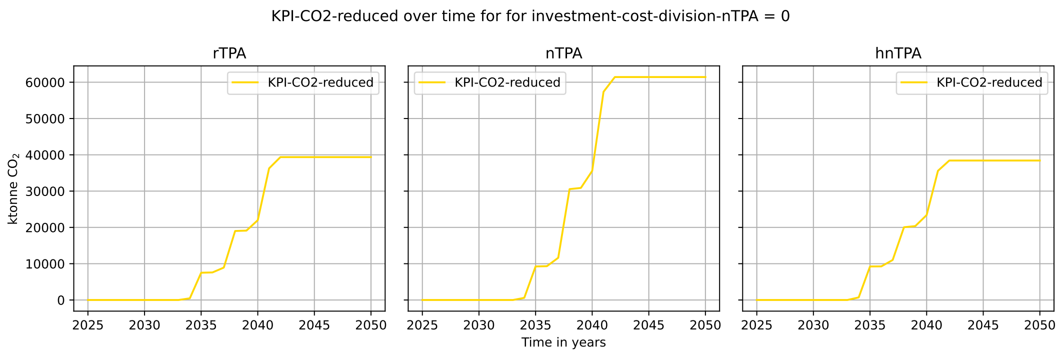
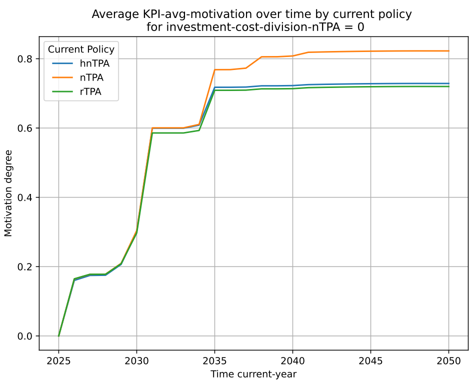


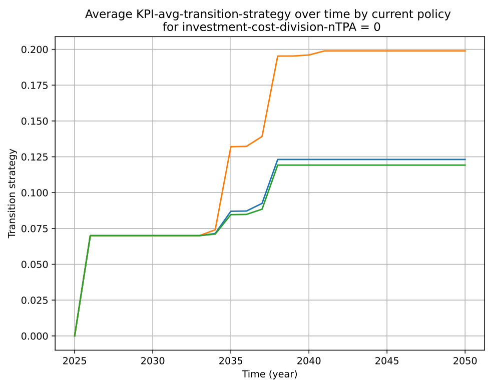
Figure 12: Experiment 1: impact of prioritization order on CO_2 reduction in ktonne per TPA regime over time

Remarkable however is that the hnTPA regime marginally affects the hydrogen demand in figure 11 and depicts only a short period of accelerating CO_2 reduction around 2034 in figure 12. This can be explained by figure 13, where the hnTPA and nTPA regime have a higher average motivation degree (MD) from year 2031 (figure 13a). However, the average MD does not mature enough before the switch from nTPA to rTPA for hnTPA in 2033 to reach a high enough MD to embrace a more ambitious transition strategy (figure 13b) and thus increase hydrogen off-take. This implicates policy makers should consider an extended negotiation period in hnTPA to encourage ambitious hydrogen adoption for a longer period of time and to stretch along with the maturing market and growing motivation.

Another notable aspect is that despite the higher hydrogen off-take for nTPA in figure 11, the starting point of the transition is not earlier for nTPA and hnTPA due to the too low MD in figure 13a as well. In the year 2030, the new industries with a high capacity enter, which increases the average motivation degree as these industries score better on the CBA. Since the CBA is the most weighted motivational factor, this defines the starting point of the hydrogen transition in the region. These results imply that the components of the motivation degree, such as the CBA-factor, do not have enough time to develop within the short nTPA phase of hnTPA. As a result, the hnTPA regime does not affect the behavioural thresholds as desired.



(a) Average motivation degree

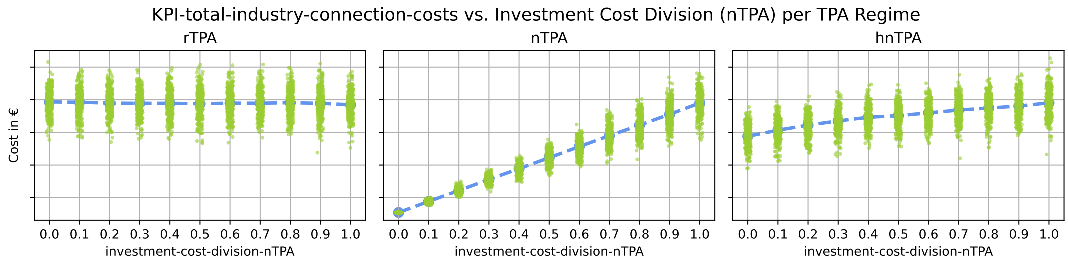


(b) Average transition strategy

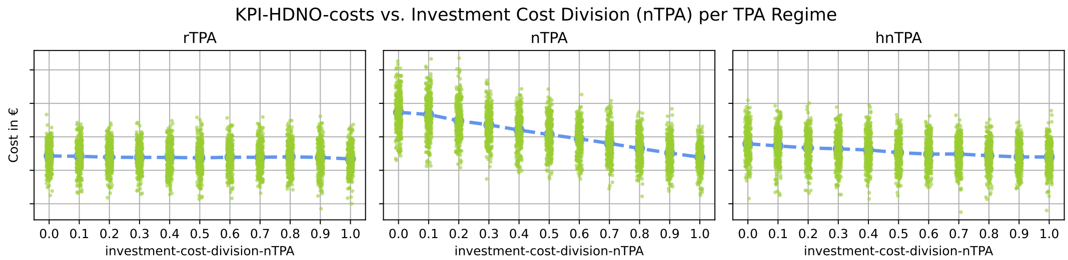
Figure 13: Experiment 1: the impact of prioritization order per TPA regime

6.2 Experiment 2: the impact of the investment cost division of TPA regimes

The second distinction between the TPA regimes is the difference in investment-cost-division-nTPA (cost division). A division of costs between the HDNO and the industry of e.g. 0.4 indicates the industry pays 40% of the variable connection investment, the HDNO 60%. Figure 14aa how these policies impact the cost for the industries, and figure 14bb for the HDNO. As the figure indicates, the higher the value of the cost division, the more the industries have to pay and the lower the cost for the HDNO. In the hnTPA regime, there seems to be a slightly visible trend over the cost division, which means that early-adopting industries bear the fruits of negotiation in its early phases.



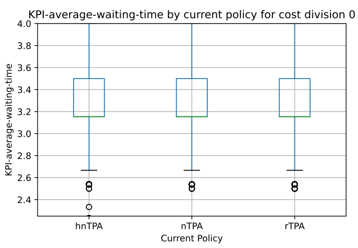
(a) Total connection costs for industries (CaPex)



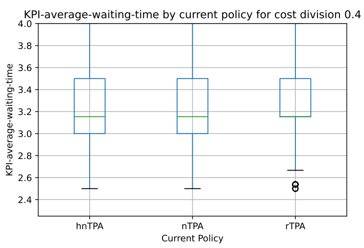
(b) Total connection costs for the HDNO

Figure 14: Experiment 2: stripplots of the infrastructure costs per investment cost division scenario for the TPA regimes

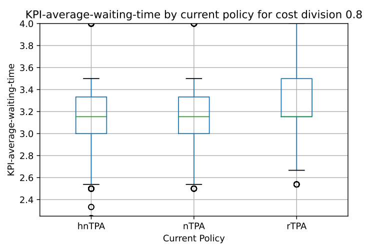
When researching how this investment cost division influences the pace of the hydrogen transition, figure 15 shows the average waiting time for a selection of cost divisions. Here, it can be derived that a higher cost division in nTPA and hnTPA results in shorter waiting times compared to the rTPA regime. While the median of the average wait time is 3.15 in each figure for each policy, the nTPA and hnTPA boxplot in figure 15b and 15c however show that a higher cost division results in lower inter-quartile ranges and thus lower average waiting times compared to the rTPA regime.



(a) Cost division = 0



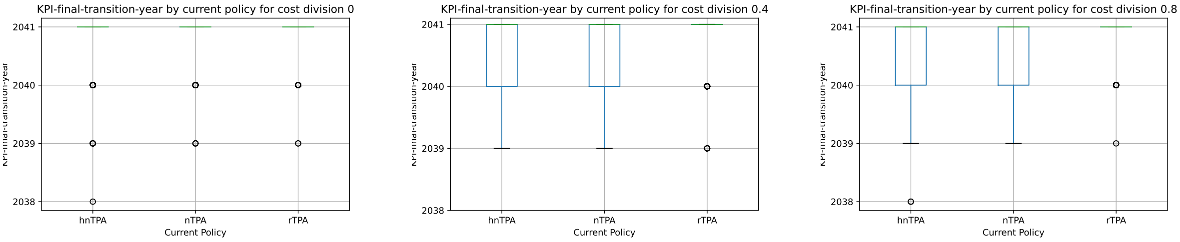
(b) Cost division = 0.4



(c) Cost division = 0.8

Figure 15: Experiment 2: boxplots of average waiting time for different values of investment-cost-division-nTPA per TPA regime

Figure 16 displays boxplots for the final transition year by policy. All policies show a median transition year of 2041, suggesting the region completes the transition right around 2041. In rTPA, this is even the only value in the inter-quartile range, the entire lower range of 2039-2040 is considered outlier territory. This indicates rTPA delays the transition compared to nTPA and hnTPA, where the inter-quartile range is lower. The regimes of nTPA and hnTPA appear to reflect that financial incentives speed up development of the regional industrial hydrogen market.



(a) Cost division = 0 (b) Cost division = 0.4 (c) Cost division = 0.8

Figure 16: Experiment 2: boxplots of the final year of transition for different values of investment-cost-division-nTPA per TPA regime

With regard to the pace of the hydrogen transition, the prioritization mechanism on its own has no influence and financial incentives due to the cost division play a big role. When industries bear the full connection cost (cost-division = 0), all three regimes show identical waiting times and transition years (figure 15a and 16a). In the case study, the new, financially good-looking industries entering in 2030 cause submissions to cluster due to the sudden motivation thresholds being met, leaving prioritization rules ineffective.

At moderate (0.4) and high (0.8) cost division, nTPA and hnTPA perform similarly, both significantly shortening waiting times and advancing completion compared to rTPA, which lacks negotiated cost advantages. This advantage is reflected in the number of industries transitioned over time (see figure 17), where both negotiation regimes outperform the regulated regime. The similar performance of nTPA and hnTPA indicates the short negotiation window from hnTPA is fruitful. Even though the switch to rTPA has no negotiation on prioritization order, its queue is being processed based on decisions made during the earlier phase. Combined with the cost division, the CBA and peer pressure factor from the motivation degree receive higher scores leading to advantageous results even after switching to rTPA. These findings suggest a cost division is beneficial to speed up the hydrogen transition in the region and essential to complement the prioritization mechanism.

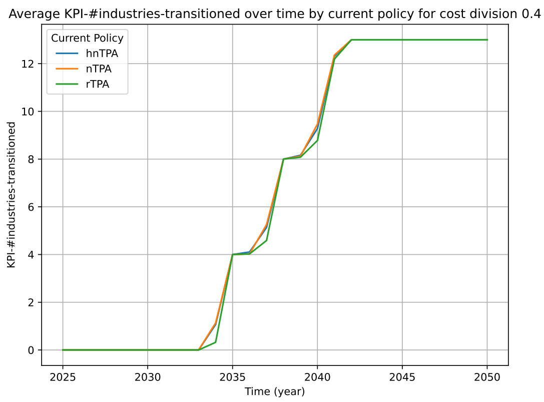


Figure 17: Experiment 3: Number of industries transitioned over time under each TPA regime with cost-division = 0.4

7 Sensitivity analysis

A sensitivity analysis was performed to assess the impact and robustness of model parameters. extensive results can be found in appendix F.2. Table 5 gives an the overview of the sensitivity analysis design, including what parameters were varied, what methods were used and what range of values were assigned during the sensitivity analysis.

The economic parameters were analysed due to the uncertainty in the energy market regarding the development of hydrogen prices. The construction capacity was chosen to see how this constraint impacts the model and to see how HDNOs can influence this. Sensitivity analysis of the behavioural parameters allows to explore how differences in industrial decision-making influence the pace and scale of hydrogen adoption. As stakeholder behaviour under third-party access regimes is highly uncertain, testing these behavioural parameters helps evaluate the robustness of the model outcomes and identify which behavioural parameters might accelerate the transition in practice.

Table 5: Overview of the sensitivity analysis design

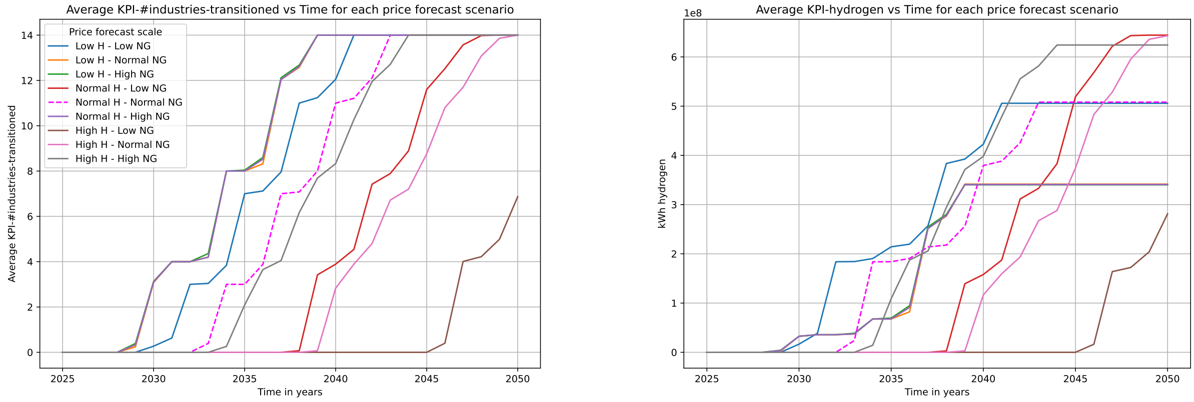
Parameter	**Method**	**Given value**	**Range**
Economic parameters			
naturalgas-price-scale, hydrogen-price-scale	Scenario	1, 1 (see appendix H)	+/- 20% from base value
HDNO parameters			
construction-capacity	OFAT	4	[0, 14], increments of 1
Agent behavioural parameters			
weight-CBA, weight-peer-pressure, weight-waiting-list	Scenario	0.6, 0.2, 0.2	[0, 1], increments of 0.1, where the sum of all weights is 1.
strategy-threshold-low, strategy-threshold-high	Scenario	0.7, 0.9	[0.1, 1], increments of 0.1, where strategy-threshold-low < strategy-threshold-high.
max-distance-peers	OFAT	10	[0, 800], increments of 100

Sensitivity analysis of the energy prices

Uncertainty in hydrogen and natural gas prices was tested by scaling forecasted prices by factors of 0.8, 1.0, and 1.2, creating nine price scenarios (see figure 18). Results show that while adoption slopes remain relatively similar, the timing of transitions is highly sensitive to the relative price of hydrogen versus natural gas (figure 18a). Cheaper hydrogen relative to gas (e.g., low H, high NG) accelerates transitions, whereas expensive hydrogen delays adoption. This confirms that relative price competitiveness, not absolute hydrogen cost, is the main driver of transition timing.

However, faster transitions do not always lead to higher hydrogen off-take (figure 18b). Due to model assumptions limiting post-transition strategy updates (A29), delayed but more ambitious transitions can result in higher cumulative hydrogen demand.

The price sensitivity analysis highlights the crucial role of the energy price in shaping transition dynamics. Future improvements of the model could benefit from allowing dynamic strategy updates after initial transition to better capture real-world investment behaviour.



(a) Number of industries submitted request over time

(b) Amount of hydrogen over time

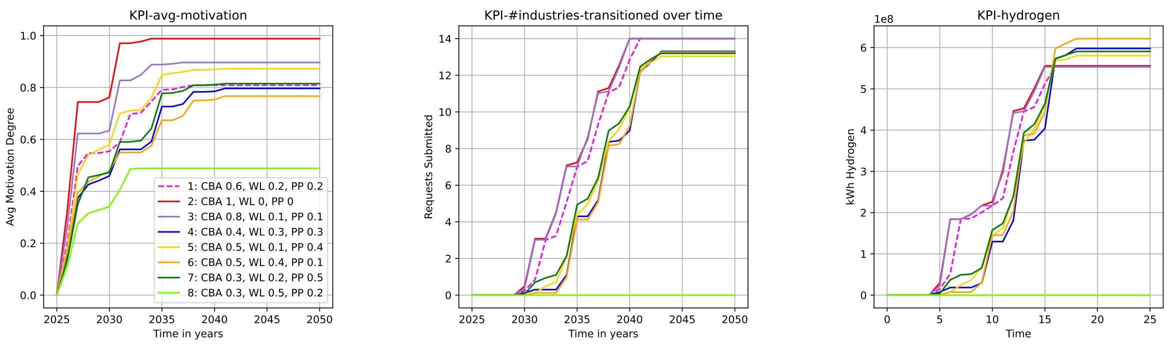
Figure 18: Sensitivity analysis of different price forecast scenarios

Sensitivity analysis of the HDNO parameter

The variable construction capacity, representing the maximum number of connections that can be constructed simultaneously, was varied to assess its impact on transition speed. Higher capacities lead to faster early transitions, but do not significantly change the final end-point of hydrogen transition within the system modelled. The appears to be a saturation point in the model, beyond which additional capacity has limited impact, as motivational thresholds are not reached earlier in the process. This indicates that while infrastructure expansion accelerates early adoption, stimulating behavioural motivation ultimately influences full system transition. For HDNOs, increasing capacity should be paired with measures to stimulate early demand.

Sensitivity analysis of behavioural parameters

The sensitivity analysis of motivation weights shows that the pace of hydrogen transition is strongly influenced by how much weight industries assign to cost-benefit analysis (CBA), peer pressure (PP), and waiting list (WL) position. Scenarios with a higher CBA weight result in faster transitions (figure 19a, 19b), as agents base decisions on internal financial feasibility rather than waiting for external signals. In contrast, scenarios where waiting list or peer pressure have more weight lead to delayed transitions, reflecting industries' dependency on others' behaviour.



(a) Average motivation degree over time

(b) Number of industries transitioned over time

(c) Amount of hydrogen over time

Figure 19: Sensitivity analysis of different weight combinations

While differences in transition timing are significant, the total hydrogen off-take across different weight combinations remains relatively close (figure 19c), suggesting that delayed transitions can still result in substantial hydrogen demand once adoption occurs.

These results imply that economic feasibility remains the primary driver of early adoption, but behavioural incentives such as enhancing peer visibility or using waiting lists strategically could help accelerate the transition. For HDNOs and policy makers, this highlights the importance of not only improving hydrogen's economic competitiveness, but also creating behavioural signals that encourage industries to move earlier.

Influencing behavioural signals can have significant impact on the motivation of industries, as the sensitivity analysis of the parameter max-peer-distance showed. This variable defines the maximum range within which industries perceive other industries as their peers. In scenarios with smaller peer ranges, the motivation degree is significantly lower compared to the scenarios with broader peer networks. This suggests that too narrow a reference group weakens the social reinforcement effect. Therefore, policies or communication strategies that focus on behavioural signals such as enhancing the visibility of hydrogen projects within the regional clusters could amplify the positive feedback loops essential to accelerate early hydrogen adoption.

Other behavioural parameters analysed are the strategy thresholds at which industries switch from conservative to ambitious hydrogen transition strategies. This analysis shows that lower strategy thresholds enable industries to adopt a more ambitious strategy early on, leading to significant higher hydrogen consumption. The analysis of the submission threshold, the threshold which defines the minimum motivation degree industries must reach in order to request a hydrogen transition, showed that higher thresholds delay transitions and reduce the number of industries adopting hydrogen.

These results implicate that the model is highly sensitive to the different threshold settings, especially in determining long-term hydrogen demand. It shows early-mover incentives are critical to ensure ambitious hydrogen strategies and an early take-off of the hydrogen transition.

8 Discussion and reflection

This chapter discusses and reflects on the academic relevance of this research in 8.1. The significance of research for stakeholders outside the academic world is described in 8.2. Lastly, a reflection on the use of artificial intelligence is given in 8.3.

8.1 Academic reflection and insights

The literature review in section 1.2 highlighted a significant gap in the understanding of how regulatory frameworks, such as TPA regimes, influence stakeholder behaviour and hydrogen deployment at the regional level. Existing research predominantly adopts a techno-economic perspective [15], [17]–[20], focusing on cost optimization and economic feasibility of hydrogen technologies. Realistic stakeholder behaviour, such as industry decision-making beyond cost and demand and the role of the network operator in current literature is limited [16]–[18], [20], which needs future research [22]–[24]. [21] states behavioural, institutional and political barriers have been largely ignored in literature related to hydrogen.

This study addresses this gap by exploring the implications of different TPA regimes on the development of regional hydrogen markets, specifically within a Cluster 6 case study in the Netherlands. The research employs a comprehensive methodology that includes desk research, expert interviews, and agent-based modelling to simulate the effects of different TPA regimes. This approach provides a deeper system understanding of how TPA regimes can be structured by HDNOs and how the regimes influence the complexified behaviour of stakeholders and the pace of infrastructure development.

The new academic insights gained from this study contribute to the academic debate by adopting a socio-economic perspective, demonstrating how regulatory frameworks, specifically TPA regimes, influence stakeholder behaviour and hydrogen transition outcomes. This study examined how negotiation in TPA regimes can be structured by HDNOs, giving system operators a significant role in the research compared to previous literature. The industries were complexified by attributing the motivation degree and decision choices of industries, which and contributes to the gap of simplified stakeholder behaviour.

8.2 Societal relevance beyond the case study

The findings from the Cluster 6 case study provide valuable insights, of which several recommendations can be made for system operators and network operators (sections 8.2.1 and 8.2.2). These valuable insights from the Cluster 6 case study can be generalized to other Cluster 6 regions or countries with similar characteristics in industrial areas, such as high temperature energy demands, emerging hydrogen networks and regulatory frameworks that influence stakeholder behaviour. The dynamics observed in Cluster 6, such as the impact of TPA regimes on hydrogen adoption and the role of HDNOs in shaping market expectations, are likely to hold in broader contexts where similar conditions exist. The regulatory and financial uncertainty found in this case study hold in the case study's province and likely other regions as well, as became clear in the interviews (C.4). The behavioural and institutional findings of this study highlight the importance of well-designed regulatory frameworks such as TPA regimes, supportive financial conditions, and governance clarity in accelerating the hydrogen transition. These insights can inform policymakers and system operators in other regions or countries to design regulatory frameworks that respond to behavioural incentives and are economically efficient.

However, several model assumptions and case-specific circumstances limit the generalization of the findings from the Cluster 6 case study to other Cluster 6 regions and beyond. For instance, the model assumes a homogenous population of industries within the case study, which may not reflect the diversity of industrial profiles in other regions or countries. In addition, the case study begins with a few industries and expands the industrial area in 2030, resulting in a region with 14 industries. The size of the industrial area in number of industries and the size of their energy demand might differ in other regions as well, which affects the influence of peer pressure in the region and the thresholds for HDNOs to start constructing the hydrogen network. Moreover, this case study presents fortunate circumstances for constructing a hydrogen network, such as closeness to the hydrogen backbone and relatively nearby industries in the region. These circumstances may not present in other case studies, which may be located further away from the backbone. There, local supply is needed in order to establish a regional hydrogen network, which is not taken into account in this model.

8.2.1 Recommendations for system operators

System operators, specifically the hydrogen distribution network operator, play a central role in enabling and accelerating regional hydrogen transition. Next to their technical role of building and operating infrastructure, HDNOs shape market expectations and triggering positive feedback loops due to the HDNO's responsibility to shape the negotiation terms for access conditions in the nTPA and hnTPA regime. The findings of this study serve as a grounding for some HDNO recommendations.

Use negotiation terms to incentivize ambitious transition strategies
In nTPA and hnTPA regimes, HDNOs can shape industrial behaviour through the design of access rules. Introducing prioritization based on volume has proven to be a motivator for industries to opt for larger-scale transitions. Introducing criteria for a prioritization mechanism can create a competitive dynamic, which can stimulate regional hydrogen transition.

Target rollout towards visible early adopters for peer pressure effects
HDNOs should start their exploration for hydrogen infrastructure development in regions with high visibility to other industries. As peer pressure is a strong behavioural motivator, early connections in central and visible areas can generate spillover effects across the network.

Improve perceived access by communicating expansion plans
Other ways to improve visibility of hydrogen transition include communication of hydrogen projects and expansion plans. Again, visible commitment from other stakeholders can have a positive influence on the peer pressure.

Advocate for price support and consider partial cost absorption
Relieving industries from connection costs by dividing investment costs has proven to be an effective measure to accelerate hydrogen transition. In addition, hydrogen price scenarios heavily influence adoption. This implicates HDNOs should coordinate with governments to advocate for price guarantees or subsidies. Where feasible, HDNOs (especially DSOs with broader energy system responsibilities) could consider absorbing a greater share of initial connection costs to reduce the burden on first movers and make hydrogen more attractive compared to grid electrification.

Design waiting list mechanisms to trigger competition
Limits on construction capacity can be used as a behavioural lever. The waiting list pressure, as shown in the model, encourages industries to influence their own pace of hydrogen transition and act more ambitiously. HDNOs should ensure the queueing systems and construction capacity constraints are designed transparently to support fair but motivating competition for access.

Reduce uncertainty through transparent roles and rules
In the current early phase of designing the governance for regional hydrogen networks, HDNO roles and responsibilities remain unclear as the interviews indicated. By providing the intentions of access conditions, cost-sharing structures, and infrastructure development strategies, DSOs can build trust and lower adoption barriers, even with the absence of complete regulation and an assigned HDNO. DSOs can support this by maintaining open communication with the industries and local governments.

Altogether, these findings suggest that the HDNO is not just a passive infrastructure provider, but a strategic actor who can steer dynamics through institutional influence, behavioural insight and proactive communication. By adopting a proactive stance that responds to behavioural signals within the regulatory framework in place, system operators can play a decisive role in accelerating the hydrogen transition in a socially inclusive and economically efficient.

8.2.2 Recommendations for policymakers

Scenario-based price guarantees
To address the high sensitivity of hydrogen adoption to the energy prices of hydrogen and natural gas, a scenario-based price guarantee could be implemented. This aims to reduce financial uncertainty and feasibility for industrial users, which can help to bringing forward the starting point of the hydrogen transition and lower the threshold for industries to adopt a more ambitious transition strategy.

Increase visibility of hydrogen transition plans in Cluster 6 areas
Peer pressure is a strong behavioural driver, but it depends on visibility, as the sensitivity analysis showed. Policymakers and HNDOs should facilitate this visibility by supporting platforms or regional hydrogen project plans, connect industries in transition dialogues and make early movers visible. This can strengthen the peer influence and create a positive feedback loop for hydrogen adoption.

Consider an extended negotiation regime on distribution level
To encourage ambitious early-phase hydrogen adoption and bear the fruits of negotiation, it should be considered to extend the nTPA timeline for the hybrid negotiated TPA regime. As the model showed, the hnTPA regime has positive influence on the timeline of the hydrogen transition. However, the flexibility nTPA offers on long term has desirable impact on the hydrogen off-take in the region as well. By extending the period of nTPA, significant impact in later phases of the hydrogen transition could be seen as well.

Support flexible prioritization rules in early-phase access regimes
In the period before rTPA becomes mandatory, the Ministry should encourage HDNOs to adopt transparent prioritization rules that reward e.g. high-volume and low-cost projects. Other prioritization mechanisms should be explored as well. The negotiation terms should encourage economically sound adoption and help HDNOs maximize impact within limited construction capacity.

Trigger more ambitious strategies through targeted behavioural levers
Further revelation of the sensitivity analysis include that the hydrogen off-take is highly influenced by behavioural thresholds, specific points at which industries commit to more ambitious strategies. Policymakers should support instruments that lower these behavioural thresholds, aiming to persuade hesitant actors to transition earlier and to choose a more ambitious strategy.

8.3 Reflection on the use of artificial intelligence in the research

The availability of AI tools offers new opportunities in academic research. Generative AI (ChatGPT) was used during this thesis as a supportive tool to enhance efficiency and clarity, without replacing critical thinking. It proved useful for verification and debugging in NetLogo, refining Python scripts for figures, and solving LaTeX formatting issues. In the modelling and writing phases, AI served as a sparring partner to structure ideas, "initiate a train of thought" and improve phrasing when needed. These contributions supported the research process by saving time and allowing me to focus on more valuable aspects of the research, while all analyses, interpretations, and final decisions remained within my own responsibility as the researcher.

9 Conclusions

This research aims to bridge the knowledge gap in the development of regional industrial hydrogen markets, focussing on the influence of third-party access (TPA) regimes. It researches behaviours and challenges encountered by industries within Cluster 6, the decentralized regional system which fall outside the five main industry clusters in the Netherlands. It seeks to explore how the different TPA mechanisms might speed up or delay regional transition to hydrogen. It aims to provide insight into how industries respond to these regulatory differences and how network operators and policy makers can anticipate on this.

9.1 Answering the research questions

Sub-question 1: What different institutional mechanisms regarding third-party access applicable to Cluster 6 can be identified?
Third-party access refers to access to (hydrogen) infrastructure by parties who do not control the concerning infrastructure. According to the European Hydrogen and Gas Decarbonisation Package, Member States are allowed to implement different forms of TPA. The Decarbonisation Package distinguishes several forms of TPA regimes for hydrogen, ranging from *regulated* third-party access (rTPA), whereby the national regulator sets tariffs and access conditions, to *negotiated* third-party access (nTPA), whereby the hydrogen network operator and its customers are free to determine tariff and access conditions by negotiations. The middle form is *hybrid negotiated* third-party access (hnTPA), where nTPA holds first, and then rTPA. It seems however that permanently ongoing nTPA is not an option.

Interviews revealed that experts predict a hnTPA regime will hold for distribution level in Cluster 6 where the regime will switch from nTPA to rTPA from 1 January 2033, as the Minister of Climate and Energy Policy had indicated his intention to make use of the same option on transmission level. During the nTPA phase on distribution level, negotiation will take place on several aspects. One aspect is the prioritization order, which defines in what order Cluster 6 industries will be connected. In contrast to *first come, first serve* under the rTPA regime, alternative prioritization methods could be implemented during nTPA, such as prioritizing projects with high hydrogen demand and low infrastructure costs, or development based on most efficient grid architecture. A second aspect for negotiation is additional aspects in the contract, such as the division of investment costs, discounts for constant off-take, spread of development costs over time or contract durations. However, negotiation on fundamental contractual terms is less likely, as drastic changes once rTPA applies are undesirable.

Sub-question 2: How do third-party access regimes shape the rights, constraints and strategic decision-making of key stakeholders in Cluster 6's hydrogen market?
Third-party access regimes, particularly nTPA, significantly shape the rights, constraints, stakeholder interactions and strategic decision-making of key stakeholders in Cluster 6's hydrogen market. While these mechanisms introduce opportunities for strategic collaboration and flexible market development, they also introduce regulatory uncertainties around regulatory clarity of cost allocation and stakeholder roles. This limits the ability of actors to make confident decisions, ultimately delaying hydrogen infrastructure development and adoption.

The analysis of TPA regimes revealed that hydrogen distribution network operators (HDNOs) gain flexibility under nTPA to set their conditions for negotiation, such as the prioritization methods and cost-sharing agreements. This allows them to align development with technical efficiency and economic viability, rather than restrictive access rules (e.g. first come, first served). Likewise, industries gain space to engage in negotiations around infrastructure costs, contractual durations and connection terms, especially benefitting early movers willing to invest in hydrogen early on.

Ministry of Climate and Energy Policy and ACM are tasked with regulatory oversight by ensuring transparency, collaboration and balanced market conditions. Despite these formal rights, interviews revealed two unresolved key challenges on distribution level, impacting the behaviour of stakeholders and the progress of the regional hydrogen development: uncertainty regarding stakeholder roles and uncertainty regarding financial responsibilities. No formal designation exists for HDNOs, and regulations primarily focus on hydrogen transmission network operators. Simultaneously, it remains unclear who will bear the high costs for hydrogen infrastructure and connections, causing hesitation among industries considering hydrogen adoption.

These uncertainties shape stakeholder strategies. DSOs are preparing for a possible HDNO role, positioning themselves in anticipation of future legislation about potential HDNO responsibilities. The municipality in the case study plays recognizes the importance of a supportive policy environment and has taken on a coordinating and facilitating role. It aims to create favourable local conditions to attract industries that match the energy profile and sustainability and regional goals of the municipality.

Industries, in contrast, remain cautious. Regulatory and financial uncertainty discourages early investment, especially among early adopters who rely on the commitment of individual industries for success of the project. The industries often favour hybrid solutions that combine hydrogen with other energy sources to mitigate risks. Rather than committing fully, hydrogen is often treated as a secondary or backup option, dependent on future price competitiveness and a stable regulatory landscape.

Sub-question 3: How can the key system components of the regional hydrogen market system Cluster 6 be modelled?
The key components of the regional hydrogen market system in Cluster 6 can be modelled through an agent-based modelling framework that captures the interaction between industrial stakeholders, TPA regimes and HDNO-led infrastructure development, to assess how targeted interventions and TPA regimes can guide regional decarbonisation under uncertainty.

Central to the system are potential industrial hydrogen users and the regional hydrogen infrastructure, including the distribution grid, system connection, and inflow from the national backbone. In the environment at the system boundary are TPA regimes and associated policy instruments. TPA regimes are modelled as external scenarios that fall outside agent control but influence their opportunities, constraints and decision-making. External factors such as energy price forecasts, the EU ETS, and Dutch carbon tax are included, while national hydrogen production and non-industrial demand are excluded to maintain focus on regional dynamics.

At the core of the model are industrial agents whose decisions to adopt hydrogen are based on a motivation degree. This is calculated using a weighted combination of three behavioural factors identified: economic attractiveness via cost-benefit analysis, social influence through peer pressure, and infrastructural access as reflected by waiting list pressure. Strategic behaviour is also shaped by threshold values that determine when agents adopt more ambitious hydrogen transition strategies, based on patterns observed in interviews.

A key role is played by the HDNO, a rule-based institutional actor responsible for infrastructure planning and rollout. While not an agent in the traditional sense, the HDNO sets connection rules based on the TPA regime in place and expands the network in phases based on construction capacity, indirectly shaping agent behaviour through waiting list pressure and access limitations.

Sub-question 4: How do different third-party access regimes affect hydrogen deployment in the Cluster 6 case study?
The results indicate that the third-party access regime plays a central role in shaping both the speed and scale of hydrogen deployment in Cluster 6. Industries' ability to successfully join the hydrogen network and the pace at which they do so is shaped by both institutional rules and behavioural dynamics.

Across all regimes, nTPA yields the most favourable outcomes for hydrogen off-take and CO_2 reduction. This is driven by the prioritization mechanism, which incentivizes more ambitious transition strategies among industries. Allowing nTPA, or an initial negotiation window in hnTPA, rewards larger, cost-efficient projects with prioritized access, resulting in higher hydrogen demand and greater CO_2 reduction compared to rTPA. However, the motivation of industries in hnTPA does not seem to develop enough under the early nTPA phase to profit from the ambitious behaviour negotiation allows, resulting in much lower hydrogen off-take compared to nTPA.

Regarding the pace of hydrogen transition, agents can only influence their individual pace under the negotiated prioritization. The waiting list mechanism implemented by the HDNO encourages industries to adjust their hydrogen demand to pass other industries in the queue and receive a connection earlier. However, this incentive does not affect the average waiting times, the final year of transition, or the starting point of transition.

This suggests that prioritization alone does not trigger earlier or faster transitions. The phenomenon might also be attributed to the case study context: in early years, too few industries industries reach the submission threshold to trigger network expansion. When new, financially stronger industries enter in 2030, connection requests cluster due to capacity constraints, reducing the effectiveness of prioritization. Another explanation is that industries in the model do not submit early to skip the queue, but only respond once placed on it.

The pace of hydrogen off-take is mainly driven by the investment cost division. Under the cost negotiation terms, industries are partially relieved of investment costs, resulting in lower average waiting times and an earlier final year of transition on average. The similar performance of nTPA and hnTPA on these KPIs indicate that the highest impact of cost division is in the early years and the short negotiation window from hnTPA is effective. Although the rTPA phase of hnTPA lacks prioritization negotiation, its queue is processed based on earlier decisions. Combined with the cost division, this leads to stronger CBA outcomes and peer pressure effects early on, enabling solid results even after switching to rTPA.

Sub-question 5: What are possible additions to and fillings of the regulatory framework of third-party access that will support the hydrogen transition of Cluster 6?
The findings of this study suggest that while third-party access regimes with negotiation provide institutional flexibility and grants the opportunity for hydrogen distribution network operator to implement incentives for ambitious industrial transitions, they are not sufficient on their own yet. To enhance the effectiveness of TPA regimes in supporting hydrogen deployment, several additions to the regulatory framework are recommended.

Firstly, policymakers should clarify the roles and responsibilities of regional actors involved in hydrogen distribution, particularly the designation of a HDNO. Legal and financial uncertainty, such as unclear (cost) responsibilities between the government, industries, and HDNOs, currently hampers investment decisions and delays transition. Clearer allocation of these responsibilities would reduce hesitation among stakeholders and improve early-stage decision-making. In addition, an extended negotiation regime in hnTPA should be considered, to encourage ambitious hydrogen adoption for a longer period of time and to stretch along with the maturing market.

Secondly, system operators should design prioritization and cost-sharing schemes that reward ambitious projects while ensuring predictability and transparency. For example, connection prioritization based on hydrogen demand and grid efficiency, could motivate industries for quicker and more ambitious transition, as demonstrated in this study. Taking social responsibility by introducing different cost division models as tested could take away financial uncertainties and further stimulate uptake without overburdening industries.

Finally, both key stakeholders could integrate behavioural incentives into the negotiated TPA framework to enhance the motivational impact of institutional mechanisms. These include visibility-enhancing measures such as public commitment from early adopters, transparent rollout planning by the HDNO, and transparent prioritization mechanisms. Such additions could strengthen peer effects and motivation degrees in the early years, as sensitivity analysis showed a large network of peers and high visibility within the regional industrial area can amplify the positive feedback loops to accelerate early hydrogen adoption.

Main research question: To what extent do third-party access regimes of hydrogen distribution network operators affect the hydrogen transition of Cluster 6?
This research shows that third-party access regimes significantly influence both the speed and scale of hydrogen adoption in within the case study of of the Cluster 6 area. The flexibility introduced by nTPA and hnTPA regimes enables strategic behaviour among industries, such as increasing hydrogen demand to secure earlier access. When supported by partial investment cost relief, these mechanisms lead to faster and more substantial hydrogen deployment compared to the more rigid rTPA regime. The hnTPA regime introduces temporary flexibility but fails to significantly outperform rTPA due to persistent high hydrogen prices and insufficient motivation among industries in the early years.

Overall, TPA regimes and the negotiation terms implemented strongly affect both the behaviour of stakeholders and the pace of infrastructure development. However, flexibility in (hybrid) negotiated TPA regimes alone does not guarantee success: economic feasibility, economic security and role clarity are crucial enablers. The findings highlight that a well-designed TPA regime influencing behavioural dynamics, when coupled with supportive financial conditions and governance clarity, can serve as a powerful driver of regional hydrogen transitions in Cluster 6.

9.2 Limitations and future research

Literature availability
As the roll-out of hydrogen infrastructure is relatively new in the Netherlands and Europe, not much academic literature is available on the topic, specifically on the niche topic of roll-out of regional industrial hydrogen networks and the behaviour of stakeholders and institutional mechanisms in relation to this topic. On the one hand, this shows the relevance and uniqueness of the study. On the other hand, this limits the academic sources or the available literature on regulation of this topic, as it does not exist yet. This makes it more challenging to create a model close to reality and lowers the certainty and reliability of the model.

Noteworthy is the usage of the Decarbonisation Package as a basis for the third-party access regimes modelled in this research, where the regulation and directive do not distinguish legislation between transmission and distribution hydrogen networks yet. As TPA regulation for distribution networks is still under development, the desk research can only reflect current proposals or drafts, not established practices. Future research might await more legislative certainty from the EU and Dutch national government to be able to specify the institutional mechanisms of TPA with more reliability and security.

Interviews
Although interviews partly remedy the lack of literature, this method has its limitations regarding the size of the stakeholder group. While the interviewed group is diverse and both of the most important stakeholders in this study are represented (DSOs who desire to become HDNOs and industries through Cluster 6 and municipality), the size of the interview group may limit the representativeness of the findings. While valuable insights were obtained, a broader sample would improve the generalizability and help ensure that a wider range of perspectives are captured.

However, this thesis applied a comprehensive methodology of analysing literature, conducting interviews and building an agent-based model, all within the limited time scope of a MSc thesis. This requires an allocation of time and resources, thus the choice was made to spend more time on the main modelling methodology part of the study. The time constraint combined with the limited availability of some stakeholders, mostly the unavailability of industrial stakeholders within the case study for individual interviews due to busy schedules of the companies, explains the shortcoming. However, in future work, more in-depth expert interviews should be added to have a larger and more complete stakeholder recruitment and create a more comprehensive understanding of the stakeholders.

Uncertainties from interviews
Some uncertainties arisen from interviews are left out of scope of decision-making in the model, such as the uncertainty of stakeholder roles. This uncertainty however has major implications for the regional industrial hydrogen transition. Another noteworthy uncertainty from interviews is the construction of the national backbone. Currently, there are no plans to integrate regional system connections.

These uncertainties fall outside the model but influence key preconditions, which may limit the applicability of the model outcomes to real-world decision-making. Therefore, further research could focus on how to coordinate a system connection for regional distribution networks. In addition, it should focus on clarity of stakeholder roles and financial responsibility in the development of hydrogen networks, such as the role and responsibility of the national government, municipality and companies and the suitability of DSOs or other parties such as HyNetworks to become HDNO.

Case study
Another important limitation of the study is the availability of case studies. As only one case study meeting the requirements was available and chosen as an input for the model, not all results are directly generalisable to the population in Cluster 6. In addition, part of the agents in the agent-based model are based on the assumption of the municipality that the industrial area will grow, which is uncertain. This assumption seemed to cause a cluster of submissions due to the financially attractive new industries in the results, which might make it more difficult to distinct the effects of the negotiation terms.

Furthermore, the industrial area has homogenous industry profiles, as all industries are in the agrifood and food processing sector with the exception of one industry in the agricultural sector. Therefore, the choice was made to create homogenous industry profiles. This might not reflect reality, as the agricultural company has a large capacity and a different temperature demand than the food industries, which impacts the suitability of hydrogen as decarbonizing energy fuel.

Future research should focus on gathering additional case studies and create more diverse profiles of industries and their sectors, to create more diverse applications types besides thermal application, such as raw material and power generation. This will make the results more generalizable to and insightful for the rest of Cluster 6 and give insight in how the application of hydrogen and thus the demand and motivation affects the development of the region.

Industry agents
In future research, the behaviour of industries in the model could be made more complex as well. In this research, an attempt was made to complicate stakeholder behaviour in hydrogen simulation models aside from demand profiles by introducing more complex decision-making. However, in an attempt to decarbonize, only hydrogen was offered as an option, while more decarbonization technologies are available. In addition, more actions could be taken aside from switching an energy percentage to hydrogen, such as using hydrogen as a back-up source only or moving away as an industry to a country as mentioned in the interviews. Moreover, natural gas consumption profiles were assumed constant over the years, but realistic fluctuations here could be added as well.

Currently, the industry agents are modelled similarly due to the homogenous population in the case study, as mentioned before. In addition, the new industries arising in 2030 have a homogenous natural gas consumption profile as described in the interviews. This results in comparable behaviour among these industries, as their cost-benefit analysis shows feasible outcomes around the same time. In addition, the incentives now used in the motivation degree consisted of the waiting list, peer pressure and cost-benefit analysis only. In future research, agent characteristics could be made more complex, by introducing more diverse industry profiles and considering more factors in the decision-making and options for decarbonization as well.

Finally, the model only considers the first step of transition to hydrogen from the industry and does not allow for industries to grow in hydrogen demand after several years. Since hydrogen is in its infancy, focusing on the first transition is valuable given that this is where the focus for HDNOs and policymakers currently lies. In doing so, the model avoids 'predicting the future' because there is still so much uncertainty here in e.g. energy prices. However, it could be argued that this limits the insight the model offers to a few years. In future research, further transition to hydrogen once transitioned could be taken into account as well to bring the model closer to reality.

Third-party access regimes
No literature was found on specifics of negotiation terms. However, negotiation terms can be freely defined by HDNOs, which justifies relying on interviews with expert DSOs for speculations on possible realistic negotiation terms.

However, from the results of these interviews, only a selection of options for the nTPA regime was chosen, the prioritization method based on volume and grid investment and the division of investment costs. Due to time constraints, no further negotiation terms were researched, which leaves room for future research. In future research, more options for negotiation terms should be researched, such as prioritization based most efficient grid architecture, contract duration and the allowance for spread of initial development cost as indicated in the Decarbonization Package. This would give a wider view on how different negotiation terms impact the development of the industrial hydrogen network and allow HDNOs to make an reasoned choice for certain negotiation terms. In addition, the year where hnTPA switches from nTPA to rTPA has not yet been determined. Future research could explore further how other timelines of hnTPA impact the hydrogen development.

Cost benefit analysis
The cost-benefit analysis is simplified and may not capture the full complexity of real-world financial decision-making. While the CBA calculation itself is verified and transition strategies and motivation degree behave as intended due to the method of calculating the normalised value of the cost benefit analysis, future research could refine the financial modelling and calculations to improve realism and reliability of the financial indicators ROI and NPV. In addition, the bounds of these normalised value were set by trial and error as no literature was available. The values might be relative to each other and case specific. Future research could further refine these bounds as well. Lastly, future research could benefit from experimentation with other aspects of the costs for more insights for HDNOs in what aspects are interesting for negotiation, such as the hydrogen tariffs.

Scope
Within the scope of the model, it was chosen to focus on the industries and HDNO, as industries mainly dictate the development of the hydrogen network. Available supply through the backbone was assumed due to the fortunate circumstances in the case study. This means emergence of other local suppliers was not considered. In addition, no storage was taken into account. Future research should expand the scope and add these stakeholders to the stakeholder recruitment for interviews and implement them as agent in the model to create a more complete system, as these stakeholders impact the development of the hydrogen network as well.

One other big assumption defining the scope was the availability of green hydrogen only, due to the main driving factor to transition to hydrogen in Cluster 6 is to decarbonize. However, as the availability of green hydrogen is uncertain, future research could create hydrogen scenarios of the blue, green and grey hydrogen and see how this impacts the decision-making of industries to switch to hydrogen. Combining this with implementing local supply, it would allow to reflect the supply bottlenecks, mainly for green hydrogen in the model, and capture competition among industries for limited green hydrogen. Additionally, it would allow for industries to have blue or grey hydrogen as a transitional option and strategically respond to CO_2 prices.

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A Literature selection

Table 6 gives an overview of the selected articles in this paper, including the methods used, how stakeholder behaviour comes forward in the paper and if it is about hydrogen or not.

Table 6: Overview of selected literature

Title	**Author, Year, and Reference**	**Methodology**	**Stakeholder Behaviour in the Literature**	**H_2**
Local Energy Community to Support Hydrogen Production and Network Flexibility	M. Ferrara, F. Mottola, D. Proto, A. Ricca and M. Valenti, 2024, [15]	Strategy for optimal scheduling of a community's resources with case study analysis.	Simplified as production and demand, DSO included.	Yes
Green Hydrogen Value Chains: Integrated Framework for Developing and Assessing Viable Scenarios with a Case Study	Y. Li, F. Angizeh, M. A. Jafari, J. Chen and A. Klebnikov, 2024, [16]	Framework development to navigate complexities of green hydrogen value chain. Forecast future costs using an optimization algorithm.	Simplified as production and demand, end-use and production nodes. No DSO or HDNO included.	Yes
Assessment of the green hydrogen value chain in cases of the local industry in Chile applying an optimization model	R. Carmona, R. Miranda, P. Rodriguez, R. Garrido, D. Serafini, A. Rodriguez, M. Mena, A. Fernandez Gil, J. Valdes and Y. Masip, 2024, [17]	Optimization modeling of green hydrogen value chain in a local industry, considering demand profiles, renewable participation targets, electricity supply sources, levelized costs of energy and hydrogen and technological options.	Simplified with current demand profiles and electricity supply sources. No DSO or HDNO included.	Yes
Hydrogen energy systems: A critical review of technologies, applications, trends and challenges	M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei and D. Hissel, 2021, [20]	Literature review of state-of-the-art and prospects of hydrogen technologies and their application in power systems.	Confirms simplification and absence of DSO role in current research.	Yes
Business analysis of the hydrogen refueling station infrastructure and the role of the pricing system	J. Michalski, U. Bünger and C. Stiller, 2011, [18]	Optimization model of hydrogen value chain in transport sector. Impact of pricing mechanisms between different steps of the hydrogen value chain on the finances of stakeholders.	More complex stakeholder definition, represents stakeholders through investors. No DSO or HDNO included.	Yes
Economic feasibility of green hydrogen in providing flexibility to medium-voltage distribution grids in the presence of local-heat systems	S. Ghaemi, X. Li and M. Mulder, 2023, [19]	Incentive-based gaming model, where dynamic grid prices are determined by the DSO, which guides adjustment of output and consumption.	More complex stakeholder representation, incentive-based, not regulation-based. DSO included.	Yes
Policy design for green hydrogen	N. Farrell, 2023, [21]	Literature review, framework for policy development.	Confirms simplification.	Yes
Blockchain-based Local Energy Marketplace Agent-Based Modeling and Simulation	A. Boumaiza, A. Sanfilippo, 2023, [24]	Evaluation of demand response profiles using ABM.	Bottom-up approach for power usage, Machine learning (ML) forecasting models employed to predict energy consumption data in a housing community, DSO regulates the market for maximum social welfare by ensuring clearance and market balance.	No
An Agent-Based Model of Electricity Consumer: Smart Metering Policy Implications in Europe	J. Vasiljevska1, J. Douw, A. Mengolini, I. Nikolic, 2017, [23]	Evaluating the impact of ABM of different smart metering policies on electricity consumer behaviour using ABM.	Household agents have dynamic preferences on types of electricity contracts, offered by tbe DSO. Development of preferences depends on personal values, memory, attitudes, and the degree of interaction in a social network structure.	No
Evaluating the Evolution of Distribution Networks under Different Regulatory Frameworks with Multi-Agent Modelling	M. M. De Villena, R. Fonteneau, A. Gautier and D. Ernst, 2019, [22]	Evaluating the effect of different regulatory frameworks on the evolution of distribution networks using ABM.	The rational consumers can choose to adopt distributed energy resources. The DSO can adjust the distribution tariff within regulated boundaries from the environment. The evolution of the distribution network is simulated by computing the actions of the agents.	No

B Regulations

This appendix gives an overview of all relevant regulations identified, using the criteria described in chapter 2. Table 7 below gives an overview of the documents analysed. Section B.1 gives an overview of the regulations and their topics. Section B.2 gives an overview of the articles identified from the regulation. Next, B.3 gives an overview of the articles identified from the directive.

In these documents, several definitions regarding the subject apply. For clarity, it is important to distinct the different operator definitions. Firstly, the hydrogen network operator (HNO) is a more general term for the legal person that carries out tasks related to hydrogen transport and operation, maintenance, network development and long-term availability of the system to meet reasonable demands for hydrogen transport in a hydrogen network in a given area. The definition of the hydrogen distribution network operator (HDNO) is similar, but more specific for a hydrogen distribution network in a given area. For this research, regulation for both of these terms is of relevance.

Table 7: List of analysed policy documents

Policy Document or Additional Literature	**Content**
EU Hydrogen and Gas Decarbonisation Package Regulation [13]	Detailed article on the hydrogen market and network development among other subjects, directly applicable in Member States
EU Hydrogen and Gas Decarbonisation Package Directive [12]	Detailed article on the hydrogen market and network development among other subjects, to be transposed into national law before it is applicable

B.1 Summary of regulations based on groupings

The analysed regulations can be grouped based on their topics. Table 8 below shows an overview of the regulations per topic. Some articles fit multiple topics.

Table 8: Overview of identified articles based on topic

Topic	**Associated articles with IDs**
General	EUR7, EUD12, EUD14
Network development	EUR1, EUR6, EUR9, EUD11, EUD16, EUD17
Cooperation	EUR3, EUR4, EUR5, EUR12, EUD6, EUD14, EUD15
Unbundling	EUR8, EUD2, EUD4, EUD13, EUD18
Third-party access	EUR10, EUD5, EUD10
Customer rights	EUD1, EUD3, EUD8, EUD9, EUD11, EUD15
Tariffs	EUR2, EUR11, EUD7

Firstly, the general articles cover regulation for the general responsibilities of all active actors in the hydrogen market. The general tasks for hydrogen network operators are described (operating, maintaining and developing a secure and reliable long-term hydrogen system). The Member State is responsible to assign HNO's.

Secondly, articles on network development specify rules for the development of hydrogen networks. For example, if allowed by the Member State, HNO's can spread their network development costs over time by letting future users pay part of the initial costs. In addition, HNO's are allowed to refuse access or connection to the hydrogen system on the basis of the lack of capacity or lack of connection. The planning process for both the national and regional network development, development plans have to be submitted, based on an extensive consultation process with relevant stakeholders. Relevant for a regional industrial hydrogen market here is providing information on the delivering of hydrogen to end-users in hard-to-decarbonise sectors, taking into account the greenhouse gas reduction potential and the energy and cost-efficiency in relation to other options. The solutions have to be demand-sided, which does not require new infrastructure investments. This encourages a focus on efficiency and avoids overbuilding infrastructure.

Thirdly, the articles on cooperation outline several rules to ensure effective cooperation between (hydrogen) network operators and a competitive and efficient hydrogen market.

The fourth topic of articles is about unbundling of the accounts of hydrogen undertakings. There should be a separation of regulatory assets, based on the activities of the undertaking. In addition, vertical unbundling should be applied without delay in the hydrogen sector, which means HDNO's should be independent in terms of legal form, organisation and decision-making from other activities not related to hydrogen distribution, in case of vertical integration. There are other types of unbundling next to the ownership unbundling (OU) mentioned above (independent transmission operator and independent system operator), but OU is the default and also used on transmission level, which is why it is assumed OU will also be adopted on distribution level, see assumption A41.

The fifth topic is about third-party access, which can be divided into two options. The first option is regulated third-party access means HDNO's shall offer their service on a non-discriminatory basis to all network users, the same for contractual terms and conditions for the same service and are transparent about this. The second option is to enable Member States to allow the use of negotiated third-party access until 31 December 2032, where parties are able to negotiate access to hydrogen networks in good faith.

Next is customer rights, these articles describe how customers should be protected and empowered to make the most efficient energy choices, for example by clear contractual rights and transparent information. They should be able to choose their own supplier and enter into contracts with multiple suppliers to secure their hydrogen requirements.

Lastly, the articles on tariffs describe that tariffs, or their calculation methods, should be transparent, non-discriminatory, reflect the actual costs and be approved by regulatory authorities. The tariffs between hydrogen distribution and transmission levels should be left to the regulatory authorities. However, suppliers are free to determine their hydrogen price, but Member States shall take action to ensure reasonable prices for the final customer.

B.2 EU Hydrogen and Gas Decarbonisation Package Regulation

The EU hydrogen and Gas Decarbonisation Package Regulation is analysed. This regulation is directly applicable in the Netherlands. Table 9 below gives an overview of all relevant articles identified. The articles have given a newly assigned article ID and the subject is briefly described in the table.

Table 9: Relevant EU Hydrogen and Gas Decarbonisation Package Regulation Articles

Article number	**Assigned Article ID**	**Article Subject**
10	EUR1	Spread of network development costs
13	EUR2	Tariff setting and capacity allocation
22	EUR3	Cooperation and effectiveness of regional network operations
44	EUR4	EU DSO entity
83	EUR5	Regional structures
86	EUR6	Early phase access conditions
3(a-n)	EUR7	General principles
5.1	EUR8	Separation fo ragulatory asset bases
5.3	EUR9	Spread of network development costs
7.1, 7.2, 7.4, 7.5, 7.8	EUR10	Third-party access
17.1 & 17.2	EUR11	Tariffs
56	EUR12	Cooperation

Article EUR1 allows hydrogen network operators to spread network development costs over time by allowing Member States to provide for the possibility that future users pay part of the initial costs. This is called inter-temporal cost allocation. If the Dutch government implements this, it covers the financial risk of hydrogen network operators.
EUR2 states that tariff setting for HDNO and capacity allocation between transmission and distribution levels for hydrogen should be left to the regulatory authorities.
EUR3 explains Member States should promote cooperation and monitor effectiveness of network operations at regional level. The cooperation at regional level should be compatible with progress towards a competitive and efficient internal market for natural gas and hydrogen.
EUR4 pledges the need for a European entity for distribution system operators (EU DSO entity) to increase efficiency in the hydrogen distribution networks and ensure close cooperation. Its tasks are to ensure efficiency, transparency and representativeness among EU hydrogen distribution network operators.
EUR5 states more effective progress could be approach through an approach at regional level, thus hydrogen transmission network operators should set up regional structures within the overall cooperation structure.
EUR6 explains early access to hydrogen networks in the early phase of market for hydrogen development should be conditioned to ensure efficient operation, non-discrimination and transparency for network users while preserving sufficient flexibility for hydrogen network operators.
EUR7 outlines the responsibilities of all active actors in the hydrogen market to follow certain principles, such as following market rules based on supply and demand with a customer-centred and efficient approach.
EUR8 is about the separation of regulatory assets. It tells the regulated services for hydrogen provided by the HNO should comply with the requirements for unbundling as laid down in EUD18 of the Directive, see B.3.
EUR9 tells regulatory authorities can allow hydrogen network operators to spread the recovery through network access tariffs of hydrogen network costs over time in order to ensure that future users duly contribute to initial hydrogen network development costs.
EUR10 is about third-party access concerning HNO's. It outlines HNO's shall offer their service on a non-discriminatory basis to all network users, the same for contractual terms and conditions for the same service and are transparent about this. It tells hydrogen network operators shall regularly assess market demand for new investments, taking security of supply and efficiency into account. From 1 January 2033, or in case of regulated third-party access on

the hydrogen network according to EUD10 (see B.3), EUR11 shall apply tariffs for access to hydrogen networks and the corresponding obligations from EUR11 shall apply to HNO's.
EUR11 tells tariffs, or their calculation methods, should be approved by regulatory authorities and be transparent, reflecting the actual costs incurred and non-discriminatory. Tariffs for network access shall not restrict market liquidity or distort trade and should converge with other hydrogen network operators' tariffs in close cooperation with the relevant authorities.
EUR12 tells hydrogen distribution network operators shall cooperate with other HDNO's and HTNO's to coordinate maintenance, network development and operations to maximize capacity and minimize energy consumption to operate the hydrogen system.
The regulation also tells about the significant gap between the costs of renewable and low-carbon hydrogen production and the market price of less sustainable alternatives. This emphasizes the need for public intervention to provide incentives until such time that hydrogen technologies and inputs are sufficiently competitive. This support plays a vital role in achieving the objectives of the Union's energy policy: decarbonisation, among market transparency, diversification and security of supply.

B.3 EU Hydrogen and Gas Decarbonisation Package Directive

Secondly, the EU hydrogen and Gas Decarbonisation Package Directive is analysed. This regulation is to be transposed into national law before it is applicable in the Netherlands. As in B.2, a table 10 is given with an overview of all relevant articles. The articles have given a newly assigned article ID and the subject is briefly described in the table.

Table 10: Relevant EU Hydrogen and Gas Decarbonisation Package Regulation Articles

Article number	**Assigned Article ID**	**Article Subject**
28	EUD1	Customer protection and empowerment
66	EUD2	Vertical unbunding
72	EUD3	Supplier choice
80	EUD4	Lighter regulatory framework for hydrogen distribution networks
84	EUD5	Third-party access
126	EUD6	Co-location
4.1	EUD7	Hydrogen price
11.1-11.11	EUD8	Basic contractual rights
26.2	EUD9	Protection of remote customers
35.1-35.5	EUD10	Third-party access
38.1 & 38.2	EUD11	Refusal of access and connection
43	EUD12	Designation of HDNO's
46.1-46.4	EUD13	Unbundling of DSO's and HDNO's
50.1, 50.3, 50.4	EUD14	Tasks of HNO's
54.1-54.3	EUD15	Confidentiality for HNO's
55.2(b, d & f)	EUD16	Hydrogen network development
56.1-56.6	EUD17	Hydrogen distribution network development
75.1-75.6	EUD18	Unbundling

EUD1 states market rules should protect and empower customers to make the most energy efficient choices, in order for hydrogen to be fully embedded in energy transition.
EUD2 tells us vertical unbundling should be applied without delay in the hydrogen sector to prevent costly ex post unbundling in case the sector develops strong vertical integration.

EUD3 states large non-household customers, engaged in large-scale commercial activities (such as industries) should be able to choose their suppliers and enter into contracts with several suppliers to secure their hydrogen requirements to develop internal market competition. They should be protected against exclusivity clauses, where competing or complementary offers are excluded.
EUD4 concludes hydrogen distribution networks, which mainly serve the purpose of supplying directly connected customers, should benefit from a lighter regulatory framework in relation to vertical unbundling and network planning.
EUD5 states hydrogen networks should be subject to third-party access in order to ensure competition and a level playing field in the market for hydrogen supply. EUD5 also enables Member States to allow the use of negotiated third-party access (NTPA) until 31 December 2032 to ensure flexibility for operators and reduce administrative costs during the ramp-up phase of the market for hydrogen. Regulated third party access on the basis of regulated access tariffs should be the default-rule in the long term.
EUD6 states HNO's should cooperate with connected and neighbouring HNO's to ensure the most efficient connection for co-location. This means hydrogen production and consumption take place in the same location or are located as closely as possible for high hydrogen quality, cost and environmental impact minimization and prevention of hydrogen leaks.
EUD7 states suppliers are free to determine the price at which they supply hydrogen, but Member States shall take appropriate actions to ensure reasonable prices for the final customers.
EUD8 states some basic contractual rights for customers, such as clear contractual conditions, notice of any modification of these conditions and transparent information.
EUD9 states final customers in remote areas who are connected to the hydrogen system should be protected to ensure contractual transparency and competitive, transparent and non-discriminatory prices.
EUD10 complements EUD5 and tells us how third-party access to hydrogen is regulated. Member States have to implement a system of regulated third-party access to hydrogen networks based on published tariffs and applied objectively, without discrimination between any hydrogen network users. In case of implementing negotiated third party access for the restricted period, regulatory authorities should take the necessary measures for hydrogen network users to be able to negotiate access to hydrogen networks and to ensure the parties are obliged to negotiate the access in good faith. Regulatory authorities shall provide guidance to hydrogen network users on how negotiated tariffs are to be affected wehen regulated third-party access is introduced.
EUD11 tells us HNO's are allowed to refuse access or connection to the hydrogen system on the basis of lack of capacity or lack of connection. Member States should ensure HNO's make the necessary enhancements as far as it is economic to do so or when a potential customer is willing to pay for them.
EUD12 states Member States are responsible of designating HDNO's who act according to EUD13 and EUD14.
EUD13 tells that HDNO's should be independent in terms of legal form, organisation and decision making from other activities not relating to hydrogen distribution if they are part of a vertically integrated undertaking. This shall be monitored by regulatory authorities so the HDNO cannot take advantage of its vertical integration to distort competition.
EUD14 lays out the general tasks of hydrogen network operators. This includes being responsible for operating, maintaining and developing a secure and reliable long-term hydrogen system and infrastructure for hydrogen transport in close cooperation with connected HNO's. In addition, the HNO needs to provide the operator and user with sufficient information. HNO's shall not discriminate between hydrogen system users and take all reasonable measures to minimise hydrogen emissions. All needed reports concerning leaks, repair or replacement on possible hydrogen leak detection have to be submitted to the competent authorities. Additionally, HNO's shall be responsible for ensuring efficient hydrogen quality management in their

networks. Lastly, HNO's shall be responsible for balancing in their networks as from 1 January 2033.
EUD15 tells confidentiality of commercially sensitive information shall be preserved by HNO's. However, information necessary for competition and the efficient functioning of the market shall be made public.
EUD16 tells us the planning process for national network development includes extensive stakeholder consultation, including the HDNO's. The information has to be detailed, in particular about the delivering of hydrogen to end-users in hard-to-decarbonise sectors, taking into account the greenhouse gas reduction potential and the energy and cost-efficiency in relation to other options. The solutions have to be demand-sided, which does not require new infrastructure investments. This encourages a focus on efficiency and avoids overbuilding infrastructure, particularly relevant for regional networks.
EUD17 dives deeper into the hydrogen distribution network development plan, to be examined and approved by regulatory authorities. HDNO's have to submit a four-yearly plan to regulatory authorities for the hydrogen network infrastructure they aim to develop, in close cooperation with other (distribution system) operators. These plans include information on capacity needs as negotiated between hydrogen distribution network users and HDNO's. It includes information on potential future hard-to-decarbonise end-users, taking into account the potential greenhouse gas reduction and energy and cost-efficiency in relation to other options, and the location of the end-users. The development has to be based on a consultation process that is open to the relevant stakeholders to enable their early and effective participation in the planning process.
EUD18 outlines that the accounts of hydrogen undertakings are unbundled. They shall separate accounts for each of their activities (distribution, storage et cetera) as they would be required to do if the activities in question were carried out by separate undertakings. Infrastructure assets and revenue of the undertakings shall be allocated to the relevant accounts.

C Interviews

This appendix gives an overview of the summaries of all interviews conducted. All summaries are structured around key topics discussed during the interview.

C.1 Interview with DSO 1

This interview was conducted to gain insights into DSOs, potential hydrogen distribution network operators, and third-party access.

Regulatory framework
One of the main challenges in the decarbonization package, according to the interviewee, is the attempt to impose a mature structure, similar to the gas market, on the emerging hydrogen market. Due to unbundling rules, integrated companies no longer exist, meaning that multiple companies must invest and take risks rather than a single company managing both production, transport and supply.

Furthermore, the current directive lacks sufficient clarity, as it still needs to be incorporated into national law. While the legislation defines principles at a high level, the detailed regulations that grid operators require—such as role definitions, responsibilities, and criteria for being designated as a hydrogen network operator—are still absent. Until these details are clarified, grid operators are organizing themselves based on their expectations of the final legislation.

Connection order and prioritization
Under regulated third-party access, a “first come, first served” principle is likely to apply, meaning that customers who apply first will receive their connections first. However, with negotiated third-party access, the connection order might differ. Regardless of the approach, it is essential that network operators act transparently and without discrimination.

The interviewee suggests alternative prioritization methods, such as:

- *Efficient grid architecture*: Developing the network in the most logical and cost-effective way.
- *Social prioritization*: Favouring projects that align with broader societal benefits.
- *Balancing feed-in and offtake*: Since balancing hydrogen within the grid is cheaper than purchasing from the transmission system operator (TSO), maintaining local balance can be a cost-effective priority.
- *Volume and grid investment*: Giving priority to projects that require minimal grid investment while delivering large volumes.

Negotiation aspects
The interviewee is sceptical about the extent of negotiations, believing that they will primarily involve additional aspects rather than fundamental contractual terms like tariffs. Possible negotiation points include:

- Discounts for consistent feed-in or offtake.
- Spreading development costs over time.
- Contract durations to ensure long-term customer commitments and reduce financial risks for network operators.

Negotiated third-party access offers advantages, such as more flexibility in setting policies and determining connection order. However, the interviewee does not expect significant differences in negotiation policies among different network operators.

When asked about compromise willingness from network operator perspective, the interviewee emphasized that it depends on the business case, which must ensure a certain return on investment. The most critical moment is the *Financial Investment Decision (FID)*—the point at which the network's construction is decided. At this stage, a minimum number of customers is required. Compromises, such as temporary discounts, may be offered to kickstart network development. Once the network is operational, there is generally more room for compromise, as risks are lower.

To avoid drastic tariff changes, it is advisable to align initial negotiated tariffs with the future regulated tariff structure. However, for many industries, transport tariffs are not a major cost factor. The interviewee expects hydrogen transport tariffs to be *two to three times higher* than those for natural gas, depending on pipeline lengths and the number of customers sharing the costs. An option in negotiations could be to link the number of customers to distribution tariff reductions.

Motivation of network operators
Network operators are driven by both systemic and financial motivations to invest in hydrogen networks:

- *Systemic motivation*: Hydrogen is needed to support the energy system by alleviating pressure on the electricity grid and helping achieve climate goals.
- *Financial motivation*: A viable business case is required, with sufficient contracts and a minimum return on investment.

These motivations can sometimes conflict. However, the roll-out of a regional hydrogen distribution network represents only a small portion of a distribution system operator's total expenditures.

Local supply and production
Contrary to the assumption that demand must precede supply (as stated by [7]), the interviewee noted that *local hydrogen supply can drive local demand*, particularly in standalone networks. Even once stand-alone networks are connected to the backbone, local production can remain attractive from a financial and/or system point of view but imported hydrogen might be less expensive compared to locally produced hydrogen. However, it is uncertain how this will develop and depends on the individual business cases.

C.2 Interview with DSO 2

This interview was conducted to gain insights into DSOs, potential hydrogen distribution network operators, and third-party access. The summary is structured around key topics discussed during the interview.

Challenges of hydrogen
Hydrogen differs significantly from other energy carriers, such as green gas, leading to several challenges. According to the interviewee, the main challenges include:

- *Technical challenges*
- *Uncertainty about the future of hydrogen*
- *Social acceptance*
- *Absence of regulation* (the most pressing challenge)

Key questions for DSOs include:

- Should hydrogen be used in the residential sector or solely in industries?
- How can the DSO facilitate hydrogen distribution while managing the existing gas network?

Currently, there is no regulation at the distribution level, leaving DSOs in a grey area. As regulated companies, DSOs must adhere to strict procedures and ensure gas and electricity connections. However, since hydrogen does not yet fall under their official scope, pilot projects require extensive permissions and approvals, making implementation time-consuming.

Regulatory framework
Present regulations focus primarily on Transmission System Operators (TSOs), but DSOs have distinct structures and requirements. TSOs primarily serve large industrial consumers with greater capacity needs, more flexibility, and a stronger obligation to decarbonize. By contrast, DSOs cater to a much larger number of smaller customers, including households, who cannot be mandated to decarbonize.

In the industrial sector, hydrogen adoption is likely to be driven by regulations and a lack of viable alternatives. In the residential sector, adoption will depend on personal motivation and future energy tariffs, alongside competing options like electrification. Lessons can be learned from TSO regulations, but they cannot be directly applied to DSOs due to market differences.

The interviewee highlights the necessity of *negotiated third-party access*, which would enable DSOs to establish their own hydrogen networks using the hydrogen backbone. They see value in investing in this backbone to support distribution networks in smaller energy clusters. Additionally, the interviewee notes the *German model*, which allows for hydrogen blending, fostering a more gradual market transition compared to the Netherlands, where regulations demand a direct shift to 100% hydrogen.

Negotiation aspects
Under negotiated third-party access, several aspects could be subject to negotiation, including:

- Investment cost division between DSOs, customers, and potentially the government.
- Clustering customers to improve feasibility; DSOs prefer supplying hydrogen to communities or clusters rather than isolated users.

The energy transition—whether involving hydrogen or not—entails long-term costs. Infrastructure investments will lead to higher energy tariffs for consumers, with electricity costs expected to rise in the short term (10 years) due to necessary grid reinforcements. In the case of hydrogen, a key question is *who will bear these costs.*

While DSOs have a social responsibility to facilitate the energy transition, overall strategy lies with the government. Given that hydrogen adoption is initially unlikely to be financially attractive, *government strategy and possible subsidies* are critical.

Cost considerations
There are two primary cost factors:

- *Infrastructure costs* for DSOs.
- *Retrofitting costs* for customers.

The interviewee stresses that hydrogen development is deeply influenced by political and international factors, including:

- *Natural gas prices* affected by geopolitical events (e.g., the war in Russia, Middle East tensions).
- *Policy shifts* in major economies like the U.S., which impact innovation and energy transition investments.

Hydrogen adoption can also be *locally motivated*, for instance by grid congestion or other regional factors that drive demand. Historically, Dutch local hydrogen projects have often emerged due to customer-driven demand for alternatives.

Internal research on *system integration* indicates that without hydrogen and power-to-gas- technology, *electricity grid investment costs could be three to five times higher.*

C.3 Interview with Cluster 6

As part of this study, an expert working for Cluster 6 was interviewed to discuss key topics related to energy transition and the role of hydrogen.

What is Cluster 6?
Cluster 6 is the collective name for all industries scattered throughout the Netherlands that fall outside the five major industrial clusters. The organization was established due to the lack of representation for these industries in government discussions on the energy transition within the Dutch industrial sector. It represents 400 companies, of which 200 fall under the EU Emissions Trading System (EU ETS).

Cluster 6 aims to provide insight into the challenges these industries face in the energy transition. Because companies within this cluster tend to be internally focused, Cluster 6 offers them a network of governmental parties and grid operators while also representing their interests in discussions with policymakers.

Energy transition in Cluster 6
Despite a growing interest in hydrogen among Cluster 6 industries, its large-scale adoption remains a distant prospect. The primary reason is cost. Hydrogen remains significantly more expensive than other energy sources. In addition, hydrogen infrastructure is often located far from Cluster 6 industries, meaning they are not considered and prioritized in national planning.

Currently, most companies within Cluster 6 are exploring electrification as the first option, as hydrogen is financially and logistically out of reach. However, energy costs in the Netherlands are already higher than in neighbouring countries. As a result, international companies often prefer to invest elsewhere, where they can achieve greater CO_2 reductions per euro invested. This dynamic leads to reduced investment in Dutch industry.

To help companies overcome energy transition challenges, Cluster 6 often seeks opportunities for collaboration between neighbouring businesses. This has led to the initiation of innovative projects, such as utilizing residual heat for nearby residential areas or creating industrial zones where transportation is jointly operated using hydrogen-powered vehicles.

Interest in hydrogen
Hydrogen interest is primarily seen in high-temperature industries, where electrification is not a viable alternative, and in the chemical sector, which uses hydrogen as a raw material.

A small group of forward-thinking entrepreneurs within Cluster 6 strongly believes that hydrogen is a necessity for the future. These companies are willing to invest early despite the high costs, hoping to accelerate market development. However, the majority of industries view hydrogen as a secondary option. They would only consider using it if it becomes affordable. Currently, the most likely scenarios for hydrogen adoption include:

- No hydrogen use at all
- Partial transition to hydrogen (e.g. blending with natural gas)
- Hydrogen as a backup energy source

A study by Cluster 6 found that *73% of all industrial sustainability plans cannot proceed before 2030 due to the lack of necessary energy infrastructure.* While electricity infrastructure is already a bottleneck, hydrogen infrastructure is even further behind, creating a major dilemma for companies.

One sector struggling with energy transition is greenhouse farming. These businesses are highly entrepreneurial and creative in their energy use. Some greenhouses are exploring geothermal energy as an option, while others are considering small nuclear power plants or even hydrogen. Greenhouse farming does however not fall within the scope of Cluster 6.

Dutch hydrogen transition strategy

According to the interviewee, the current Dutch hydrogen transition strategy may not be optimized. The sector expected to move first—industry—has the *lowest willingness to pay* for hydrogen. Meanwhile, sectors like transport may be better suited as first movers, as fossil fuel costs for petrol and diesel continue to rise.

Another potential early adopter could be the residential sector, particularly in historic city centres. In these areas, using hydrogen could be more cost-effective than retrofitting old buildings with insulation and electric heating.

Barriers for hydrogen adoption

Several barriers are preventing regional industries from adopting hydrogen:

1. *Lack of coordination and leadership*
    - No single party is responsible for initiating cooperation within industrial areas.
    - Municipalities or consortiums are needed to facilitate collaboration.
    - The role of key stakeholders remains unclear.
2. *Regulatory uncertainty*
    - The role of key stakeholders, such as regional grid operators, remains unclear, making it difficult to assign costs and responsibilities.
    - Regulatory clarity is urgently needed to guide decision-making. Industries are uncertain about what steps to take regarding sustainability.
    - Many companies want to act now due to rising costs if they do not reduce CO_2-emissions. These costs include, EU ETS, CO_2-tax and higher gas prices, which is eating up industries' their investment budget. However, once a connection to a grid is received, more challenges can arise such as the costs of connection, if a Cluster 6 industry is located far away from the backbone.
3. *Dependence on renewable energy*
    - Green hydrogen production requires a reliable supply of renewable electricity.
    - Regulations impose strict requirements on green hydrogen production, such as limiting the age of renewable equipment to three years in order to call it green hydrogen, making it harder to utilize existing renewable capacity. The interviewee tells the regulation might become even more strict, requiring the renewables to be produced with completely new equipment in order to call it green hydrogen.
4. *Subsidy challenges*
    - While subsidies are available, they come with complex rules and conditions.
    - Many companies find the application process discouraging, limiting their access to financial support.

Negotiation and cost allocation

A major concern for Cluster 6 industries is *how investment costs for hydrogen infrastructure will be divided.* Several negotiation points were discussed during the interview:

- *Prioritization system*
    - There is criticism on the first-come-first-served (FCFS) system, as industries feel FCFS is an unfair way to allocate energy infrastructure.

  - They are open to alternative prioritization methods, such as connecting companies based on their *potential sustainability impact.*

- *Spreading development costs*
  - Early adopters should not bear the full financial burden of developing the hydrogen network.
  - Future users should contribute to these initial infrastructure costs to make investments more viable.

- *High connection costs*
  - Connecting to a hydrogen network and developing regional distribution grids is expensive.
  - The question remains: *who will cover these costs, and what are the social cost implications?*

- *Need for industrial customer protection*
  - Scattered industries in Cluster 6 are often at a disadvantage due to their *location.*
  - They face higher costs and struggle to compete with industries in better-connected regions or other countries.
  - Ensuring fair access to hydrogen and energy transition infrastructure is essential to maintain competitiveness.

C.4 Meeting on the development of a regional hydrogen network

As part of this study, a meeting was attended with parties interested in developing a regional hydrogen network. Stakeholders present included representatives from the city council of the respective municipality, a representative for the province, a network operator, a company engaged in renewable energy development, and industrial companies. The hydrogen project is still in its initial phase, with ongoing technical, financial, and organizational feasibility studies.

Objective of the meeting
The primary goal of the meeting was to discuss the results of the feasibility studies and clarify the interests and concerns of the various stakeholders involved in the development of a regional hydrogen network.

Challenges identified
During the feasibility studies and discussions, several challenges were identified. While technical feasibility is not considered a major hurdle, significant uncertainties remain in the following areas:

1. *Uncertainty of national regulation*
2. *Uncertainty of hydrogen pricing*
3. *Construction of the national backbone*
4. *Unclear role distribution among stakeholders*

Challenge 1: uncertainty of national regulation
One of the main concerns raised by industries is the inconsistency of Dutch policy regarding hydrogen. The lack of stable and long-term policies creates uncertainty, making it difficult for industries to commit to hydrogen-related investments.

Industries currently feel pressured to transition to sustainable options, driven by mechanisms such as carbon taxation. However, they face a lack of financially viable alternatives that fit their processes. Many companies cannot electrify due to the unavailability of a sufficient electrical grid connection. At the same time, grid congestion has now gained political attention, according to municipal representatives.

Another regulatory concern is the uncertainty surrounding nitrogen oxide (NOx) emissions produced when burning hydrogen with air. Industries fear being penalized for sustainability efforts if regulations on these nitrogen emissions remain unclear. A possible technical solution—splitting oxygen from nitrogen before combustion—would require further investment.

The province expressed its intention to bundle local initiatives with all provinces, in order to urge Gasunie and the ministry for regulatory clarity. Among provinces, it is seen that similar projects have similar interests among companies, all with similar motivation, but all run into the same problem of unclear regulation.

Challenge 2: uncertainty of the hydrogen price
Industries agreed that a partial transition to hydrogen (e.g., 20% volume) is realistic and feasible, provided there is security of supply and clarity on pricing. Hydrogen is an expensive energy carrier compared to natural gas, up to four times as expensive. In addition, it remains unclear how the hydrogen market will develop, making it difficult to predict investment payback periods. This uncertainty reduces the attractiveness of hydrogen adoption.

To mitigate supply security concerns in the early stages, the use of grey and blue hydrogen was proposed, drawing a parallel with the transition to electric vehicles, which initially relied on non-renewable electricity. However, industries emphasized that a clear timeline for transitioning to green hydrogen is necessary to support long-term planning.

Challenge 3: construction of the national backbone
Currently, Hynetworks is developing the national hydrogen grid. However, there are no plans to integrate regional system connections. The current approach focuses only on direct connections to industrial companies, excluding connections to regional distribution networks. This creates barriers for investment decisions at the regional level. However, the parties agree that other transport methods than pipelines, such as hydrogen storage tanks, are impractical given the large volumes required at industrial scale.

A proposed solution is to establish cooperation between Hynetworks and the DSO. This partnership would involve setting up technical, legal, and financial agreements, ensuring the use of interchangeable standards, and developing future scenarios with varying volumes and connection needs. Such measures could significantly accelerate regional hydrogen adoption.

Challenge 4: unclear role distribution
Another key challenge is the lack of clarity regarding stakeholder roles and financial responsibilities. Industries stressed that they cannot bear all investment costs alone. Defining who is responsible for which tasks—and how costs are distributed—is essential for moving forward with the regional hydrogen network.

Motivation for hydrogen
The meeting highlighted that industries play a crucial role in initiating the development of a regional industrial hydrogen market. There appears to be industry support for breaking the "chicken-and-egg" problem, as some companies expressed willingness to invest in the branching off the backbone in advance, anticipating a future mature market.

This way, costs can be saved as constructing a branch on an operating hydrogen backbone is more costly than co-developing and being incorporated in the design. In addition, the waiting for the construction to finish once system connection with the branch is made is shorter with less expensive cables, as these costs are expected to rise in the future.

Financial considerations
Financial factors play a decisive role in industries' decision-making. Partial hydrogen adoption (e.g., 20% rather than a full 100% transition) is seen as more feasible due to cost considerations. Additionally, transport tariffs are a significant concern. Hydrogen transport costs decrease as more participants join the network, leading industries to request concrete information on expected tariff levels.

From system operator perspective it was noted that, despite the high investment costs for hydrogen infrastructure, these are still lower than the costs of reinforcing the electricity grid. For industries however, given the limitations of electrical grid expansion, there is no viable alternative to hydrogen in many cases.

Non-financial considerations
Beyond financial concerns, several non-financial factors drive industries' (dis)interest in hydrogen:

- *Lack of alternatives for decarbonization*: Electrification is often unfeasible due to grid congestion.

- *Unique case-specific conditions*: The unique circumstances presenting in this case are particularly favourable for transitioning to hydrogen, such as high temperature combustion processes and an advantageous location in relation to the hydrogen backbone.
- *Global competitiveness*: Rising energy costs in the Netherlands drive industries to consider relocating to countries with lower energy prices. If one company does not relocate, competitors might, leading to competitive disadvantages.

C.5 Interview with city council of respective municipality

As part of this study, an interview was conducted with the city councel of the municipality involved in the case study to discuss the plans and developments of the hydrogen project.

The start of the hydrogen project
The hydrogen project was initiated by motivated entrepreneurs in the region. It began with a single entrepreneur committed to sustainability, who purchased a hydrogen-powered tractor. This sparked further interest, leading the city council to explore the potential for hydrogen applications in the municipality and area. Currently, the primary focus is on *industrial applications.*

The existing industrial area has shown interest in hydrogen for several reasons:

- *Grid limitations*: Electrification is not feasible due to the lack of available grid connections.
- *Energy security*: Companies prefer a *hybrid energy solution* to avoid dependence on a single energy source. A gas network suitable for hydrogen offers a future-proof alternative alongside natural gas and/or electricity.

Role of the city council
The city council acts as both a project developer and an authority in the hydrogen project. Its tasks can be divided into:

- As an *authority*:
  - Issuing permits
  - Managing land ownership
- As a *project developer*:
  - Facilitating the project
  - Creating the project plan and structure
  - Coordinating working groups and ensuring that all stakeholders' interests are considered

A significant role of the city council is *lobbying* to address legal and regulatory barriers. Since hydrogen projects are still relatively new, they frequently encounter regulatory challenges. The municipality, in collaboration with the province, escalates these issues to the national government to push for adequate regulations.

In early stages of the project, safety concerns were a challenge. Currently, the biggest issue is the *lack of clarity regarding the grid operator.* Companies hesitate to commit without concrete agreements with the party who will manage the hydrogen network, which impacts their willingness to connect.

Another task the city council deals with is *securing and managing subsidies.* In this case, funding programs as SD++ and provincial initiatives for sustainable industrial areas are particularly relevant.

Industries in the region
The industrial area primarily consists of *food processing* industries with high-temperature energy demands and *greenhouse farming* with lower temperature needs.

Although greenhouse farming requires lower temperatures, one particular greenhouse company plays a crucial role in the project due to its high energy demand and expertise in energy management. However, this company also has alternative sustainability options that may be more attractive. Hydrogen could serve as an effective energy source during peak hours, rather than as a baseload energy solution.

As the agricultural company is an important economic player in the city council, local authorities want to ensure it remains competitive and has clear sustainability prospects.

Initially, the strategy of the industries will be to mix 20% hydrogen with natural gas themselves. Depending on the price development of hydrogen and natural gas and the CO_2 tax, hydrogen will be more or less integrated into industrial processes.

Hydrogen integration
The initial strategy for industrial hydrogen adoption will be to *blend 20% hydrogen with natural gas.* The extent to which hydrogen will be further integrated depends on hydrogen price developments, natural gas prices and CO_2 taxation policies.

Expansion of the industrial area
There is a desire for new industrial areas in the region, which is why the city council is planning to expand the industrial area and is actively working on creating conditions for a sustainable industrial zone by developing a hydrogen network. New companies will follow the same energy approach as existing businesses, likely starting with a 20% hydrogen-natural gas mix.

To attract the right companies to, the city council collaborates with regional development corporation (regionale ontwikkelmaatschappij ROM). Here, the city council indicates the business climate they wish to establish with corresponding selection criteria. The ROM facilitates connections between the city council and potential new companies interested in this area.

Currently, the municipality has food industries and agricultural businesses, but it is not desirable to attract more greenhouse farming, due to the lower environmental category. The city council desires to attract industries of *environmental category four or higher*, which is one of the selection criteria. Industrial areas with a lower category are not unique due to their lower temperature demand. Industries with a temperature demand of 200 degrees Celsius or higher fit with the range where hydrogen becomes interesting.

Another selection criterion is the *agrifood sector.* The hydrogen project is in an agricultural area, which means a lot of food is produced and processed. By keeping the entire production chain of producing and processing in the same area, a specialism is created.

D Model Assumptions

In table 11 presents an overview of the model assumptions, including their assumption ID, description and reasoning. For clarity, the table is divided into the categories hydrogen value chain, cost-benefit analysis, construction, industries and HDNO.

Table 11: Overview of model assumptions

Assumption ID	Description	Reasoning
		Hydrogen value chain
A1	In the model, pipelines are the only method of transport and distribution.	Despite other transportation methods available, only pipelines are considered given the demarcation and research goal of investigating the development of the regional industrial hydrogen grid. Pipelines can, however, be effective for delivering hydrogen to a large number of high-capacity users [32].
A2	The purchase of hydrogen only occurs if an industry is connected via pipeline support.	Because of A1, pipelines are the only method of transport and only way of purchasing hydrogen.
A3	In the model, only new pipelines are constructed.	It is expected only a few existing natural gas pipelines can be repurposed for hydrogen. However, any roll-out of a regional network infrastructure would mainly require new pipelines, especially in the first phase [7], which is why the assumption is of only new pipelines is made.
A4	In the model, no renewal of pipelines is needed.	A hydrogen pipeline's lifespan is regarded as lengthy and spread over several decades [72].
A5	The emergence of suppliers is not taken into account in this model as a system connection to the backbone is assumed.	According to [7] regional production of hydrogen is less defining for the initial development of regional hydrogen infrastructure than potential demand. Considering the economic perspective, it is more logical that hydrogen production follows the hydrogen demand, because the demand comes from existing companies and production projects start from scratch. It is hard to predict the location of regional production supply and it is expected (in 2035) to be relatively small outside the five Clusters. Therefore, the option of a system connection to the backbone is assumed.
A6	Patch 0 0 is assumed to be the location for the system connection from where the industries connect. The distance in meters to the system connection is maximum around 308 meters.	Each industry needs a distance to the point from where they will be connected. It is assumed all industries get connected to the same point, which is assumed to be the system connection at patch 0 0. This distance is set by setting the max-pxcor and max-pycor in the NetLogo world to 16, and using the distance-scale parameter of 14 to scale the NetLogo distance to a max of 308 meters rounded for the furthest patch 16 16. This distance is based on internal documents from the case study.
A7	No storage is taken into account.	Storage plays a big role in strategically shifting demand and supply across seasons and to buffer short-term supply and demand shortages [30]. This study examines how regulatory conditions can influence the conditions for the development of a market over the scope of 25 years. This sets the time step of the model to years, which does not take into account hourly demand fluctuations. In other words, this study does not aim to match hydrogen supply and demand hourly or seasonally, which is why no storage is taken into account.

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Table 11 – Continued from previous page

Assumption ID	Description	Reasoning
A8	Only industrial end-users are taken into account.	This is based on the demarcation and research question of this project.
A9	In the model, only pure hydrogen is in the network.	Based on EUR4 (appendix B.2) of the EU Hydrogen and Gas Decarbonisation Package Regulation: production and use of hydrogen in its pure form in the dedicated hydrogen system should be prioritised, as blending of hydrogen into the gas system is less efficient compared to its pure form and diminishes the value of hydrogen. Blending in the network should be avoided.
A10	Only green hydrogen is considered and is assumed to be available.	This is because of the main driving factor in Cluster 6 for the potential rollout of regional grid infrastructure: to replace natural gas for heat production to decarbonise [7], which eliminates the demand for grey hydrogen. Currently, grey hydrogen is predominant and cheaper, while green hydrogen is less available and prices are higher. However, the current rise in natural gas prices, along with growing CO_2 prices, may also make green hydrogen more affordable and available [31]. In addition, the scarcity of green hydrogen will also be reflected in is price.
A11	No further consideration is given to e.g. efficiency of hydrogen versus natural gas.	With the replacement of natural gas by hydrogen, the corresponding hydrogen volume from gas consumption is calculated. No account is taken of energy losses in any conversions.
	Cost-benefit analysis	
A12	Costs such as labour and maintenance are excluded in the CBA.	It is assumed these will not differ from the operations with natural gas. It can however be argued that additional necessary training or extra maintenance due to hydrogen safety requirements could increase the costs, but this is expected to be minor [61].
A13	From 2050 onwards, the price forecasts will be assumed constant to the year of 2050.	In the cost benefit analysis the industries perform in the model, they calculate 18 years ahead, due to the construction duration of 3 years and common timespan of 15 years to perform a CBA. This means that from 2033, the calculation exceeds the year 2050. As it is very difficult to predict prices, especially so far as 2050, prices are assumed constant to prevent possible erroneous speculation.
A14	The EU ETS emission market will be adapted in such a way it will stay maintainable in 2050 and have realistic prices for the emission rights.	[69] predicts skyrocketing prices for the EU ETS emission allowances in the early to mid-2040s, if it where the only tool used to guarantee the equilibrium between offer and demand of allowances. The report highlights a new design is needed in order to be compatible with the a low GHG emissions environment from 2040 onwards. Therefore, in this research it is assumed it is likely the market will be reformed or a price cap might be introduced to maintain the instrument. Based on logic, high prices are still likely, but in a more reasonable range. For that reason, the prediction of [69] is adopted until 2040. Between 2041 and 2050, it is assumed the price will rise to 250 €/tCO_2. See appendix H.
A15	The EU ETS cap is assumed to be incorporated in the price of emission allowances.	The EU ETS cap is simplified by assuming it is included in the emission allowance price. Due to the EU ETS cap, there is a decreasing amount of allowances available, which as a result rises the price of the emission allowances.

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Table 11 – Continued from previous page

Assumption ID	Description	Reasoning
A16	The energy supplier charges the EU ETS fully to the customer (industries).	EU ETS-2 requires fuel suppliers to monitor, report and hand in CO_2 emissions from their supplied fuels. If the fuel supplier delivers to sectors included in EU ETS-2, EU ETS will be charged on these fuels from 2027. Because fuel suppliers have to buy emission rights, they will pass on these costs to the industries.
A17	All technologies for retrofitting industrial equipment for hydrogen transition is available.	According to the technology development timeline for industrial equipment showing time required for R&D, modelling, demonstration and commercial readiness from [61], all technologies can be ready end of this year (2025), which is why we assume all technologies are available.
A18	The retrofitting data for a food boiler can be used as a proxy for an agricultural heating boiler.	Food steam boilers and agricultural heating boilers have similar conditions, such as the moderate temperature, similar regulatory and safety requirements and similar complexity (compared to e.g. chemical and paper steam boilers). As the data for a food steam boiler are available, it is assumed the conversion challenges and costs are similar, which makes the food steam boiler a fitted proxy for an agricultural heating boiler. A CPH requires extra changes beyond those of a boiler (due to its dual function), making the estimation less accurate and certain.
A19	In the model, mixing costs for a capacity of 1 MW costs €100.000 and 10 MW €200.000.	If the transition strategy includes mixing of natural gas with hydrogen, a mixing station is necessary, as hydrogen cannot be mixed with natural gas in the pipelines (A9). Given the unavailable data for the mixing station, an expert estimate was used which estimated the cost between €100.000 and €200.000 euro's. In the model, it is assumed mixing a capacity of 1 MW costs €100.000 and 10 MW €200.000. For that reason, we can follow the same formula 7 as for retrofitting, where a scale-up factor of 0.301 can be assumed.
A20	It is assumed the costs for a hydrogen pipeline is 600 €/m.	Based on [73], the costs for replacing a natural gas pipe can be around 300-500 €/m. As this source is from 2019 and hydrogen pipelines must meet many (safety) requirements, it is estimated the cost for a hydrogen pipeline is a bit higher and lies around 600 €/m.
A21	The one-time connection fee for a hydrogen connection is €58.050 per connection.	According to [62], the cost for a one-time connection fee for gas is €38.700, it is assumed these costs are higher for hydrogen, as connecting a new hydrogen infrastructure is estimated to be more costly for the same the reasons mentioned in A20. Therefore, the estimation of the natural gas connection fee is multiplied by 1.5.
	Construction	
A22	In the model, nothing happens when construction is taking place.	For simplification of the model, all industries wait for construction to be over before setting new motivation degrees, conducting CBAs and submitting requests.

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Table 11 – Continued from previous page

Assumption ID	Description	Reasoning
A23	The threshold for the HDNO to start constructing the regional hydrogen network and establish a system connection is assumed at three industries minimum willing to connect, and not financially motivated.	In the model, once industries submit a request for connection and there is not a system-connection yet, it needs to be checked if the amount of industries meets the threshold set by the HDNO. As described in C.1 and C.2, network operators feel both a systemic motivation that hydrogen is needed to support the energy system by alleviating pressure on the electricity grid and social responsibility to facilitate energy transition. In addition, network operators have a financial motivation, which requires a viable business case with sufficient contracts and a minimum ROI. However, despite high investment costs for hydrogen infrastructure, these costs are still lower for network operators than the costs of reinforcing the electricity grid C.4. Based on these insights, it is assumed the HDNO will establish the system connection and roll out the distribution network once three industries or more submit a request for a connection (A23). Once the system connection is accessible, the threshold is set at one industry. No further financial threshold for the HDNO is considered.
A24	Industries will enter the waiting list until capacity of the HDNO is available (A24).	Based on EUD11 (see appendix B.3) from the EU directive, HNOs are allowed to refuse access or connection to the hydrogen system on the basis of lack of capacity or lack of connection. Therefore, industries have to wait until enough capacity is available again.
A25	Construction duration is estimated to take between one and four years with a maximum of four industries per construction.	This is based on benchmarking of green gas fitters and an expert estimation. It is assumed that constructing connections for four neighbouring industries takes two years, based on benchmarking of green gas fitters and an expert estimation. No more than four industries will be constructed at the same time, the rest will be put on the waiting list. Constructing one industry or two industries near each other takes only a year. If three or more industries are more scattered, the construction takes three years. Lastly, if the system connection needs to be established, the construction takes an extra year.
A26	The difference between the estimated construction duration used in the CBA and the actual construction duration, once determined, does not affect the financial feasibility, CBA outcomes, or an industry's decision to request a connection.	It should be noted that, as the industries do not know how long the construction duration will be, they will calculate their CBA taking into account a construction duration of three years in their time horizon, which might be different from their actual construction duration.
Industries		
A27	Industry agents do not influence the policies and rules set in the environment.	The rules are set by the ministry of climate and energy policy, ACM and hydrogen network operators, which are modelled as the environment. Despite indirect influence on these policies due to e.g. stakeholder consultation, it is assumed that there is no influence of industry agents on these policies.
A28	Natural gas consumption profiles are constant over the years.	The natural gas consumption profiles are obtained from the Stedin data bases and assumed to be constant over the years.

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Table 11 – Continued from previous page

Assumption ID	Description	Reasoning
A29	Once transitioned to hydrogen, industries do not transition further.	For simplification of the model, the model only considers the first step of transition to hydrogen from the industry and does not allow for industries to grow in hydrogen demand after several years. However, it is likely that once the price of hydrogen lowers and more security of supply is reached, the industries might increase their hydrogen demand (see C.5). It could be argued that this assumption limits the insight the model offers to a few years. On the other hand, focusing on the first transition is valuable given that this is where the focus for HDNOs and policymakers currently lies, as hydrogen networks are at its infancy. In doing so, the model avoids 'predicting the future' because there is still so much uncertainty here in e.g. energy prices. However, in future research further transition to hydrogen once transitioned could be taken into account as well to bring the model closer to reality.
A30	Industries only conduct an alternative CBA when they are on the waiting list and the prioritization order is based on hydrogen quantity and invent costs. The industries then want to influence or maintain their position on the list to secure and speed up their energy transition.	If too much industries are requesting a connection, the industries are put on a waiting list. In rTPA, the prioritization order of this waiting list is based on first come first serve, but in rTPA industries can see if they can increase their hydrogen demand, so they reach a higher position in the waiting list or do not risk losing their position in the waiting list. This is done by setting an alternative transition strategy and review if this is financially feasible. Due to the hesitance for the new technology and the general preference among Cluster 6 industries and the case study to start with a partial transition to hydrogen where it is blended with natural gas (C.3, C.4). Therefore, it is assumed industries only consider conducting an alternative CBA in case of nTPA when they are on the waiting list.
A31	The maximum distance in which industries perceive other industries their peers and experience peer pressure from them is 140 meters.	This is an assumption and in NetLogo distance not multiplied with distance-scale).
A32	Industries have a strategy of 7%, 20% or 40%, which can increase if the alternative strategy is adopted, but does not become much higher.	This is based on the interview C.3 and C.5, where it becomes clear the industries are hesitant for transitioning to hydrogen and prefer a partial transition to hydrogen. Additionally, industries prefer a hybrid energy solution to avoid dependence on a single energy source, which makes it unlikely they will transition to for example 100% hydrogen. Dependent on the development of hydrogen prices, industries might increase their hydrogen consumption, but for this research looking into the development of regional industrial hydrogen networks, this is out of scope (A29).
A33	Industries only react to their waiting list position once they are on the waiting list.	The industries react to the waiting list mechanism once they are inside the waiting list. They do not anticipate on the waiting list beforehand. This is a model limitation and could be further developed in future research.
A34	The industries are operating on full capacity for 65% of the year.	Based on an estimation from the data from Stedin data bases, the industries in the model operate 65% of the year on full capacity on average. This means they operate 5694 hours a year.

Continued on next page

Table 11 – Continued from previous page

Assumption ID	Description	Reasoning
A35	In 2030, all new industries expected to settle in the area will be present in the model at once.	In the case study, they expect around 10 new industries settling in the area with a total demand of 20 MW by 2030, see C.5. Therefore, in the model, these new industries all arise in 2030. As these industries are all expected to be food industries, no different behaviour or changes in parameters such as operating hours are needed.
A36	The strategic behaviour of industries to relocate their industries abroad where energy prices are cheaper (C.4) has been excluded from the scope.	The model focusses on regional hydrogen development and not international strategies. In addition, it reduces complexity of the model.
A37	The cost division is assumed to be between HDNOs and customers and not between other (governmental) stakeholders.	This is assumed for this study, based on the three motivations from the DSO perspective mentioned in section 4.2. This includes the systemic motivation to support the energy system, the social responsibility motivation to facilitate energy transition and help achieve climate goals and the financial motivation that the costs for hydrogen infrastructure is lower than reinforcing the electricity grid.
A38	The sector has no impact on the decision-making of the industries.	In the case study, the industrial area consists of food processing industries with high-temperature energy demands and one greenhouse farming with lower temperature needs. These stakeholders are the end-users considered for the scope within the industrial area in this study. The case study however excludes other sectors outside agrifood and agriculture from the end-use. Due to the little diversity in sectors, it is assumed the sector has no impact on the decision-making of agents.
A39	The application considered is thermal applications only.	In the case study, application as raw material does not occur. The majority of industries in the case study are food processing industries with high-temperature demand, and only one industry is an agricultural industry with low-temperature demand. As we assume the sector has no impact on the decision-making of industries (A38), no distinction between application based on sector can be made. This excludes application as raw material or for power generation.
HDNO		
A40	It is assumed the DSOs are most likely to become HNDO.	This is based on hydrogen pilot projects and exploratory projects currently being performed by current DSOs (e.g. see C.4) due to the existing expertise knowledge on gas infrastructure and capacity. This also became clear from the interviews, where DSOs show strategic behaviour to explore the possibility and feasibility of hydrogen while not being HDNO yet, as described in 4.3. Additionally, the phenomenon of Gasunie establishing subsidiary company HyNetworks on national level shows the same could happen on regional level. Therefore, references to DSOs and HDNOs can be used interchangeably.
A41	It is assumed Ownership Unbundling (OU) is adopted on hydrogen distribution level	This is similar to the hydrogen transmission level. This is based on the Gas Act, which states that Gasunie group companies are allowed to develop and manage hydrogen pipelines or installations, including the transport of hydrogen, as long as the Dutch ownership unbundling rules are observed.

E Formalized model in pseudo-code

The translation of the conceptual model to a formalized model is described in this appendix. The description of the narrative is was made using pseudo-code, a mathematically defined representation of the system by specifying the rules and equations governing the behaviour of the agent and the protocols of the different TPA regimes in section.

Agent decision rules and behaviours

Each industry follows a decision cycle at every simulation tick representing one year. All industries are in a phase. This can either be planning, construction or operationalization.

If an industry is planning, it means they are preparing for energy transition and debating if they want to transition to hydrogen. Planning industries firstly determine their transition strategy, based on the motivation degree in place. Next, they conduct a cost benefit analysis and determine their financial feasibility. The next step is to see recalculate their motivation-degree and see if they want to submit a request for connection to hydrogen. The pseudo-code 1 below shows the logic:

```
For each industry with [phase = "planning"]:
    Ask to do:
        determine-transition-strategy
        conduct-cost-benefit-analysis
        determine-feasibility
        calculate-motivation
        submit-request?
End for
```

Pseudo-code 1: Industries planning for hydrogen transition

The first step described in 1 of determination of the transition strategy is based on thresholds. If the motivation degree reaches a certain threshold, the transition strategy is set higher. As indicated in section 5.1.2, each transition strategy has an energy percentage of hydrogen being transitioned with a corresponding strategy of mixing or retrofitting. See pseudo-code 2 for the logic.

```
If motivation-degree <= threshold1 then:
    set transition-strategy 0.07 ;; 7% with mixing
    set mixing? true
    set retrofitting false
Else if motivation-degree >= threshold1 and < threshold2 then:
    set transition-strategy 0.2 ;; 20% with retrofitting
    set mixing? false
    set retrofitting? true
Else if motivation-degree >= threshold 2 then:
    set transition-strategy 0.4 ;; 40% with retrofitting
    set mixing? false
    set retrofitting? true
End if
```

Pseudo-code 2: Determine transition strategy

The next step for planning industries is to conduct the cost benefit analysis and determine the feasibility. Pseudo-code 3 below shows the logic. For a more elaborate explanation of the elements included in benefits, OpEx and CapEx, see section 5.1.2.

```
;; Calculate financial elements based on current transition strategy
```

```
set benefits calculate-benefits
set OPEX calculate-OPEX
set CAPEX calculate-CAPEX
;; Discounted cash flow
let discount-sum 0
For year in CBA-horizon:
    let discounted-value (benefits [year] - OPEX[year]) / (1 + discount-rate) ^ year
    set discounted-sum discounted-sum + discounted-value
End for

;; Financial metrics
set NPV discounted-sum - CAPEX
set ROI ((sum benefits - sum OPEX) / CAPEX) * 100

;; Store results
Append NPV to NPV-history
Append ROI to ROI-history
```

Pseudo-code 3: Conduct cost-benefit analysis and determine feasibility

Lastly, the planning industries calculate their motivation-degree based on the three factors of CBA, peer pressure and the waiting list. Next, planning industries determine if they want to submit a request or not. This is shown below in pseudo-code 4.

```
;; Compute normalized CBA metrics
CBA-norm = ( (NPV - npv_min) / (npv_max - npv_min)
            + (ROI - roi_min) / (roi_max - roi_min) ) / 2
;; Compute peer pressure factor
set total-peers length(my-peers)
set transitioning-peers count(my-peers with (phase = "construction" or "operationalization") or financial-feasible = true)
If total_peers > 0 then:
    set transitioning_peers / total_peers
Else: 0
;; Compute waiting list factor (only applies under nTPA/hnTPA)
If current-policy = "nTPA" or ("hnTPA" and current-year < 2033) then:
    set WL-position position of self in waiting_list
    set WL-norm 1 - (WL-position / length(waiting-list))
Else:
    set WL-norm 0
End if
;; Combine factors using predefined weights
set motivation-degree weight-CBA * CBA-norm + weight-PP * PP-norm + weight-WL * WL-norm

;; Determine if you want to submit a request or not.
If motivation-degree >= motivation-threshold then:
    submit connection-request
End if
```

Pseudo-code 4: Calculate motivation and submit request?

Once industries' requests get accepted, industries enter the phase of construction. As nothing happens during construction, the whole model waits until construction is finished. Once construction is finished, the industries enter a phase of operationalization and update their CO_2 avoidance and hydrogen and natural gas consumption and capacity, see pseudo-code 5.

```
If industry request is accepted then:
    Set phase to "construction"

```

```
IF current year = construction-end-year then:
    For each industry with phase = "construction":
        Set phase to "operationalization"
        Update CO2-avoidance
        Update hydrogen and NG consumption
        Update hydrogen and NG capacity
```

Pseudo-code 5: Industries in construction or operationalization

Influence of policies

According to the different TPA regime chosen in the model, the connection and negotiation procedures differ. In rTPA, the protocol is to process the connection request on a FCFS basis. The implications of this is the waiting-list factor being zero, since negotiation is not possible. In nTPA, the protocol is to process the connection via negotiation rules set up by the HDNO, which is that larger capacities with lower connection costs are connected first. The implication of this is the waiting list factor becoming active, which feeds back into the motivation computation. In hnTPA, the protocol is to initially operate as nTPA and then switch to rTPA in 2033. A simplified formal version for processing connection requests under different TPA regimes can be written as shown in pseudo-code 6.

```
If current-policy = "rTPA" then:
    Process waiting-list in submission order FCFS.
Else if current-policy = "nTPA" then:
    Aid in initializing the network by dividing the investment costs more and
        bare more costs as HDNO.
    Rank connection request based on negotiation rules: order of highest
        quantity / connection cost ratio.
    Process highest-ranked requests first.
    ;; Implications of the industries:
    For each industry with [phase = "planning"]:
        Ask to do:
            Conduct cost benefit analysis with investment-cost-division.
            If self in waiting-list:
                Conduct-cost-benefit-analysis with alternative transition
                    strategy. If NPV > 0 and ROI > 0 then:
                    set transition-strategy alternative-strategy
                End if
            End if
    End for
Else if current-policy = "hnTPA" then:
    If current-year < 2033 then:
        Follow nTPA regime.
    Else:
        Switch to rTPA regime.
    End if
End if
```

Pseudo-code 6: Policy protocols

F Extensive valuation of the model implementation, results and outputs

This appendix describes the additional results for the model verification (F.1), sensitivity analysis (F.2) and model validation (F.3).

F.1 Additional results of the model verification

Recording and tracking agent behaviour
The model can be verified by looking into the agent behaviour as defined, to make sure the model is operating as expected at the level of the agent, in addition to correct operation at the level of the system where any emergent behaviours will most likely be visible [53].

Agent behaviour was checked during the software implementation to verify behaviour with completed blocks of the model. For these purposes, various print and show statements were placed in various parts of the code to display the inputs, states and outputs of agents. Some examples are:

- print (word "My NPV is: " NPV ", my ROI is: " ROI)
- show "Threshold is not yet reached"
- print (word "Industry " who " is done constructing and is now in phase" phase)
- print (word "I " who " will submit-request with motivation degree " motivation-degree)
- ...

These simple technique checks if agents enter specific parts of code and has contributed to the verification of the model.

Single agent testing
Because of the complex nature of the model, consisting of multiple agents, the model can be verified further by exploring the behaviour of a single agent. The first step of single-agent testing is to make explicit predictions of what we theoretically expect the agent to do when we provide well-defined inputs to agents. Here, the tracking of agent behaviour can again be used to see if all works correctly [53]. The short tests described below are confirmed.

- When the threshold for the minimum number of industries with request for connection required to start construction is set to 1, only one industry can transition. The wait time is two years, as constructing the system connection takes one year, and constructing one industry connection takes another year.
- Set the motivation degree just below the cut-off for request submission, then the agent does not submit the request.
- Setting the CaPex very low (e.g. 1000) and the installation size very big, the NPV and benefits become very high.

Another approach with single agent testing is to create extreme conditions to push limits of the parameters and agent behaviour. This can define the edges of normal behaviour and ensures there are no errors such as division by zero or if unexpected behaviour occurs, checking if it is the result of an implementation error or coding choice [53]. The short tests described below are confirmed.

- Setting the weight of the peer pressure to 1 and the other variables to zero leads to the motivation degree consisting of peer pressure only. This leads to no transition, as the industry has no other peers who will increase the peer pressure.
- Set the hydrogen-price to zero for all years. This results in a minimal OpEx, the benefits are very high and the NPV is very positive.
- Set the capacity demand of natural gas to zero for all the years. There should be no hydrogen demand, no benefits, and an NPV below zero. The agent should not be financial feasible and not submit a requestion. This verification test led to an error for division by zero in the KPIs where the KPI-hydrogen-NG-ratio is calculated by dividing the hydrogen consumption by zero, which was resolved.
- Setting the CapEx to zero results in a crash in the ROI calculation, which was solved.

Interaction testing
After testing a single agent, agent interaction needs to be verified by following the same tests as defined for single agent testing. In this test, two agents are present. It is important to check whether we get the desired or unintended interaction.

- If industries are near enough, they should become each other's peers. If one of them transitions, the normalized unweighted peer pressure value should be one.

Multi-agent testing
Once the model is verified in a minimal setting, the model can be verified with all agents present through all the same theoretical prediction and breaking the agent tests as used before. Those tests were verified as well.

F.2 Additional results of the sensitivity analysis

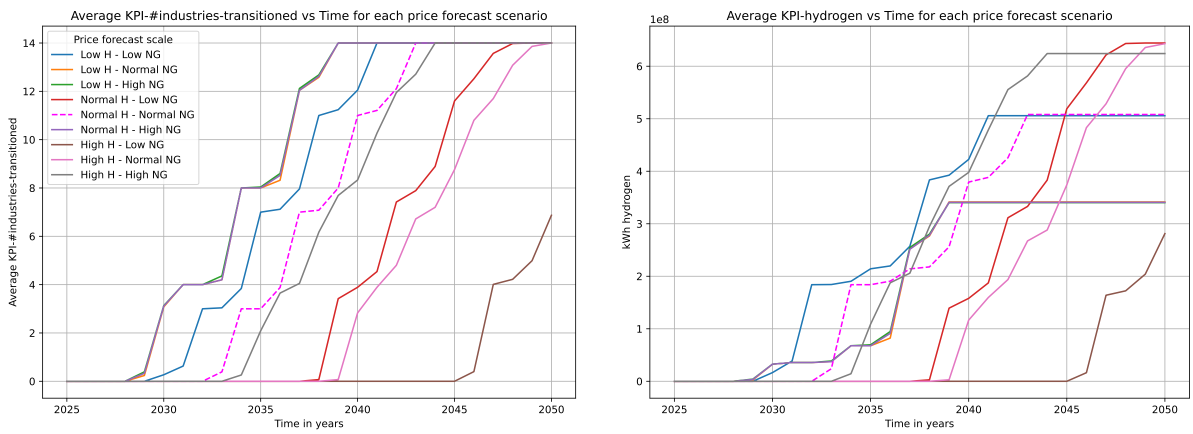
Sensitivity analysis was performed following the six-step plan for sensitivity analysis for ABMs from [55] as described in section 3.4. Table 12 repeats the overview of the sensitivity analysis design.

Table 12: Repetition of table: overview of the sensitivity analysis design

Parameter	Method	Given value	Range
Economic parameters			
naturalgas-price-scale, hydrogen-price-scale	Scenario	1, 1 (see appendix H)	+/- 20% from base value
HDNO parameters			
construction-capacity	OFAT	4	[0, 14], increments of 1
Agent behavioural parameters			
weight-CBA, weight-peer-pressure, weight-waiting-list	Scenario	0.6, 0.2, 0.2	[0, 1], increments of 0.1, where the sum of all weights is 1.
strategy-threshold-low, strategy-threshold-high	Scenario	0.7, 0.9	[0.1, 1], increments of 0.1, where strategy-threshold-low < strategy-threshold-high.
max-distance-peers	OFAT	10	[0, 800], increments of 100
npv-max, npv-min, roi-max, roi-min	Scenario		

Sensitivity analysis of parameters naturalgas-price-scale and hydrogen-price-scale
As outlined in the conceptual model (section 5.1) and price forecasts (appendix H), there is uncertainty in the energy market regarding the development of hydrogen and natural gas prices.

This uncertainty demands a closer examination of how different pricing scenarios impact model behaviour. The variables naturalgas-price-scale and hydrogen-price-scale were used to explore this effect by scaling the forecasted prices by factors of 0.8, 1.0 and 1.2, resulting in nine unique scenarios combining low, normal and high price levels. Figure 20 shows the sensitivity analysis outcome of these scenarios. The analyses were performed in the rTPA regime, with exception of the weights later in this appendix, which was performed in the nTPA regime.



(a) Number of industries submitted request over time

(b) Amount of hydrogen over time

Figure 20: Repetition of figure: sensitivity analysis of different price forecast scenarios

As expected, the model is highly sensitive to price variations. In figure 20a, it can be observed that the slope of adoption remains relatively constant, but the timing of transition varies significant depending on the relative price scales. Transitions are notably delayed in scenarios where hydrogen is expensive (e.g., high H, low NG), as industries struggle to reach a favourable cost-benefit analysis (CBA) score.

Interestingly, scenarios where hydrogen is relatively cheaper than natural gas—such as low H, high NG (green), low H, normal NG (orange), and normal H, high NG (purple)—show overlapping and accelerated transition trajectories. This pattern implies that the relative price competitiveness of hydrogen, rather than its absolute cost, is the key driver of transition timing.

Figure 20b further shows that faster hydrogen transition does not always correlate with more hydrogen off-take. Some high-hydrogen-price scenarios exhibit unexpectedly high hydrogen usage over time. This counter-intuitive result stems from model assumptions: once industries transition, they do not revise their strategy (see A29). Consequently, early transitions under cautious strategies lead to lower long-term off-take, while delayed but more ambitious transitions may yield higher consumption.

The price sensitivity analysis highlights the crucial role of the energy price in shaping transition dynamics. While relative energy prices clearly influence adoption timing, the model limitation where no further transition is considered beyond initial transition significantly affects long-term hydrogen demand, which indicates room for future research. Lastly, the simulation results should be treated with caution, as the sensitivity and uncertainty to the price forecasts is high. Future work might include a more thorough exploration of the economic drivers to reduce uncertainty.

Sensitivity analysis of parameter construction-capacity
The variable construction capacity represents the maximum number of industrial connections to the hydrogen network that can be constructed simultaneously. It reflects the HDNO's operational capacity to expand infrastructure in parallel. Figure 21 presents the results of the sensitivity analysis, showing how varying construction capacities affect the number of industries transitioned over time.

The results indicate the model is highly sensitive to the construction capacity. Scenarios with higher capacities exhibit steeper slopes in the transition curve, meaning that a greater number of industries are able (and willing) to connect to the hydrogen network. This highlights the importance of sufficient infrastructure roll-out capacity for HDNOs to enable accelerated transition to hydrogen.

Interestingly, there seems to be a saturation point around a construction capacity of 7. While increasing beyond this threshold leads to faster uptake in the early phases (notably by year 2035), the overall time at which the transition is completed (around year 2038) remains relatively unchanged. This suggests that while construction capacity strongly affects the tempo of early transitions, it does not necessarily shift the final end-point of adoption in the system modelled.

This effect can be attributed to the behavioural dimension of the case study in the model. Not all industries in the case study are motivated to transition early, due to the absence of a high enough motivation degree, meaning that excess construction capacity is not fully utilized until the motivational thresholds are reached.

These findings suggest that while expanding construction capacity is an enabler of rapid transition, it is not sufficient on its own. The pace of hydrogen adoption is jointly determined by behavioural motivation. For HDNOs, this implies that investments in capacity should be accompanied with strategies to stimulate early industry demand to fully use the acceleration potential of increased build-out capacity.

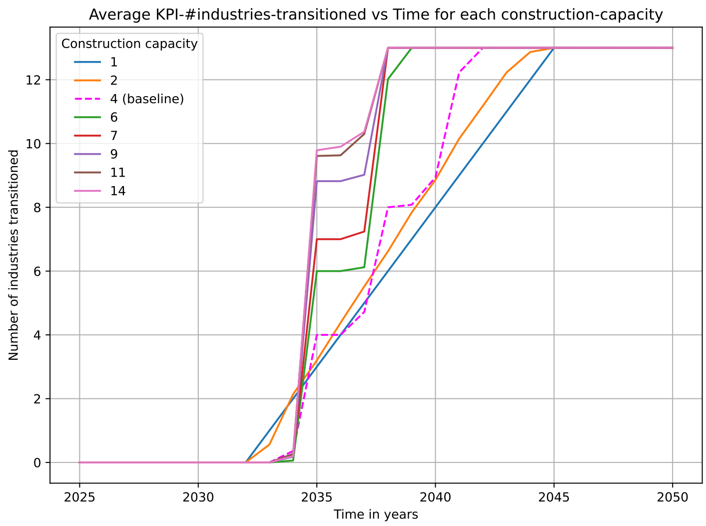
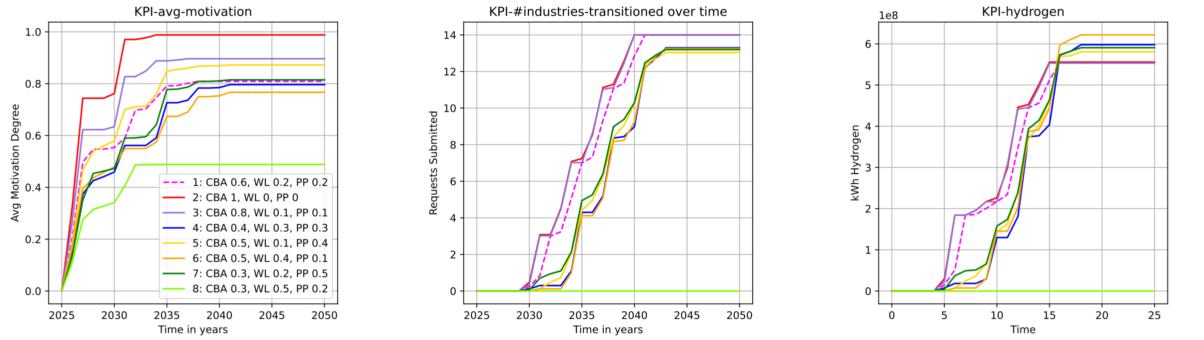


Figure 21: Sensitivity analysis of construction capacity and the number of industries transitioned over time

Sensitivity analysis of parameters weight-CBA, weight-peer-pressure and weight-waiting-list
The motivation degree is a key behavioural metric in the model, determined by weighted contributions from CBA, peer pressure (PP), and the waiting list (WL). To explore this mechanism, the weights were varied widely in the sensitivity analysis and nine combinations of weights (ranging from 0 to 1 in increments of 0.1) were selected to display, see table 13 for the combinations. Important to note is that this experiment is under the nTPA regime, where all three motivational factors are active. Figure 22 presents the outcomes, with combination 1 (CBA 0.6, WL 0.2, PP 0.2) representing the baseline.

Table 13: Weight combinations for cost-benefit analysis (CBA), waiting list (WL), and peer pressure (PP) for sensitivity analysis

Combination	CBA	WL	PP
1 (baseline)	0.6	0.2	0.2
2	1.0	0.0	0.0
3	0.8	0.1	0.1
4	0.4	0.3	0.3
5	0.5	0.1	0.4
6	0.5	0.4	0.1
7	0.3	0.2	0.5
8	0.3	0.5	0.2



(a) Average motivation degree over time

(b) Number of industries transitioned over time

(c) Amount of hydrogen over time

Figure 22: Repetition of figure: sensitivity analysis of different weight combinations

As can be seen from figure 22a, the average motivation over time is highly dictated by the weight of the CBA. This weight is determined independently of other agents' behaviour in the model. Combinations where the CBA outcomes are heavily considered by industries develop more quickly and to higher values. Combinations where more weight is given to the waiting list or peer pressure develop slower over time, as can be expected. It reflects the wait-and-see attitude of industries and dependency on other agents.

The number of industries who are transitioned over time in figure 22b shows when industries are transitioned. Corresponding to the outcomes of figure 22a where the average motivation degree of combination 8 does not transcend the submission-threshold, no requests for connection are made and no hydrogen is consumed in figure 22b and 22c respectively. The reason why the average motivation degree does not reach higher than 0.5 is that the weight of the waiting list is too high compared to the peer pressure and CBA. Industries might become financially feasible and receive peer pressure because their neighbours are financially feasible as well, but no one enters the waiting list as no one submits a request. This is due to the too low motivation-degree, where there is no incentive from the weighting list, which makes it computationally impossible to increase the motivation-degree.

What can be derived from figure 22b is that high peer pressure accelerates transition more compared to a high weighting of the waiting list. This can be derived when comparing combination 5, (CBA 0.5, WL 0.1 and PP 0.4), to combination 6, (CBA 0.5, WL 0.4 and PP 0.1).

The last figure shows that more weighted CBA in combinations 1, 2 and 3 results in quicker energy transition. The impact of the waiting list and peer pressure is more delayed, as this depends on having already filed a request and on peers becoming financially feasibility and start transitioning. Noticeable is combination 6, where the weight of the waiting list is 0.4 and more hydrogen is adopted. This is a logical result, as the industries receive more incentive to increase their hydrogen off-take to reach a higher position in the waiting-list and have a higher chance of quicker transition. The combinations show that a more balanced combination of weights (combination 4, 5, 6 and 7) instead of a highly weighted CBA result in a more hesitant hydrogen transition, but more hydrogen off-take.

To conclude, the weights impact the pace of transition by a few years, however their impact on total hydrogen demand within the nTPA regime is nuanced. More evenly distributed weights delay the transition due to dependency on the behaviour of other agents, but can be beneficial for the quantity of hydrogen off-take. The results suggest that HDNOs could influence the quantity hydrogen transition by creating incentives such as the waiting list during the nTPA regime to introduce competition and create ambition. The pace of hydrogen transition is mostly influenced by the CBA results, which implicates policy design should focus on improving the economic conditions for hydrogen as a fuel. The influence of peer pressure by creating visibility of peers will be researched further in section later in this appendix under max-distance-peers.

Sensitivity analysis of parameters strategy-threshold-low and strategy-threshold-high

As highlighted in section the sensitivity of the price forecasts for natural gas and hydrogen, the strategy-threshold-low and strategy-threshold-high are behavioural parameters which define when industries switch from conservative to ambitious hydrogen strategies (e.g. from blending 7% to retrofitting with 20% or 40% hydrogen). These thresholds were tested across several combinations between 0 and 1, where the low threshold remained below the high, see figure 23 for the results and table 14 for the different scenarios.

Table 14: Submission threshold scenarios for sensitivity analysis

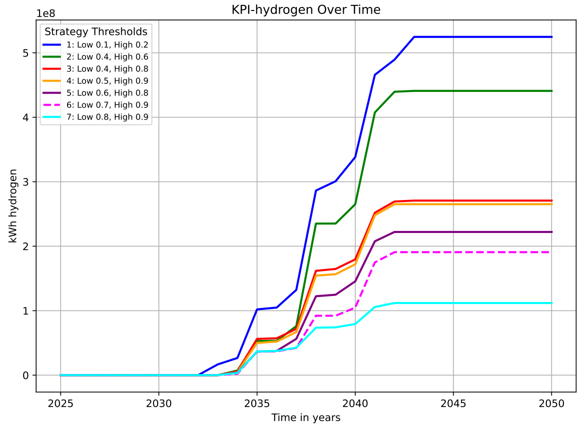
Scenario	strategy-threshold-low	strategy-threshold-high
1	0.1	0.2
2	0.4	0.6
3	0.4	0.8
4	0.5	0.9
5	0.6	0.8
6 (baseline)	0.7	0.9
7	0.8	0.9

Figure 23a shows that hydrogen off-take is highly sensitive by the thresholds. Lower threshold scenarios (scenario 1–4) enable industries to adopt more ambitious strategies early on, leading to significantly higher hydrogen consumption compared to the baseline (scenario 6) or higher-threshold scenarios (e.g., scenario 7).

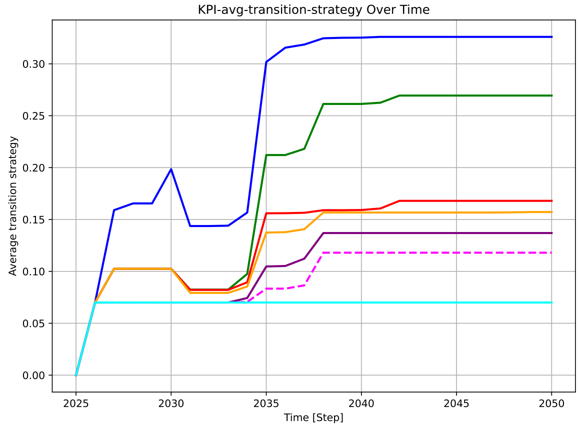
The choice for the more ambitious transition strategy is illustrated in 23b, which shows the average transition strategy over time. Here, a transition strategy of e.g. 0.07 means that 7 energy % of the current natural gas consumption is converted to hydrogen. Notably, scenario 1 reaches an average transition strategy of around 0.33 maximum, while the baseline (scenario 6) flatlines at 0.12 or 0.07 in scenario 7. Remarkable in this figure is the strange curve around year 5. This corresponds to the entry of new industries in 2030, which start with the adoption of a more cautious strategy. Starting with a cautious strategy of 7% initially is modelled for all industries.

Figure 23c and 23d illustrate the shift from mixing to retrofitting. In figure 23c, scenario 1, 2, 6 and 7 are displayed with the number of industries mixing and retrofitting over time. As can be seen from the timeline, the retrofitting line increases later in time, which is in line with the average transition strategy (figure 23b) as the industries tend to become more ambitious over time. Figure 23d shows the number of industries mixing or retrofitting per scenario. Striking is that even a small increase in the low threshold (e.g., from 0.7 to 0.8) significantly reduces the number of industries opting to retrofit. This points to a tipping-point behaviour, where small changes in threshold values can create large systemic effects.

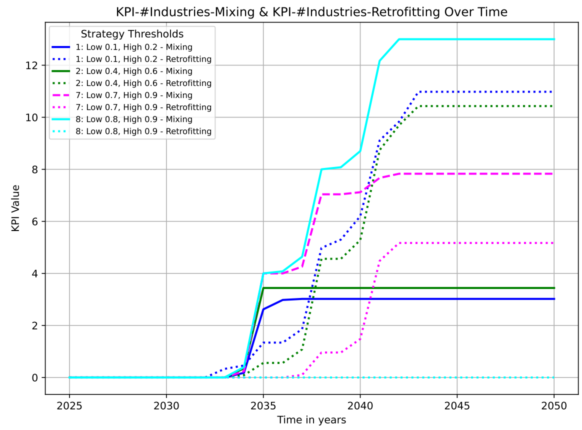
To conclude, the model is highly sensitive to strategy threshold settings, especially in determining long-term hydrogen demand. Unrealistically low thresholds can produce overly ambitious adoption patterns not supported by empirical data from the interview findings in section 4.2. This highlights the need for careful calibration of behavioural parameters based on these real-world observations, as small changes can result in large impacts on model outcomes. However, it also shows that influencing the behavioural thresholds in such a way that industries feel less cautious and adopt an ambitious strategy early on can be an affective approach for HDNOs and policy makers to increase hydrogen off-take in the early phases.



(a) Amount of hydrogen over time



(b) Average transition strategy over time



(c) Number of industries mixing and retrofitting over time

(d) Transition strategy of mixing or retrofitting

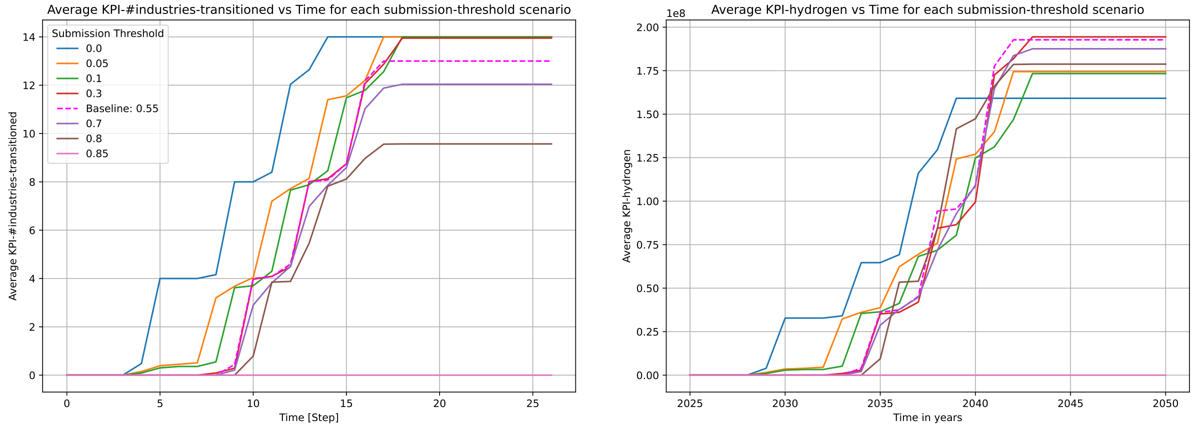
Figure 23: Sensitivity analysis of the high and low strategy threshold in different combinations

Sensitivity analysis of parameter submission-threshold

The submission-threshold defines the minimum motivation degree an industry must reach to request a hydrogen connection. Since this threshold is based on assumptions and expected to significantly affect behaviour, it was selected for sensitivity analysis and varied between 0 and 1 in increments of 0.05. Selected results are shown in Figure 24.

Figure 24a demonstrates that a small increase in the submission-threshold (from 0.0 to 0.05) already delays the transition due to the time required for motivation to build. Peer pressure starts with zero as no peers are transitioned yet, the industries are not in a waiting list (yet) as they have not submitted a request and the CBA outcomes might not be so attractive in the initial years. Beyond a threshold of 0.55, the pace and timing of transition remain consistent, but the total number of transitioned industries declines as fewer agents reach the required motivation degree.

From a threshold of 0.85 and above, no transitions occur. This is linked to the rTPA policy, where the waiting list does not actively incentivize agents. In this policy context, the maximum motivation degree achievable under baseline settings is about 0.8 (as the weight for WL is 0.2), meaning thresholds above this value become functionally unreachable.



(a) Amount of hydrogen over time

(b) Average transition strategy over time

Figure 24: Sensitivity analysis of the submission threshold

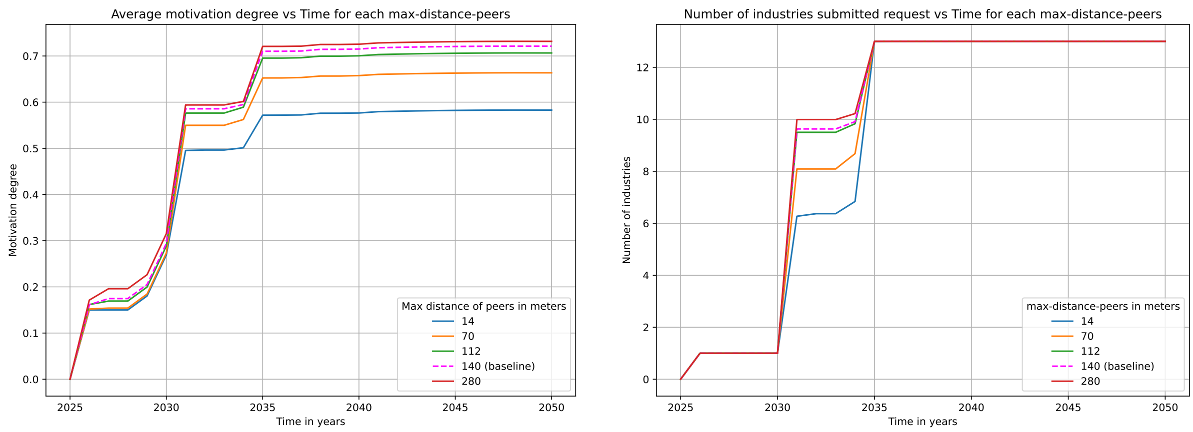
Sensitivity analysis of parameter max-distance-peers

The variable max-distance-peers defines the maximum range within which industries perceive other industries as their peers. Although the distance is in NetLogo scale, it is translated to the assumed real-world scale using the model's distance-scale parameter in the legend of figure 25. As the max-distance-peers plays a critical role in determining the influence of peer pressure on the overall motivation degree of industries, it is interesting to explore the impact of the parameter through sensitivity analysis, see figure 25.

The sensitivity analysis was conducted under the rTPA mechanism, with the weights of the peer pressure, waiting list and CBA set at 0.2, 0.2 and 0.6 respectively. As figure 25a shows, the motivation degree is clearly influenced by the maximum number of peers. In scenarios with smaller peer ranges (e.g. max-distance-peers = 14 or 70 meters), the motivation degree is significantly lower compared to the scenarios with broader peer networks. This suggests that too narrow a reference group weakens the social reinforcement effect. Notably, the results reveal a tipping point around the baseline value of max-distance-peers = 140 meters. Beyond this range, increasing the peer range has marginal effects on motivation.

This tipping point is similarly reflected in the number of industries submitting requests, as shown in figure 25b. While total adoption levels eventually coincide, early-phase hydrogen transition is higher when peer ranges are broader. This indicates that although long-term market saturation may be comparable, the initial speed and momentum of adoption are significantly shaped by the perceived visibility of peers.

These findings confirm that the effect of peer pressure in industrial decision-making is conditional on the spatial awareness. A too limited peer network weakens the behaviour mechanism and reduces early participation. Therefore, policies or communication strategies that enhance visibility of hydrogen projects within the regional clusters could amplify the positive feedback loops essential to accelerate early hydrogen adoption.



(a) The motivation degree over time

(b) Number of industries submitted request over time

Figure 25: Sensitivity analysis of max-distance-peers

F.3 Additional results of the model validation

As described in the methodology section 3.4, validation through experts has been partly done throughout the whole process by basing assumptions on interviews and expert insights and recommendations, and building the model in close collaboration with experts. In this section, validation is complemented by literature.

Validation of agent behaviour

In this study, agent behaviour regarding hydrogen adoption is partially driven by the CBA weight, representing how strong an agent is influenced by economic evaluation, compared to peer influence and the waiting list. Based on the sensitivity analysis, a nominal weight of 0.6 was assigned to the CBA component, and 0.2 for the waiting list and peer pressure each.

To ensure the weighting structure applied in the model accurately reflects real-world decision making in infrastructure contexts, it is compared to literature. Firstly, the sustainable decision-making framework proposed by [70], which supports the inclusion of environmental/technical, economic, and political/social factors in infrastructure planning models. The three dimensions is reflected in the design of this model as well, where agents are influenced by a weighted combination of the cost-benefit analysis, peer pressure, and perceived waiting list urgency. Each of these drivers correspond to the a core dimension of [70].

CBA corresponds to the environmental/technical axis of the framework. In this dimension, environmental impact and technical feasibility is assessed using CBA. The CBA's role in rating alternatives justifies its use as a weighted driver in agent decisions. The peer pressure corresponds to the political/social dimension of the framework, where the probability of acceptance of an alternative, based on how much one actor (e.g., industry) can influence another. Lastly, the waiting list reflects both political/social and economic urgency and opportunity. The perceived urgency of a long queue impacts strategic decisions, as supported by the framework's focus on bargaining behaviour and stakeholder interests. As such, the weighting structure applied in this model is not arbitrary, but is aligned with established frameworks for sustainability-focused decision-making.

Secondly, [74] assess how industrial production can be managed towards sustainability goals, by focusing on technological innovations of large-scale, process-oriented firms such as the agrifood industry in this case study. Three influential factors for change in technologies are identified which can be compared to this study's transition to hydrogen. The first is awareness of pressure due to external pressure upon the production system, which can be compared to the CBA-factor, where high costs such as EU ETS and CO_2 tax pressure industries to transition. Next, informal interactions with firm-external actors are also important, which is captured in the PP-factor, where neighbouring industries push the hydrogen transition of oneself. Last, the availability of a mature firm-internal technology network, which can be loosely compared to the WL-factor, which motivates to get early access to the available hydrogen network.

When comparing the weighting for CBA to literature, this reflects the findings from [71] on the Dutch CBA practice for spatial infrastructures. The paper reveals that while CBA is widely accepted as necessary, there is no consensus on how much value should be assigned to it in spatial-infrastructure decision-making. Economists typically believe that CBA is undervalued, while spatial planners argue the opposite. However, even those sceptical of CBA are not categorically opposed to its use and support a subtle role, where CBA contributes significantly, but not exclusively to decision-making.

While the decisions are made by industries and not economists or spatial planners, the general idea and nuance supports the chosen weighting in the model: CBA is influential (0.6), but not dominant (e.g. 1). The sensitivity analysis explored a full range of alternative weights, see chapter 7 and appendix F.2, resulting in the selected default weight, which aims to reflect a balance between the motivations of the industries as described in 4.2.

Validation of cost-benefit analysis

During the validation of the cost-benefit analysis' outcomes, the net present value (NPV) and return on investment (ROI) metrics showed values that deviate significantly from expected real-world benchmarks. These anomalies appear to result from underlying assumptions in the calculation of the costs and benefits of the model, where the simplified cost estimations do not encompass all costs. This may not fully capture the complexities of real-world financial decision-making.

However, in the calculation of the motivation degree, the outcomes of the cost-benefit analysis are normalized to CBA-norm, a value between 0 and 1, which then factors into the calculation for the motivation degree (see pseudo-code 4). By selecting the maximum and minimum boundary of the normalized score carefully using trail and error, the anomalous outcomes are therefore taken into consideration and accounted for. However, these bounds are difficult to determine as no literature was available and might be case specific and relative to each other. This means the model might not hold for other case studies. This indicates future research could further refine these bounds.

While the CBA calculation itself works correctly (see appendix F.1) and transition strategies and motivation degree behave as intended due to the method of calculating the normalised value of the cost benefit analysis, the economic outputs should be interpreted with caution. Further refinement of the financial modelling and calculations is recommended to improve the realism and reliability of these indicators in future research.

G Model parameters and variables

This appendix gives an overview of all agent parameters (table 15) and the model parameters (table 16) used in the model that needed to develop the formalization. They are listed alongside the type, range and description. Additionally, their sources and assumptions are indicated where available or necessary. For an overview of the KPIs, see table 4 in chapter 5.2.

Table 15: Agent variables

`Variable`	**Type**	**Range/Values**	**Description**
Identity			
`sector`	String	"Food" or "Agriculture"	Possible sectors in the model based on the case study (Section C.5).
`installation-size`	Float	1.5 - 50	Capacity of the industry in MW.
`distance-to-system-connection`	Float	0 - 308	Distance to patch 0 0, assumed to be system connection (Assumption 6).
`phase`	String	"Planning", "Construction", "Operationalization"	Indicates the phase in which the industry situates.
`connected?`	Boolean	true / false	Is an industry connected to the network or not.
Strategic and decision variables			
`motivation-degree`	Float	[0, 1]	Indicates the level of motivation.
`CBA-norm, WL-norm, PP-norm`	Float	[0, 1]	Normalized factors determining the motivation degree.
`transition-strategy`	Float	0.07, 0.2 or 0.4 (default)	Predefined energy percentage of hydrogen to be transitioned (see A32).
`alternative-transition-strategy`	Float	transition-strategy + 0.1	Alternative strategy for when an agent wants to move higher in the waiting list.
`request-submitted?`	Boolean	true / false	Indicates if an industry has submitted a request for connection or not.
`mixing?`	Boolean	true / false	Is it the transition strategy for an industry to mix hydrogen with natural gas or not.
`retrofitting?`	Boolean	true / false	Is it the transition strategy for an industry to retrofit or not.
`year-submitted-request`	integer	2025 - 2050	The year the industry has submitted its request for a hydrogen connection.
`year-became-operational`	integer	2025 - 2050	The year the industry has finished its construction and starts operating with hydrogen.
Capacity, consumption and emissions			
`yearly-NG-capacity`	List	-	Capacity of natural gas demand in kWh/h for each year (data from Stedin databases).
`potential-yearly-H-capacity`	List	-	Possible hydrogen demand in kWh/h for each year.

Continued on next page

Table 15 continued from previous page

Parameter	Type	Range/Values	Description
`yearly-H-capacity`	List	-	Hydrogen demand in kWh/h for each year once connected.
`yearly-NG-consumption`	List	-	Actual consumption of natural gas in kWh/h for each year (data from Stedin databases).
`potential-yearly-H-consumption`	List	-	Possible hydrogen consumption in kWh/h for each year.
`yearly-H-consumption`	List	-	Actual hydrogen consumption in kWh/h for each year once connected.
`potential-CO2-avoidance`	List	-	CO_2 that could be avoided if transitioning to hydrogen in tCO_2 per year.
`CO2-avoidance`	Float	-	CO_2 avoided after transition to hydrogen in tCO_2 per year.
Financial performance and investment data			
`financial-feasible`	Boolean	true / false	Indicates financial feasibility based on NPV.
`NPV-history`	List	-	History of NPV calculations from cost-benefit analysis.
`ROI-history`	List	-	History of ROI calculations from cost-benefit analysis.
`potential-connection-costs`	Float	58050 or more	Estimated pipeline connection costs in euros.
`ind-connection-costs`	Float	58050 or more	Actual pipeline connection costs in euros once connected.

Table 16: Model parameters and variables

Parameter/Variable	Type	Range/Values	Description
Price and tax forecasts			
`natural-gas-price`	List	(see H)	The price prediction of natural gas for each year in €/kWh.
`hydrogen-price`	List	(see H)	The price prediction of hydrogen for each year in €/kWh.
`CO2-tax-below-50`	List	(see H)	The price prediction CO2 tax each year in €/tCO_2 for emissions above 50 ktonne.
`CO2-tax-above-50`	List	(see H)	The price prediction CO2 tax each year in €/tCO_2 for emissions below 50 ktonne.
`EU-ETS-1`	List	(see H)	The price prediction of EU ETS for each year in €/tCO_2, for all industrial installations above 20 MW.
`EU-ETS-2`	List	(see H)	The price prediction of EU ETS for each year in €/tCO_2, for all industrial installations below 20 MW.
Timeline and Construction			
`start-year`	Integer	2025	The start year of the simulation.

Continued on next page

Table 15 continued from previous page

Parameter	Type	Range/Values	Description
`current-year`	Integer	2025 - 2050	The current year of the simulation.
`end-year`	Integer	2050	The end year of the simulation.
`operating-hours`	Integer	5694	Number of hours the industries operate in a year on full capacity. Based on an estimation of the data from Stedin, 65% of the hours in a year industries are operating (A34).
`new-industries-arising-year`	Integer	2030	The year new industries arise in the model (see A35).
`hnTPA-switch-year`	Integer	2033	The year the hnTPA switches from nTPA to rTPA.
`construction-happening`	Boolean	true / false	Indicates wheater construction is happening in the model or not.
`construction-duration-proxy`	Integer	3	The average number of years it takes to construct the hydrogen infrastructure, used as an estimate for industries to set the time horizon for their CBA (see A26).
`construction-duration`	Integer	1 - 4	The actual number of years it takes to construct the hydrogen infrastructure (see A25).
`construction-capacity`	Integer	4	The number of industries a HDNO has the capacity for to construct at the same time.
`construction-end-year`	Integer	2025 - 2050	The year the construction ends.
`operation-duration`	Integer	15	The number of years the industries want to operate with the new hydrogen infrastructure to win back investments, sets the time horizon for the CBA. Adapted from [57], indicating the length of the assessment period for gas infrastructure investments.
`HDNO-construction-threshold`	Integer	3	The minimum number of industries with request required to start construction (see A23).
`distance-scale`	Integer	14	Parameter used to scale the NetLogo distance in the patches to an assumed real-world distance in meters, for distance-to-system-connection, see A6.
`initial-n-industries`	Integer	4	Initial number of industries present in the model, based on the case study.
Cost and conversion parameters			
`H-tariffs-relative-to-NG-tariffs`	Float	2, 2.5, 3	The hydrogen tariffs relative to the natural gas tariffs, as explained in 5.1.3 and C. Implemented as a slider.
`m3-NG-to-kwh`	Float	9.75556	Conversion parameter to calculate amount of kWh per m^3 natural gas, adapted from [33].

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Table 15 continued from previous page

Parameter	Type	Range/Values	Description
`NG-to-CO2`	Float	0.000203966	Conversion parameter to calculate tCO2/kWh natural gas, adapted from [33].
`pipeline-cost-per-meter`	Integer	600	The cost of a hydrogen pipeline per meter (see A20).
`discount-rate`	Float	0.02	The discount rate to calculate the present value of future cash flows, adapted from [33].
`naturalgas-price-scale`	Float	0.8, 1.0, 1.2	The scale of the natural gas price, which can be multiplied with natural-gas-price. Mainly used for sensitivity analysis.
`hydrogen-price-scale`	Float	0.8, 1.0, 1.2	The scale of the hydrogen price, which can be multiplied with natural-gas-price. Mainly used for sensitivity analysis.
Policy variables			
`current-policy`	String	"nTPA", "rTPA", "hnTPA"	The policy currently in place, indicated by a chooser.
`investment-cost-division-nTPA`	Float	0, 0.2, 0.4, 0.6, 0.8, 1	The division of costs between the HDNO and the industry. e.g. 0.4 indicates the industry pays 40% of the connection investment, the HDNO 60%.
Agent behavioural rules			
`max-distance-peers`	Integer	400	The maximum distance range for peers, where all other industries within this range can be seen as peers for the industry concerned in meters (A31.
`submission-threshold`	Float	0.55	The threshold for the motivation-degree of industries to exceed in order to submit a request.
`strategy-threshold-low`	Float	0.7	The threshold for the motivation-degree of industries to exceed in order to switch to a more ambitious transition-strategy.
`strategy-threshold-high`	Float	0.9	The threshold for the motivation-degree of industries to exceed in order to switch to an even more ambitious transition-strategy.
`weight-cba`	Float	[0, 1]	The weight for the CBA-norm in the calculation for the motivation degree, implemented as a slider.
`weight-waiting-list`	Float	[0, 1]	The weight for the WL-norm in the calculation for the motivation degree, implemented as a slider.
`weight-peer-pressure`	Float	[0, 1]	The weight for the PP-norm in the calculation for the motivation degree, implemented as a slider.

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Table 15 continued from previous page

Parameter	Type	Range/Values	Description
`npv-min, npv-max`	Float	-300000, 3000000	The minimum and maximum boundary for normalizing the NPV score in the calculation of the CBA-factor for the motivation degree. This value was set using trial and error.
`roi-min, roi-max`	Float	-200, 300	The minimum and maximum boundary for normalizing the ROI score in the calculation of the CBA-factor for the motivation degree. This value was set using trial and error.
HDNO and network properties			
`system-connected?`	Boolean	true / false	Indicates if the system connection is constructed already or not.
`total-costs-HDNO`	Integer	3000000+	The cost for establishing the hydrogen network (connections and system connection) for the HDNO.
`waiting-list`	List	-	List containing all industries that are currently on the waiting list for a system connection (if any).

H Price forecasts

In this appendix, the price forecasts used in the model are given. All forecast values used in calculations of the cost-benefit analysis are assumed to be constant from 2050 onwards, see A13.

Table 17: Price forecasts used in the model

Year	**Natural gas price**[1] **(€/kWh)**	**Green hydrogen price**[2] **(€/kWh)**	**CO_2 tax below 50 Ktonne**[3] **(€/tCO_2)**	**CO_2 tax equal or above 50 Ktonne**[4] **(€/tCO_2)**	**EU ETS emission allowance price**[5] **(€/tCO_2)**
2025	0.174	0.139	87	87	72.50
2026	0.156	0.135	100	100	72.50
2027	0.138	0.131	112	112	72.50
2028	0.120	0.127	125	147	72.50
2029	0.103	0.123	138	182	72.50
2030	0.085	0.119	150	216	72.50
2031	0.085	0.118	150	216	78.25
2032	0.085	0.117	150	216	84.00
2033	0.085	0.115	150	216	89.75
2034	0.085	0.114	150	216	95.50
2035	0.085	0.113	150	216	101.25
2036	0.085	0.111	150	216	107.00
2037	0.085	0.110	150	216	112.75
2038	0.085	0.109	150	216	118.50
2039	0.085	0.108	150	216	124.25
2040	0.085	0.106	150	216	130.00
2041	0.085	0.105	150	216	138.79
2042	0.085	0.104	150	216	148.64
2043	0.085	0.102	150	216	158.18
2044	0.085	0.101	150	216	168.87
2045	0.085	0.100	150	216	180.28
2046	0.085	0.098	150	216	192.46
2047	0.085	0.097	150	216	205.47
2048	0.085	0.096	150	216	219.35
2049	0.085	0.094	150	216	234.17
2050	0.085	0.093	150	216	250.00

[1] The natural gas price is adapted from [75]. 2025 and 2030 were given, other years are interpolated, years after 2030 are assumed constant, following the method from [33]. Increased by 5% to accomodate higher price estimates.
[2] The green hydrogen price is adapted from [76]. 2025 and 2030 were given, other years are interpolated, years after 2030 are assumed constant, following the method from [33].
[3] The CO_2 tax price for emissions below 50 Ktonne is adapted from [65] and interpolated for other years. Years

after 2030 are assumed constant.

[4] The CO_2 tax price for emissions equal or above 50 Ktonne is adapted from [65] and interpolated for other years. Years after 2030 are assumed constant.

[5] The EU ETS emission price is firstly adapted from [69] with a constant price between 70 and 75 €/tCO_2 between 2025 and 2030 and a linear increase from 2031 to 2040 to 130 €/tCO_2. From 2041 to 2050, an exponential growth to 250 €/tCO_2 is assumed.

Green hydrogen price

Speculation on the course of future hydrogen production costs and the hydrogen price varies a lot and depends on many different factors [77], [78], which is why a deeper explanation of the hydrogen price forecast is necessary.

According to [78], the average hydrogen price in 2022 "at the pump" was 10 €/kg (€0.300 per kWh). This price should be lowered to at least 6 €/kg (€0.180 per kWh) to compete with other fuels.

[78] estimates the production price for green hydrogen between 3.60 and 5.80 €/kg (€0.108 and €0.174 per kWh) in 2030. However, fortunate developments and circumstances could lower this to 2.50 €/kg (€0.075 per kWh) in 2030. It is important to note that these figures refer only to the production cost and do not include additional expenses such as transport, distribution, storage, taxes, and profit margins. [76] also predicts a steady decline in global production costs for green hydrogen, from 3.70 to 4.90 €/kg (€0.111 to €0.147 per kWh) in 2020, to €1.83 to 3.67 €/kg (€0.055 to €0.110 per kWh) in 2030, and further decreasing to between 1 and 2.87 €/kg (€0.030 and €0.086 per kWh) in 2050. Similarly, [78] forecasts an average hydrogen production cost of 1.20 €/kg (€0.036 per kWh) in 2050. However, these costs are strongly dependent on factors such as scalability of hydrogen production, the decline in renewable electricity costs and the effectiveness and continuing of policy measures supporting hydrogen [77].

Next to production costs, market conditions and infrastructure play a crucial role in the final hydrogen price. [77] provides an indicative hydrogen price range between 8 and 15 €/kg (€0.240 and €0.450 per kWh) for the period between 2027 and 2030, depending on supply conditions and volume. Since this study includes less cost-intensive transport via pipelines for large volumes, the hydrogen price would likely fall within the lower end of this range. However, [77] also highlights potential technical risks and the immature market, which could drive costs higher. As the market matures, hydrogen prices are expected to decrease between 2030 and 2040.

Looking at international developments, [79] suggests that by the end of this decade, newly installed green hydrogen production facilities in Brazil, China, India, Spain, and Sweden could produce hydrogen up to 18% cheaper than existing grey hydrogen plants, even without subsidies. Green hydrogen is also expected to become more cost-competitive than blue hydrogen by 2030.

This paint a picture of a quickly evolving hydrogen market, where productions are expected to decrease significantly, but the final hydrogen prices will also depend on infrastructure, policy measures and the pace at which the market matures. In this study, the hydrogen price of [33] and [76] is used. To accommodate higher price estimates, this price has been increased slightly at 5%.

EU ETS emission price

[69] predicts a constant EU ETS emission price between 70 and 75 €/tCO_2 between 2025 and 2030, followed by a linear increase from 2031 to 2040 to 130 €/tCO_2 and an exponential growth to 500 €/tCO_2 from 2041 to 2050 under the current market design. The paper explains that

the current market design includes a market mechanism of market stability reserve (MSR), which aims to provide stability to the EU ETS market. This market design with MSR will cause skyrocketing prices in the early to mid-2040s, if it where the only tool used to guarantee the equilibrium between offer and demand of allowances. The report highlights a new design is needed in order to be compatible with the a low GHG emissions environment from 2040 onwards.

As a price of 500 €/tCO_2 seems very unlikely, it is assumed the market design of EU ETS will be adapted in such a way that it will be maintainable as an instrument in the CO_2 market (see A14). It is likely the market will be reformed or a price cap might be introduced to maintain the instrument. Based on logic, high prices are still likely, but in a more reasonable range. For that reason, the prediction of [69] is adopted until 2040. Between 2041 and 2050, it is assumed the price will rise to 250 €/tCO_2.