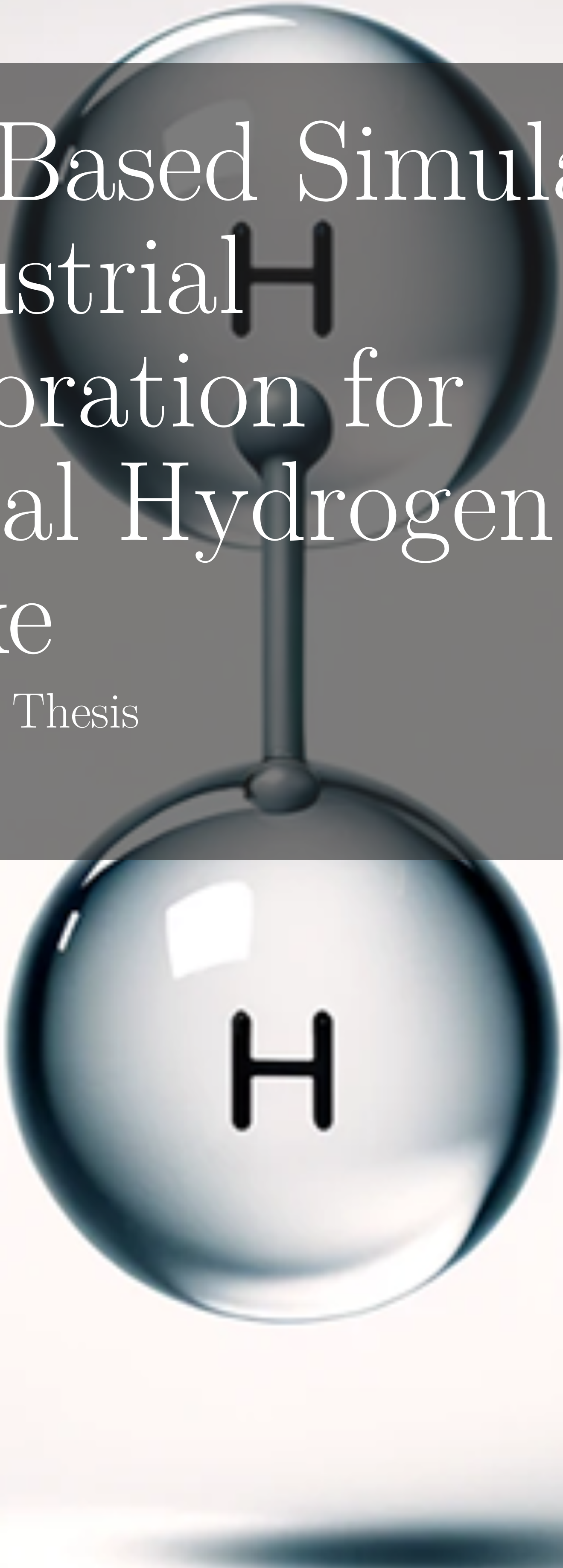

Agent-Based Simulation of Industrial Collaboration for Regional Hydrogen Off-take

CoSEM Master Thesis

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Agent-Based Simulation of Industrial Collaboration for Regional Hydrogen Off-take

by

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Preface

I feel fortunate to have been part of this master's program for two years where real-life problems intersect with academic research. During this time, I had the opportunity to meet, listen to, and engage in discussions with many esteemed academics who are experts in their fields, which has been incredibly inspiring.

Stedin has played an integral role in the second year of my master's program. Starting with a JIP project, continuing as an intern, and now concluding my studies with this master's thesis project, I am immensely grateful for the opportunities and experiences provided by the company. Every person I worked with at Stedin holds a special place in my life.

I would like to extend my heartfelt gratitude to my academic supervisors: Dr. Amineh Ghorbani, for sharing her extensive experience, supportive guidance, and critical insights; Renske van't Veer, for her unwavering readiness to support and assist me, and for her patient, attentive listening and valuable feedback; and Prof. Dr. Zofia Lukszo, for her precise perspectives and her leadership role in my committee. I also owe many thanks to my company supervisors, Iman, Edward, and Tayebeh, for their continuous support, keen interest in my work, and for always finding time to discuss my inquiries.

I am deeply grateful to all my committee members for their patience, guidance, and support throughout the thesis process, especially during challenging moments. Additionally, I want to thank everyone in my committee for making exceptions during this holiday period to accommodate my graduation schedule.

Moreover, I would like to express my profound gratitude to my fiancée, Aslı Yasemin Dönmez for her unwavering support, my parents, Necla and Mehmet, for making me who I am, and all other members of my extended family, and my cherished friends. Their unwavering belief in me and their constant support throughout this challenging journey have been invaluable. Although this research bears my name, it has been a collaborative effort, and the contributions of this incredible team have been crucial.

I hope that this research will make significant contributions to both academia and practice, and that it will be beneficial to all. I wish you an enjoyable reading experience.

Emre Ateş
Delft, August 2024

Summary

Hydrogen is becoming an increasingly important part of various energy system transformation strategies. Given its economic potential, enhancing the Netherlands' involvement in the global hydrogen value chain is a strategic objective. Hydrogen is especially effective in reducing emissions in sectors that are challenging to electrify. Consequently, hydrogen carriers will play a pivotal role in the Netherlands by providing high-temperature heat and raw materials to energy-intensive industries. For electrolysis-based hydrogen production to be successful, government support through subsidies and regulatory planning across the entire energy generation value chain is essential. Industrial clusters are expected to be the main centers for sustainable hydrogen supply and demand. However, developing such infrastructure carries significant risks, including the potential underutilization of the network due to low levels of supply and demand. Therefore, careful steps are being taken to ensure certainty, guided by trends in hydrogen market development and the necessity for accurate trajectory predictions.

In the phased hydrogen roll-out plan in the Netherlands, companies outside the five big cluster (categorized as Cluster 6) rank lower due to their distance from the major demand points and lack of concentrated hydrogen demand. This translates to higher risk of mismatched supply and demand for the built infrastructure. Cluster 6 companies have relatively less economic competitiveness for hydrogen transition due to higher initial investment costs for on-site hydrogen generation without the benefits of economies of scale, limited access to decarbonization subsidies, which are essential due to their lack of equity for such initiatives. The technical feasibility of these projects is often constrained by the congested electricity grid, complicating the connection of electrolyzers.

Full-scale substitution of natural gas with hydrogen requires a secure backbone connection, but the lower precedence in the roll-out plan fosters uncertainty and hesitancy among Cluster 6 industries. Despite being small and dispersed, these companies collectively represent a significant natural gas consumers for heating processes and potential hydrogen users. Their lack of power and size hinders their ability to obtain subsidies and create viable business cases, potentially leading to partial or indecisive switching to hydrogen in their regions. This could delay the development of regional hydrogen infrastructure and result in a sub-optimal network configuration, increasing uncertainty for system operators and users.

The research aims to address the knowledge gap in the hydrogen roll-out from the demand side, specifically its application as a substitute for natural gas. It focuses on the challenges faced by particularly smaller users like those in Cluster 6 which struggle to keep up with infrastructural developments, highlighting the need for developing strategies to ensure efficient regional network development. The research emphasizes the knowledge gap on collaborative action through clustering, and forming hydrogen-based industrial community energy systems (CES). It points out to the under-explored body of knowledge due its differences with the existing CES formations, including varying process heat requirements, higher asset specificity and investment costs, and evolving support schemes. The study aims to explore whether and how collective action can overcome technical, economic, and institutional limitations for dispersed, smaller potential hydrogen users with different sectoral dynamics, facilitating their transition to hydrogen. Ultimately, it seeks to provide insights into the conditions necessary for successful demand off-take and efficient regional infrastructure development with the main research question:

"To what extent can collective action facilitate hydrogen off-take in regions where small-sized companies operate in diverse sectors and are located far from the planned hydrogen backbone?"

Using a modeling approach and agent-based simulation, the research analyzes emergent system behavior among industry actors as they interact with each other and their environment, share resources, and plan collective investments for hydrogen production. The method allows for comparative analysis of system behavior under different organizing principles, agent interactions, and government policy interventions, assessing the relative effects of these actions within the current technical and institutional limitations faced by industrial customers.

Industrial heating is the most prominent use of hydrogen for Cluster 6 companies where the temperature needs of processes are a key factor in hydrogen use for heat applications. Hydrogen technology offers zero-emission solutions for all temperature levels but is particularly advantageous for medium and high-temperature processes. This makes metal, cement, ceramic, and glass industries primary off-takers in their region. In contrast, low and medium-temperature processes have more technology alternatives that do not center around hydrogen. However, these sectors still rely heavily on natural gas and its infrastructure, and the feasibility of alternatives like electrification is constrained by existing electricity infrastructure limitations, making them secondary hydrogen off-takers in their region.

Four main possible contribution of collective action for hydrogen projects are identified in the research. By pooling electricity connection capacities and using curtailed generation power, it enhances the net power capacity for electrolyzers. Furthermore, it increases economic feasibility through economies of scale and enables smaller companies to participate in larger electrolyzer investments, meeting subsidy application limits. Additionally, collective action improves permitting processes by fostering sectoral diversity and stronger relationships with local governments, emphasizing broader societal benefits.

Agent-based modeling creates an appropriate framework for simulating the interactions between agents and their environments, reflecting the core components of real-life processes. This research lays the groundwork for utilizing modeling approaches in the study of hydrogen-based community energy systems, a field that remains largely underexplored in the literature.

The simulation model results highlight that collective investment is crucial for enabling successful transitions to hydrogen, when individual efforts by a few companies often fall short. On top of the collaboration arising from power capacity and subsidy access limitations, a unified strategy rather than independent attempts proves to be essential for achieving desired regional performance. When hydrogen growth is driven mainly by individual investments, the transition becomes more challenging and is delayed because it hinders the inclusion and participation of other sector players. In contrast, scenarios dominated by collective investments yield earlier, more inclusive and effective results.

Collective action's effectiveness decreases as less motivated sectors become more dominant in a region setting. The simulation results indicate a non-linear relationship between collective action contribution and the presence of highly dependent sectors, with regional hydrogen share increasing exponentially as the number of hydrogen-dependent companies rises. These "launching customers" play a crucial role in initiating transitions by overcoming initial reluctance and actively participating in collective investment. Their transformative power grows non-linearly with their size in the region, significantly boosting the impact of collective investment.

Relaxing subsidy access has shown adverse effects on regional hydrogen development, especially where collective action is essential. Although easing eligibility conditions encourages more individual efforts, it reduces firms' interdependence and weakens regional cooperation, overshadowing the benefits of collective investment. Therefore, if collective action has a promising effect in a regional setting, increasing entry barriers could potentially yield better results. Conversely, in regions where most sectors are secondary off-takers, subsidy relaxation improves regional hydrogen off-take performance.

Designing region-specific policy instruments is essential for effective hydrogen development, as sectoral configurations significantly influence collective action. In regions with hydrogen-dependent sectors, setting higher eligibility criteria for subsidies can encourage regional collaboration, leading to more economically viable projects and reducing underutilization risks. Increasing awareness of each other's transition plans through local government platforms can enhance communication and collaboration, which is crucial for forming hydrogen-based community energy systems due to their asset-specific nature. Furthermore, promoting collaboration and inclusiveness by engaging both primary and secondary off-takers, along with offering various support schemes, can drive a more comprehensive and effective regional transition to hydrogen. These strategies collectively help regions avoid fragmented transition efforts and achieve a unified, efficient transition to hydrogen use.

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Abbreviations

Abbreviation	Definition
ABM	Agent Based Modelling
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CES	Community Energy Systems
CES	Cluster Energy Strategy
CoSEM	Complex Systems Engineering & Management
DSO	Distribution System Operator
EoI	Expression of Interest
EU	European Union
ETS	Emissions Trading System
HTH	High Temperature Heat
ICES	Integrated Community Energy Systems
InCES	Industrial Community Energy Systems
IS	Industrial Symbiosis
LCOH	Levelised Cost of Hydrogen
LOHC	Liquid Organic Hydrogen Carriers
MG	Micro Grid
NPV	Net Present Value
ODE	Opslag Duurzame Energie
OFAT	One Factor at a Time
OPEX	Operational Expenditure
OWE	Opschaling volledig hernieuwbare Waterstofproductie via Elektrolyse
PEMEC	Proton Exchange Membrane Electrolysis Cell
RES	Renewable Energy Source
ROI	Return on Investment
SDE	Stimulering Duurzame Energieproductie
SMR	Steam Methane Reforming

Note: CES is used to refer to both "Community Energy Systems" and "Cluster Energy Strategy" in this report. The context in which CES is used will clarify its specific meaning.

1

Introduction

In the introductory chapter, the report begins by providing background information (Section 1.1), followed by a statement of the problem (Section 1.2). The knowledge gap in the literature and the research questions are defined (Section 1.3), along with the research approach (Section 1.4). Then, the practical and scientific contribution of research (Section 1.5) and its relevance to the CoSEM program (Section 1.6) is discussed. Lastly, the outline of the report is presented (Section 1.7).

1.1. Background

Hydrogen has become an integral part of numerous energy system transformation strategies [1, 2]. The target of expanding the capacity of domestic green hydrogen production by 2030 is set to 4 GW in Dutch government plans [3] and due to its economic potential, the country's increasing penetration to global hydrogen value chain is considered as a strategic goal [4].

Green hydrogen, produced through water electrolysis using renewable electricity [5, 6], is considered as a promising solution for reducing greenhouse gas emissions [7] and meeting the climate goals set by the Paris Agreement [8]. However, the majority of the current demand for hydrogen production is met by fossil fuels such as natural gas, oil, and coal, as they are currently the most cost-effective option [9].

The interest in green hydrogen as a zero-emission fuel has grown significantly [10]. The anticipation of affordable surplus renewable energy has driven the potential for a hydrogen industry largely based on electrolysis-derived hydrogen [11, 12]. Hydrogen as a zero-emission fuel is particularly effective in reducing emissions in sectors that are difficult to directly electrify, such as the metal, glass and ceramics industries [13, 14]. Therefore, hydrogen carriers will play a crucial role in countries such as the Netherlands with large share of energy-intensive industries, serving as a source of high-temperature heat and as a raw material [15]. High temperatures are essential for industries such as ceramics (1000°C-1200°C), chemicals (in high-temperature processes), metals (∼1200°C), and glass (1500°C-2000+°C), where alternatives to gas are limited [16].

The fundamental elements of the hydrogen value chain—production, storage, transportation, and end-use—have evolved at different rates and are at various stages of development globally [17]. In the Netherlands, developments in the green hydrogen value chain are considered to be in their early stages [15].

For the production stage, electrolysis based hydrogen cannot succeed without extensive, well-balanced, and advanced support throughout the entire energy generation value chain. Currently, green hydrogen is two to three times more costly than blue hydrogen, which is produced from fossil fuels with carbon capture and storage. Moreover, utilizing hydrogen for end users is also more expensive compared to fossil fuels [18].

Companies have a direct influence on the development of the green hydrogen value chain, mainly through their investment decisions, while governments have a more indirect influence through support policies such as subsidies. One notable instance of beneficial policy measures include financial support for electrolyzers and hydrogen such as EU's State Aid in 2022 [19] or SDE, OWE subsidy schemes implemented in the Netherlands [20, 21].

Industrial experts perceive another crucial role of the government as providing planning security through regulations and target setting [22]. This draws attentions to transportation part of the value chain that connects industrial clusters, ports, offshore sites, storage facilities, and neighboring countries. It is anticipated that industrial clusters will be the primary hubs for the development of a sustainable hydrogen supply and demand in the Netherlands. National climate strategies and Cluster Energy Strategy (CES) reports indicate that all major industrial clusters and large companies across the Netherlands will require hydrogen transport infrastructure in the medium term, ideally before 2030 [23]. As the hydrogen market matures, these clusters will eventually be physically interconnected [24].

Before the infrastructure is developed, it is crucial to have a clear understanding of the future use of such an investment. Conversely, the widespread adoption of hydrogen off-take necessitates certainty regarding the development of the infrastructure. To resolve this typical chicken-and-egg problem, the Dutch government has tasked Gasunie with initiating preparations and discussions with potential users to develop the transport network into a single, integrated transmission network [25].

Due to the limited resources of transmission system operators, steps are taken cautiously, with a focus on ensuring certainty. The primary concern is the significant risk of developing and operating a pipeline-based hydrogen transport network that may result in low levels of supply and demand, under utilizing the built infrastructure. Various trends in hydrogen market development could either widen or narrow down the financial gap between the invested capital and the expected returns from the infrastructure. However, the precise trajectory of these trends remains unpredictable and depends on a multitude of factors [26].

1.2. Problem statement

The phased roll-out plan for hydrogen in the Netherlands revolves around the planned national hydrogen transport backbone and prioritises five major industrial clusters, the nearby locations from which it passes and finally the companies outside the major industrial clusters, the so-called 'Cluster 6' companies. An undeniable number of decentralized Cluster 6 industrial sites, including those in the metal, ceramics, cement, and glass industries, require high-temperature heat for their processes and currently rely on natural gas for this purpose [27]. The main reason behind their low ranking in the phased plan is the lack of large volumes of concentrated hydrogen demand in these regions. Hence, the risk of not having sufficient supply and demand to match the built or refurbished infrastructure capacity is particularly high for these regional industrial users. Since the currently planned national network does not have a reach to the majority of the Cluster 6 companies, regional distribution networks will be needed for their participation to the connected larger network [23]. However, investments for distribution infrastructure need to demonstrate an energy-economic necessity and feasibility for both national and regional system operators' plans [25].

In addition to the uncertainty resulting from the infrastructure, economical concerns become more evident on Cluster 6 companies' transition to hydrogen demand due to their relatively smaller gas consumption. Use of hydrogen as fuel is significantly more expensive than natural gas, which is currently supplied through the established natural gas network [18]. Next to the high operating costs, initial investment costs for on-site generation become more noticeable for these companies without the advantage of economies of scale, increases costs and risk exposure on small businesses in concern. Furthermore, companies in Cluster 6 highlight issues about not making optimal use of subsidies and indicate that their applications for decarbonisation subsidies are either not accepted or only partially accepted [28]. However, these subsidies are essential for companies in the industry, as they lack the necessary equity to execute such initiatives independently [22, 29, 30]. Industry experts from the sector desire for subsidies with more relaxed prerequisites to better facilitate the initial scale-up [22]. As a result, current outlook shows less room for investment in innovation and competitiveness for regional hydrogen development. Furthermore, lack of widespread applications of hydrogen in industry creates a cold-feet problem among industrial users and showcases the dependency on other users' plans [28].

There are few regional standalone green hydrogen production initiatives in their early phases by decentral industries to scale up hydrogen supply and demand in their regions. In certain cases the technical feasibility of these initiatives is limited by the electricity grid capacity, as connecting an electrolyzer to the highly congested grid is a critical limiting factor but also offers opportunities to utilize curtailed renewable energy [27].

Furthermore, the industry experts view the transformation of gas transportation infrastructure as a significant challenge for hydrogen transition, highlighting the urgent need for strategic investments in R&D and public-private projects to create a hydrogen transit network that connects production and consumption sites [29]. They agree on the fact that full scale substitution of natural gas use with hydrogen requires a backbone connection due to security of supply concerns [27]. However, the uncertainty to receive a connection from the hydrogen backbone increases for these industries whose precedence is lower in the roll out plan and leads to hesitancy in including hydrogen into their transition plans. This situation may lead to non-optimal outcomes in network planning for distribution system operators by causing scenarios where the switch to hydrogen in regions either does not start, starts but remains at low volumes, or is initiated only by certain users, thus spreading the transition over many years and increasing the risk of redundant efforts for distribution network development.

Although these companies from different industries are dispersed and relatively small emitters of CO2, together they make up a relatively large number of Emissions Trading System (ETS) participants and considerable potential users of hydrogen. Individually they have less power and size to obtain subsidies, create business cases and generate hydrogen within the limitations of highly congested electricity grid [30, 27]. This situation may lead to indecisive or partial switching behaviour to hydrogen, delaying the development of regional hydrogen infrastructure, resulting in a sub-optimal network configuration and increasing the uncertainty for both system operators and users of regional hydrogen networks [31]. Therefore approaches are needed to address underlying problems of regional hydrogen demand development to ensure an efficient infrastructure roll out.

1.3. Knowledge gap and research questions

The majority of the studies related to hydrogen value chain developments adopt a purely techno-economic perspective. They mainly analyze technical aspects or costs, modeling their development based on simplified rational behaviors [32, 33], and often overlook the involvement of stakeholders and social context. To mitigate the risk of an inefficient and sub-optimal infrastructure roll-out, past research has primarily focused on identifying the cost-optimal design mix for hydrogen transport and distribution network elements [34, 35, 36, 37]. This approach uses projected demand and supply as inputs, even though both are highly uncertain, interdependent, as well as tied to the timeline of the roll-out plan.

There is still substantial scope for investigating the hydrogen roll-out from the demand side. In the industrial context, hydrogen is mainly viewed in the literature as a storage alternative to optimize multi-carrier energy systems, enhancing the efficiency of renewable electricity systems. However, there is a significant gap in its application as a substitute for natural gas in end-use. Additionally, the unique dynamics and dependencies that different sectors and companies inherit during this transition are largely overlooked.

The identified problem offers a unique and undiscovered context for countries like the Netherlands, where the phased hydrogen roadmap puts ambiguity on regional transition. In particular, addressing the disadvantages of smaller users, such as in Cluster 6, to technically and economically catch-up with the infrastructural developments is essential to developing strategies for effective and timely transition.

Through semi-structured interviews with industry experts from the Netherlands, literature contributes to the understanding and organizing of views and suggestions on government support schemes, technical and economic limitations, and potential pathways for a hydrogen value chain [22, 29]. However, there is an absence of research on testing these views and suggestions through modeling or qualitative approaches, resulting in a knowledge gap connecting these qualitative insights to the actual system behavior.

One way of increasing the likelihood of efficient regional network development is seen as the collaborative action that clustering facilitates. [38] refers to several studies around the world on how environmental and economic benefits can be achieved through the efficient use of energy resources, especially in energy-intensive industrial clusters. Furthermore, there are emerging stand alone hydrogen production initiatives in the Netherlands showing how decentralized industries can be initial customers, creating branches from the main infrastructure [39], and how parts of the regional gas grid can be converted from natural gas to hydrogen [40].

There is wide range of past studies [41, 42, 43] about integrated community energy systems, industrial symbiosis, however, main focus of such collaborative actions are electricity as energy carrier. The knowledge gap for hydrogen based (industrial) community energy systems that serves the need for gas and heat is critical as they differ from existing CES formations significantly due to the complex needs of heat-intensive industries, including varying process heat requirements, infrastructure challenges, high investment costs, and evolving support schemes. These unique dynamics necessitate a sector-specific approach, distinguishing them from common industrial energy systems. Furthermore, the spread of realized successful use cases of hydrogen within the industry also possess a social dimension, as they influence the attitudes of other users towards the transition.

Therefore, using a socio-technical approach, the objective of the proposed research is to explore how collective action could be used to overcome identified technical, economic and institutional limitations for potential hydrogen users who are dispersed, far from the planned backbone, small in size and have different sectoral dynamics, to facilitate their transition to hydrogen. Consequently, it will provide insights on whether and under what conditions a demand off take will be realized in a region and the dynamics that are prevalent, thereby shedding light on efficient infrastructure development. The main research question is as follows:

"To what extent can collective action facilitate hydrogen off-take in regions where small-sized companies operate in diverse sectors and are located far from the planned hydrogen backbone?"

The sub-questions below are formulated to guide the exploration of the main research question:

1. Which group of industries (actors) and purpose of hydrogen use should be the concern of the regional hydrogen off-take?
2. What are the limitations that collective action could address to scale up the regional hydrogen transition?
3. How can the key components of a system of regional hydrogen off-take among industrial actors be modeled?
4. How does the availability of collective investment options affect the regional hydrogen off-take?
5. What role does sectoral configuration in the region play in the performance of regional hydrogen off-take?
6. How do changes in current government support settings, particularly regarding subsidy eligibility conditions, affect regional hydrogen off-take?

1.4. Research approach

Complementing the qualitative and quantitative methods, simulations can significantly enhance the analysis of socio-technical systems by leveraging computational power, investigating multiple variables and scenarios that covers longer periods.

The proposed research aims to analyze the emergent system behaviour when the identified industry actors are provided with options to interact with each other and with their environments, share resources, plan a collective investment together, affect and get affected by other actor's decisions. A modelling approach, and agent-based simulation method are employed to examine whether and under what conditions collective action can lead to a successful regional hydrogen off-take that ensures efficient infrastructural development. The emergent behaviours will be analyzed within technical and institutional limitations the industrial customers are currently experiencing.

The research utilizes both qualitative and quantitative research methods. It starts with desk research and literature review in order to deepen the understanding on the key system components, actors and their interactions, decision processes and to gather essential data. Cluster energy strategy documents, stakeholder interviews, government letters, national hydrogen roadmaps and strategy documents and publications from various ongoing national hydrogen research programmes are utilized to identify and conceptualize the most relevant parts of the real life processes. On the other hand, literature review provided information about the technical elements of the system and formed the basis for conceptualizing agent behaviours.

Furthermore, collaboration with distribution system operator (DSO) Stedin during the research enabled to conduct meetings with sector experts from both technical and institutional domain. This helped to increase the validity of the research by integrating expert inputs for modelling technical elements and also ensuring the conformity to institutional perspectives. All gathered insights contributed to the purpose of simulation model building.

Major contribution is provided with refining, conceptualizing and formalizing the components and interactions of agents in a complex system. They are then transferred into simulation environment by implementing in Netlogo software. Experimental research is used to conduct controlled experiments to determine cause-and-effect relationships, verify and understand the model dynamics. Furthermore, case study research method is utilized for in-depth examination of identified cases of regions within their real-life context. Stedin has contributed considerably on making necessary model inputs available to select and experiment on the case studies that are relevant to the problem situation.

1.5. Contribution of research

This study enriches the existing body of knowledge on hydrogen energy systems by emphasizing the importance of collective action in regional hydrogen infrastructure development, particularly for small-sized companies in diverse sectors, which have been largely overlooked in the literature. By employing agent based modeling, the research provides a sophisticated method to simulate interactions among companies, enabling detailed exploration of stakeholder dynamics and policy scenarios. Integrating insights from technical, economic, and institutional perspectives, the study offers a holistic view and a framework adaptable for other renewable energy technologies. This work contributes to the academic discourse on designing effective policy instruments to support the transition to sustainable energy systems.

In terms of practical implications, testing and understanding the system behaviour under different settings help infrastructure providers and hydrogen industry actors to better anticipate the results of possible actions. By steering and incentivizing the behaviour in the system towards more promising direction, risk of delays in hydrogen transition and a suboptimal network development could be mitigated.

1.6. Relevance for CoSEM

The main purpose of the research is to contribute to the development of regional hydrogen systems which constitutes an important example for complex socio-technical systems. The existing socio-technical design of the energy systems are highly complex and inherits deep uncertainty. Therefore, integration of hydrogen technology requires a complex problem solving approach and design 'within' the existing socio-technical system. The study integrates the technical, institutional and multi actor perspectives that forms the basis of CoSEM program while approaching to the problems. The study acknowledges the fact that successful interventions can only be possible when these aspects are considered together in the design. By building an agent based model within the socio-technical context, simulating the behaviour of stakeholders that interact according to the formal and informal institutions within an environment constrained by technical factors, the research aims to investigate whether and under what conditions collaboration among actors from diverse set of sectors can contribute to the development of regional hydrogen roll out. Consequently, it will help to guide and steer the system behaviour more effectively in favor of the whole society.

1.7. Outline of the report

The rest of the paper is structured as follows: Chapter 2 reviews the current literature on local energy systems more in depth and explains relevancy to hydrogen based systems that this study is concern. The methodology of the research is presented in Chapter 3. While answering first two sub questions of the research, the chapter explains the modelling steps taken while building the agent based model.

Subsequently, Chapter 6 examines the model outcome's sensitivity to certain parameters and identifies the baseline model as reference for the experiments. Chapter 7 delivers the detailed analysis of the experiment results, followed by the conclusion and discussions in Chapters 8 and 9.

2

Literature Review

This section focuses on the relevant literature related to the subject of this research. The areas that appear to have the most similarities with this research are selected and examined.

2.1. Local energy systems

Local energy communities in the current setting typically rely on centralized energy systems for their power supply. This top-down system architecture has emerged due to the economies of scale and the capability to transport conventional fuels, such as gas, to desired locations. However, advancements in technology and the economy have led to a shift in energy production and consumption, fostering a more decentralized approach [43]. Energy systems are transitioning towards a hybrid model that combines top-down and bottom-up approaches. This shift is driven by the need to address vulnerabilities and weaknesses [44], and particularly, in the case of hydrogen, the lack of centralized energy infrastructure. Local energy systems not only ensure self-sufficiency in energy supply but also provide essential system functions to the broader energy network. Having the power to control both generation and demand for energy, they often lead to the emergence of new ideas and practices in energy system management.

[43] introduces concept of integrated community energy systems (ICESs) as an multi-dimensional approach to reorganize local energy systems by incorporating distributed energy resources, demand-side management, storage and engaging local communities. By incorporating the characteristics of other energy system integration alternatives and implementing them in a local energy system, the concept of ICESs provides more comprehensive approach. [45] provides a comprehensive definition of ICESs as a method that involves various aspects to meet the energy needs of a local community. This includes utilizing high-efficiency co-generation or tri-generation, renewable energy technologies, innovative energy storage solutions, electric vehicles, and demand-side measures. Integrated energy systems can be implemented locally by integrating rooftop PV, small-scale wind turbines, district heating, and community energy storage or biogas and hydrogen production systems. As far as location specificity is concerned for ICESs, the benefit of expanding the system to a wider range of demand patterns and the integration of more sources for generating and consuming energy. This increases the system's flexibility and overall value that can be obtained. However, these systems have boundaries concerning the energy technologies included and the availability of infrastructure [43].

Beyond ICES, several other options for integrating energy systems exist such as energy hubs and community energy systems (CES) [43]. Although these options are primarily designed and characterized around energy systems using electricity as an energy carrier, they may share overlapping characteristics with hydrogen-based energy systems.

In certain cases, gas systems can take a part in energy hubs where numerous energy carriers are optimally dispatched to manage the energy flows within a certain district. These systems encompass technologies for storing, converting, and distributing electricity, heat, gas, and other fuels to the final consumers [46].

Community energy systems refer to the production of electricity and/or heat on a small, local scale, which may be managed by or for local residents, or designed to provide them with direct benefits [47]. On top of the vast CES literature, which mainly addresses community formation between household and neighborhood [48], [42] focuses on the elements that influence industrial businesses' willingness to invest in an industrial community energy system (InCES) with a statistical analysis on empirical data. It highlights the intrinsic differences in decision-making methods between industrial enterprises and households, as well as the conditions in which an InCES can be formed in an industrial cluster. The results of the study show that bigger companies are more willing to accept the risks associated with participating in InCES with lower return on investment (ROI) expectations and could act like the initiators of such projects in their regions [42].

Another example of collective action involving energy among industries is the concept of industrial symbiosis (IS). IS is a type of industrial ecosystem that involves the organized exchange of water, energy, or material flows. In this system, corporations can utilize waste flows from one company as valuable resources for other companies [42].

Relevance to hydrogen case

There is an extensive literature regarding the integration of energy systems with different configurations, purposes, technologies and roles of community, hub or group formation. Considering the electricity-intensive literature, a significant scope remains undiscovered for hydrogen. Similar to few studies mentioned previously, this study centers on an industrial community energy system; however, it distinctively focuses on collective hydrogen generation in an industrial heating context.

Due to its unique characteristics, it is challenging to fit hydrogen technology into existing local energy system contexts. For instance, locational proximity does not stand to be an essential concern for industrial community energy systems for electricity since power can be transferred to any participant of the connected electricity grid, which has a nation-wide span, especially in developed countries [42]. On the contrary, collectively generated hydrogen flow is limited by the connectivity of the customers, conditions on the reuse of existing grid, or sometimes simply depend on a new pipeline connection. With this relative location specificity, it resembles industrial symbiosis applications, although synergies from by-product and waste sharing are not in the foreground.

Due to its reliance on electricity for generation, problems or opportunities in distributed power systems and the power grid are relevant for hydrogen community energy systems as well. Hydrogen integrated CESs could play an important role in the issues that [43] listed as technological issues for ICESs, such as intermittency of local renewable energy sources (RES), storage, load and grid defection, and local balancing of supply and demand. Furthermore, socio-economic issues such as willingness to pay, initial costs, financing and support schemes; and institutional issues such as ownership are also valid for hydrogen based CESs.

2.2. Hydrogen in community energy systems context

The role of hydrogen in community energy systems has been explored across various studies, highlighting its potential to support fuel cell vehicles, manage peak solar generation, and integrate with the natural gas network. For instance, [49] examines hydrogen within community energy systems by analyzing its role in supporting fuel cell vehicles and managing peak solar generation. It highlights hydrogen's potential to integrate with the natural gas network. While the study does not explicitly address energy cooperatives or collective investments, it implies the need for community-level involvement.

Building on this, [50] delves into a wind/photovoltaic-hydrogen production system, emphasizing hydrogen's capabilities in energy storage and balancing supply and demand. This study complements [51], which focuses on hydrogen production from offshore wind power, advocating for large-scale hydrogen industry development and community-level energy management through multi-energy cooperative power supplies for diverse sectors like transportation and industrial processes.

Furthering the discourse, [52] explores hydrogen's integration into community energy systems, particularly in multi-energy community microgrids (MGs). It explores how hydrogen can be integrated alongside electricity and thermal loads, as well as used as a transportation fuel, within a cooperative game approach for demand response scheduling. The purpose of using hydrogen is to maximize flexibility potential and optimize demand-side management, aiming to reduce total system cost and improve business cases for energy cooperatives and collective investments in multi-energy MGs.

In the context of optimizing renewable energy utilization, [53] investigates hydrogen storage within a near-zero energy community system. By incorporating hydrogen alongside electricity and heat storage, this study aims to achieve optimal energy management and higher renewable energy proportions. Similarly, [54] proposes a multi-time scale operation optimization model to refine energy storage and utilization strategies.

Furthermore, [55] introduces a master-slave game-based optimization strategy, incorporating carbon capture and hydrogen storage devices for cooperative dispatch in a community integrated energy system. This strategy aims to achieve carbon neutrality, reinforcing the pivotal role of hydrogen in advancing sustainable energy solutions within community frameworks.

Moreover, HyDelta, the national research programme conducted by a public-private partnership focuses on various aspects of hydrogen implementation and published research outcomes about safety, quality, socio-economic aspects and standardization. [27]'s emphasis on ongoing stand alone project initiatives in the Netherlands gives a comprehensive snapshot of the current situation on regional hydrogen demand development. It inspects nine case studies, none of which are realized at present, around the Netherlands by conducting stakeholder interviews. The insights from the interviews confirm the relevancy of collective hydrogen production and consumption and reinforces the validity of this research. It presents important enablers, barriers and drivers for these initiatives which are referred in several parts of this study. On the other hand, the most recent research project HyRegion examines potential future hydrogen demand and production at regional level, identifies concentration areas suitable for hydrogen infrastructure, and explores various options for the organization and regulation of regional hydrogen infrastructure [31]. Although it focuses on larger natural gas consumers, follows a descriptive approach and does not include stand alone production in the regions, research provides an important validation opportunity with its methodology and once again emphasizes the relevancy and importance of the subject of the research.

2.3. Hydrogen in industrial symbiosis context

The exploration of hydrogen within the context of industrial symbiosis has revealed synergies mainly with biomass, waste, and hydrogen generation. Researchers have demonstrated approaches to optimize resource utilization and improve energy production. For instance, [56] integrates anaerobic digestion, cogeneration, photovoltaic, and hydrogen production technologies to develop a model that maximizes resource utilization from agricultural and municipal waste for hydrogen generation. This model not only enhances energy production but also significantly reduces carbon footprints and improves economic viability.

Similarly, [57] proposes a renewable-based hydrogen and power supply facility that utilizes fermentation and solar-driven electrolysis, showcasing another innovative method for sustainable hydrogen production. Complementing these findings, [58] presents a case study from Italy that focuses on cost-efficient hydrogen production from locally sourced organic waste. Their multi-echelon, multi-objective network design model integrates biogas and hydrogen production plants, optimizing plant locations to minimize transportation emissions, energy consumption, and carbon footprint, while balancing environmental and economic parameters.

Other literature on industrial symbiosis, while not as explicitly focused on symbiosis characteristics, still highlights the role of hydrogen in urban-industrial contexts. For instance, [59] and [60] examine the use of hydrogen as a storage medium to facilitate symbiosis between eco-cities and industrial systems, particularly within heat and power systems in industrial sites. Extending this idea, [61] explores hydrogen's role in a multi-energy urban-industrial symbiosis context, further emphasizing its potential as a key component in integrated energy storage solutions.

Overall, research in industrial symbiosis contributes to generation of hydrogen by utilizing the electricity generated from by-products, waste, and biomass. The diverse approaches and case studies illustrate hydrogen's versatility in reducing carbon footprints, optimizing resource utilization, and promoting sustainable industrial practices. Next to the existing power supplies for hydrogen generation such as solar, thermal; fermentation, anaerobic digestion processes are shown to be decreasing the system cost for hydrogen supply and facilitate important symbiotic relationship between municipal waste, agriculture and industries. However, main focus of the studies are to prove the technological feasibility of the generation processes, techno-economic viability of using waste to generate hydrogen.

2.4. Identified gap and contribution of the research

In recent years, there has been growing interest in use of hydrogen in integrated energy systems. There is consensus among researchers that the hydrogen provides significant opportunities for long and short term energy storage and electricity demand-supply balancing, higher utilization of intermittent renewable energy sources. However, the purpose of hydrogen use in the literature regarding integrated energy systems remains limited to power system related issues, and the use cases for the hydrogen gas itself remains as a gap.

Although it is not the direct focus, community energy systems and energy cooperatives are mentioned in the same context with hydrogen for such opportunities. In order to prove the technical potential in multi energy community systems where hydrogen, in general, acts as one of the storage technologies, mainly techno-economic analysis are conducted through optimization methods. Industrial symbiosis literature is also derived from similar hydrogen use purposes but it additionally includes the technical feasibility of hydrogen production in a symbiotic manner between industries or within urban structures.

On the other hand, comprehensive literature that studies technical, social and institutional aspects of formation of community energy systems for households and neighborhoods [48] or industrial community power systems [42, 41] do not exist for hydrogen based (industrial) community energy systems that serves the need for gas and heat demand.

Although they share similarities with community energy systems for electricity, hydrogen based industrial communities are expected to differ in many areas. While drivers of electricity intensive industries and processes are mainly related to cheap, secure and efficient way of supplying electricity, for gas consuming heat intensive industries the problem becomes more multifaceted due to the constraints such as varying process heat needs, infrastructure availability, radical changes in business operations, maturity of the technologies, higher investment costs and still evolving support schemes. These characteristics challenge the term ”industrial” with its general use, and requires closer look to each sector requirements, motivations and availability of other options. In the industrial context, value given to one unit of energy becomes subjected to different factors depending on the energy carrier. Therefore, although household communities, industrial community energy systems and symbiosis for electricity share similar drivers and challenges regarding technical, environmental, financial, institutional perspectives, hydrogen based industrial community systems offer unique and undiscovered dynamics. Therefore, the study offers valuable contribution to the literature with its focus on techno-economical and institutional dynamics behind community formation for hydrogen use by using agent based modelling approach.

3
Methodology

The chapter explains the agent based modelling, its place in socio-technical context, use in the academic literature. It continues with the method's suitability for this research, its benefits and weaknesses. The chapter then continues with the description of modeling methodology followed in this research.

3.1. What is agent-based modeling (ABM)?

Agent-based modeling (ABM) is a methodology used to create formal models of real-world systems composed of individual entities (such as atoms, cells, animals, people, or institutions) that interact repeatedly with each other and/or their environment. The key characteristic of ABM is the clear and direct correspondence [62]:

- between the individual components in the real-world system and the corresponding elements in the model (the agents),
- and between the interactions in the real-world system and those of the agents within the model.

In the natural sciences and engineering, computer simulations predominantly utilize equation-based modeling, such as for the dynamics of gases, fluids, or solid bodies [63]. This method typically represents entities within the target system using either average properties or single representative agents [62]. However, this approach poses challenges when applied to complex social systems, where most system behaviors lack formal mathematical descriptions. Agent-based modeling (ABM) offers a more suitable alternative for simulating such systems. While agent behaviors and interactions can be formalized with equations, they are more commonly defined by rules, such as if-then statements or logical operations in ABMs [63]. In an agent-based model, the system's individual units and their interactions are explicitly and individually modeled [62]. This approach provides greater flexibility and allows for the incorporation of individual behavioral variations ("heterogeneity") and random influences or variations ("stochasticity") [63].

3.2. ABMs in socio-technical systems

Socio-technical research on transformation processes encompasses a broader spectrum of social factors, integrating economic and technical elements from the perspectives of various stakeholders [64]. Socio-technical systems mainly consist of two intricately linked subsystems: a physical network comprising technical artifacts and a social network comprising actors [65]. The objective of socio-technical transition research is to comprehend technological and social change through the analysis of their enabling and inhibiting causes and the formulation of policy recommendations for guiding socio-technical systems [66].

Assuming the accurate modeling of real actors' behavior, agent-based simulations provide insight into how the technical and social subsystems of an infrastructure co-evolve. They allow researchers to observe the emergent overall system behavior resulting from their interactions across different system levels and time scales. These simulations are crucial as they can help identify what an improved system might look like. Using computers to run numerous simulations with agent-based models enables an extensive exploration of the "decision space." This approach allows for detailed preliminary analyses of potential outcomes and reveals system characteristics before the actual system is constructed. It is especially advantageous for systems developed over long periods or when the risks of incorrect operational decisions are substantial [65].

3.3. Use of agent based models

In ABMs, agents represent a variety of autonomous entities capable of making independent decisions and interacting with both each other and their environment [67, 68]. This method captures individual decisions and enables the analysis of the collective behavior that emerges within the system [69]. ABMs are particularly effective for analyzing institutional changes and policy interventions by exploring various scenarios and comparing how agents' behaviors evolve under different conditions [70, 71]. Key strengths of ABMs are [72]:

- It simplifies the representation of reality, making research more manageable and eliminating the need for complex analytical solutions and mathematical formulations [69, 71].
- Using a bottom-up approach, it is well-suited for analyzing the complex emergent behaviors by examining the interactions among basic components [73, 74].
- It includes the time variable, allowing researchers to analyze various scenarios to understand the relationships between inputs, variables, and outcomes, thus enhancing the depth of investigation [69, 71].

The ABM approach has already shown to offer valuable insights when used to analyze the dynamics of various types of collective actions [41, 75, 76]. The method is also gaining prominence as a valuable tool in the literature for investigating energy systems [77], especially to simulate the interactions between agents in bottom-up community energy systems for households [48, 78, 72, 79] and for industries [41, 42, 80].

3.4. ABM in this research

Agent-based simulation method is most effective for modeling complex systems especially when the following conditions exist [81]:

- The problem involves distributed, autonomous actors
- The subsystems (agents) function in a highly dynamic environment
- Subsystem interactions are flexible, driven by reactive or proactive behaviors, cooperation or competition, or social factors like trust or empathy

In light of this, agent-based modelling approach fits well to the intentions of the research. This research explores the potential of cooperation among diverse set of autonomous industrial users from different sectors for enabling regional transition to hydrogen. Moreover, it analyzes how different regional sector configurations and the use of government support schemes could play a role in facilitating the potential of community formation. The environment that actors are operating in is highly dynamic with changing techo-economic conditions in time such as technological developments, commodity prices and involves uncertainty for infrastructure developments, accessing and securing subsidies etc. The research also touches upon social factors such as cold-feet problem in starting the transition, peer-pressure and decisions of others. The fact that the problem situation and research is about industrial actors, their interactions with each other and with their environment, it is trivial that an agent-based simulation approach is needed to answer the research questions in this study.

Assuming a sufficiently accurate representation of reality, agent based modelling allows to bring together the technical and institutional elements of the problem situation that agents are facing. Building on this, it facilitates the ground for comparative analysis of the emergent system behaviour under different organizing principles of hydrogen roll out, ways of agent interactions, government policy interventions. By this way, it will be aimed to reveal the relative effect of different actions on the success of hydrogen roll out. This approach will contribute to the literature by helping to anticipate the effect of different support schemes, advantage or disadvantage of collective investment over other alternatives, region's potential for hydrogen development through its characteristics. This is especially important in the case of giving large investment decisions for regional infrastructures. By utilizing virtual environments, experiments and analyses can be conducted on various real regional settings, system behaviour can be monitored over long periods, agent's behaviour can be traced back the and the understanding of actions' effect can be deepened.

ABM simulation method provides a granular approach, capturing the diversity and complexity of individual actions and decisions. Given the significance of individual characteristics, decision-making, and interactions in the analysis of collective action and the bottom-up nature of community energy systems, ABM is a preferred as a simulation method for this study.

One drawback regarding ABMs is their dependency on highly specific data and knowledge about agent behavior rules. Given the intricacies of the real world, an ABM cannot encompass all the details of actual decision-making processes. However, ABM can support decision-makers by offering valuable insights into key variables that influence these processes [72]. In instances where this specific data and knowledge is lacking, assumptions were made or reasonable substitutes for the necessary data were employed. These assumptions, along with their effects on the accuracy of the model outcomes, are thoroughly documented in the relevant parts of the Section 4.3.

3.5. Modeling methodology

3.5.1. Model conceptualization and formalization

For determining the relevant and critical concepts involved in hydrogen investments and development of regional hydrogen production and consumption, desk research, grey and academic literature, expert meetings will be utilized. The reports of national hydrogen research programmes take snapshots of the current situation, reveal main processes that companies undergo while transitioning to hydrogen, highlight major factors and painpoints involved in the current outlook. Academic literature will contribute to develop scientifically sound assumptions and proxies for certain concepts. Furthermore, expert meetings will help to discover more in depth insights about the sector and processes. Together, they contribute to a simulation model that represents major building blocks of the real life processes.

3.5.2. Data collection

The conceptualized model will be based on quantitative data from various sources. The effort will be made for using quantitative proxies for qualitative concepts such as willingness/motivation for hydrogen transition. According to the specificity, data to be used in the research could be categorized into four:

- **Company specific data:** Companies will presumably be the agents in the simulation model. Per company, data related to the energy demand, power availability and sector in which they operate in will be collected from Stedin's gas consumer databases. These data quantitatively represent demand and supply via gas volume and power capacity. On the other hand, qualitative information about companies such as cultural, social, behavioral or intra-company characteristics will not be part of the modelling process.
- **Sector specific data:** Information about sectors' varying internal process characteristics and hydrogen technology's role in their decarbonization will constitute the sector specific data and be valid for all companies operating in that sector. Data for the related subjects could be sourced from interviews with sector representatives. However, due to the scope considerations of the research, these data will be procured and approximated from the results of academic studies.
- **Region specific data:** Similar to the company specific information, regarding the power availability in the region, future expected additions of renewable energy capacity data for the region will be collected from Stedin's databases.
- **Environment data:** This category represents all other data which are same for all agents, regions or sectors without any specificity. For instance, for the commodity prices such as natural gas, electricity, CO2 etc. mainly government and private sector sources and their forecasts will be used. Furthermore, the data required for simulating subsidy conditions are already available in public sources. Moreover, the cost data for process equipment and electrolyzers, energy conversion and efficiency ratios, solar capacity factors for the Netherlands etc. will be obtained from academic

literature.

Finally, for the certain model parameters arising from the way the reality will be represented, data may not be readily available or derivable from the existing sources. Therefore, uncertainty and sensitivity analysis will be used in a complementary and supportive manner to assign values.

3.5.3. Software implementation

Conceptualized model could be implemented via both Python and Netlogo. Mesa is a Python library designed for agent-based modeling, and it comes with a default model class and agent class. Similarly, NetLogo is a programmable environment specifically designed for creating and running multi-agent models. Due to the past experience with the NetLogo environment, it will be used in this study.

3.5.4. Model verification

The model verification will take place after the successful implementation of the conceptualized model in NetLogo. This verification process will ensure that the conceptualized agent interactions and behaviors are accurately translated into the software implementation. Recording and tracking agent behaviour, single agent testing, interaction testing in a minimal model and multi-agent testing techniques will be employed to verify the built model.

3.5.5. Model validation

Verification focuses on whether the model was built correctly, ensuring the implementation matches the conceptual design, whereas, validation addresses whether the right model was built to answer the problem owner's questions and produce convincing outcomes. This modelling step ensures that the experimental results are valuable to the problem owner [82].

The conventional approach to validation examines if the model accurately mirrors the real-world system [83], typically by comparing experimental outcomes with real-world data. However, these traditional validation techniques are not always suitable for agent-based simulations ([84] as cited in [82]).

When there is no real system for comparison or if the model is predicting potential future scenarios, validation cannot simply compare computed behavior to actual system behavior. Instead, the validation for these types of models centers on whether the model is useful and persuasive in demonstrating how a system might operate or what its potential states could be. In fact, the true value of the model lies not in its experimental results, but in the deeper insight and knowledge it provides [82]. This situation applies to the subject of this research where an actual system of collaboration in regional hydrogen off take is not readily available for a real life comparison. However, the model outcome is useful for deepening the insight and knowledge of the potential future states of the system, and this can be validated using various methods that are identified by [82]. Two of these methods, which are not included in this study, are:

- Historic replay is one of the methods that needs extensive detail on an already realized system behaviour. The model parameters are configured to the setting of the historic system and the validity of the results are checked via comparison of model outcomes. This method is not suitable for this research due to the lack of observable regional hydrogen development to replicate with the built model.
- The model replication approach involves developing a second agent-based model with an alternative system structure or employing a different modeling technique, ideally by a separate research team to eliminate bias. Comparing the outcomes of these models can offer substantial validation insights. Although it is a strong and effective method, it necessitates substantial amount of time and effort that is not feasible under the scope of the study.

More suitable validation methods for this study include literature comparison and expert validation. The simulated situation in this study does not have a directly comparable equivalent in real-life observations or in any existing study from the literature. Instead, observed emergent system behaviour during the experimentation will be compared with the expectations or predictions of grey literature such as hydrogen research programmes. Similarly, employed methodologies in model conceptualization will be discussed in comparison with other modelling attempts. Furthermore, results of cost calculations and weights of the cost elements will be validated via both operational electrolyzer projects and academic research results.

Moreover, the project is conducted by a close collaboration with the experts from Stedin. This allows to consult opinions of experts from diverse backgrounds and integrate their input through modelling process. Regular meetings and discussions over concepts and their implementation will contribute to the model validation process.

3.5.6. Experiment setting

Identifying the case study

The use of real case study helps to reflect actual conditions with the conceptualised model, increases the added value of the research since it provides a more meaningful context for interpreting the results. As a result, it provides actionable recommendations to policy makers and stakeholders with greater confidence and support. Several factors taken into account when identifying the appropriate case study and what they aim to address can be summarized as:

- **Proximity to the planned hydrogen backbone:** Focusing on situations where receiving a connection from backbone is unlikely and there is need for showcasing regional hydrogen demand development before receiving a connection
- **Proximity between companies in the region:** Staying in line with the feasibility of pipeline use as transportation mean for hydrogen between potential participants of the collective action
- **Number of gas consumers in the region:** Increasing possible interactions taking place between agents and avoiding the potential bias that might occur in cases of disproportionality between agents
- **Gas consumption volume of the companies:** Highlighting the effect on small sized gas consumers and avoiding possible dominating power of larger consumers on the results
- **Diversity of sectors in the region:** Reflecting the characteristic of Cluster 6 companies and being able to conclude generalizable insights

Proximity to the planned hydrogen backbone

As stated in the problem formulation, the focus is on the regions far from the planned national transmission line. By excluding the regions close to the backbone, the aim is to rule out the expectations of a near future connection to the national transmission line, which could influence and complicate the decision making processes of the companies in the simulation. Therefore, by staying within Stedin's jurisdiction as shown with shaded area in Figure 3.1, regions that remain approximately at the centre of the ring-shaped hydrogen backbone are considered as candidates. Identified regions are circled in red in the Figure 3.1 adapted from [85].

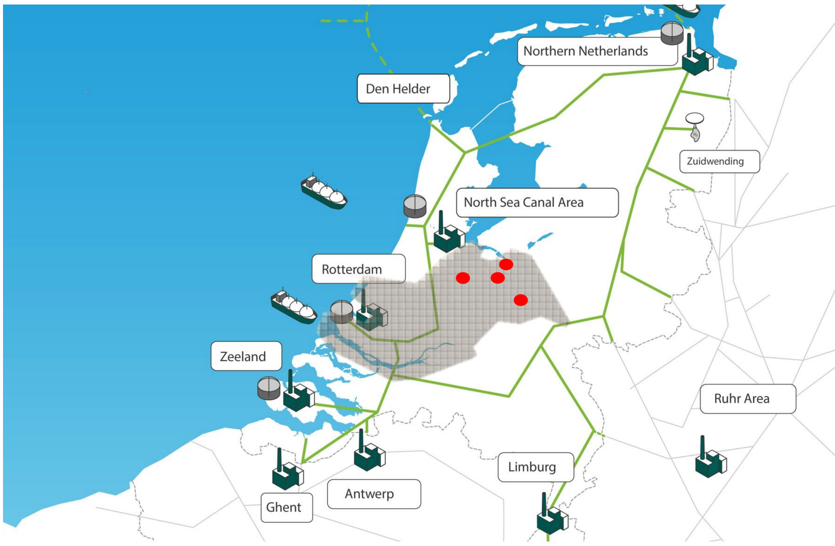


Figure 3.1: Layout of the planned national hydrogen backbone of Gasunie, adapted from [85] (Red circles and shaded areas are added on the figure indicating the candidate regions and Stedin's jurisdiction areas)

Proximity between companies in the region

As discussed in Chapter 2, the characteristics of the community energy system for hydrogen production differ from those for electricity and proximity becomes an important factor. This is because the electricity produced by the members of a collective energy system (CES) can be distributed from the collective power plant and shared among members via the existing electricity grid. On the other hand, a hydrogen CES will require a dedicated and either newly built or refurbished fixed pipeline path for hydrogen to flow through.

Although Cluster 6 companies are not concentrated in specific regions as in other industrial clusters, a certain degree of proximity between companies is sought as a criterion. Another reason is that, as the transportation part of the value chain is outside the scope of the conceptual model, care was taken in the selection of case studies to stay within manageable and realistic limits in terms of distances between companies that might be candidates for interconnected pipeline infrastructure. Driving and walking distances between the most distant companies are determined from Google Maps application and used as proxy for this factor.

Number of gas consumers in the region

With fewer agents, the decisions and strategies of individual companies can have a disproportionate effect on the overall dynamics of the model. It can also limit the diversity of decision-making processes, leading to less realistic outcomes. On the other hand, with more companies, collective investment decisions become more complex, creating a richer network of interactions, more complicated dynamics, and a wider range of strategies and decision-making processes to explore. As a result, regions with few gas-using companies are eliminated from the consideration while identifying the case study.

Gas consumption volume of the companies

Gas consumption volumes are correlated with company size in the study. The study focuses on small companies with the idea that cooperation and economies of scale are more valuable for their cases. Economic, technical and institutional barriers are more relevant for small companies as explained in detail in Chapter 1. Another reason for this consideration is that the large companies tend to have a significant impact on the results by dominating the evolution of the results, overshadowing the effect of other much smaller companies' decisions making and over-exploiting the sources such as regional renewable energy sources included in the conceptual model. Therefore, companies with gas consumption between 10,000-1,000,000 m3 are included in the study. Annual natural gas consumption of companies for one of the potential case study region can be seen in Table 4.2 in Appendix B.

Diversity of sectors in the region

As argued in Chapter 1, sectoral diversity is one of the important characteristics of cluster 6 companies that differentiates them from the other five clusters. This is also one of the pillars of the research question that the study aims to investigate, namely the effect on hydrogen uptake. Therefore, the selected case study is expected to reflect a certain level of diversity in terms of the number of different sectors.

Potential case studies

After consideration, four possible case studies are identified. For the companies in these regions, the installed solar rooftop capacity, the available unused grid connection capacity and the annual natural gas consumption data are retrieved from the Stedin databases. In addition, the solar farm capacity planned to be installed in the regions in the near future was used from the subsidy results report published for electricity distribution companies. An overall summary of the potential case study regions is given in Table 3.1.

Table 3.1: Details about the potential case study regions

Case	Case Name	Number of companies	Sector variety	Furthest distance (km)	Total grid capacity (kw)	Total solar capacity (kwp)	Total planned RES capacity (kwp)	Annual natural gas consumption (m3/u)
1	HydroLow	16	5	10,1	5,785	544	4,316	1,352,027
2	HydroModerate	14	3	3,8	6,762	23	10,229	2,974,290
3	HydroHigh	9	4	6,6	1,079	154	3,225	579,411
4	HydroControl	15	4	9,6	10,170	1,009	3,363	1,607,230

Note: The region names are not presented explicitly to avoid possible confidentiality issues

All identified case studies demonstrate appropriate qualifications for the study. Due to the availability of more complete data on companies' grid and solar rooftop capacities, Case 4 (HydroControl) is selected for further experiments.

Experiments

Once the case study has been selected, the first set of experiments is carried out through sensitivity analysis. These experiments will examine the sensitivity of the model to a range of parameter values that are unknown or uncertain. The results will be used to build a baseline model, which will then be used to conduct experiments, each aimed at answering the related sub-questions of the research.

Experiment 1 - The impact of collective investment

"How does the availability of collective investment options affect the regional hydrogen off-take?"

The objective of this experiment is to investigate the impact of collective action on hydrogen offtake in the region. The procurement options available to companies in the baseline model will be limited to generating hydrogen through individually owned electrolysers or, if available, purchasing hydrogen from a pipeline connection. The implementation of the collective investment option in the model on top of the baseline model is achieved by activating the relevant switch on the interface, which then activates the relevant parts of the code.

This experiment forms the backbone of the study and will help to convey the main message of the research. The introduction of the collective investment option will, in a sense, serve as a secondary baseline model. In subsequent experiments, the subject of investigation will be extended to both cases, with and without collective investment. This will enrich the comparative discussions and help the insights to grow cumulatively by building on each other.

Experiment 2 - The impact of sectoral configuration

"What role does sectoral distribution in the region play in the performance of regional hydrogen off-take?"

All discussions and experiments up to the second experiment will be carried out with the selected region with a certain number of companies operating in certain sectors. Obviously, this specific mix of sectors is not to be expected in every other region. In fact, some of the regions presented in this chapter accommodate quite different mix of industries with different levels of natural gas consumption. Sectoral diversity is one of the main pillars of the problem formulation and research. This pillar is materialised in the conceptual model through the sectoral hydrogen dependency ranking, which is used to determine the companies' ROI expectations, the size of their investment plans in a single step and their willingness to rely on local generation in their supply mix.

Table 3.2: Sector contributions to the region's total gas consumption under different scenarios

Case	Case Name	Horticulture	Cement	Chemical	Food	Metal	Paper	Textile	Sectoral Hydrogen Dependency (Weighted Average)
1	HydroLow	52%	-	18%	15%	12%	2%	-	4.8
2	HydroModerate	-	3%	-	83%	14%	-	-	5.8
3	HydroHigh	-	-	7%	10%	35%	-	48%	6.4
4	HydroControl	-	4%	14%	28%	55%	-	-	8.0

It is important to reiterate that this experiment does not run the simulation for different case studies, but rather applies different sectoral mixes in other regions' gas consumption to the original case study. This is done by assigning the same companies to different sectors and obtaining approximately the same sectoral distribution of gas consumption, everything else such as power capacities being the same as in the original case study. Table 3.2 shows the sectoral distribution of the case studies determined previously. Here, HydroControl case is the original case study and will serve as a reference in the experiment.

Experiment 3 - The impact of government support on subsidies

"How do changes in current government support settings, particularly regarding subsidy eligibility conditions, affect regional hydrogen off-take?"

Subsidies are an integral part of the hydrogen investment plans. Relatively smaller consumption volumes of the companies in Cluster 6 and the gradual transition plans to hydrogen in modules/production lines lead to smaller investment steps in the hydrogen transition and consequently to smaller electrolyser capacities. These conditions imply disadvantages for companies willing to apply for subsidies due to the minimum capacity requirements. Table 4.2 in Appendix B shows how the incremental electrolyser capacities would look for companies under different possible production line settings that they might have. In fact, in the production line scenarios for the companies (between the assigned minimum and maximum number of production lines), many of the electrolyser capacity plans remain below the SDE++ subsidy limit of 500kw, which is similar to the current problem faced by Cluster 6 companies when considering applying for the subsidy.

Therefore, the minimum subsidy limit, which is currently set at 500 kW in the SDE subsidy scheme, will be varied both upwards and downwards. The results will help to better understand the impact of such a change in eligibility rules and provide insights on how to use such government intervention under different conditions.

4

ABM of collaborative hydrogen off-take

This chapter explains the modelling steps applied in building the simulation model, which ultimately answers subquestion 3. This model will be then used to address sub-questions 4, 5, and 6, corresponding to the planned experiments.

For the first subquestion, in alignment with the problem definition, subsections on actor and system identification will delineate the relevant parts of the supply chain, groups of actors, sectors, and the use purposes of hydrogen that could be included within the scope of the simulation process.

Regarding the second subquestion, building on the identified barriers to hydrogen scale-up described in the problem definition, the potential of collective action to address these barriers will be discussed in several different subsections during the conceptualization efforts.

Identifying and conceptualizing relevant real-life processes in hydrogen production investments and regional hydrogen off-take, followed by the development of the agent-based simulation model, will address the third subquestion.

4.1. Actor identification

Many industrial operations require heating at low medium and high temperatures. The major industries in the Netherlands are concentrated in the large industrial clusters, although medium and small-sized companies dispersed throughout the country also demand significant amounts of thermal energy. At this point, the Dutch gas transport infrastructure has 350 industrial delivery sites for the delivery of natural gas. Various industries utilize medium to high temperature heat in their operations. These include ceramic industries operating at temperatures between 1000°C - 1200°C, food industries at below 150°C, chemical industry involving high temperatures, metal industry up to 1200°C, the paper industry at 150°C, and the glass industry at between 1500°C - 2000°C and higher temperatures [16].

Temperatures below 500°C offer opportunities for process advancements to decrease the amount of heat needed. Electrification may be a viable alternative for medium temperature heating (100°C-400°C), but its feasibility and cost-effectiveness depend on the specific application. Temperatures exceeding 500°C primarily need the use of low carbon alternatives such as biogas, biomethane, or natural gas with carbon capture storage [16].

For industrial applications requiring high temperature heat (HTH, >500 °C), there are few viable alternatives to traditional natural gas-fired heating other than renewable fuels such as clean hydrogen or biomethane [39] and hydrogen is becoming increasingly viable for the high-temperature industrial industry [16]. According to the Cluster 6 energy strategy documents, electrification is not regarded a viable alternative for heat demand of more than 200 °C with the current technologies [30].

Actor selection is done according to the relevancy of hydrogen for the sectors. Hydrogen appears to be a feasible option for all above mentioned medium-high temperature heat sectors. Since hydrogen is more prevalent for ceramic, metal and glass industries, these sectors can be considered as primary hydrogen off-takers in their regions. However, other alternatives such as electrification, increasing heat efficiency could be more predominant for food, chemical and horticulture industries, making them secondary hydrogen off-taker sectors. This difference in the equally available options for different sectors is reflected as "sectoral hydrogen dependency" in the model as a part of companies' motivation for transitioning to hydrogen. More explanation regarding these concepts will be discussed later in the section.

4.2. System identification and decomposition

Hydrogen value chain

The hydrogen value chain can be divided into four categories: production, transportation, storage, and end use, as shown in Figure 4.1. The components of the value chain highlighted in green are within the scope of this study, while those highlighted in grey play an indirect role in the project's scope.

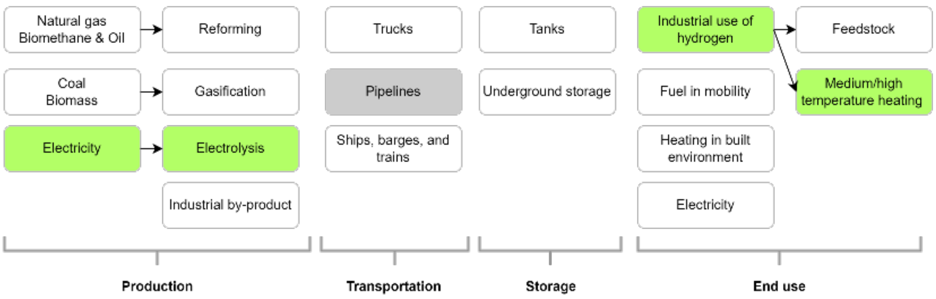


Figure 4.1: Overview of the elements of hydrogen value chain, adapted from [16]

Production

There are several methods for producing hydrogen, primarily categorized as reforming, gasification, and electrolysis. Currently, Steam Methane Reforming (SMR) is the predominant technology, which accounts for 6% of global natural gas usage to produce 70 million tonnes of hydrogen. The second major technology is coal gasification which produces 23% of the world's hydrogen demand by consuming 107 million tonnes of coal globally. Oil and electricity contribute to a minor share of hydrogen production today [86]. Hydrogen production is often categorized into 'grey,' 'blue,' and 'green' hydrogen. 'Grey' hydrogen involves methods that emit CO2. 'Blue' hydrogen uses the same methods as grey but incorporates carbon capture technologies to sequester or reuse CO2 emissions. 'Green' hydrogen, which is carbon-neutral, is typically produced via electrolysis powered by renewable energy sources. Hydrogen production technology considered in the study is electrolysis which consumes electricity both directly from a renewable energy source and electricity grid.

Electrolysis involves splitting water molecules into hydrogen and oxygen using electricity. The primary electrolysis technologies are Alkaline and PEM, both of which yield hydrogen of relatively high purity. The levelized cost of hydrogen (LCOH) produced via electrolysis is significantly influenced by electricity prices. Additionally, factors such as efficiency, capital expenditures (CAPEX), load hours, and scale also substantially impact the LCOH [16]. Therefore, more emphasis is placed in the study on capital expenditures, its evolution in relation to economies of scale and the components of the electricity cost.

Transportation

Hydrogen can be transported from its production site in various ways: as a gas via pipelines, as a pure liquid in tubes and tanks mounted on trucks, ships, or trains, or by converting it into other carriers such as methanol, ammonia, or liquid organic hydrogen carriers (LOHC). Each transportation method has unique infrastructure, pressurization, storage, and conversion requirements, along with associated costs. Recent studies, such as [39] and [31], focus on the break-even points for different transportation methods based on volume and distance. Pipelines show a cost advantage when transporting large volumes of hydrogen, offering the lowest costs per kilogram when feasible. For short distances and low volumes, methods like LOHC trucks are more cost-effective. Although transportation options vary economically under different conditions, their costs in general range between 0.2 - 0.8 €/kg. According to [39]'s hydrogen cost decomposition analysis for industrial heating value chains, the total cost of domestic green hydrogen is calculated at 3.77 €/kg for pipelines and 3.85 €/kg for LOHC. This indicates that the costs associated with pipeline routes and LOHC trucks do not differ significantly, primarily because transportation costs contribute minimally to the total levelized costs of supply. Since electricity and investment costs together account for over 80% of the levelized cost of hydrogen [16], the emphasis is mainly placed on detailing their effects, while transportation costs are not included in the investment cost calculations of companies. Additionally, incorporating transportation into cost benefit analysis of hydrogen investments would necessitate identifying the location of planned individual or collective electrolyzers, checking for existing pipeline connections between community members, and examining the technical and operational feasibility of converting these pipelines for hydrogen use, dealing with other pipeline users that want to continue using natural gas etc. These requirements extend far beyond the scope of the project and divert it from its main objective, turning it into a problem of optimal network planning.

The second important assumption regarding transportation is that, in the conceptual model, hydrogen purchase is assumed to occur only if the region is connected via pipeline transportation. This means that, in addition to their own local production, companies are given the option to buy hydrogen only through pipeline supply. Moreover, since industrial customers have cited having a pipeline connection as a prerequisite for a complete transition, the study's main focus is to determine whether conditions get mature enough for the region to receive a connection from the national hydrogen grid. In other words, the study does not aim to identify the best hydrogen transportation method for the region. Instead, it examines whether and under what conditions hydrogen uptake via standalone projects can lead to feasible conditions for a successful transition through pipeline development. The role of other carriers in this development is not within the scope of the study.

Storage

Storage in the hydrogen value chain is another important step due to the reliance on intermittent energy sources in its production, lack of continuous supply as it is the case for natural gas. [87] outlines characteristics that can determine the most suitable hydrogen storage option for a given situation. These include the application (whether a specific carrier is used for end-use or a particular pressure is required), the compatibility with the hydrogen delivery method, the quantity of hydrogen, the storage duration, available energy forms (such as electricity or waste heat), geological characteristics for storage, future expansion needs, maintenance requirements, and capital costs. Due to similar concerns as with transportation, hydrogen storage is not included within the scope of this study. This is mainly because the time resolution of the simulation model is set to years, whereas storage needs arise from weekly, daily, or even hourly variations in supply and demand. However, the study assumes that electrolyzers operate concurrently with the factory's working shifts, with grid electricity often supplementing the intermittency of renewable energy sources.

End Use

Processes that use hydrogen as feedstock or in the mobility sector with hydrogen fuel cells require higher purity levels of hydrogen. Consuming hydrogen from the pipeline, which has a standardized purity level, may not be suitable for certain consumers. However, within the scope of Cluster 6 companies, hydrogen consumption as feedstock is not widespread. Although the chemical industry is a significant user of hydrogen feedstock, the majority of operations are concentrated in five large clusters. Therefore, the focus is exclusively put on industrial heating as the end use. More details about the types of actors and their temperature requirements are discussed in the previous actor identification section.

Estimating the potential future hydrogen demand for the dispersed Cluster 6 HTH activities is challenging due to the need for location and process-specific evaluations to determine if hydrogen is a viable alternative for decarbonization. The existing demand for natural gas for HTH provides a reliable indication of the heating demand levels for these industries [39]. The demand-side load profile remains steady to maintain the process temperature and prevent the need for reheating [16].

Access to certain users' annual natural gas consumption data is available through Stedin's database. It is assumed that all natural gas consumption is for heating purposes. The fact that demand profile for heating purposes is relatively steady throughout the year supports the assumption regarding the time resolution of the simulation. When needed for specific calculations, such as power capacity needs, daily and monthly gas demand is derived with the assumption of stable consumption throughout the year.

4.3. Relevant concepts used in the conceptual model

Concepts used in the simulation model can be categorized into three groups where companies plan for their hydrogen transition, check its feasibility and realize their project plans.

4.3.1. Planning for the transition

The relationships between concepts in transition planning phase are shown in Figure 4.2. In order to determine the size and supply mix of hydrogen transition plan, several concepts such as motivation degree, number of production lines, sectoral hydrogen dependency and expression of interest are used.

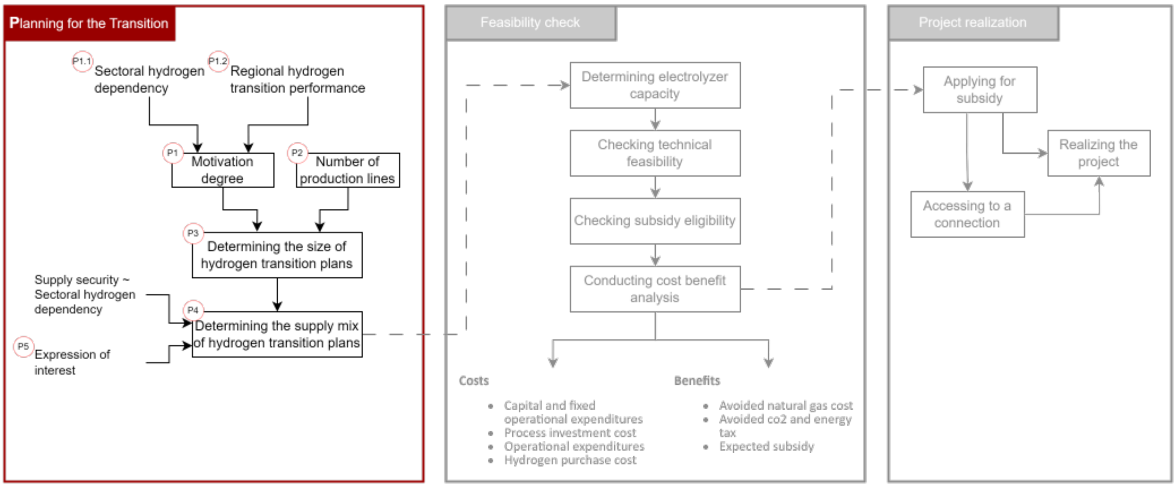


Figure 4.2: Concepts used in hydrogen transition planning

P1. Motivation degree of agents

It is acknowledged that the motivation or desire to transition to hydrogen can vary significantly among companies. Some companies may adopt a strategic approach, investing early to capture the market, while others may have a more conservative attitude, prioritizing profitability from the initial phase [88]. The availability of other equally effective clean technologies that fits into a company's needs can also influence the transition to hydrogen; the more alternatives available, the less motivated companies are to pursue hydrogen technology. This trend is evident in strategy documents from various clusters, as indecisive behaviors are observed among companies in sectors where multiple promising technologies exist [28, 30, 31]. There are numerous approaches to identify a company's willingness to transition to hydrogen. In this study, the concept of motivation degree is developed to capture the impact of two factors which are sectoral hydrogen dependency and regional hydrogen transition performance.

P1.1. Sectoral hydrogen dependency

Sectoral hydrogen dependency is closely related to the availability of alternative options besides hydrogen. This concept, developed in the model, has a value range from 0 to 10, with 10 corresponding to the highest dependency on hydrogen. It is determined at the sector level and automatically assigned to agents operating within that sector. The intended meaning of this concept is directly linked to the number of feasible transition pathways for specific sectors, which could include waste heat, electrification, biogas, hydrogen, etc.

As mentioned at the beginning of this chapter, when considering industrial heating, the discussion about available options narrows down to the temperature requirements of the process within that sector. The capability of transition pathways is highly dependent on the temperature levels they can provide. Therefore, to quantify the sectoral hydrogen dependency concept, temperature requirements of the sectors are used as the reference.

The process temperatures referenced from [89, 90] are presented in Tables A.1 and A.2 in Appendix A. The temperature intervals and ranges specified in these studies have been adjusted according to a scale from 0 to 10, resulting in a hydrogen dependency score for each sector, as shown in Table 4.1 below.

Table 4.1: Assigned hydrogen dependency scores per sector

Sector	Hydrogen dependency score
Metal	10
Cement	9
Glass	8
Ceramic	8
Chemical	6
Food	5
Paper	5
Textile	4
Wood	3
Agriculture	3

P1.2. Regional hydrogen transition performance

The second factor included in the motivation degree, the regional hydrogen transition performance factor, is related to the hesitancy, or ”cold feet,” that companies experience when considering such investments. This issue also applies to new technologies such as hydrogen, where the lack of widespread use cases leads to users getting cold feet. Companies focused on innovation suggest that sharing successful examples of CO2 reduction can help mitigate this hesitancy regarding process innovations. Cluster 6 companies emphasize a clear need for information on possibilities and best practices [30].

Therefore, the development of hydrogen demand in a region by peer companies is assumed to positively influence other companies' motivation to transition to hydrogen. This factor is quantified by dividing the total hydrogen use in the region by the total potential hydrogen use, resulting in the regional hydrogen share. This factor is recalculated at each time step (year) to update the motivation degrees of companies based on most recent developments in hydrogen consumption in the simulation.

The weighted average of these two factors, both scaled between 0 and 10, determines the motivation degree for each company in the simulation. The contribution of sectoral hydrogen dependency to the motivation degree remains constant throughout the simulation. In contrast, the contribution of regional hydrogen performance is dynamic and updated at each time step. The assumption about the relative importance of these factors over the other (their weights in calculating the motivation degree) can impact the outcomes of the model, therefore, the effect of the parameter will be investigated further with the sensitivity analysis in Chapter 6. How this motivation degree value is used throughout the conceptual model will be explained under relevant parts of this section.

P2. Number of production lines

The logic of using the number of production lines that companies have is to find a reference representing their expected gradual transition to hydrogen. Ideally, one-to-one interviews with companies regarding their probable transition paths would provide the exact information needed for the conceptual model. Instead, the decision is made to proceed based on the number of production lines. However, this information is still quite specific and difficult to access. Searching for the average size of currently available natural gas and hydrogen boilers does not yield a viable option for this concept, as such equipment exists in almost all possible capacities.

Nevertheless, Stedin's past projects with companies having five natural gas boilers and converting several of them to hydrogen as trial cases provided a clue for assigning a reference number. On the minimum end, having only one production line is never considered, as it implies a full transition plan, which is assumed to be unrealistic. Therefore, the number of production lines/modules is considered to range between 2-5. When applied to the companies' heat demand from the example case study, the resulting incremental electrolyzer capacities are calculated as shown in Table 4.2. These capacities, corresponding to each number of production lines, are calculated by dividing the kWh equivalent of natural gas consumption by the number of operating hours, integrating efficiency factors. For some smaller companies, assigning more than 2, 3, or 4 production lines resulted in electrolyzer capacities of less than 50kW. Hence, an upper limit is set on the possible number of production lines for these smaller companies.

Table 4.2: Possible electrolyzer capacities for companies

	Annual natural gas consumption		Electrolyzer capacity per # of production lines					# of production lines	
Company	**(m3)**	**(kWh)**	5	4	3	2	1	Min	Max
1	316,715	3,138,373	302	377	503	754	1509	2	5
2	307,166	3,043,751	293	366	488	732	1463	2	5
3	173,142	1,715,688	165	206	275	412	825	2	5
4	164,397	1,629,033	157	196	261	392	783	2	5
5	147,247	1,459,091	140	175	234	351	701	2	5
6	95,431	945,639	91	114	152	227	455	2	5
7	81,899	811,549	78	98	130	195	390	2	5
8	61,388	608,302	58	73	97	146	292	2	5
9	50,100	496,448	48	60	80	119	239	2	4
10	47,322	468,920	45	56	75	113	225	2	4
11	45,627	452,124	43	54	72	109	217	2	4
12	43,904	435,051	42	52	70	105	209	2	4
13	30,655	303,765	29	37	49	73	146	2	3
14	27,601	273,502	26	33	44	66	131	2	2
15	14,636	145,030	14	17	23	35	70	2	2

The minimum and maximum number of production lines in Table 4.2 for the companies are identified based on these considerations. Within their respective ranges, companies are randomly assigned a number of production lines in simulation runs. This parameter is important as it determines the size of the plans in the simulations. However, having a randomized approach integrates meaningful uncertainty into the modeling effort. Although the logic of production lines/modules tries to bring a structure and methodology into the process, companies may not necessarily follow this path. Other technical constraints, affected by technological development and innovation, may influence the transition. As a result, the uncertainty arising from varying magnitudes of increment steps is acceptable for the variety in model outcomes. Different than deterministic models, one of the important power and purpose of using agent based models is the representation of uncertainty inherent in real-world systems. Therefore, the discussed uncertainty included in the model fits for the purpose of the study.

In the conceptualized model, agents first determine how many of their production lines/modules they would like to convert to hydrogen in one step. This is decided in proportion to their motivation degree. This decision corresponds to a certain share of the company's demand. Then, the decision about the supply mix follows, with the portion allocated for production constituting the production demand for which the electrolyzer capacity is calculated.

P3. Determining the size of hydrogen transition plans

Industrial hydrogen off-takers are expected to have a certain degree of flexibility in their transition to hydrogen compared to mobility and built environment. Hence, this supports the development of local hydrogen grid infrastructure around them. Although the regions with industrial off-takers offer more potential for infrastructure development, this potential is limited. Not all industrial users in such regions are expected to fully transition to hydrogen before a reliable supply connection is established. Overall, the majority of standalone hydrogen project initiatives in the Netherlands do not intend to operate independently in the future, but instead expect to depend on a connection to the main infrastructure [27].

This limitation also defines the simulated time window for this study. Currently, electricity and natural gas infrastructures are regulated, requiring system operators to provide infrastructure upon client request. In contrast, the same level of responsibility has not yet been assigned to system operators for hydrogen infrastructure. Existing small-scale hydrogen pipeline networks are independently built and managed by private parties. Future expectations for hydrogen infrastructure envision it being regulated similarly to electricity and natural gas, with system operators having the same scope of responsibilities and obligations [25].

Therefore, simulation is focused on the so called "transition period" if and until such a regulation for hydrogen is introduced. During this period, companies are expected to gradually increase their hydrogen demand and parallel use of natural gas and hydrogen for a certain period is expected due to energy security concerns, especially for the local hydrogen production cases [27].

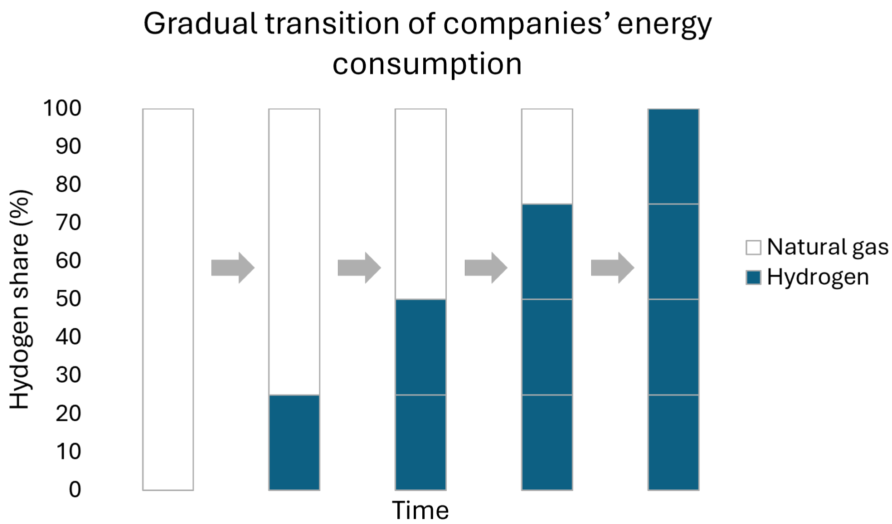


Figure 4.3: Gradual increase in companies' hydrogen consumption

Two methods are considered in the conceptual model to represent the gradual increase in hydrogen demand. The first method involves blending hydrogen into natural gas either at the network level or directly at the factory before it is fed into the equipment. The latter option is included in the scope of this study since it does not require major changes in the process equipment of the consumer. This approach allows businesses to transition gradually and make incremental investments, which is more practical than attempting to achieve 100% decarbonization all at once [27].

Second method used in the model is to convert current production lines in stages. For instance, several production lines that currently operate with natural gas burners, boilers, and ovens can be gradually replaced with hydrogen-compatible equipment. This step-by-step conversion as shown in Figure 4.3 allows companies to observe and experiment with the new hydrogen applications without putting business operations at high risk, a well-known and followed practice within the industry.

The same logic is reflected in the modeling practice, where companies plan their hydrogen transition gradually and decide how many production lines to convert to hydrogen by using burners, boilers, and ovens. It is assumed that the companies' motivation degree for the transition will influence how ambitious their decisions will be—in modeling terms, how many of the production modules they will be willing to change in one step. Assuming that a company with the maximum motivation degree would have converted all of its production lines to hydrogen at once, each company decides on how many to switch in direct proportion to their motivation degree.

P4. Determining the supply mix of hydrogen transition plans

Standalone projects located farther from the backbone are perceived as harder to implement, particularly in terms of supply security. Supply security is a significant issue in these regional grids and often drives the need for a backbone connection. This implies that not all industrial end-users intend to satisfy their natural gas requirements entirely with locally produced hydrogen, as the security of hydrogen supply is lower than that of natural gas [27]. Therefore, in the modeling practice, the concern for supply security is reflected in companies' transition plans. As they transition to hydrogen and become more dependent on its supply, risks such as intermittency in production, smaller capacities, and limited storage facilities could further raise concerns about supply security.

This concern is translated into companies' plans for hydrogen transition, where the supply mix consists of local production and purchasing. In the scope of the project, the portion planned to be bought by the companies is assumed to be transported via pipeline. This mix, determined by the company, reflects their envisioned plans as if a pipeline will be laid in their regions or with the desire for it to be laid. However, these plans may not be realized as desired since the eligibility of a pipeline connection depends not only on a single company's transition request but also on the overall regional demand influenced by other companies' plans. This aspect related to the realization of the plans will be further detailed later in the section.

The decision on how much local production or purchasing should contribute to the supply mix could depend on several factors. One factor could be a company's willingness to increase its vertical integration, meaning owning and controlling more steps in its supply chain. Another motive could be related to the company's hydrogen purity requirements; however, as explained earlier in this section, such demand is negligible among Cluster 6 companies. Other social aspects, such as cultural and behavioral factors, could also influence the desired supply mix, but these will not be part of this project. Based on the previous discussions in this chapter, the need for supply security stands out as a shared value for all companies and can be used to determine the supply mix. Therefore, in the simulation model, as a company's awareness or concern for supply security increases, the share of purchasing in their transition plans increases.

In its article about developing an energy security index, [91] mentions the concept of "preparedness for supply disruption" that fits well to the intended use in this study. Preferring the supply of pipelines over the local generation mainly originates from the desire to decrease supply disruptions and could depend on how vulnerable a company is for such disruptions. Supply disruption in case of hydrogen production via electrolysis could occur in the event of power disruptions. Based on that, electricity grid connection capacity of companies could correspond to the preparedness as regardless of fluctuations in renewable energy sources, company could continue producing hydrogen by its undistributed electricity supply capacity. However, scaling these grid capacity figures to 0-10 turned out to be problematic since it means that one company's supply security level depends on the maximum and minimum available grid capacity in the region.

Moreover, [92] examines the varying levels of energy security risks from the perspective of energy intensity. The energy footprint per unit of output is considered crucial in determining the energy security challenge. The lower the energy intensity of an activity, the higher the likelihood of maintaining a diversified energy supply portfolio. To this end, sectoral hydrogen dependency parameter developed for the sectors via temperature requirements is also in line with the energy intensity of sectors. Therefore, this parameter will substitute for the supply security concept required to decide on the supply mix of companies.

P5. Expression of interest

Another applied concept relates to the expression of interest (EoI) observed in the planning of the hydrogen backbone. The hydrogen infrastructure rollout plan in the Netherlands prioritizes the five industrial clusters, followed by regions located near the backbone, and finally the remaining parts of the country. Potential users of the hydrogen infrastructure can indicate their interest through the EoI process. Gasunie initiated a regional EoI process at the beginning of 2021, initially targeting the clusters where the demand for hydrogen and related services appears to be most pressing [93].

This phased approach in hydrogen infrastructure development and the gradual start of the EoI process for different regions increases uncertainty, especially for the consumers this study concerns. Companies are uncertain when discussions, planning, and the collection of expressions of interest will begin for their region. For several years, there may be no consideration to connect their region to the national transmission line due to technical, political, economic, or social issues. On the contrary, a more accelerated timeline could also be possible. Therefore, this uncertainty in the real process is reflected by varying the time companies start including a ”buying” portion in their investment plans.

As previously explained, after companies determine the volume they are willing to convert to hydrogen, they determine the mix of its supply. This step is available to companies only if the EoI collection is activated in the related time step. The activation of EoI collection is designed to occur randomly within the first ten years of the simulation, in parallel with the infrastructure plans.

4.3.2. Feasibility check

The relationships between concepts in feasibility check phase are shown in Figure 4.4. After determining the electrolyzer capacity based on the transition plan in the previous phase, technical feasibility of the project, eligibility for subsidy and economic feasibility is checked, respectively.

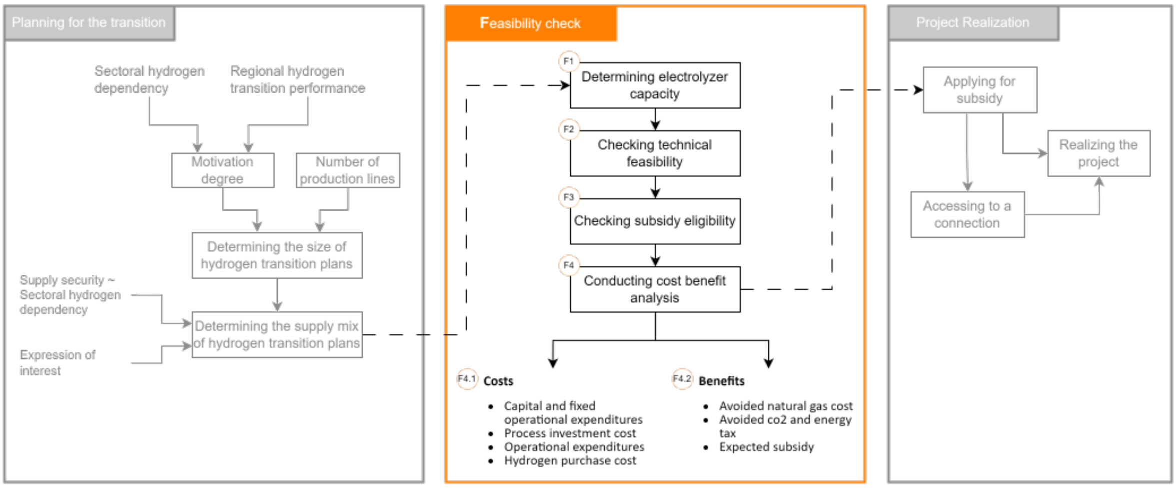


Figure 4.4: Concepts used in project feasibility check

F1. Determining electrolyzer capacity

Another step in planning for hydrogen production is determining the size of the electrolyzer capacity. Generally, the supply of electricity and the demand profile for hydrogen are the main determinants in the sizing decision of the electrolyzer. Numerous studies focus on finding the optimal electrolyzer size under different objectives and conditions. For instance, in [94], the capacity of the power-to-hydrogen system is determined using various power sources to achieve the most cost-effective hydrogen generation that meets the refueling schedule of waste transportation vehicles. In regions with renewable surplus production, [95] investigated how electrolysis systems should be sized according to the power grid capacity and the regional demand for electricity. The main objective of this study is the efficient and cost-effective utilization of renewable surpluses.

As observed in the literature, the dimensioning the electrolyzer depends on various factors such as power supply characteristics, grid capacity, installed solar capacity, the price for each power source, availability of storage, demand profile of business operations, trading opportunities, internal company dynamics, and more. Since finding the optimal electrolyzer size under these complex constraints is beyond the primary objective of this study, the calculation of the electrolyzer capacity is based solely on the demand factor of the companies. It is assumed that companies will be supplied with a consistent amount of produced hydrogen during their 8-hour working shifts on weekdays throughout the year. Consequently, the envisioned electrolyzer in the simulated system operates to provide a uniform output during every working hour of the year. This methodology could result in more conservative capacities, meaning larger capacities, as companies might prefer to run their electrolyzers during periods of renewable surplus, which may not necessarily align with the factory's working hours. This limitation of the methodology will be considered when interpreting the study's results.

F2. Checking technical feasibility (Power capacity)

This section of the conceptual model addresses the technical aspect of the formulated problem in the study. The power source is always a critical component of hydrogen investment projects. As noted in [94], [95], and [96], power grid capacity is a key factor to consider when integrating an electrolyzer into the current energy system. In certain cases, it acts as a limiting factor on the electrolyzer dimensions or decreases the utilization rate of the electrolyzers. While an installed capacity might operate adequately and fully during periods of renewable surplus, times without sun and wind leave the power grid as the only option. In such cases, the electrolyzer's effective capacity is determined by what the grid can supply. When electrolyzers become an essential part of the energy supply, sufficient capacity for power supply needs to be allocated among available options. There could be scenarios where the installed renewable power capacity already ensures the necessary power, or a certain degree of grid supply might be required.

Regarding the source of power, the SDE++ subsidy scheme imposes limitations on the maximum number of hours that the grid can be used to generate hydrogen annually, if the subsidy is applied to the electrolyzer. The primary motive is to sustain green hydrogen production without relying on polluting energy sources. For grid-connected electrolyzers, the allowed production hours are 2,190 for 2024, gradually increasing to 5,460 hours by 2029 [21]. Within the context of the simulation model, due to the assumption that electrolyzer operation is limited to working hours, the production hours always remain within the subsidy limits.

When examining regional standalone project initiatives, the GROHW project in the Overijssel region was initially planned to start with a 5 MW electrolyzer and gradually increase its hydrogen production capacity to 30 MW to meet the needs of the local industry and part of the mobility sector. However, due to severe grid congestion, obtaining an electric connection is not feasible. Consequently, it is likely that a 2.5 MW electrolyzer will be employed during the initial phase. The Hessenpoort initiative was partly driven by the significant congestion of the electric grid in the region. In fact, the grid station in the area was the first in the province to stop accepting renewable electricity feed-in. Additionally, the region is uniquely positioned to increase its renewable production due to the abundance of available space for renewable development, but this expansion is constrained by the available infrastructure capacity. The coalition involved in the Hessenpoort initiative is collaborating closely with Enexis to test collective contracts for grid capacity. This collaboration aims to enable more intelligent utilization of the limited grid capacity available. The objective of these collective agreements is to facilitate the collective utilization of grid capacity in a more efficient manner than is currently possible individually. This also allows certain companies which are prohibited from supplying their excess solar energy to the grid, to have access to a direct consumer. The collective utilization of the grid capacity provides additional space as long as participants adhere to the collective peak capacity agreed upon in the contract with the system operator [27].

One of the collective contracts is named "group ATO," which serves as a secondary capacity contract in addition to what consumers currently have. The peak electricity consumption of group members is aggregated, and the total peak is set as the group's new maximum contracted capacity. Under the condition of always staying within this new limit, companies can scale up their operations and internally coordinate and balance their peaks. Cable pooling on the other hand is sharing a large connection on the network among different customers in the same region, optimizing the use of the connection. For example, to benefit from the non-overlapping production of solar and wind energy, these two installations are combined into one connection. Although this concept is quite new and currently only applied to combining sustainable generation, the methodology offers significant potential for using existing connections more efficiently.

In light of the available collective contract options for the power grid connection, the sharing of power capacities is included in the model. The installed rooftop solar capacity of a company in the region, after accounting for the monthly solar capacity factor, can be used to integrate a collective electrolyzer in the region. In certain cases, companies do not fully utilize their contracted grid capacity, leaving some unused transportation capacity. Another source of slack capacity comes from the difference between physical capacity and contracted capacity. Within the physical capacity that the infrastructure is ready to supply, customers choose to contract a certain portion according to their demand and future growth plans. If there is a difference between the two capacities, it can also be used for an electrolyzer connection. In the simulation model, all the sources of individual companies that could offer room for power capacity are assumed to be pooled and offered for the use of a collective investment.

Another source of power considered in the model is regional renewable energy plants, such as solar farms. Preferably, power plants that experience curtailment due to feed-in congestion are included in the simulation. However, no concrete example could be found for this situation under Stedin's jurisdiction. Instead, newly planned solar farm investments are taken into consideration. Although such projects typically sell their production capacities through power purchasing agreements (PPA) before realizing the projects, they are considered more suitable to be included as currently available capacities for supplying electrolyzers in the region. These approved renewable power generation capacities are accessed through SDE++ subsidy results sent to the grid operators to plan their connections in the coming period. It should be noted that only SDE++ approved project capacities are included in the study, although other planned investments outside the scope of SDE may exist.

The level of detail in the modeling considers the average historical monthly capacity factors while integrating offered capacities from rooftop solar generation and regional solar farms. Although hourly capacity factors are available, for simplicity, monthly average figures are calculated as shown in Table 4.3 from [97]'s database. Therefore, monthly varying average capacity factors are applied to the available solar generation capacity (kWp) in the region to determine if it will be sufficient to keep the electrolyzer operational during shift hours throughout the year. For example, if 1000 kWp of solar capacity can be allocated for a collective electrolyzer investment, the lowest availability factor in December becomes the bottleneck, reducing the actual power capacity contribution to an average of 80 kW.

Table 4.3: Average monthly solar capacity factors, calculated from

	January	February	March	April	May	June	July	August	September	October	November	December
Average solar capacity factor	9.0%	16.0%	26.0%	37.0%	40.0%	41.0%	40.0%	37.0%	30.0%	20.0%	11.0%	8.0%

In the conceptualized model, to supply part of the the constant power demand of the planned electrolyzer, the adequacy of the sum of installed rooftop solar capacities is checked first. If this initial source is not sufficient, it is supplemented with the capacity offered from a regional renewable power plant. As the final option, the sufficiency of pooled grid capacities is assessed to integrate the electrolyzer into the system. This methodology allows companies in the simulation to utilize idle and individually redundant capacities within the context of a collective investment, reflecting the emerging real-world applications.

F3. Checking subsidy eligibility

This part of the conceptual model represents the institutional lever of the formulated problem in the study. According to the review of standalone projects in the Netherlands [27], these projects are entirely dependent on obtaining subsidies and are not anticipated to be financially viable without them.

Subsidies in general can be designed to support either the investment or operational aspects of projects. There are often minimum and maximum amounts that can be requested per unit (kW or CO2), along with a minimum electrolyzer capacity. Available subsidies are structured to cover the unprofitable component of the project. The amount of money received at the end of the year is calculated based on the average price of hydrogen. For example, if a company is granted a subsidy of 6 €/kg of hydrogen and the average market price of hydrogen is 4 €/kg in the same year, the applicant receives 2 €/kg. If the market price turns out to be 9 €/kg, it means the project is not "unprofitable," and no money is received from the subsidy. Subsidies are generally granted for 7 to 15 years, and only one application is accepted per location. Additionally, combining different subsidies for the same project is not allowed [20], [21]. There are two types of subsidy schemes that offer support for hydrogen electrolyzer investments.

OWE is a relatively new subsidy scheme introduced to primarily support companies with fewer than 250 employees, annual revenue of less than €50 million, and electrolyzer projects with capacities under

50 MW. As the capacity of the electrolyzer and the size of the company increase, the offered subsidy percentages decrease. Unlike common practice, applicants can also include investment expenditures in their subsidy requests. Applicants choose the portion of the total investment and operation cost they want to be subsidized. This amount is divided by the electrolyzer capacity to determine the applicant's subsidy ranking (€/kW). Although the ranking is calculated by € per kW of installed electrolyzer capacity, the money is received per kilogram of hydrogen equivalent, and it must be between €1.76 and €9.00/kg of hydrogen [20].

Although it is one of the important and suitable subsidy schemes for small-scale companies, its characteristics significantly increase the complexity of the modeling process. In the simulation model, companies will determine the subsidy amount to request based on their willingness to transition to hydrogen. In the case of the OWE subsidy, decisions on the levels of subsidy requests for both the investment and operation parts need to be made separately, complicating the reflection of companies' willingness in their final subsidy ranking decision. In reality, applicants could position themselves better and more easily within this two-sided subsidy scheme. However, within the conceptualization assumptions of this simulation context, it does not add significant value to the research.

The SDE++ subsidy scheme, on the other hand, only covers the operational period of the project. It offers subsidies for a wide spectrum of projects, including renewable electricity, gas, heat, low-carbon heat, and low-carbon production. Electrolyzer projects fall under the low-carbon production category and include two types: grid-connected and direct connection to a renewable power plant. Applications are only eligible for the SDE++ subsidy if the hydrogen production capacity exceeds 500 kW. Conditions regarding the electricity consumption of the projects are detailed in a previous subsection. The minimum and maximum prices to be asked per kWh of hydrogen in this subsidy are 0.0634 €/kWh and 0.1550 €/kWh, respectively. One important feature of SDE++ is that it allows applications to realize and operate one production installation with several parties. The partnership is intended to continue throughout the duration of the grant, and all partners are expected to remain involved [21].

The functioning of the SDE++ subsidy scheme offers a more straightforward and convenient context to reflect agents' willingness to realize their projects. A single price is asked and received from the subsidy, and the ranking is also done using the same units as the asking price. Additionally, the partnership clause of the scheme facilitates collective investment opportunities, aligning with the research's intention to explore this potential. SDE++ also captures the general characteristics of subsidy scheme design in the Netherlands, making it a sufficient representation of the subsidy concept in the model.

It is important to note that the concept of the corrective amount is not included in the modeling, and it is assumed that applicants receive the full amount without any adjustment based on the realized market price of hydrogen. Given that gray hydrogen is currently considerably cheaper than the costly process of green hydrogen production, this assumption is supported by the expectation that the corrective amount will not be significant and the unprofitable gap will persist for the foreseeable future. In the medium and long term, economies of scale and the anticipated increase in renewable energy will likely contribute to maintaining this unprofitable gap.

To summarize, the most important conditions for eligibility for the subsidy application are staying within the minimum and maximum limits for the asking price, applying for an electrolyzer larger than 500 kW, and keeping production hours that use grid connection within the prescribed limits. As previously explained, the production hour condition is already satisfied by operating the electrolyzer during working hours. For the asking price limits, agents in the simulation determine their prices within the specified range, and business case calculations follow (to be be explained further later in the section). Therefore, subsidy feasibility in the simulation model primarily depends on meeting the minimum capacity requirement.

Depending on their willingness to transition, decision on supply mix, and most importantly, the volume of their heat demand, an electrolyzer capacity is determined. However, consistent with arguments from companies in the Cluster 6, there is significant potential for the planned electrolyzer to be smaller than 500 kW, considering the gradual transition and gas consumption size of the companies. Table 4.2 in Appendix B exemplifies the possible electrolyzer capacities from the case study chosen for the simulation. Individual and collective electrolyzers that fit within the power constraints are then evaluated to ensure their capacities meet the eligibility criteria for the subsidy application.

F4. Conducting cost-benefit analysis

For industries, the financial justification for engaging in a project is crucial. The economic feasibility of investments is often assessed through cost-benefit analysis (CBA) [41]. CBA is a reputable method in the field of project analysis due to its extensive application and analytical capabilities, rooted in a sub-field of economics known as welfare economics. It is typically employed to address questions such as "Which projects should be constructed?" and has captivated the interest of economic analysts, theorists, and decision-makers. Welfare changes associated with the project are compared to the conditions that would exist in the absence of the project. In other words, all welfare impacts are determined by comparing conditions with the project to those without the project. This method is used to calculate both cost and benefit measures. Certain projects necessitate lengthy timelines, during which the timing of benefits does not correspond with the timing of costs. This characteristic can obstruct economic assessments, resulting in an apples-and-oranges problem. The value of a unit today and a unit in a future period is not indifferent to project owners. Therefore, it is common to conduct all cost and benefit assessments in current currency. Consequently, a net present value (NPV) for a proposed project can be determined by employing a selected discount rate. The project is deemed advantageous if the net present value exceeds zero [98]. To scale it to percentages, the NPV of the project can be divided by the cost of investment, and the resulting ratio gives the return on investment for the project, as shown in Equation 4.1. This ratio represents the share of the project cost that is covered by the net return from the project.

$$\begin{aligned}\text{ROI} &= \left(\frac{\text{Current Value of Investment} - \text{Cost of Investment}}{\text{Cost of Investment}}\right) \times 100 \\ &= \left(\frac{\text{Net Profit}}{\text{Cost of Investment}}\right) \times 100\end{aligned} \tag{4.1}$$

In addition to the resulting ROI value of a project, the expected rate of return of the project owners plays an essential role for the potential members of a community energy system [43], [99]. Therefore, the concept of the expected rate of return is used in the modeling practice, assigned to each company and used as a benchmark for whether or not to agree with the business case of the project plan. While studies and surveys to understand the motives behind participating in a collective investment are conducted at the individual consumer or household level [100, 48], the same depth of analysis is lacking for companies and businesses. Due to limited access to the real expectations of industries from such electrolyzer project investments, the magnitude of the expected ROI is linked to the company sector's dependency on hydrogen. Sectoral hydrogen dependency is a characteristic of the sectors that also applies to the companies operating within them, as previously explained in the section. The concept of expected ROI is anticipated to play a critical role in the simulation. To determine a suitable range for this parameter and investigate its effect on the model output, a sensitivity analysis will be conducted.

Despite its widespread use, it is important to acknowledge that net present value (NPV) is an incomplete metric. The reasonable disclosure of unmonetized project impacts should accompany any economic measure that is computed and reported during the decision-making process [98].

F4.1. Costs in cost-benefit analysis

Within the scope of the project, the cost items included in the cost-benefit analysis are capital expenditures and fixed operational expenditures for the electrolyzer, the cost of electricity during operation, the cost of purchasing hydrogen from the market, and process investments for hydrogen-ready equipment in production floors. All these cost items are calculated over a 15-year project lifetime, and the NPV is calculated using a predetermined discount rate.

F4.1.1 Capital and fixed operational expenditures of electrolyzer

The investment cost of expensive projects such as electrolyzers is one of the significant barriers to realizing these projects. This issue is particularly pronounced for small-sized Cluster 6 companies, who believe that collective investment could provide substantial benefits. The term "economies of scale" is defined as the reduction in the unit cost of a technology by moving from small units to larger batches, resulting from decreasing fixed unit costs, increasing technological learning, and other factors. [101] provides a detailed analysis of power-to-gas systems, referring to economies of scale as the cost reduction achieved through upscaling, which involves an increase in size, scale, and capacity.

The scale factor method is a commonly used approach to reflect logarithmic relationships (Equation 4.2), where C_b represents the equipment cost being questioned at the capacity S_b, and C_a and S_a are the reference costs and capacities whose values are already known. The factor f is the scale factor, which depends on the technology. According to the "six-tenths rule," the scale factor can be taken as 0.6 in the absence of specific data [102].

$$C_b = C_a \times \left(\frac{S_b}{S_a}\right)^f \tag{4.2}$$

Electrolyzer systems are composed of a variety of individual components, leading to different sets of scaling effects and influences on the overall system costs. The investigated systems are divided into distinct modules and components to employ a modular approach by [101]. Based on several cost data available in the literature, [101] identifies approximate scale factors for proton exchange membrane electrolysis cell (PEMEC) electrolyzers to be 0.72 for capacities of less than 5 MW and 0.82 for capacities greater than 5 MW. The higher scale factor indicates that the marginal benefit of upscaling on cost decreases as the electrolyzer size increases. Reference specific investment cost estimations for a 5 MW electrolyzer are used as a basis for the electrolyzer capex calculations:

Table 4.4: Reference specific unit investment costs and share of fixed cost over the years, adapted from [101]

Year of installation	**Specific investment cost (€/kwe)**	**Fixed operational cost (%of Capex)**
2020	970	2.05
2030	530	2.1
2040	340	2.1
2050	290	2.1

Capex is assumed to be paid in equal installments over the three-year construction period, followed by annual fixed operation costs calculated as a percentage of Capex during the operation period.

F4.1.2. Process investment costs

A second investment item required for the hydrogen transition is the conversion of current industrial natural gas heating technologies to run on hydrogen. There are various technical requirements and challenges related to cost, time frame, and the maturity of the technologies for each sector's equipment. The core equipment used in industry to generate thermal energy is categorized in [103] as high-heat direct-fired kilns and furnaces, steam-raising boilers, hot water boilers, and low-temperature processes for toasting, baking, grilling, roasting, and drying. The study reveals valuable proxies for the unit thermal capacity of hydrogen-burning heat equipment per sector:

It should be noted that in the simulation, hydrogen-burning industrial equipment is assumed to be ready for use in each sector. However, technologies may demonstrate different levels of development timelines before becoming available for industrial use. Nevertheless, [103]'s projections for all sectors anticipate the start of demonstrations for the majority of hydrogen-ready equipment by 2025, which is already taken as the starting year of the simulation. Another assumption is that the process investment cost is only incurred for hydrogen transition plans that involve converting more than 20% of natural gas consumption to hydrogen. The majority of existing natural gas-burning equipment is already compatible with up to a 20% hydrogen mixture, and blending does not incur major costs. Additionally, the economies of scale effect on hydrogen equipment is disregarded due to a lack of information on its impact.

F4.1.3. Operational expenditures

Table 4.5: Unit investment cost of hydrogen equipment per sector

Sector	**Equipment type**	**Estimated load factor**	**Unit equipment cost (€/kw)**	**Source**
Metal	Furnace	0.45	393	[90]
Glass	Glass furnace	0.75	649	
Food	Steam boiler	0.5	1259	
Ceramic	Kiln	0.4	1416	
Cement	Lime kiln	0.75	944	
Chemical	Furnace	0.7	1259	
Paper	Steam boiler	0.6	1259	
Textile	Steam boiler	0.6	1259	
Wood	Steam boiler	0.6	1259	
Agriculture	CHP	0.5	700	[89]

Among various operational expenditures, electricity cost stands out as the most significant cost item by far. In its recent analysis, [104] demonstrates that the cost of electricity accounts for 77.6% of the levelized cost calculation for electrolysis. The second largest item is the investment cost, with a 15.4% share. Other operational expenditures, including the cost of water, correspond to 4% of the total hydrogen cost per kilogram. Therefore, in the modeling, the main effort is dedicated to accurately reflecting electricity costs in the simulation due to their significant impact on the overall cost calculations.

The electricity cost of an electrolyzer, in its simplest form, is calculated by multiplying electricity consumption (kWh) by the corresponding electricity price (€/kWh). By changing electricity consumption behavior during the day or year, and making bilateral agreements such as PPA contracts for electricity purchase, consumers can optimize their electricity consumption in real-world practices.

In the conceptualized model, the electrolyzer is assumed to run every hour of the day at full capacity. According to the availability of power sources throughout the year, the electrolyzer consumes electricity from each source, prioritizing renewable generation. Consumption from solar generation takes into account the capacity factor, which varies throughout the year. Therefore, electricity consumption largely depends on the grid in winter months and on solar generation in summer months. Price estimations for solar generation are linked to the average annual PPA price development in the Netherlands, while wholesale market price projections are used for electricity supplied from the grid. To summarize, in the conceptualized model, the electrolyzer consumes the same amount of electricity every working hour of the year. However, depending on the average monthly availability, the supply mix of electricity changes throughout the year. Another assumption is that electricity prices are considered constant throughout the year, although in reality, they fluctuate depending on market conditions, weather conditions, and the balance of supply and demand.

It is important to note that publicly available PPA and wholesale market electricity prices and forecasts are the results of bilateral agreements and market outcomes. However, they constitute only a small portion of the actual amount paid by consumers. In addition to the market price, network costs, taxes, fees, levies, value-added tax, renewable, environmental, and capacity taxes are included, depending on the country. To better reflect the cost of electricity use to a consumer, a detailed analysis was conducted to reveal the average share of these additional costs in the final price. According to [105]'s yearly published electricity price component breakdown for the Netherlands, the average for the last three years shows that the wholesale price corresponds to 38% of the total price. Therefore, publicly available price forecasts are adjusted with the addition of network and tax components to better represent the real costs in the conceptualized model.

Price forecasts used in the model for wholesale electricity and solar/PPA electricity can be found in Table C.1 in Appendix C.

F4.1.4. Hydrogen purchase cost

In the modeling practice, the option to purchase hydrogen in addition to standalone production is also made available in the transition plans for companies. Within the scope of the study, hydrogen purchase is carried out via pipeline when the infrastructure becomes available for the region. When it is part of the supply mix of the transition plan, the purchase cost is calculated for the entire investment time horizon. Publicly available hydrogen price scenarios are utilized for future years. Price forecasts used in the model for hydrogen market prices can be found in Table C.1 in Appendix C.

F4.2. Benefits in cost-benefit analysis

For the benefit side of the CBA, four types of financial benefits are considered as a result of the planned investment.

F4.2.1. Avoided natural gas cost

Investment in the hydrogen transition entails substituting a certain amount of natural gas consumption with an energy-equivalent amount of hydrogen. Therefore, the benefit arises from not purchasing the substituted amount of natural gas. Although natural gas consumption decreases to a certain degree, subscription fees for the capacity remain the same for the natural gas connections. The only benefit considered is the avoided cost due to purchasing less natural gas. This benefit is calculated over the investment period, with the annual avoided natural gas consumption multiplied by the corresponding year's price.

Similar to the structure of electricity pricing, natural gas pricing includes market price along with network and tax costs. A detailed analysis of the components that make up the natural gas price for consumers shows that, on average, network and taxes constitute 75% of the final price [106], which is larger than the share for electricity. Therefore, this effect is taken into consideration when setting up the price formation using publicly available gas market price projections. Price forecasts used in the model for gas purchase price can be found in Table C.1 in Appendix C.

F4.2.2. Avoided CO2 and energy tax

There are two energy taxes in the Netherlands: the energy tax and the sustainable energy supplement (ODE). Energy companies collect the energy tax and ODE for each kilowatt hour of electricity and cubic meter of natural gas consumed, and they transfer the revenues to the government. Certain exemptions or tax refunds exist for sectors such as agriculture, metallurgical, and mineralogical processes. However, announcements indicate that starting from 2025, these exemptions will be removed [107]. Currently, greenhouse businesses are required to pay a levy determined by the average emissions of the greenhouse sector. With the new decision, the amount will depend on each company's emissions, and the lowered energy tax rate for the sector will gradually reach the same level as other industries by 2030 [108]. 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 modeling.

The CO2 tax applied to industry emissions is an important instrument in the Netherlands to reach the industry's emission reduction target of 4 tons. In its recent proposal to the cabinet, the government takes confident steps to further increase the CO2 tax rate on the industry [109]. Price projections from the proposal are also integrated into the modeling process. From January 1, 2025, the greenhouse horticulture sector will implement a carbon levy on CO2 emissions, which will be comparable to the current industry system [110].

In light of the developments and the government's stance on enforcing the CO2 tax, the same level of CO2 tax is applied to all sectors included in the simulation. Annual CO2 emissions that will be avoided with the hydrogen investment plan are calculated over the investment period, and multiplying this by the corresponding year's CO2 tax contributes as a benefit in the cost-benefit analysis. Price forecasts used in the model for CO2 tax can be found in Table C.1 in Appendix C.

F4.2.3. Expected subsidy

As previously mentioned, there is ample evidence from participants of standalone initiatives that subsidies are vital for realizing their projects. Therefore, the first assumption made in the simulation model is that every investment plan includes a subsidy application. Given its critical role in shaping the business case, it is sensible to expect companies to include the expected cash flow from a subsidy when evaluating the feasibility of an investment plan. This consideration is reflected in the "expected subsidy" concept. As shown in Equation 4.3, the expected subsidy to be received in a year is calculated by multiplying the amount of money to be received for the total produced hydrogen by its probability of occurrence.

$$\text{Expected subsidy cash flow (€)} = \text{Hydrogen production (kWh)} \times \text{Subsidy asking price} \left(\frac{€}{\text{kWh}}\right) \times \text{Probability to receive the subsidy} \tag{4.3}$$

The real decision process for determining the price to ask from a subsidy can vary greatly and depend on many factors. These include the company's willingness to realize the project, company culture, the vision of the management team, market conditions, competitiveness of the subsidy, government policies, and technological developments, among others. One way to calculate this price could be to find a breakeven price that is believed to make the investment feasible. This price might not fall within the allowed range of asking prices, leading companies to decide not to apply for the subsidy at all. However, as seen in the recent Hydrogen Bank subsidy auction case, winning prices were far from making the investments economically feasible and were completely unrelated to current market conditions [111]. This indicates that the decision on how much to ask from a subsidy does not solely depend on creating a business case but also on other factors such as motivation to transition, being an initiator of new technology, and securing a strategic position before the technology scales up.

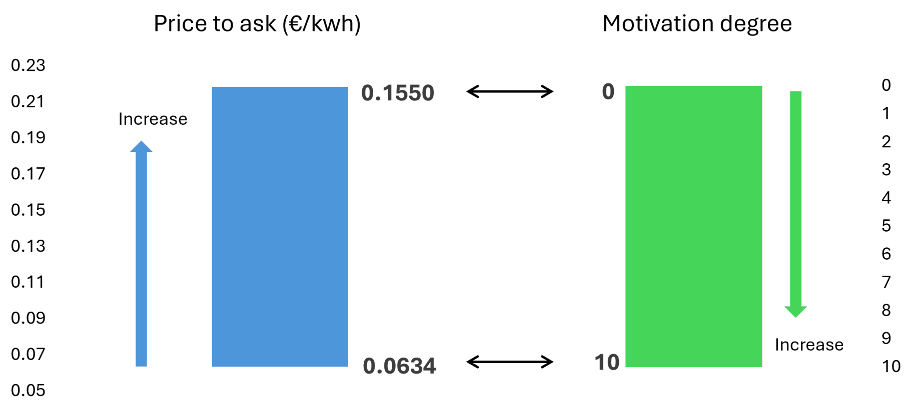


Figure 4.5: Corresponding asking price for the motivation degree values

Therefore, in the modeling practice, it is ensured that companies will determine a price that is always within the allowed range and based on their motivation or willingness to transition to hydrogen. The motivation degree concept developed for the study is directly used to determine the price. The reasoning behind this methodology is that highly motivated applicants do not depend on receiving high subsidies and are willing to realize the project with lesser amounts. By doing so, they aim to increase their chances of being granted the subsidy. As the components of the motivation degree value suggest, a company's sectoral dependency on hydrogen could lead to such inevitable behavior, and a regional movement towards hydrogen could incentivize a positive attitude among companies to secure a winning application for the subsidy.

Based on this reasoning, an agent with the highest motivation degree (10) is expected to apply with the lowest price that can be asked and vice versa (see Figure 4.5). For values in between, linear proportionality is used to determine the corresponding asking prices.

4.3.3. Project realization

The relationships between concepts in project realization phase are shown in Figure 4.6. When projects prove to be feasible in the previous stage, companies apply for the subsidy and depending on receiving the access to national transmission line, projects are realized.

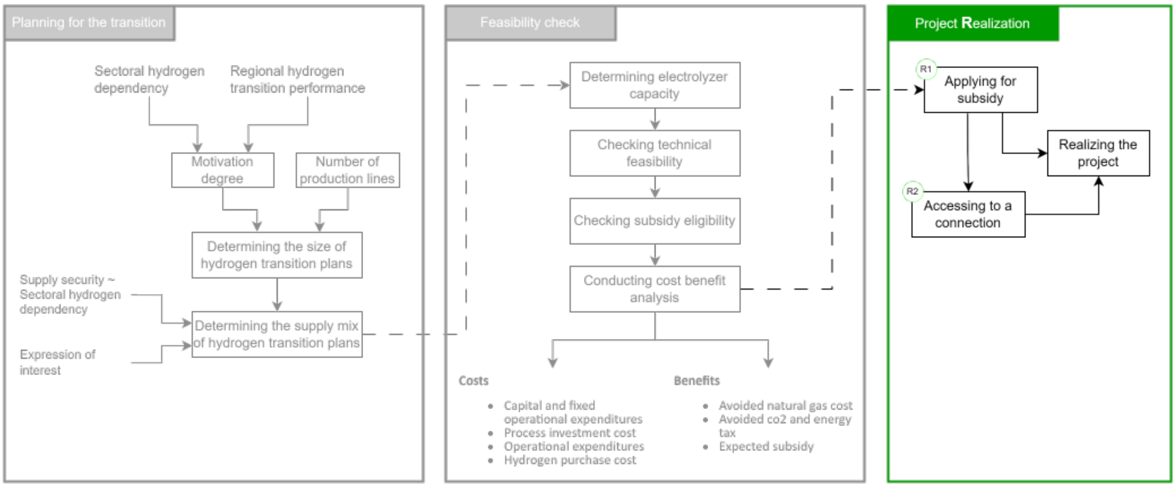


Figure 4.6: Concepts used in project realization

R1. Applying for subsidy

Application rounds for the SDE++ subsidy occur in the autumn of each year, with a total budget of €8 billion allocated for all categories [21]. When applications satisfy all conditions, companies can submit their requests. The subsidy scheme functions as an auction, where applicants' subsidy requests per kW or per avoided CO2 are ranked from the lowest to the highest. Starting from the lowest (meaning the minimum money asked per avoided CO2 emission), applications are accepted until the subsidy budget is exhausted.

Real-life conditions can significantly influence the results of the subsidy auction. Factors such as the total number of applications, the price competitiveness of the requests, and the allocation of the subsidy budget across categories introduce uncertainties that increase the complexity of the real life auction process. For example, in a recent Hydrogen Bank auction, €720 million was provided to seven hydrogen projects. A total of 132 bids were submitted within the price range of €0.37 - €0.48 per kilogram of hydrogen. Due to fierce competition, winning bids were between €0.37/kg and €0.48/kg, which are neither representative of real market conditions nor expected when considering the allowed price range [111].

In the modeling practice, this auction mechanism is simplified to focus on where the requested price falls within the minimum and maximum range. The effect of one company's application on others' winning probabilities is ignored due to the complexity and scope of the research. Instead, each application is assessed according to its position within the allowed asking price range. As shown in Figure 4.7, the maximum price limit is associated with a receiving probability of 0.1, while the minimum price is associated with a receiving probability of 0.9. Subsidy requests that fall in between are assigned probabilities with linear proportionality. This methodology aims to reflect the competitiveness of the requests into the winning probability, which is a significant part of the real practice. However, it disregards the possible effects of the mentioned noise factors.

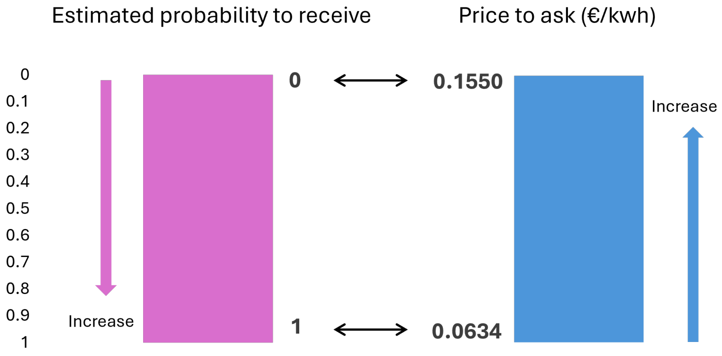


Figure 4.7: Corresponding estimated probability for the subsidy asking price

Permitting processes

Obtaining permits is crucial for applying new technologies and independently generating energy. Companies often face long waiting periods before they can generate energy independently or test innovative technologies. This issue is frequently cited by Cluster 6 companies as a significant barrier, leading to postponements and even cancellations of attempts. The stalling effect on projects, combined with the complexity and uncertainty of the permitting process, hinders companies' initiatives for innovative projects such as hydrogen generation. Maintaining a close relationship with local governments and responsible authorities is considered necessary and can accelerate the permitting process [30].

The role of local government in obtaining permits is also frequently recognized by ongoing standalone project initiatives as essential for navigating economic, legislative, and societal barriers [27]. For instance, in the GROHW project, the local government decided to support the project after realizing its societal and economic benefits for the community. Consequently, participants have high expectations for a smooth permitting process. Standalone hydrogen initiatives require ongoing, long-term support from a diverse array of stakeholders to overcome continual obstacles. To increase support and maintain stakeholder engagement, the project must be communicated in a manner that highlights its broader societal benefits.

For example, in the Agriport A7 project, the initiators and off-takers are data centers in the region aiming to decarbonize their energy-intensive operations and improve their public image. However, it is expected that the local government may be hesitant to support the initiative if it solely benefits the data centers rather than the broader community. The project's success is believed to depend on the utilization of excess energy to benefit the greenhouse economy, primarily by promoting the perception that the project will benefit the wider community, not just the data centers [27].

In light of insights from cluster strategy reports [30] and considerations of standalone initiatives [27], the number of companies participating in the project and the diversity of sectors involved are observed to be critical for developing strong relationships with local governments by spreading benefits to larger and more diverse parts of society. Therefore, while individual projects face the highest probability of delays due to their minimal societal benefit (involving only one company and sector), a formation where all companies join and maximum sectoral diversity is achieved would encounter the least barriers in terms of permitting and delays.

It is important to note that, in the real process, permits for location, environmental impact analysis, and other requirements must be ready for the subsidy application. This process does not continue in parallel with the construction phase. While the considerations regarding the permitting process have been discussed, they are left out of the study's scope since their validation in the model may not be feasible. However, the possible effects of permitting processes on the results will be discussed when interpreting the findings.

R2. Accessing to a connection

It is explained that a connection to continuous supply of hydrogen with a pipeline connection is inevitable for companies to complete their full transition. The underlying idea with this concept is that the hydrogen generation level in the region should reach a certain level before a pipeline connection is worthwhile for users for their full transition or security of supply. This is mainly a representation of the region's motivation to be an active part of the hydrogen transition and connected network.

Several studies [39, 39, 31] have been conducted to analyse the break-even points of different transport modes with respect to varying distances and volumes. While these techno-economic analyses provide an important scientific benchmark for the siting of a pipeline, they do not match the function required by the conceptual model in this study because it does not fully incorporate the decision making of the infrastructure provider. In order to better integrate the intended concept, the gas consumption of the region, i.e. the consumption of the actors included in the model, is used as a reference point to determine a threshold capacity. Companies in the region have certain amount of heat demand, and the threshold parameter, expressed as a percentage, then determines how much of the demand must already being generated by hydrogen investments in the region in order to be eligible for a pipeline connection.

It is important to recognise that the identified threshold volume will not be a value that fully utilises the investment in the pipeline. It is anticipated that such infrastructures will not be fully utilised at least until a certain maturity in hydrogen development has been reached. Furthermore, it should be noted that in reality the connection provided will also include potential consumers other than industry, such as the built environment, mobility, etc. Consequently, the parameter value only encompasses the aggregate demand of the agents encompassed by the model and should be interpreted in light of these considerations.

In summary, the threshold is the minimum regional hydrogen production volume that must be achieved in order to be granted a pipeline connection. In the conceptual model, meeting the threshold means having access to a continuous supply of cheap hydrogen. The pace of transition after this point is designed to be much faster, with supply made available on demand. This implies that the time step at which the threshold is reached represents a pivotal point in the development of the region, and subsequent developments are of lesser significance in the context of the study. Due to its anticipated impact on model outcomes, this parameter's effect on results will be further investigated with the sensitivity analysis in Chapter 6.

4.4. Formalization

After providing a detailed description of the concepts used in the model, this section will explain the agents' decision flows, their interactions, and how these concepts are integrated into the simulation's narrative. Modeling language tends to take more mechanical steps when translating the real storyline and the agents' decision-making processes into pieces of code. In reality, however, decision-making steps are more intertwined, often occurring in parallel, and coming out naturally within their context. Conversely, the narrative in simulation code must follow a more structured, mutually exclusive, and collectively exhaustive approach to avoid any possible loopholes.

Agents' interactions with their environment and each other in the conceptual model can be divided into three parts.

4.4.1. Individual investment

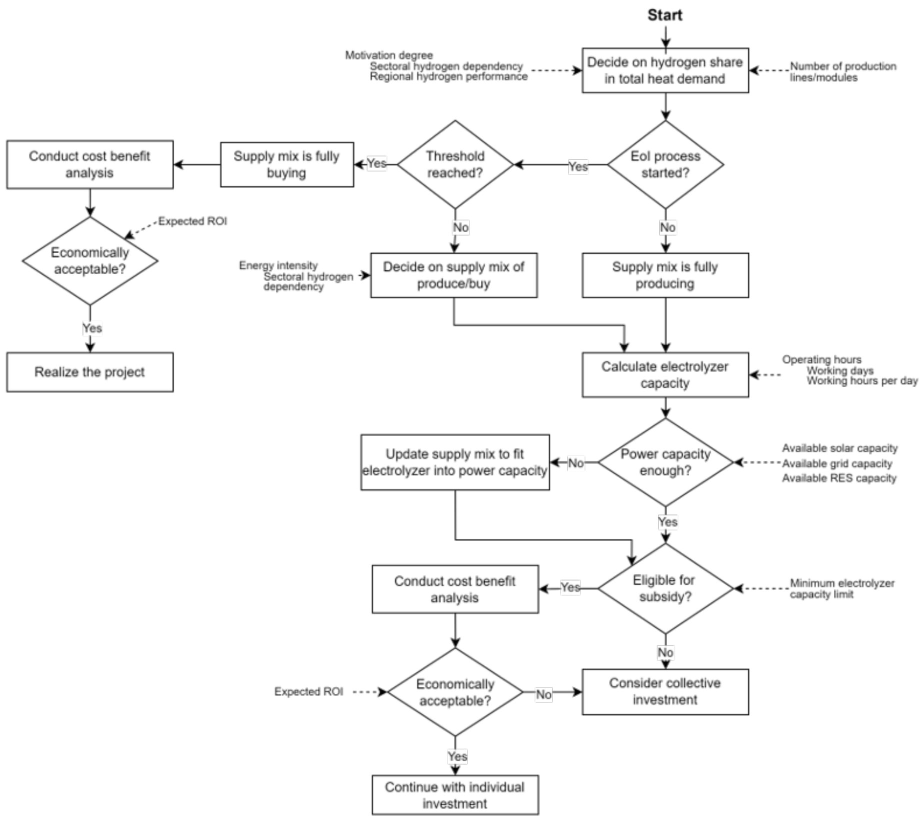


Figure 4.8: Decision flow in agents' first attempt with individual investment plans

Companies start every new year (each time tick in the simulation) by determining the volume of their hydrogen transition plan. This volume is defined in multiples of their production lines/modules and, in fact, translates to how many of their natural gas boilers/ovens will be converted to hydrogen. As discussed in the conceptualization section, a higher motivation degree means more ambitious plans, involving the conversion of more modules in one step.

If the region has already reached the threshold level and is connected to the national transmission line, companies evaluate the economic feasibility of purchasing the planned volume of hydrogen. If expressions of interest are being received from potential consumers in the region, companies incorporate these buying plans into their supply strategies based on their processes' energy intensity levels. When the region is not yet considered for a pipeline connection, all investment plans have to be made through a standalone production.

Based on the portion of production in their supply plans, agents calculate the electrolyzer capacity needed to supply sufficient hydrogen for their operations. Companies then assess whether available power sources can support such an electrolyzer for the year. If the power capacity is insufficient, they reduce the electrolyzer size to stay within grid limits. Next, they check eligibility for subsidies by comparing the intended electrolyzer capacity with the minimum requirement for subsidy applications. If the conditions for a subsidy are not met, the company considers forming a community to realize its transition plans. If the company's electrolyzer plan meets the subsidy conditions, it conducts a cost-benefit analysis to check economic feasibility. If the project is financially viable within the company's expectations, the agent proceeds with an individual investment. If the costs are unacceptable, the company becomes a candidate for collective investment.

In this initial part of the simulation, companies aim to realize their plans independently, using their own resources. Only when it is technically or economically unfeasible do they consider forming or joining a hydrogen energy community. The underlying assumption is that partnerships are a secondary choice due to transaction costs and increased dependencies, and are only pursued by companies when necessary.

4.4.2. Community formation

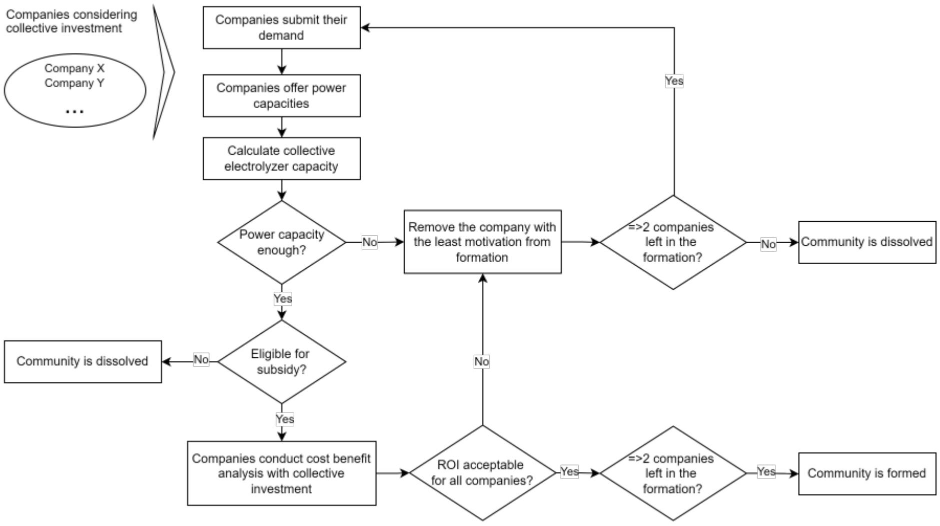


Figure 4.9: Decision flow in community formation

The steps to form a community follow a similar logic to individual attempts. Companies opting for community formation pool their investment plans and power capacities, resulting in a larger investment with greater electrolyzer capacity and shared power resources. However, if the combined power capacity is insufficient, the company with the lowest motivation degree exits the community formation process to stay within power capacity constraints. Upon the exit of any potential member, the pooling of investment plans and power capacities is repeated with the remaining candidates to continue process with the new conditions.

If eligibility for a subsidy becomes a concern, even with the presumed larger collective electrolyzer capacity, the community formation is dissolved. When the electrolyzer meets the subsidy application requirements, each company conducts a cost-benefit analysis based on the conditions provided by the collective investment. A larger electrolyzer benefits from economies of scale, and access to participants' solar generation reduces operational electricity costs, benefiting the supplier through sales. Additionally, a community subsidy asking price is determined based on the participants' average motivation degree, which is reflected in each company's cost-benefit analysis.

If all companies find the investment economically feasible compared to their own return expectations, the community successfully agrees in principle to move forward. If any company rejects the community's plan for economic reasons, the whole process is repeated after that company leaves the formation. If more than one company rejects the plan, the least motivated company exits the formation. This process continues until all remaining companies agree on the conditions of collective investment, provided there are at least two companies left in the formation.

4.4.3. Project realization

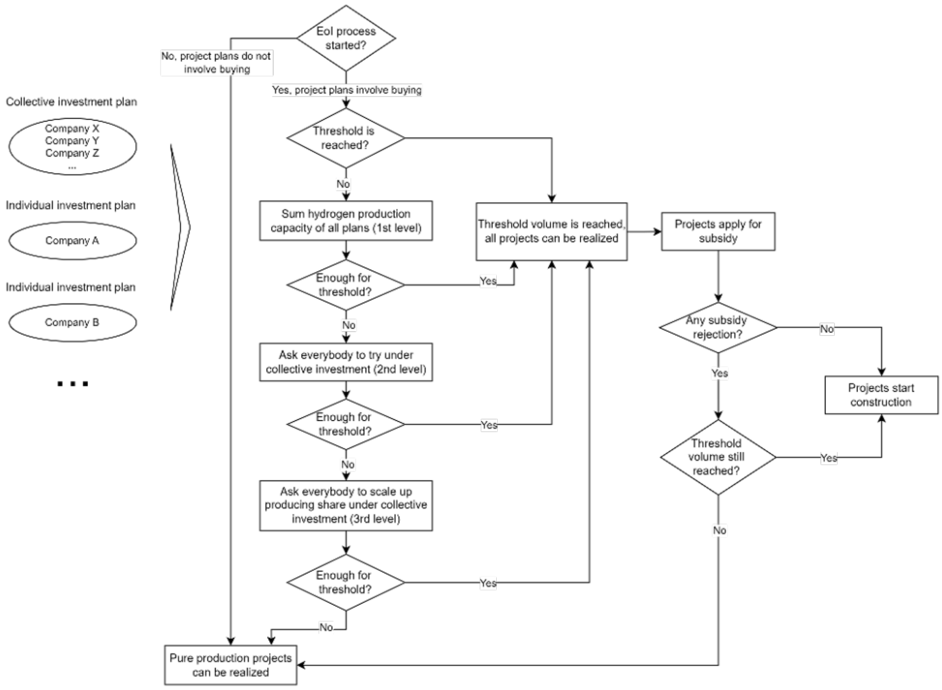


Figure 4.10: Realization of the projects

As explained previously, if the expression of interest (EoI) process has not started in the region yet, all project plans can only consist of pure standalone production and can be realized as long as they are agreed upon by the project owners. However, once companies begin incorporating a buying portion into their supply plans with the onset of the EoI process, pipeline supply becomes necessary to realize these plans. This requires an evaluation to determine if the region's potential justifies providing a pipeline connection. To assess this, the hydrogen production capacity of all investment plans agreed upon by both individuals and communities is summed. The left side of Figure 4.10 represents all projects agreed upon in principle, if any.

If the region has already accumulated sufficient production capacity through successful individual and collective investment attempts, the threshold volume may be met, allowing all projects involving pipeline supply to proceed. If the threshold volume is not reached, the current production volume in the region is summed with the planned projects (left side of Figure 4.10). This corresponds to the first trial of community formation. If the volume is still insufficient, a second trial is activated. At this point, since independently planned investments by both individual and collective attempts do not achieve enough performance, every company is included in the community formation process. By doing so, regardless of their initial plans, all companies in the region collaborate to form a community with the common aim of realizing their transition plans. This attempt potentially benefits from the larger capacity and resources of more companies and may create a more attractive environment for other companies initially excluded themselves from the plans.

If this attempt still fails to meet the required threshold volume, a third trial is initiated. Companies are asked to upgrade the portion of production in their supply mix plans. Depending on their willingness, each company adjusts its supply mix distribution in favor of increased production. This willingness is represented by the companies' energy intensity levels, the same parameter used to determine the supply mix. Proportional to their energy intensity levels, a certain part of the buying portion is transferred to the production portion. This final attempt is part of the regional community discussions, where each company, proportional to its willingness, contributes and sacrifices part of its initial plans for a common goal. If the volume is still not satisfied in this last attempt, project plans revert to pure standalone production and are realized if agreed upon.

In each of the three trials to meet the threshold through collective investment, the steps in Figure 4.9 are applied under the corresponding conditions.

It should be noted that up until the end of discussions about meeting the threshold volume, projects are in the planning phase, or in other words, in the expression of interest phase. This means there is no certainty about whether they will proceed to construction and realization. This depends on whether the projects will be granted subsidies. Therefore, if the threshold volume is reached, communities and individual companies go through the subsidy application process. In case of subsidy rejection for any project, the threshold volume sufficiency is re-evaluated with the remaining projects that received subsidies. Only after passing this final step can a decision be made to award the region with a pipeline connection, allowing project plans depending on pipeline supply to be realized.

4.4.4. Model parameters

The most important parameters specific to sectors, technologies, subsidies and cost elements are presented with tables while explaining the corresponding concepts in this section. Table 4.6 summarizes the parameters of agents. Based on the chosen case study, companies' annual natural gas consumption in m3 is converted into heat demand in kwh. Furthermore, available grid capacity in companies' connection is provided by Stedin's database. Solar rooftop capacities are approximated by converting companies' hourly feed-in volumes (kwh) into kwp by taking into account the hourly solar feed-in profiles and capacity factors. For regional RES capacity, newly approved solar capacities in the regions are summed. Number of production lines range between 2-5 and randomly assigned to companies within this range. However, range boundaries are modified per company as explained in previous sections. The expected ROI value of an agent depends on the max-ROI parameter which is the maximum allowed expected return on investment. This parameter will be subject to sensitivity analysis and the ranges are set as 0 and -1 by observing the general distribution of calculated ROIs in the model.

Table 4.6: Agent parameters used in the model

Category	Parameter/Input	Source	Current value	Unit
Demand	# of production lines	Randomized	[2, 5]	-
Demand	Heat demand	Stedin	[10k, 1000k]	m3
Investment	Expected ROI level	Sensitivity analysis	[-1, 0]	-
Power availability	Rooftop solar installed capacity	Stedin	Depends per company	kwp
Power availability	Unused grid capacity	Stedin	Depends per company	kw
Power availability	Total regional RES capacity	Stedin	Depends per region	kw

All parameter values in detail are listed in Table B.1 in Appendix B.

4.5. Software implementation

After completing the conceptualization and formalization steps, the model implementation continues with software implementation, where the narrative is translated into code. Software implementation means transferring conceptualized and formalized model into programming environment by coding. This has been implemented by using NetLogo 6.4.0 software.

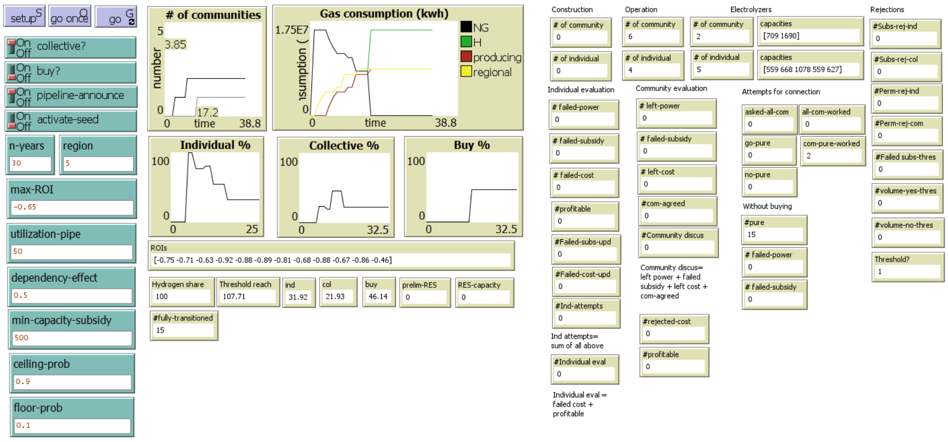


Figure 4.11: NetLogo interface

Figure 4.11 displays the NetLogo model interface. On the left side, model inputs that are subject to change and switches to apply experiments are presented. On the right side, model outputs are depicted through monitors and graphs.

The model is initialized by pressing the setup button in the lop left corner. With the setup, agents are created, their parameters are assigned with values from the input file and other model variables are initialized as described in the previous part of this chapter. The model runs in time steps, where each time step represents a period of one year. Pressing the "go once" button runs the model for one year, which ables to track the developments year by year. On the other hand, "go" button runs the model until the end year defined for the simulation with "n-years" input parameter.

4.6. Model verification

The verification step is consucted to confirm whether the software implementation is completed correctly.

4.6.1. Recording and tracking agent behaviour

Verification involves a detailed examination of individual agent behavior to ensure that the model functions as expected at the agent level [82]. To monitor the agent's behavior, prompts that appear in the interface are embedded to trigger when the agent performs specific actions. These prompts help verify that the agent is executing tasks as expected according to the conceptualized model. Initially, these checks are included in the software implementation step but are later deactivated (commented out) to save computing power.

Agent behavior tracking was implemented during the software implementation phase to verify behavior with the completed parts, debug the code, and analyze anomalies in the results. For these purposes, a total of 327 prompts were placed in various parts of the simulation code. Here are a few examples from a company agent's typical individual investment attempt:

- show "I chose the size for hydrogen"
- show "Buying percentage:"
- show "Producing percentage:"
- show "Individual electrolyzer cap is:"
- show "Grid is enough for my individual project"
- show "I can NOT apply for the individual subsidy, going with collective"
- ...

This technique has already been used to track agent behavior and check whether they enter specific sections of code. It has proven successful in identifying and debugging simple errors during software implementation and has contributed to the verification of the model.

4.6.2. Single agent testing

The step before complicating the simulation space yet with large number of agents gives opportunity to properly examine the behaviour of agents by focusing on a single agent. This step includes conducting several experiments on a single agent such as sanity checks where the agent's expected behavior is explicitly predicted when given well-defined inputs [82]. Several tests can be performed for this purpose:

- When the buying option (set buying? 1) is enabled for the region, and the threshold volume is assumed to be satisfied from the beginning (set threshold? 1), all run results show a 100% hydrogen transition for the single agent. This behavior aligns with the predicted outcomes of the conceptual model. The assumption is that, with the availability of a pipeline connection, agents will forego electrolyzer investments and instead complete their transition using the provided pipeline supply.
- The sections of the code where agents evaluate investment plans provide an opportunity for a comprehensive check on behavior and calculations. At this stage, various factors—such as planned hydrogen consumption, electrolyzer capacity, cash flows for CAPEX and OPEX, expected subsidies, process investments, avoided natural gas costs, and CO2 tax—are combined to conduct net present value calculations. The ROI value of the project is then compared with the expected ROI. At this point, outputs of almost all major concepts are accessible and open for verification.

  Extra attention is dedicated to this section with additional "show" prompts. All above-mentioned agent parameters and model parameters calculated by the single agent up to that point are also manually calculated in an Excel sheet. The results are matched to verify several included concepts, ensuring accuracy and consistency.

Another approach with the single agent testing is creating extreme conditions to push limits of the parameters and agent behaviour to ensure that errors such as division by zero does not exist or if an unexpected behaviour occurs, checking if it is the result of an implementation error or coding choice [82]. Few conducted experiments with extreme points are:

- Setting both ceiling and floor probabilities to zero does not produce any errors, but it prevents any projects from being realized due to subsidy rejections
- Setting the maximum expected ROI parameter to -2 makes all possible investment combinations profitable for the agent, while a value of +2 results in no hydrogen development in any of the runs
- Setting the "const-duration" (construction duration) parameter from its original value of 3 to 0 revealed an error due to the mismatched dimensions of arrays when combining separate cash flows from CAPEX, OPEX, subsidies, etc. NetLogo's built-in commands for summing arrays require the arrays to have the same dimensions. This section of the code was originally implemented to fit the parameter value of 3, without anticipating any changes. However, after encountering the error, this part of the code was modified to be more robust to parameter changes.
- With regards to "division by zero" errors, several complications were already faced during the software implementation step and they were mainly related to the initializing phase of the simulation (setup and 1st tick). For instance, performance measure variables are initialized with zero at the beginning of the simulation, but the code requests a percentage share calculation at each tick of the simulation. Such issues have been resolved by implementing necessary precautions.

4.6.3. Interaction testing in a minimal model

In the third step of verification, agent interactions are tested with the minimal number of agents necessary. For models with a single agent type, this test involves using two agents, while for models with multiple agent types, at least one of each type is included. The test verifies whether the basic interactions between agents occur as described in the model narrative. Specifically, it checks if agents can locate each other and interact as designed [82].

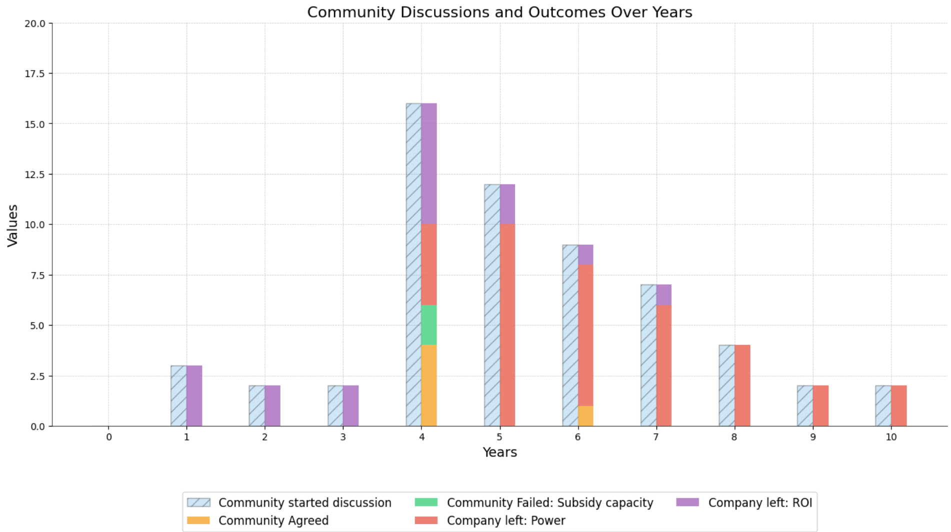
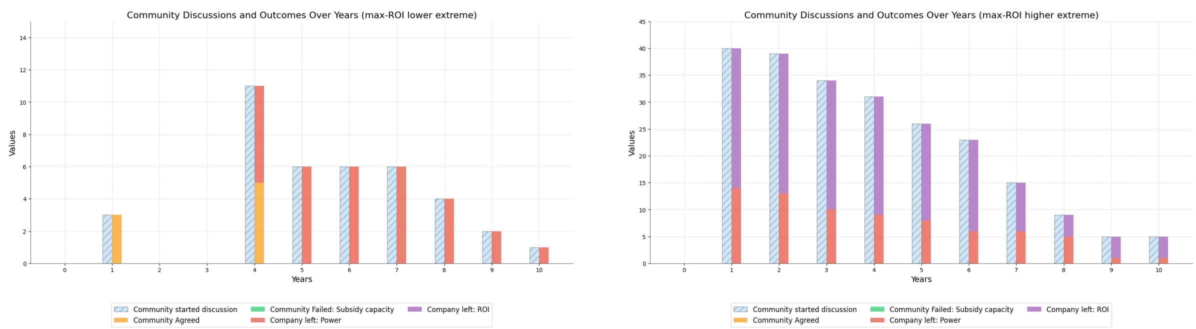


Figure 4.12: Number of times agents interacted through community discussion and results of the interactions

For this test, the variables already used for recording the results of agent interactions can be utilized. These variables were defined to track, per time step, the total number of times agents initiated discussions to form a community and to count the frequency of how it resulted. Model is run 40 times and the bars with the pattern in Figure 4.12 shows the number of times the discussion to form a community was initiated. The stacked bars next to them display the mutually exclusive and collectively exhaustive results of these discussions. It can be observed that, per year, the sum of the stacked bar consistently equals the value in the bar with pattern. This consistency proves that the two agents interact as designed, with all interactions occurring as specified in the conceptual model, ensuring that no interactions are lost.



(a) max-ROI at lower extreme(-2) **(b)** max-ROI at higher extreme(+2)

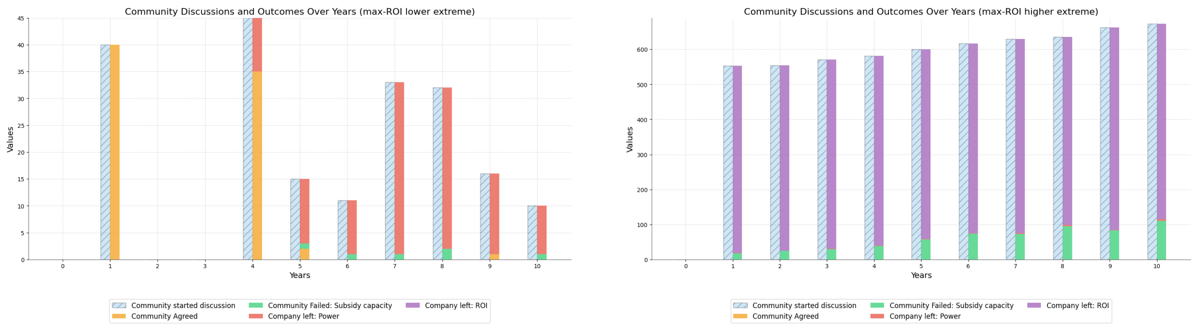
Figure 4.13: Number of times agents interacted through community discussion and results of the interactions

The same sanity and extreme condition tests are conducted with the minimal model. One of the extreme condition tests, using the lower and higher extreme values of the maximum expected ROI (max-ROI) in this two-agent setting, is presented in Figure 4.13. The analysis showed consistent results in the number of interactions and their corresponding outcomes, proving the verification of the minimal model under this extreme condition.

4.6.4. Multi-agent testing

Once the behavior of the minimal model aligns with the conceptual framework, it becomes necessary to verify the simulated behavior of the complete system with all agents included. The results of the same extreme parameter value test conducted on the minimal model showed consistent outcomes in the complete system, as presented in Figure 4.14.

The final check with the complete model did not reveal any different or unexpected results compared to



(a) max-ROI at lower extreme(-2)

(b) max-ROI at higher extreme(+2)

Figure 4.14: Number of times agents interacted through community discussion and results of the interactions

the previous tests. This consistency is due to the step-wise approach followed, with each test building on the previous ones.

4.6.5. Contribution of sensitivity analysis

After finalizing the modeling steps, a sensitivity analysis was conducted in Chapter 6 using several parameters. The model's outcomes were analyzed within the identified ranges of these parameters. During this analysis, a detailed reasoning and explanation of the conceptual model's behavior in response to changes in parameter values were provided. The interpretation of the model's behavior at the extreme ends of the parameter ranges revealed both expected and unanticipated outcomes, which were then justified based on the conceptualization choices made. Therefore, the verification steps taken in this section are further supported by the detailed sensitivity analysis in later parts of the report, solidifying the model's verification.

4.7. Major assumptions of the study

In the relevant parts of the methods section, all assumptions made in the modeling practice are explained and discussed in relation to the scope of the study. The potential effects of these assumptions on the results are mentioned, supported with references from the literature or referred to the validation discussion part of the report, where applicable. In this section, major assumptions are revisited and summarized before proceeding with the sensitivity analysis and application of the model.

- **Cost elements:** One important set of assumptions pertains to the cost elements included in calculating the cost of hydrogen production investments. Based on the literature review, the cost elements with the largest share in the production of a unit of hydrogen are given more attention and represented in greater detail in the modeling practice. Although the exclusion of transportation and storage costs impacts the cost outcomes, their shares are relatively smaller in the final LCOH figures. Furthermore, including these costs would necessitate broader discussions and considerations, such as determining the location of the electrolyzer, the feasibility of refurbishing pipelines and stations, and increased time resolution for storage needs, which exceed the limited scope of this research. Nonetheless, the simulation model's hydrogen cost estimates are compared and validated with results from the literature in Section 7.4.
- **Dependency on hydrogen:** Many other factors potentially impacting sectors' dependency on hydrogen are discussed in the research; however, quantification is solely linked to the temperature requirements of their processes. While a more detailed consideration of sectors' characteristics, hydrogen equipment suppliers' situations, company dynamics, investment cycles, and other factors could influence the research results, temperature requirements emerge as the most critical factor and are also used by other studies as a proxy. Another critical assumption in the model is linking companies' expected return on investment to their hydrogen dependency. Similar methodologies used in the literature are discussed more in depth in Section 7.4.
- **Transportation mean:** The study assumes that hydrogen can be purchased only if the region is connected via pipeline transportation, meaning companies can buy hydrogen solely through this

method in addition to their local production. The focus in the study is on determining whether conditions can mature for the region to connect to the national hydrogen grid, as industrial customers consider this essential for a complete transition. The study does not aim to identify the best hydrogen transportation method but rather examines if standalone projects can create feasible conditions for successful pipeline development. Investigating the effects of other transportation methods is suggested for future academic research.

- **Gradual transition:** The reflection of the gradual switching of companies to hydrogen in the model is another important assumption in the study. Although this gradual transition behavior is frequently discussed in the literature, the question of "how" this transition occurs needs to be answered for implementation in the model. Due to a lack of access to real decision-making mechanisms for planning such transitions, a stepwise conversion of production lines is used as the methodology. The lack of data on the number of production lines is another concern regarding this methodology. In the simulation, companies are randomly assigned a number of production lines, introducing meaningful uncertainty into the modeling. This randomness accounts for variability in company behavior and technological constraints, reflecting real-world conditions. Unlike deterministic models, agent-based models effectively represent inherent uncertainties, making this approach suitable for the study's purpose.
- **Electrolyzer capacity:** Another important assumption concerns the calculation of the required electrolyzer capacity. Similar to the discussion on the number of production lines, the method of calculating electrolyzer capacity impacts the results, particularly regarding subsidy eligibility and CAPEX costs. In the conceptual model, it is assumed that the electrolyzer can supply the company's processes with hydrogen during operational hours. Other methods of calculating this capacity were considered through power availability; however, discussions with experts from Stedin, as detailed in Section 7.4, highlighted this as an acceptable methodology to move forward in the research. The real process could involve determining electrolyzer capacity to capture the renewable energy production during the year, however, this requires smaller time resolution than years. Therefore, future research could emphasize capturing the effect of renewable intermittency in calculating the electrolyzer capacity.
- **Configuration of base model:** Another important consideration is the configuration of the baseline model, which is expected to closely represent the elements of the problem situation. The assumptions regarding the gradual increase in hydrogen use and the determination of electrolyzer capacity need to reflect the challenges faced by small companies in accessing subsidies due to their smaller sizes. This consideration is validated by the analyzed results from experiments, which demonstrate that this issue indeed arises in the baseline model. Consequently, the experiments and investigations are built upon this reference situation.

Other assumptions, such as the requirement for a threshold volume of production before granting the region a pipeline connection to the transmission line, setting boundaries for the expected return on investment for companies, and the weighting of the two identified factors in determining the motivation degree of companies, also require close attention. Consequently, their effects are discussed and analyzed in greater depth in Chapter 5 and 6 with uncertainty and sensitivity analysis.

5

Baseline Model

Due to the fact that the conceptualized model includes several model parameters whose values are uncertain and unknown, these parameter values will be fixed in a constructed base model in order to set a reference (baseline) point. This configured base model will establish a valid and robust basis for comparative analysis, further experimentation, model extensions and generation of meaningful insights.

In the baseline model which will serve as a reference point for future experimentation, agents will be planning and conducting their hydrogen investments only by their own individual attempts, with their available resources. Since the research intends to investigate the relative effect of collective action on the current problem situation with a comparative analysis, the collective investment will not be given as an option to agents at this stage yet. After finalizing the baseline model, potential improvements with the presence of collective investment option will be experimented in Chapter 7.

In this chapter, uncertainty in the modelling processes, how it is approached in this study, parameters that are subject to uncertainty analysis and finalized base model settings are presented.

5.1. Uncertainty in modelling practices

Uncertainty is an inherent and integral aspect of the modeling process. [112] discusses the nature of the uncertainties in the modelling in two categories. First is the uncertainty arising from the world's inherent variability and randomness which is particularly relevant to human and natural systems, especially in relation to social, economic, and technological developments. These type of uncertainties are called variability or stochastic uncertainty. Capacity factor of solar generation, innovation and development rate of hydrogen burning equipment technologies could be example of such uncertainty. The second type of uncertainty is knowledge-related and known as epistemic uncertainty. It arises from the limitations in our understanding of the system being modeled and lack of knowledge about certain processes. This uncertainty can be reduced through further research and empirical efforts [112].

[113] points out to the concept of "application niche uncertainty", which refers to whether a model is suitable for use under specific conditions. This highlights the convenient use of parameters and concepts that includes uncertainty for the specific application of the model. The concepts used in the conceptualized model are highly sophisticated and contextualized for the purposes of this study and is not developed from several other existing models. Furthermore, "structure/framework uncertainty" relates to the incomplete understanding of factors that influence the behavior of the modeled system, as well as the limitations regarding the necessary simplifications of the system. This uncertainty is suggested to be resolved by improving the scientific understanding, reconsidering the appropriate balance between model complexity and uncertainty. When model complexity is increased, the reality is better represented. However, it comes with the drawback of increased data uncertainty and input variables which degrade the model performance [114, 113].

As explained in Chapter 4, there are several model parameters in the conceptualized model that inherit epistemic uncertainty due to the lack of knowledge about their values. More details about these parameters and reasoning for the lack of knowledge are further detailed in this chapter.

Uncertainty analysis examines the impact of insufficient knowledge or possible errors in model output. When combined with sensitivity analysis, it allows the model user to better understand and assess the confidence in the model's results [113].

5.2. Methodology for setting the base model

Uncertainty analysis in this study followed a qualitative approach regarding the parameters that have epistemic uncertainty in the conceptualized model. Statistical quantitative analysis methods could be also beneficial by investigating the probability distributions of uncertain parameters, however, due to the time constraints, this aspect is left to the future research. In a qualitative uncertainty analysis, the uncertainty in each main parameter is described (Section 5.3), including the estimated magnitude of uncertainty and the potential impact on the model outcome [115]. Moreover, qualitative analysis emphasizes how well the available data meet the needs of the modeling activity and aligns with the aim of the research [113].

In light of these, several factors are taken into account when determining the parameters for the base model. Among the listed below, ”realistic values” and ”scenario goals” factors are considered for the mentioned purpose of qualitative uncertainty analysis. Furthermore, uncertainty analysis and sensitivity analysis are not strictly sequential processes. Instead, they are typically conducted through a trial-and-error approach, with each type of analysis providing insights that inform the other [113]. Based on this, the last two factors refer to the sensitivity analysis that will take place in Chapter 6 and will be used to confirm the choices made for the baseline model parameters:

- **Scenario goals**, choosing values that best represent the problem situation conditions and aligns with the research questions, corresponding experiments of the study.
- **Realistic values**, choosing values where it makes better sense in the real world conditions.
- **Central tendency**, choosing a value near the mean or median of the tested range can represent a central or typical scenario.
- **Stability and robustness**, choosing a value where the model outputs are more stable and less sensitive to small changes in the parameter will indicate more robust base model.

5.3. Elaboration on the uncertain parameters

5.3.1. Threshold generation as percentage

One important model parameter that includes high uncertainty is related to the hydrogen generation threshold required to make a pipeline connection available for the region. In fact, the threshold captures the essence of the problem that the study seeks to investigate. It represents the gradual scale-up performance of regions before they are fully connected to the national grid.

This threshold amount is a topic of discussion in business circles, potentially linked to energy-economic necessity from system operator perspective and other political decisions. Yet, no absolute numerical value exists and it is challenging to assign a value to such a concept. The results of this study will provide insight into the value of this concept. In the absence of a numerical example, it is interpreted in the model as a percentage of the total gas consumption of the companies. Companies in the region have a total heat demand, and the threshold parameter, expressed as a percentage, dictates the proportion of this demand that must be produced and consumed by regional hydrogen investments for eligibility for a pipeline connection.

In the conceptual model, reaching the threshold signifies gaining access to a continuous supply of affordable hydrogen. After this point, the transition accelerates, with hydrogen supply available on demand. This indicates that the moment the threshold is met is crucial for the region's development, while subsequent changes are less significant for the study. The most crucial aspect of the analysis is the identification of the point in time and the manner in which these companies reach that juncture.

Selection of the parameter value

For the purposes of the study's scenario objectives, the base model is expected to be capable of further improvements in terms of the identified performance metrics. The relative effects of collective investment, different sectoral configurations and government support settings are expected to be visible and measurable when compared to the base model. The base model is expected to reflect the gridlock experienced and defined as a problem in the study. Therefore, a parameter setting where the region meets the threshold volume with few individual investments and succeeds in full transition most of the time would not provide a favourable environment for the experiments. On the other hand, parameter settings could produce favourable results in terms of performance measures, but the reason for such results could be due to certain modelling choices or biased behaviour of the model. A cautious approach is taken to filter out such effects. Therefore, a setting that allows a certain level of hydrogen scale up in the region via individual attempts, letting companies try the limits of the presumed generation threshold but fail to reach full transition could be well representative of the reality and the formulated problem.

Since the parameter is linked to the regional gas demand, the range for the parameter value could span from 0% to 100% of the regional gas demand.

As it can be seen from Figure 5.1, hydrogen production and consumption progress tends to plateau around the average value of 22% with the efforts of few primary off-takers, failing to trigger other players in the region. The maximum reached hydrogen transition performance is 32% and higher levels can not be realized. In addition, although it is difficult to anticipate a real value for the generation threshold conceptualised in the model, a higher value would be more realistic as expectations are generally high before deciding to invest in infrastructure and the potential of the region is carefully examined. Therefore, the value for the parameter is determined experimentally and 50% target threshold volume value is set for the base model.

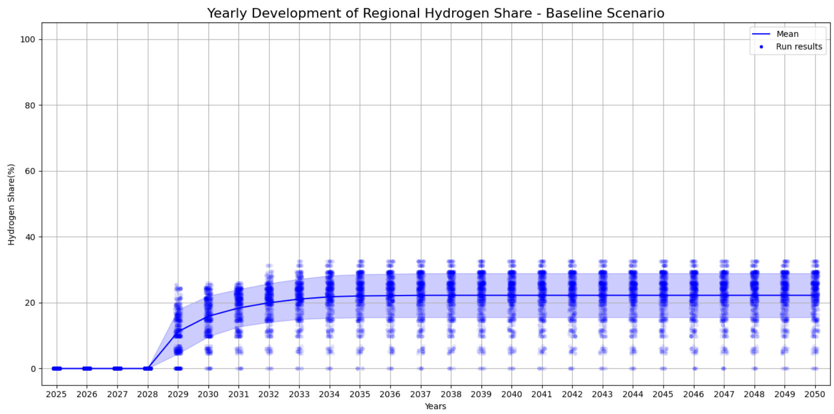


Figure 5.1: Distribution of average hydrogen share over the years

5.3.2. Expected return on investment

The expected return on investment is expected to be highly critical to the evolution of the results in the simulation, as it provides a benchmark against which companies compare the economic viability of hydrogen investment plans. It is directly linked to the realisation of the projects, which in turn will affect the regional hydrogen production. Although efforts are made to quantify costs and benefits as comprehensive as possible, the conceptualised investment process in the model imposes several assumptions that may not accurately reflect the realised costs of reality. These limitations are discussed in sections 4.7 and 8.4. Therefore, the use of a generalized industry or theoretical benchmark for the expected ROI would not be appropriate for the built model. On the other hand, the economic viability of hydrogen investments has yet to be proven and is already a limiting factor for the development of the technology. However, regardless of the economic viability of the investments with literal values, this study focuses on the relative impact of different investment options on the results under different policy and regional settings.

It should be noted that the companies are assigned expected ROI values within a range. This max-ROI parameter is the maximum value of this range, i.e. the maximum expected ROI value to be allowed for companies. Within this allowed range, companies are assigned expected ROI values depending on their sectoral hydrogen dependency (see Chapter 4).

Selection of the parameter value

A preference for more realistic values could apply to the setting of maximum ROI and threshold percentage parameters. As companies would be willing to make more profitable investments in real life, keeping the maximum expected ROI lower would be a more realistic choice. Therefore, lower maximum expected ROI levels are preferred to other possible options when setting the values.

To determine the range and values for this parameter, the model is run a number of times to gain an understanding of the resulting ROI values within the model setup. Based on these observations, the range for the parameter is determined. As no positive ROI value was observed, the minimum value of the experimental range starts at 0 and decreases to -1. This gradual decrease of the maximum ROI implies that the economic expectations of the companies are more relaxed. Increasing the parameter value increases the economic expectations from an investment and could block any investment attempts. On the other hand, relaxing the expectations by lowering the parameter value could allow any investment plan to be realized, potentially hiding the effects of other factors such as investment options, policy and regional settings. Therefore, slightly higher than the median value of the range, by trial and error, maximum expected ROI value of -0.65 is observed to keep the project realizations at the moderate level by allowing only few primary off-takers to initialize their transitions in small steps. This choice serves the aim of scenario goals to showcase the effect of other model and policy extensions via experiments by fabricating the problem situation and leaving a room for the improvement.

With the parameter setting, as seen from Figure 5.2, out of 15 companies, participation to hydrogen transition does not exceed 3 companies which are only from primary off-takers.

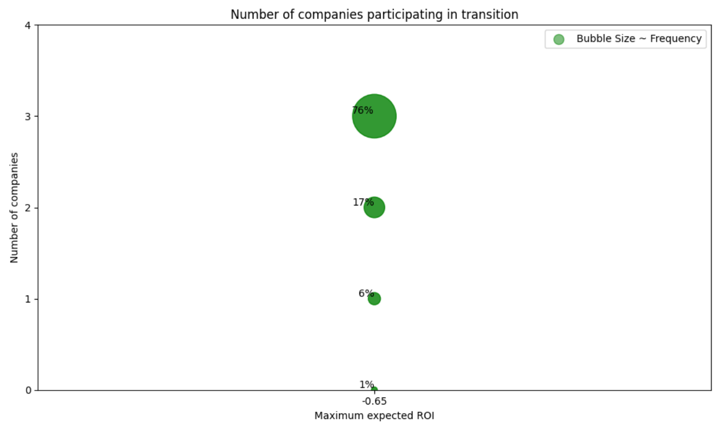


Figure 5.2: Frequency of companies participating in the transition

5.3.3. Sectoral hydrogen dependency weight

To recap the use of the motivation degree in the modelling, it is employed by companies to determine the number of production lines/modules to be converted in a single step and the amount of subsidy per kilogram of hydrogen to be requested. As previously stated in Chapter 4, two factors are considered when quantifying companies' motivation degree. One factor is the company sector's dependency on hydrogen, which is calculated by the temperature requirements of the processes in sectors. Second factor, the state of regional hydrogen development, represents the alleviation of the cold feet problem and the contribution of the learning effect. Therefore, changing the relative importance of each factor via assigned weight could give prominence to one of the factor and shift the course of the results.

Although these two factors are identified from companies' arguments in cluster energy strategy documents [30], [28] and analysis of standalone projects in the Netherlands [27], the relative importance of one factor to the other remains uncertain and difficult to quantify. As the remaining weight (1 - weight of sectoral hydrogen dependency) is automatically assigned to regional hydrogen development performance, the consideration with this parameter has dual effect. The range for this parameter could be from 0% where the effect of sectoral hydrogen dependency is eliminated, to 100% where the effect of regional hydrogen transition performance is eliminated.

Selection of the parameter value

While higher parameter values would hinder the effect of agents' actions on others, lower values could stagnate the developments from the beginning since in the early years of the simulation, regional hydrogen off-take will be at the minimum levels. Therefore, a median value as 50% is chosen for this parameter.

The value of the parameter will be varied within the range of 10–90%, with increments of 5% during the sensitivity analysis. This will help to showcase the effect of relative importance of each factor in the calculation of motivation degree.

5.3.4. Ceiling and floor probabilities

As previously stated in Chapter 4, the probability of receiving the subsidy is inversely proportional to the amount requested from the subsidy. Consequently, the minimum and maximum permitted asking price are associated with the maximum and minimum probabilities of receiving the subsidy, respectively. However, the magnitude of these lower and upper bounds for the probabilities of receiving the subsidy are model-specific parameters, and their effect on the results must be configured if they lead to unintended behaviours on the results. These values are of potential significance, as in certain instances, all subsidy applications may need to be accepted in order to satisfy the threshold volume for the region. If the upper bound of probability for the optimal (lowest) price is set at a very low level, this may result in excessive stagnation of the investment realisation and the suppression of the behaviour to be explored with the model. Furthermore, the probabilities are employed to calculate expected subsidy cash flow, which in turn affects the results of economic feasibility evaluations.

Selection of the parameter value

The range for ceiling and floor probabilities are set within 20 percentile from probability of 0% and 100%. In order to capture the effect of all combinations, a factorial design for these two parameters is followed. As a result of the executed simulation runs, the median values within these ranges are selected for the parameters.

Ceiling and floor probability parameters' effect on the model outcome will be presented in more depth via sensitivity analysis in Chapter 6.

5.4. Base model settings

In light of the considered factors in section 5.2 and characteristics of the parameters, the nominal values for the identified uncertain model parameters are determined by trial and error and conducting several factor at a time simulation runs over wide ranges presented in Table 5.1. Having the conformity to the scenario goals and taking real world conditions into consideration, the nominal values below are assigned for the base model:

Table 5.1: Nominal values of the uncertain parameters used in the baseline model

Parameter	**Name**	**Nominal value**	**Range***	**Unit**
Threshold generation as percentage	threshold-perc	50	[1; 60]	%
Maximum expected ROI	max-ROI	-0.65	[-0,05; -1]	-
Sectoral hydrogen dependency weight	dependency-weight	50	[10; 90]	%
Ceiling probability	ceiling-prob	90	[80; 100]	%
Floor probability	floor-prob	10	[0; 20]	%

*The ranges are given in the format [minimum; maximum]

Having assigned the nominal values of base model for the uncertain parameters, in the following chapter, sensitivity analysis will be conducted to ensure the current setting of the base model gives results that are robust and free from biases due to modelling choices made in the model conceptualization.

6 Sensitivity Analysis

Given the complexity of ABM, understanding the dynamics of the models can often be a difficult task. Sensitivity analysis is an useful tool in this effort, as the responses of model results to parameter changes provide insights into the underlying dynamics of the model [116]. A range of assumptions corresponds to a range of model parameter values, which in turn lead to specific model results. However, for these inferences to be credible, they should not be based on a narrow and uncertain set of assumptions. It is therefore crucial to demonstrate that the inferences are robust to parameter variation. This is particularly important when the model is attempting to explain an event that occurs under a wide range of conditions in reality [117]. This is especially relevant to the this research on the multi faceted nature of scale-up of hydrogen, which is influenced by a variety of technical, economic, and social factors.

The primary objective of sensitivity analysis is to examine the effects of changes in model parameters on the model outputs. Once validated through sensitivity analysis, the identified baseline model will become a reference point against which new hypotheses, interventions or policy changes can be tested. This iterative approach will help to build a cumulative body of knowledge.

6.1. The method for conducting sensitivity analysis

The basic concept of one-factor-at-a-time (OFAT) sensitivity analysis is to select a nominal set of parameters and vary one parameter at a time while keeping all other parameters constant. It is therefore referred to as a local method. The main application of OFAT is to reveal the relationship between the output and the varied parameter, with all other parameters at their nominal values. For example, the analysis can indicate whether the model response to certain changes is linear or non-linear, or whether there are tipping points where the output responds significantly to a small change in parameter. OFAT can provide an understanding of model mechanisms by showing these relationships. To achieve this, outputs are plotted after each parameter has been varied over a range of values [117].

Due to the time and computational constraints of this study, not all parameters of the model were included in the sensitivity analysis. Parameters whose values are unknown, uncertain or cannot be substantiated by a source are included in the analysis. In addition, due to the choices made in the conceptualisation, certain model parameters that could potentially have a significant impact on the results will be part of the analysis. These parameters are discussed while establishing the baseline model in Chapter 5.

Table 6.1 outlines selected parameters for the analysis, their nominal values and values to be varied.

The nominal parameter values are determined by preliminary trials with the parameters while establishing the baseline model. The upcoming sensitivity analysis will verify whether these values yield robust model outcomes and suitable for the baseline model.

Monitored outcomes of the model

Table 6.1: Overview of the parameters and ranges for the sensitivity analysis

Parameter	Name	Nominal value*	Range**	Unit
Threshold generation as percentage	threshold-perc	50	[1; 1; 60]	%
Maximum expected ROI	max-ROI	-0.65	[-0,05; 0,05; -1]	-
Sectoral hydrogen dependency weight	dependency-weight	50	[10; 5; 90]	%
Ceiling probability	ceiling-prob	90	[80; 5; 100]	%
Floor probability	floor-prob	10	[0; 5; 20]	%

*The ranges are given in the format [minimum; step; maximum]

As the main output of the simulation model, the share of hydrogen in the total heat consumption of the region is monitored as the parameters are varied. This is calculated by dividing the hydrogen consumption (kWh) of the region by the total heat demand (kWh) in this time step. As the focus of the study is on the progression of actions and efforts until a continuous supply of hydrogen is obtained, number of times the connection is realised is another critical performance measure of the study. Once the region has reached the production threshold for the backbone connection, it is assumed that the scale up of hydrogen takes place at a much faster rate. This assumption leads to large variations in the average hydrogen share measure, especially when some of the runs exceed the threshold and some do not for the same parameter value. Therefore, several performance measures are used to uncover the underlying effects on the results.

6.2. Results of the sensitivity analysis

A model is considered robust to a parameter if the model's key outputs and behaviours do not significantly change with variations in that parameter. This robustness implies that the model's predictions are stable, reliable, and not overly dependent on specific parameter values. The concept of small variations in output in the context of robustness and sensitivity analysis does not have a strict universal benchmark, as it can depend heavily on the specific domain, model, and the context of the analysis. It is possible that different fields may have their own standards for what constitutes a significant variation. If the model is being used for high-stakes decision-making (e.g., public health, safety-critical systems), even small variations might be significant. For instance, in economic models, a 5% variation in the results might be considered small, whereas in engineering models, a 0.5% variation could be significant. In the context of exploratory or theoretical models, as is the case in the present study, larger variations may be deemed acceptable.

6.2.1. Threshold generation as percentage

A series of experiments was conducted to investigate the impact of the threshold parameter on the average hydrogen share at the end of the simulation. The experiments were conducted with a wide range of values, from 1 to 60%, with increments of 1. The results demonstrated that the regional hydrogen share is sensitive to the assigned threshold values, as shown in Figure 6.1. In parallel to the expectations, average hydrogen share gradually decreases as threshold is set to higher values.

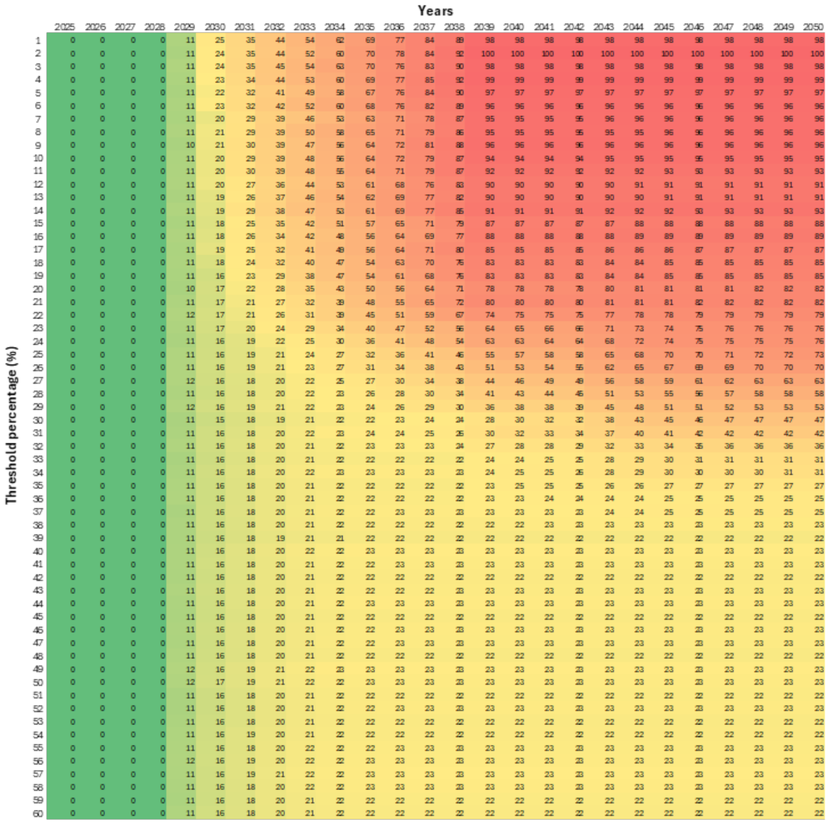


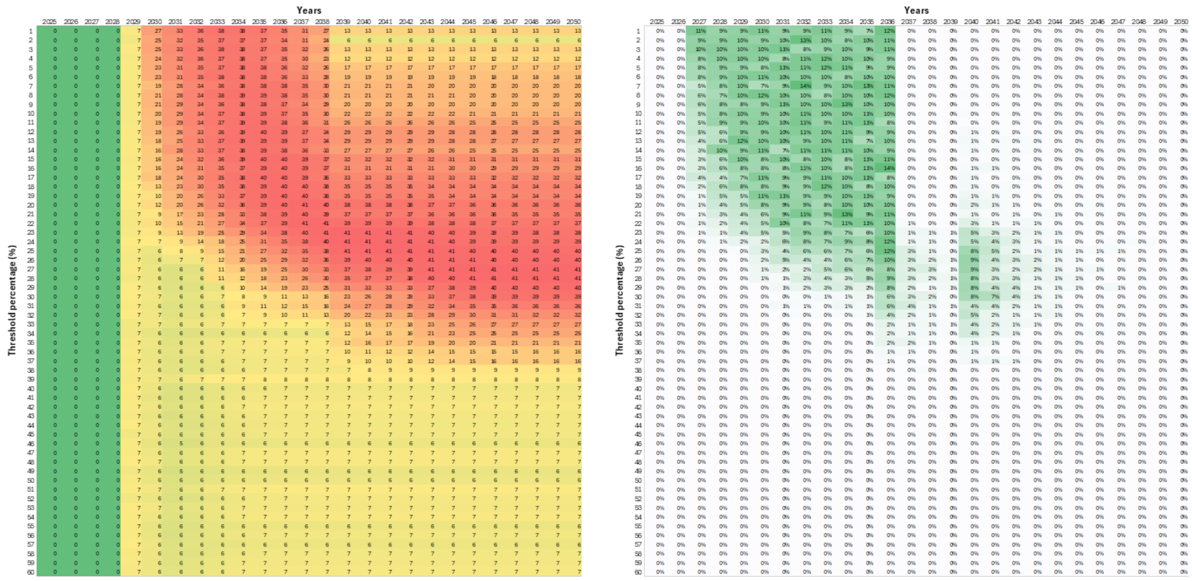
Figure 6.1: Average regional hydrogen share by varying threshold percentage values

For the lowest threshold values between 0-6%, individual investments are able to meet the threshold within first 10 years immediately after when the buying option is made available. However, as the threshold percentage increases, timing of threshold reach shifts towards the end of the first 10 years. After 6% threshold value, it takes slightly more than 10 years to reach the threshold. This delaying affect can be seen from the heat meap in Figure 6.1 where the red region gradually shifts into later years. Due to the randomness in making the buying option available in the first 10 years, the standard deviations within runs of the same parameter setting are higher at this period.

High standard deviation patterns in Figure 6.2a corresponds to the years after which the threshold is met. Since an accelerated hydrogen scale up after reaching the threshold is assumed in the model structure, the hydrogen share results in two opposite ends and leads to high variations in those years which is a natural result of the assumption. After approximately 15% threshold value, the hydrogen share deviation between different run results increase since at this level the threshold is not met with high certainty. This leads to the run results either the highest level when threshold is met or less than 15% when it is not reached. Additionally the spread of the standard deviation across the years widens since the timing shifted to the later years in the simulation. The "L" shape in high standard deviation values Figure 6.2a closely follow the pattern in threshold meeting frequency in Figure 6.2b. It should be noted that the reported deviation values are between the runs (500 runs per parameter) of the same parameter value experiment.

For the threshold values between 20-34%, average hydrogen share graph in Figure 6.3 displays two breaking points 13 and 17 years after the simulation initiation which corresponds to 2038-2039 and 2042-2043 respectively. These higher slope are attained to the realization of pipeline connection of those years, which follows the concentrated threshold reach in two years before, in 2036 and 2038 respectively.

For threshold values between 35% and 39%, the threshold is barely satisfied, occurring less than 10% of the time. This leads to lower average hydrogen share values. The results are more stable since the pattern is disrupted by less than 10% of the time with the availability of grid connection.



(a) Standard deviation between different runs of the same parameter experiment over the time steps of the simulation

(b) % of the times that threshold volume is met by varying threshold values

Figure 6.2

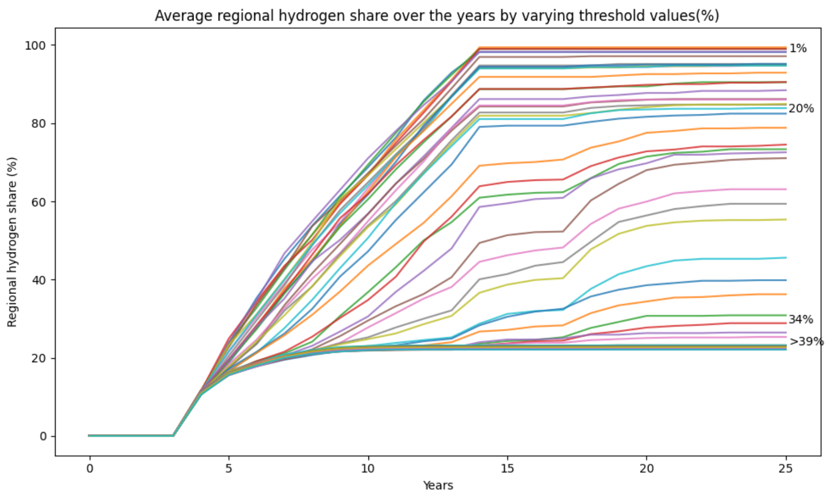


Figure 6.3: Average regional hydrogen share by varying threshold percentage values

**The % values given on the right belong to the threshold level, not to the hydrogen shares*

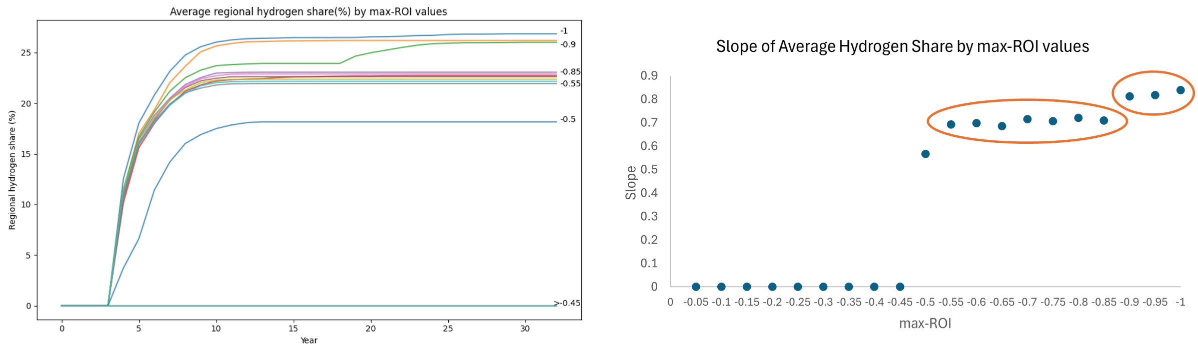
Gradual decrease in the average hydrogen share finalizes after the threshold value of 39% and stabilizes around 22.3% hydrogen share in the region, Figure 6.3. After this point, hydrogen share, meaning generation in the region, records maximum 33% level. The remaining portion needed to meet the threshold is never attained. Threshold value after 39% reveals the maximum performance of individual stand alone investment attempts of the region without the help of a pipeline connection.

Threshold value of 39% acts as a tipping point above which the results become stabilised, with outcomes becoming insensitive to further changes in the parameter. Overall, model outcomes are highly sensitive to threshold parameter as it signifies important changes in model behaviour. Hence, the assignment of values to the parameter will be done, taking this effect into consideration.

6.2.2. Maximum expected return on investment

From Figure 6.4a, it is apparent that the maximum expected ROI parameter has an impact on the model outcomes. Up to the point where the maximum allowed ROI expectation takes the value -0.45, no projects could be realised. Although the investment plans start to show better ROI values after the introduction of the purchase option in the first 10 years, this makes only a few projects acceptable, which in turn could not meet the volume required for the threshold. Individual stand-alone projects do not result in high enough ROI values compared to the maximum allowed ROI parameter. Therefore, the model results are observed to be insensitive to the parameter from the values of 0 until -0.45.

Another sign of sensitivity is shown in Figure 6.4b that the slopes of the curves are higher at high parameter values. In terms of steepness there are certain ranges that presents similar behaviour to each other. This means the marginal effect of the parameter values on the model outcomes within these ranges resembles and provides a robust range for the parameter.



(a) Average regional hydrogen share by varying max-ROI values

(b) Slope of average hydrogen share by max-ROI values

Figure 6.4: Sensitivity to maximum expected ROI: Average hydrogen share and slope of average hydrogen share

At the parameter value of -0.5, only a few individual projects become feasible. From -0.6 to -1, as illustrated in Figure 6.5a, with more flexible ROI expectations (more negative), the average hydrogen share directly increases and creates two distinguishable group in the upper part of the Figure 6.4b. Within these two highlighted groups, model yields stable results despite parameter changes which proves to be robust ranges.

As Figure 6.5b depicts, repetitive simulation runs with the same parameter values present a variation for the max-ROI values below -0.6 as a natural outcome of increased performance in hydrogen shares. It should be noted that minimum capacity addition to region's generation capacity is 500kw due to the subsidy conditions. Therefore, addition of one project affects the hydrogen share with wide intervals and 7 point variance between repetitive run results is an acceptable outcome.

Years

Maximum expected ROI (%)	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
-1.00	0	0	0	0	13	18	21	23	25	26	26	26	26	26	26	26	26	26	26	26	27	27	27	27	27	27
-0.95	0	0	0	0	11	17	19	22	24	25	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
-0.90	0	0	0	0	12	17	19	21	22	23	24	24	24	24	24	24	24	24	24	25	25	25	25	26	26	26
-0.85	0	0	0	0	10	16	18	20	21	22	22	22	22	22	23	23	23	23	23	23	23	23	23	23	23	23
-0.80	0	0	0	0	11	16	19	20	22	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
-0.75	0	0	0	0	11	16	18	20	22	22	22	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
-0.70	0	0	0	0	11	16	18	20	22	22	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
-0.65	0	0	0	0	11	16	18	20	21	21	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
-0.60	0	0	0	0	12	16	19	20	21	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
-0.55	0	0	0	0	11	16	18	20	21	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
-0.50	0	0	0	0	4	7	11	14	16	17	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
-0.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a) Average regional hydrogen share by varying max-ROI values

Years

Maximum expected ROI (%)	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
-1.00	0	0	0	0	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
-0.95	0	0	0	0	7	6	6	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
-0.90	0	0	0	0	7	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
-0.85	0	0	0	0	7	6	6	6	6	7	7	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6
-0.80	0	0	0	0	7	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
-0.75	0	0	0	0	7	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
-0.70	0	0	0	0	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
-0.65	0	0	0	0	7	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
-0.60	0	0	0	0	7	6	5	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
-0.55	0	0	0	0	7	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
-0.50	0	0	0	0	5	8	8	8	9	9	9	9	10	10	10	10	10	10	10	10	10	10	10	10	10	10
-0.45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(b) Standard deviation between different runs of the same parameter experiment for each time step of the simulation

Figure 6.5

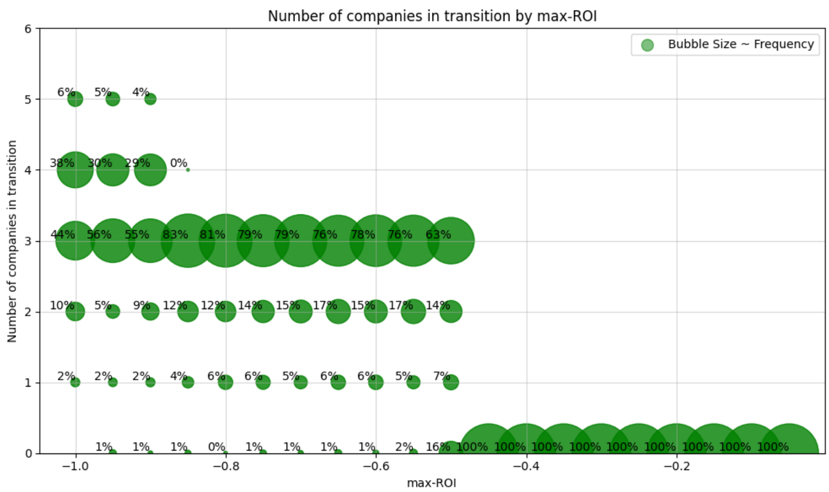


Figure 6.6: Frequency of company participation for varying max-ROI values

Underlying reason for the grouping in the results between -0.6 and -0.9, -0.9 and -1 and finally -0.5 acting as an outlier can be explained by the number of companies in transition for the different parameter values in Figure 6.6.

Above -0.9, two more companies start to be a part of the transition compared to the the level below which creates a difference in the results. Outlook in -0.5 resembles to 1st group however, 16% of the time no transition at all is observed, which lowers the average hydrogen share significantly.

6.2.3. Sectoral hydrogen dependency weight

The low weights assigned to sectoral dependency indicate that greater emphasis is placed on regional performance when determining the motivation degree of companies. Consequently, interpretations should address both perspectives. The distribution of these two factors has been observed to have a initiating effect on investment plans. When regional hydrogen development is given more weight (lower weights for sectoral dependency), the motivation degree of companies starts with low levels and increases only if generation in the region scales up. The dependence on regional performance impedes the advancement of developments, as evidenced by the weight values of until 25%, see Figure 6.7a. Upon a general look of the heat map, it becomes evident that a reduction of the effect of sectoral hydrogen dependency in the motivation degree results in a notable delay in the development of hydrogen. This is observed as the yellow regions advance further into the future on the time scale.

Years

Hydrogen dependency weight (%)	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
90	0	0	0	0	16	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
85	0	0	0	0	16	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
80	0	0	0	0	14	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
75	0	0	0	0	13	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
70	0	0	0	0	12	16	17	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
65	0	0	0	0	12	16	17	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
60	0	0	0	0	13	18	19	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
55	0	0	0	0	13	18	20	20	20	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
50	0	0	0	0	11	16	18	20	21	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
45	0	0	0	0	11	16	18	20	21	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
40	0	0	0	0	8	12	14	15	17	18	18	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
35	0	0	0	0	8	12	14	15	16	17	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
30	0	0	0	0	4	7	9	10	12	13	13	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
25	0	0	0	0	5	8	9	10	11	12	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
20	0	0	0	0	2	3	4	5	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
15	0	0	0	0	2	3	4	5	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
10	0	0	0	0	1	2	3	4	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

(a) Average regional hydrogen share by varying dependency weight values

Years

Hydrogen dependency weight (%)	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
90	0	0	0	0	5	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
85	0	0	0	0	5	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
80	0	0	0	0	6	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
75	0	0	0	0	6	4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
70	0	0	0	0	7	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
65	0	0	0	0	7	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
60	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
55	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
50	0	0	0	0	7	6	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
45	0	0	0	0	7	7	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
40	0	0	0	0	6	6	6	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
35	0	0	0	0	6	7	6	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
30	0	0	0	0	5	5	5	6	6	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
25	0	0	0	0	5	5	5	6	6	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
20	0	0	0	0	3	4	4	5	6	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
15	0	0	0	0	4	4	4	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
10	0	0	0	0	3	4	4	4	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

(b) Standard deviation between different runs of the same parameter experiment for each time step of the simulation

Figure 6.7

Since in the initial years hydrogen scale up has not started in the region, no contribution is received from regional hydrogen transition performance yet. Therefore, lowering its effect by increasing weight of sectoral hydrogen dependency gradually increases average hydrogen share in the region. Within this experimented range, model outcomes peak between weight values of 45-60%, which is followed by a drop as weight increases further. 60% weight is observed as the tipping point for the decline in hydrogen share. Upon closer examination, it is evident that the number of times that investment plans are limited by power constraints increases when the experimented weight values increases, see Figure 6.8. Companies utilise the motivation degree to determine the number of production lines to consider for the hydrogen transition in one step. As the sectoral dependency weight reaches its maximum levels, companies implement more ambitious plans into their agendas, which are then limited by their power capacities in the majority of cases. This effect blocks the developments in the region. Although it might be possible, this kind of behaviour could be considered less realistic. Therefore, it would be more favourable for the simulation purposes to keep the weight of the sectoral hydrogen dependency less than such high levels.

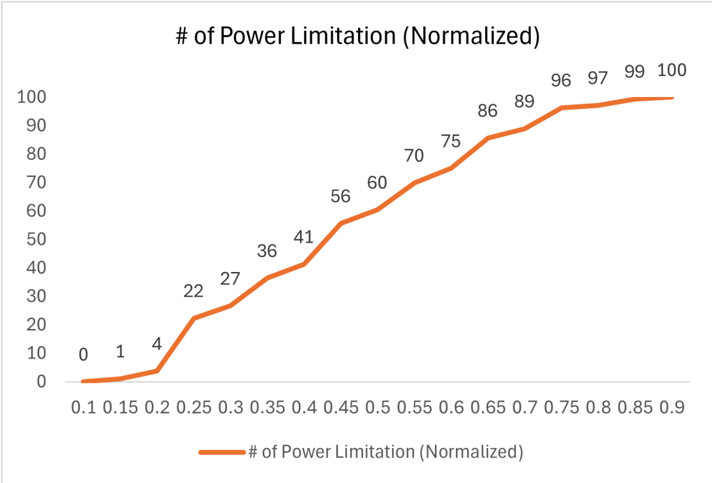


Figure 6.8: Normalized number of times that the projects are limited by power constratints during runs

It can be observed that the model yields robust results between weight values of 0 - 35% and 50-60% where resulting performance measures are closer to each other and variations between their repetitive runs range between 5-8 points. This robust range facilitates favourable conditions for model use by providing more stable results.

6.2.4. Ceiling and floor probabilities

Since these two parameters together decide on the probability assignments in the model by determining the maximum and minimum boundaries, sensitivity analysis is conducted to all combinations that their ranges result with. Therefore, five values from each makes up 25 different combinations and their effects on the outcomes are analyzed together.

One of the anticipated consequences of alterations to ceiling and floor parameter values is an increase in the acceptance rate of subsidies for such projects. This is evidenced by a reduction in the total number of rejections as probabilities shift upwards. For projects that rely solely on self-generation, there is a direct positive effect in the form of an increased probability of receiving subsidies and initiating the project. However, this does not directly relate to project plans that include a certain proportion of purchased energy, as there are threshold conditions to be met.

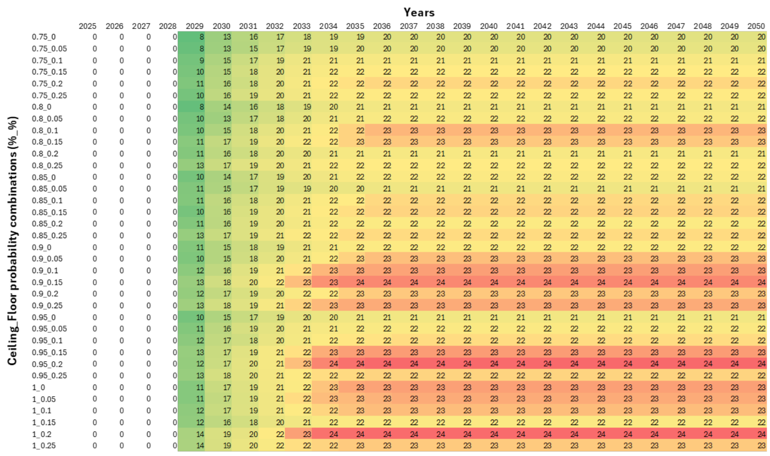


Figure 6.9: Average hydrogen share by varying ceiling and floor probability combinations

The second expected consequence of the increase in the variables is that in cost-benefit analysis calculations, the projects begin to yield more profitable return on investment (ROI) ratios for the companies involved. As the expected subsidy amount is calculated by multiplying the probability and the asking price, increasing either the floor or ceiling probability increases estimation for the benefit side of the cost-benefit analysis. However, this effect does not materialize itself in the average hydrogen share results considerably. The model demonstrates a consistent behaviour under different values for the parameter which resulting average hydrogen shares ranges between a narrow range of 20-24% as seen in Figure 6.9.

6.2.5. Implications for the baseline model

Sensitivity analysis highlighted important dynamics of the conceptual model. Wide ranges for the parameters are tested and insights are gained into smaller and more robust ranges within the wider ranges. These insights will be compared with the choices made within the baseline model.

Threshold generation as percentage

In parallel to the expectations, the threshold value exerts a significant influence on the model outcomes, see Figure 6.1. The parameter is also pivotal to define a base model that designed experiments could be conducted and compared with a sensible reference point. By using the assigned nominal values for other parameters, sensitivity analysis results showed that region is able to generate 39% of its heat demand via individual stand alone projects. While for the lower levels of threshold, certainty to reach is significantly high, for the 35-39% range this frequency drops to less than 10% of the time. Therefore a threshold target for the region which is considerably higher than the defined tipping point of 39% is more favorable in terms of scenario goals in order to see whether a collective investment can make a big difference or not. A higher value can also be considered more realistic as expectations in real life leans on higher levels.

Another advantage of setting the base model at the part of the threshold range where it could not be reached under the current circumstances eliminates the high fluctuating behaviour and variance arising from the frequency of meeting the threshold. This nominal value allows more reliable observation about the sensitivity of the model behaviour to other parameter value changes. As a result, the chosen threshold value of 50% for the base model proves to yield robust model outcomes and is suitable for further analysis with the baseline model.

Maximum expected return on investment

Sensitivity analysis for the maximum expected ROI parameter provided important insights on the economic feasibility of the projects under the assumptions of the conceptual model. At the higher values, the parameter does not allow any project development due to more stringent expectations. When values for the parameter are set to the lowest end of the range, many projects tend to be feasible. In both extreme cases, significance of economic feasibility may tend to hinder other factor's effect and could be dominating by either imposing strict conditions or cause ambiguity by flexing conditions too much. It is shown that the model behaviour is stable in each of these sub ranges, see Figure 6.4b. Therefore, the choice made for the parameter value as -0.65 in the baseline model is from the mid range where it is also line with the central tendency consideration. Conducted sensitivity analysis supports the suitability of the selected parameter value for the baseline model.

Sectoral hydrogen dependency weight

The sectoral dependency weight presented certain undesired effects at either extreme ends as explained in the sensitivity analysis results part. The highest values result from very ambitious plans, which in most cases could not be realised due to power constraints. For the lower values up to 30%, it has a delaying effect on investment due to excessive reliance on regional performance. Apart from these considerations parameter values in the experimented range varied the model outcomes in a narrow range of 18-22% hydrogen share, which represents a reliable robust range. The sectoral approach is an integral part of the research and will also be the subject of the experiments. A moderate level of sectoral dependency weight is therefore important to avoid bias in the experiments designed for different sectoral distribution settings. Being away from the extreme ends also results with the lowest standard deviation between its repetitive runs. For the chosen value of 50% in the baseline model, sensitivity analysis demonstrates robust model outcomes results. Therefore, the identified weight value for the calculation of motivation degree in the base model is suitable for the experimentation.

Ceiling and floor probabilities

The model behaviour is shown to be insensitive to the ceiling and floor probability parameters. It seems that the selected value does not significantly affect the model's output. Therefore, the parameter values from the baseline model which are close to the median of the experimented range are suitable for further analysis with the baseline model.

The model behaviour is shown to be robust, free from bias and unexpected extreme points and provide a suitable basis for further experiments with the assigned nominal values.

To conclude, sensitivity analysis is conducted by fixing all assigned nominal parameters and changing one nominal parameter at a time within its range. After thorough analysis, it is verified that the assigned nominal values in Table 6.1 fall within the robust segments of their tested ranges and show alignment with the discussed base model considerations.

7

Experiment Results

After finalizing the baseline model settings in Section 5.4, three experiments designed in Section 3.5.6 are conducted with the baseline model. It should be noted that in the baseline model, companies are only given the option to conduct individual investments where collective investment has not been introduced as an option yet.

As the reference case study, the region named as "HydroControl" in Section 3.5.6 is used for the experiments and, results of the experiments are presented in this chapter. After that, the validity of the model results are discussed at the end of the chapter.

7.1. Experiment 1 - The impact of collective investment

As explained in Section 5.4, baseline model settings are designed with a room for improvement to investigate whether and how experimental scenarios affect the performance measures. In the base scenario, the hydrogen share threshold of 50% is never achieved; instead, the region attains an average hydrogen share of 22% with minimal investments, see Figure 7.1. With the introduction of the collective investment option, the most notable effect is that the threshold volume is reached 52% of the time. However, due to subsidy rejections in some cases, the success rate for obtaining the connection falls to 36.5

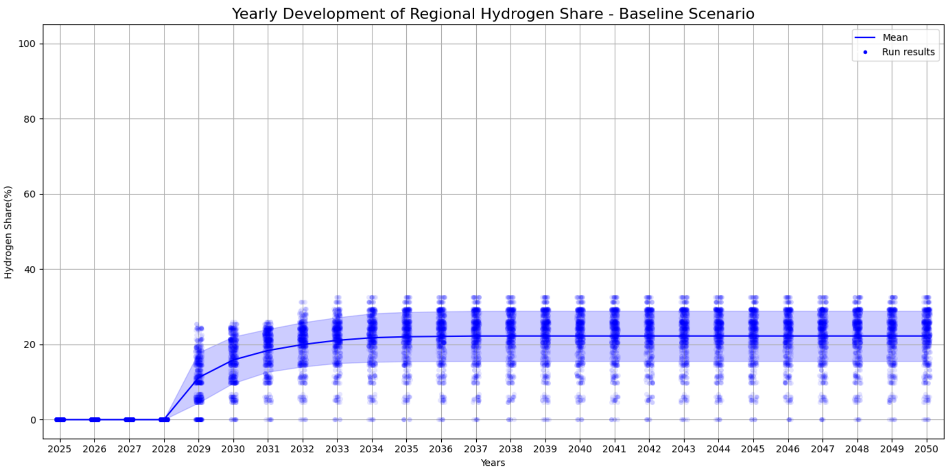


Figure 7.1: Yearly development of regional hydrogen share (Baseline scenario)

Figure 7.2 provides an in-depth analysis of how collective investment facilitates reaching the threshold level. Out of 259 runs where the region succeeded in meeting the threshold volume, the data has been normalized to 100 for clarity and is presented in Figure 7.2. To reiterate, collective investment in the conceptual model is manifested in three distinct ways. The green bars in the figure represent the first level, where companies opt for collective action due to power and subsidy limitations, leading them to form a community. At this stage, the aim is to leverage shared resources and having an upscaled electrolyzer project application. Remarkably, this collective approach accounts for 70% of the successful attempts at meeting the threshold.

The second level of collaboration comes into play when the production level achieved in the first level is insufficient to meet the threshold. At this stage, all individual and collective investment requests are consolidated under a collective umbrella. The objective here is to scale up the volume of plans by exploiting the potential offerings that collective formation could have provided. This strategy accounts for 13% of the successful attempts, represented by the blue bars in Figure 7.2.

The final approach involves each agent increasing the production portion in their plans with respect to their willingness for energy security. This method is the second most effective, responsible for 17% of all successful attempts. These three levels of collaboration highlight the crucial role of information sharing between agents, which is absent in the base scenario. When individual and collective efforts that might be independently planned are pooled together through regional collaboration and discussion (second level), or when every participant reconsiders their initial transition plans in this unified strategy (third level), the effectiveness of the region's successful transition is significantly enhanced.

Beyond the direct impact of collective investment through resource sharing and enhanced application capacities (first level), significant improvements can be achieved by fostering a collaborative environment among companies. Increased awareness of each other's plans through collaboration has a profound and undeniable impact on success.

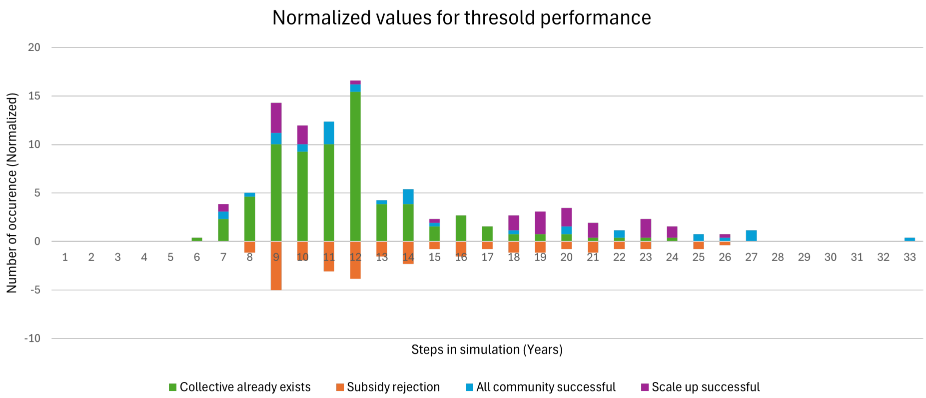


Figure 7.2: Normalized values for threshold performance

As illustrated in Figure 7.2, 70% of the times the threshold is met occur within the first 12 years. These early developments connect the region to a continuous hydrogen supply and accelerate the transition rate. Consequently, the region reaches full transition 36.5% of the time by the end of 2050.

From 2034 onwards, the progressively darker strip plot points at the 100% hydrogen share level indicate an accumulation of results around the full transition, as shown in Figure 7.3. The 100% transition grouped at the top of the graph represents the 36.5% of instances where the simulation resulted in a full transition.

The shaded area in the graph denotes the +/- one standard deviation between the results of the runs, highlighting the variation caused by accelerated scaling after the threshold is reached. The distribution of occurrences where the threshold is met, as depicted in Figure 7.2, aligns with the rapid progression observed during the corresponding years in Figure 7.3.

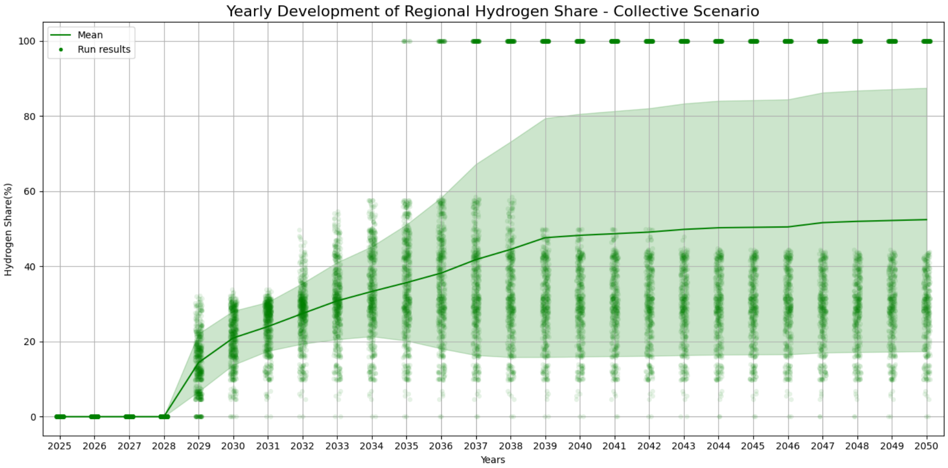


Figure 7.3: Yearly development of regional hydrogen share (Collective scenario)

Taking an overall view of the model results, it is valuable to closely examine the developments that lead to the target threshold being reached. Figure 7.4 provides a detailed look at the hydrogen share in the year the threshold is reached. In some cases, the target threshold is even exceeded, with the hydrogen share reaching as high as 58.5%.

The distribution in Figure 7.4 can be analyzed in three distinct phases. In the early years, specifically the 7th and 8th years, the hydrogen share just before reaching the threshold is lower. Between the 8th and 16th years, it stabilizes between 45-50%. After the 17th year, a decrease to the 40-45% range is observed, and the time to meet the threshold is significantly delayed compared to the general trend.

In the early years, the threshold is reached with relatively large steps, from 32-40% levels up to the 50% threshold. During this period, the abundance of energy sources enables large-scale projects. Since the agents are modelled to act individually at first and try to realise their plans independently, the highest levels of individual share is observed during these early years, as shown in Figure 7.5. However, in each of these year groups, the final investment step that makes up to the threshold level is recorded to be as a collective investment.

Table 7.1 shows that the high individual share just before reaching the threshold is always complemented by collective investment which can be seen from the disappearance of the gap between individual and collective shares.

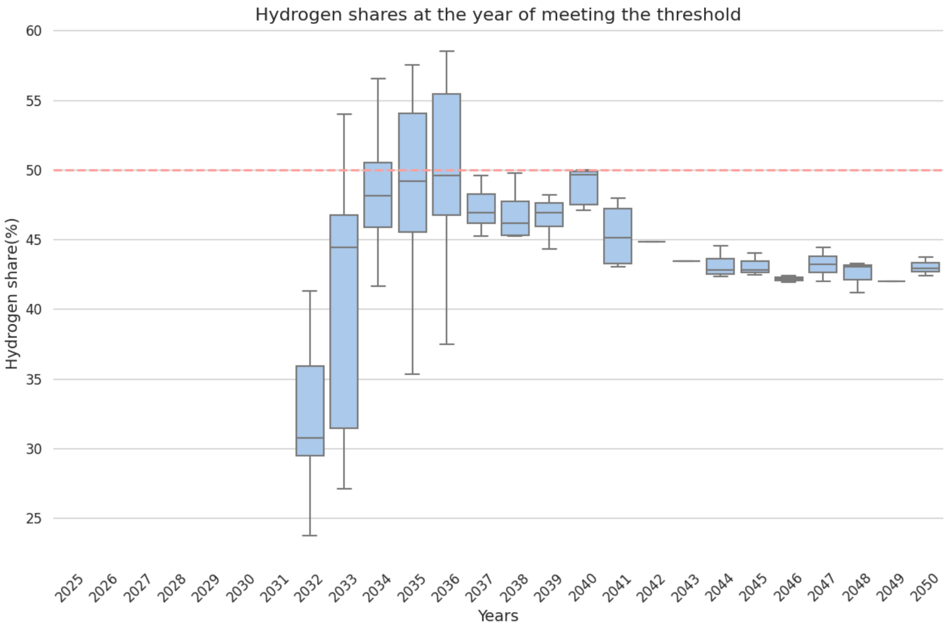


Figure 7.4: Distribution of regional hydrogen share in the year when the threshold is met

The lower hydrogen share and delayed threshold success after the 17th year in Figure 7.4 can be attributed to the reduced levels of collective investment during these occurences. Further investigation reveals that while the region achieves significant hydrogen production, the majority of investments are individual, as indicated by the higher-positioned blue box plots in Figure 7.5. This highlights the critical role of collective investment in timely and efficient threshold attainment.

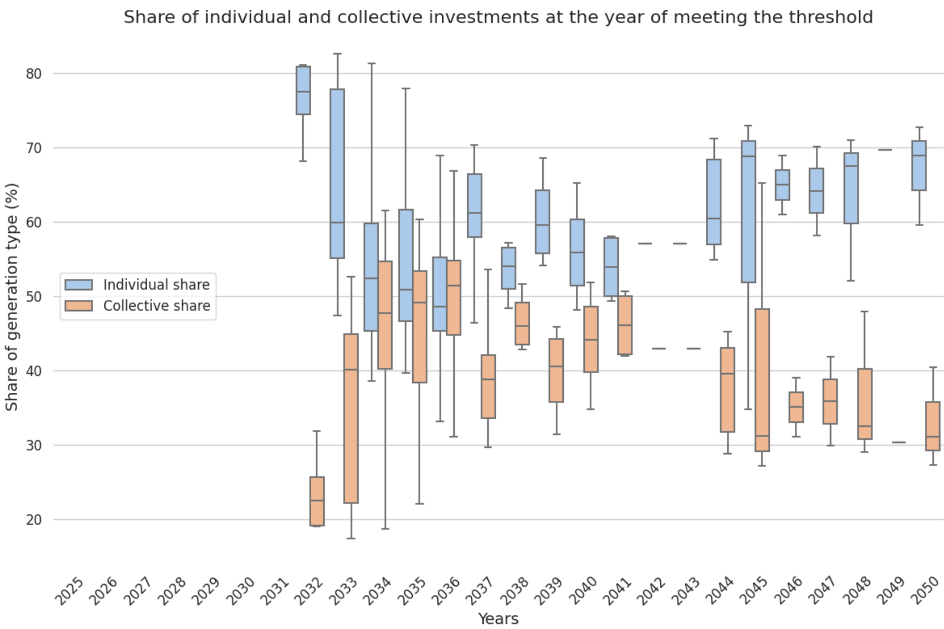


Figure 7.5: Distribution of individual and collective investment shares over the years

A closer examination reveals that efforts by a few companies from the food, cement, and chemical sectors—industries with relatively lower hydrogen dependency compared to sectors like the metal industry— have the finalising effect for reaching the target threshold volume. However, if the majority of the transition is driven by individual efforts with limited entry points for community formation, an economically viable investment environment is not established for other companies. This hinders and delays the inclusion of companies with lower motivation and higher economic expectations, stagnating the hydrogen development of the entire region.

In contrast, in scenarios where collective investment occurs earlier, the same companies that were initially less interested in switching to hydrogen manage to become part of the community formation in a way that aligns with their financial expectations.

Table 7.1: Analysis of the final investment that makes up to the threshold level

	The year of meeting threshold		**After the realization of connection**	
Time step	Individual(%)	Collective (%)	Individual(%)	Collective (%)
>=17	62.12	37.87	26.62	24.93
<=16	54.05	45.94	26.98	27.42
7-8	67.89	32.10	26.49	27.00

Furthermore, the cost per unit of achieved hydrogen share in the region is a significant indicator when comparing the baseline and collective scenarios. By dividing the total expenditure by the companies on the hydrogen transition by the achieved hydrogen consumption for both scenarios, it is evident that the collective scenario is 42.4% cheaper per kWh than the baseline scenario.

Additionally, the utilization of the region's electricity capacity differs significantly between the two scenarios. In the baseline scenario, on average, 20.6% of the available electricity grid capacity is used for hydrogen production. In contrast, the collective scenario sees this rate increase to 34.6% on average. These findings suggest that collective investment offers effective solutions for better and more efficient use of technical and economic resources at the regional level.

7.2. Experiment 2 - The impact of sectoral configuration

In this experiment, different sectoral configurations (identified in Section 3.5.6) will be applied to the original case study's setting. Table 7.2 presents the different configurations where HydroControl being the original case study.

Table 7.2: Sector contributions to the region's total gas consumption under different scenarios

Case	**Case Name**	**Horticulture**	**Cement**	**Chemical**	**Food**	**Metal**	**Paper**	**Textile**	**Sectoral Hydrogen Dependency (Weighted Average)**
1	HydroLow	52%	-	18%	15%	12%	2%	-	4.8
2	HydroModerate	-	3%	-	83%	14%	-	-	5.8
3	HydroHigh	-	-	7%	10%	35%	-	48%	6.4
4	HydroControl	-	4%	14%	28%	55%	-	-	8.0

As shown in Figure 7.6, other sectoral configurations yield considerably different results compared to the HydroControl case study, making it much harder to reach the 50% threshold in these scenarios. Hydrogen development stabilizes in the early years of the simulation, with the maximum hydrogen shares recorded by the region under different configurations being 11%, 15%, and 35% for the HydroLow, Moderate, and High cases, respectively. While collective investment has an improving effect in each of these cases, as indicated by the orange line consistently being above the blue line, it is still insufficient to provide the necessary push to reach the target threshold volume.

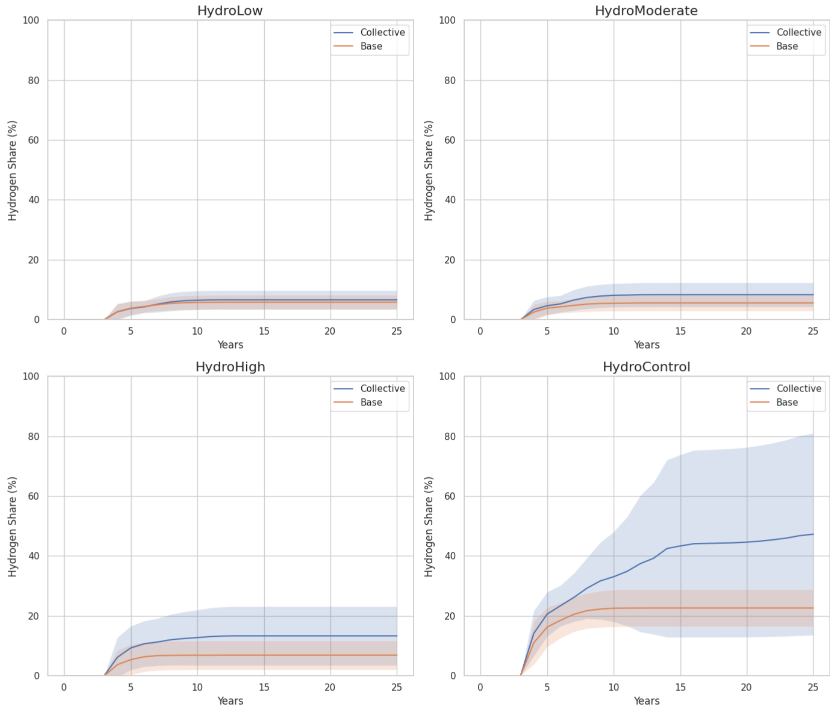


Figure 7.6: Average regional hydrogen share and ±1 standard deviation over the years under different sectoral settings

A detailed examination of how the discussions to form a community resulted in each case is provided in Figure 7.7, focusing on the results of year 15, when each case has stabilized and behavior patterns have begun to repeat, as shown in Figure 7.6. In Figure 7.7, the total number of community formation discussions is represented as 100%, with the outcomes of these discussions displayed according to their frequency.

Power capacity was not a limiting factor for the newly added sector configurations, as much of the capacity remained unused due to limited hydrogen development. Only HydroControl experiences power limitations because a portion of the capacity is already utilized by existing investments. The lack of a business case (ROI in the graph) represents the majority of the discussion outcomes. This share exceeds 95% for the worst performing HydroLow case, while it drops to around 78% for HydroControl, which shows much higher performance in hydrogen share.

The primary reason for this disparity is that companies with lower hydrogen dependency have higher economic expectations from a transition to hydrogen. This effect is more evident in the results when companies from sectors such as horticulture in HydroLow and textiles in HydroHigh hold the majority of consumption in a region.

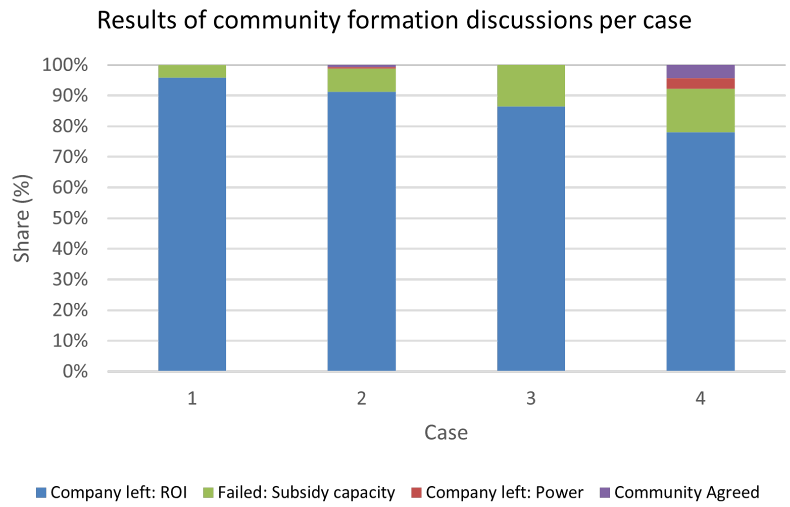


Figure 7.7: Results of community formation discussions per case

The results clearly highlight the importance of sectoral distribution for hydrogen development in the region. Examining the sector's hydrogen transition at the end of the simulation, it is evident that in all three cases, the metal industry encompasses all the successful efforts, with the cement industry also participating in HydroModerate due to collective investment.

This behaviour draws attention to Table 7.2 with the sector shares in different configurations. Considering the results for each configuration, the decreasing trend in the success of the hydrogen transition from HydroControl to HydroLow parallels the decreasing share of hydrogen-dependent industries, such as metal and cement, in the region. The gas consumption shares of highly hydrogen-dependent sectors in their regions' are 59%, 35%, 17%, and 12% for HydroControl, High, Moderate, and Low, respectively.

Therefore, the presence and share of highly hydrogen-dependent sectors in a regional setting plays a crucial and driving role in a successful transition. This, in turn, affects the transition of the region as a whole and the individual companies within it.

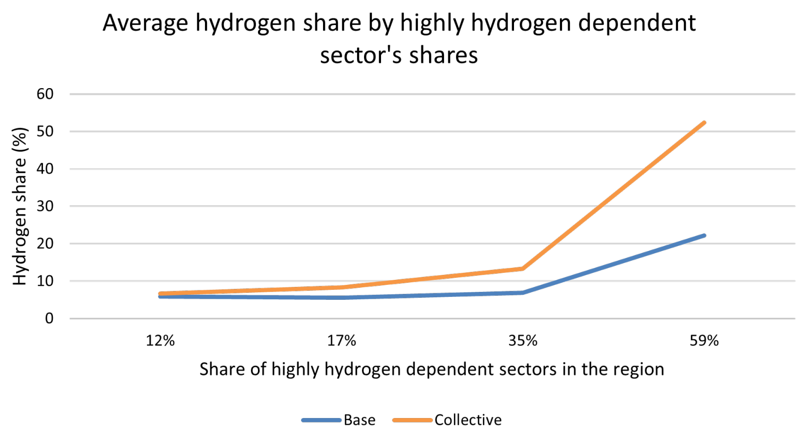


Figure 7.8: Average hydrogen share by highly hydrogen dependent sector's shares in natural gas consumption of region

As the weight of hydrogen-dependent sectors in a region decreases, the regional hydrogen share performance also declines, and the marginal contribution of collective investment diminishes.

The relationship between the contribution of collective action and the shares of hydrogen-dependent sectors in the region is non-linear. Figure 7.8 illustrates how the average hydrogen share evolves exponentially with and without collective action for different proportions of highly hydrogen-dependent sectors in a region. The exponentially widening gap between the blue and red lines in Figure 7.6 demonstrates that the contribution of collective action increases at a higher rate as the number of hydrogen-dependent companies in a region rises.

These companies initiate a collaborative framework where they can offer less motivated companies lower costs per kWh of hydrogen through economies of scale. This approach is how the transition succeeds in HydroControl case, where companies from the metal and cement industries are consistent and continuous participants in community formation. Their large volumes enable them to steer hydrogen offtake by facilitating favorable investment conditions for companies from other sectors.

In Table 7.3, the metal sector consistently participates in efforts to reach the threshold volume through both individual and collective investments. Its heavy presence not only supports other participants from the same sector but also paves the way for sectors such as food and chemicals to engage in economically attractive collective investments. These sectors might otherwise remain reluctant to attempt individual investments that do not meet their high economic return expectations.

Table 7.3: Level of participation from sectors to the investments to reach the threshold for HydroControl (Original case)

	Individual investment		Collective investment		
Industry	**#of companies**	**Sector participation (% of time)**	**#of companies**	**Sector participation (% of time)**	**Total # of companies in region**
Metal	2-3	100%	3-9	100%	9
Food	0-1	13%	0-1	38%	3
Cement	0	0%	0-1	84%	1
Chemical	0	0%	0-1	10%	2

Furthermore, individual efforts by highly hydrogen-dependent sectors establish the foundation for the region's threshold potential, alleviate the cold feet problem, and indirectly influence the investment plans of less hydrogen-dependent companies, encouraging them to increase the size of their plans (size of plans in one step). The concept of "launching customers" [27] as initiators of the transition aligns well with the analysis results and demonstrates an accelerating role in hydrogen development within the regions. The magnitude of this compounding effect by launching customers or highly hydrogen-dependent sectors grows as their share within the region increases.

7.3. Experiment 3 - The impact of government support on subsidies

Unless stated otherwise, the analysis continues with the HydroControl case configuration in this experiment. Experiments conducted thus far have used the real SDE++ subsidy limit of a minimum 500 kW electrolyser capacity. In the original case study (HydroControl), most individual trials are constrained by these subsidy conditions over the years. Figure 7.9 illustrates the normalized outcomes of individual investment planning attempts per year, highlighting the significant impact of the minimum subsidized capacity on these attempts. It should be noted that individual attempts undergo a capacity check, a minimum subsidy requirement check, and an economic feasibility check, respectively. Consequently, individual attempts rejected due to the minimum subsidy capacity do not proceed to an economic feasibility check, resulting in a notably low share of economic infeasibility (ROI) among the rejection reasons.

In contrast, Figure 7.7 from the previous experiment results shows that economic feasibility has the highest share among the outcomes of community discussions, where power capacity and minimum capacity for subsidy conditions are more easily met. However, this does not diminish the impact of the minimum subsidy capacity factor on the overall results and hydrogen development, as it remains the primary blocking factor for project attempts. Therefore, it is worth investigating different levels of this minimum capacity limit for subsidy applications to understand its broader implications.

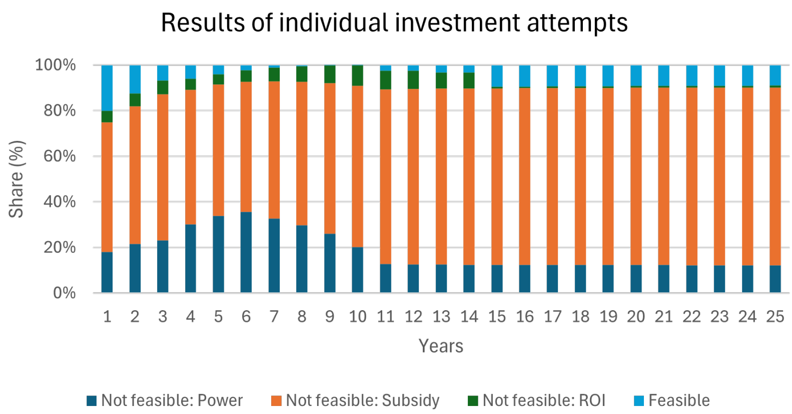


Figure 7.9: Results of individual investment attempts with minimum subsidy capacity limit = 500kw

The minimum subsidy limit was experimented with by both increasing and decreasing it from its original 500 kW value in steps of 50 kW. The results for the HydroControl case provide important insights. As shown in Figure 7.10, decreasing the subsidy limit results in worse outcomes for hydrogen transition in the region under the collective investment scenario. Compared to the original 500 kW figure, the average hydrogen share drops by 4 points when the minimum subsidy limit is set to 300 kW. Conversely, in the base scenario, where only individual attempts are considered, the hydrogen share increases by 3.5 points when the minimum capacity condition is relaxed (lowered).

The general expectation from such government support—relaxing subsidy conditions to make them more accessible—would be a behavior similar to that seen in the base scenario, represented by the blue line in Figure 7.10. More companies, despite having smaller plans, would have the opportunity to initiate their own projects if all other conditions are met. However, the improvement is limited to an increase of 3.5 points when the 300 kW limit is used and still cannot outperform the collective scenario's performance.

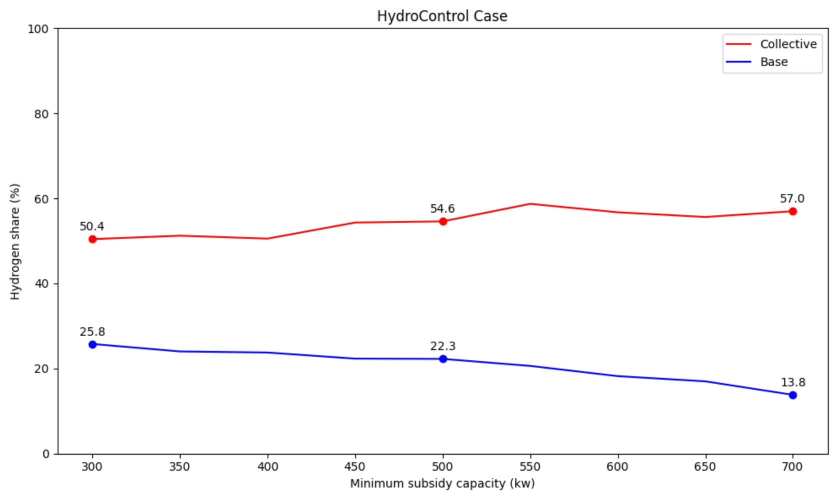


Figure 7.10: Average hydrogen share by varying minimum subsidy capacity limit

Figure 7.11 illustrates the reduced share of restrictions due to subsidy capacity compared to the HydroControl case shown in Figure 7.9. The average proportion of restrictions due to subsidy capacity decreased from 73% to 65% of all individual trials. However, limitations due to economic feasibility increased their share, becoming the new limiting factor for further improvements.

Figure 7.10 demonstrates the contrasting behaviors between the base and collective scenarios. The red line representing the collective scenario has a positive slope, while the blue line representing the base scenario has a negative slope. This reveals important insights into the use of such a government intervention tool. Easing eligibility conditions encourages a wider range of individual attempts, thereby reducing firms' dependency on others and cooperation within the region. Although this approach may initially appear more inclusive, supported by an increase in individual investments, it actually fosters individualism and overshadows the greater benefits that could be achieved through collective investment. In other words, this intervention could be misleading and create an illusion of progress.

Conversely, tightening the conditions by raising the barrier to entry has the potential to yield better results. As shown in Figure 7.10, increasing the minimum limit from 500 kW to 700 kW results in an increase of around 2.5 points in the average hydrogen share. This suggests that stricter subsidy conditions may promote more effective collective investments, leading to better overall outcomes.

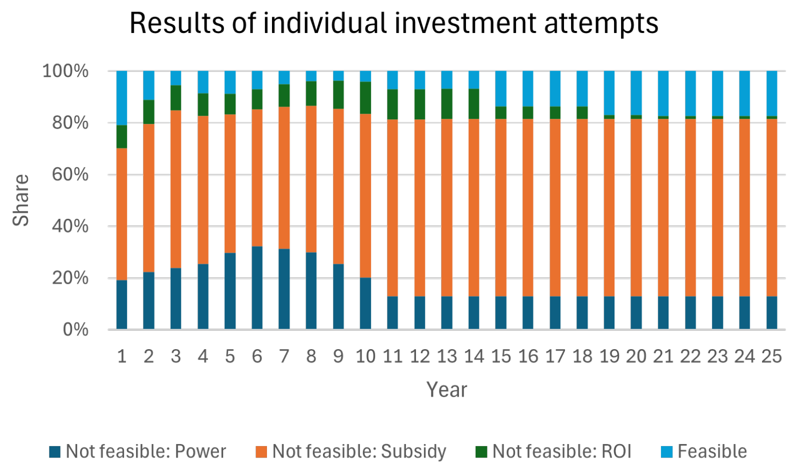


Figure 7.11: Results of individual investment attempts with minimum subsidy capacity limit = 300kw

Changes in the total cost per kWh of hydrogen consumed in the region also provide crucial insights into the impact of the intervention. Using the cost for the 500 kW setting as a reference, Table 7.4 illustrates the changes in cost. In the base case, where only individual attempts occur, lowering the minimum subsidy limit slightly reduces the cost per kWh compared to the reference case. Conversely, increasing the limit produces the worst results due to a significant reduction in the hydrogen share.

The cost changes in the case of collective investment better reveal the hidden major damage to system costs. Alongside the 4-point decrease in hydrogen shares with the lower minimum subsidy, the system cost per kWh of hydrogen consumption increases by 14.5%. This reflects the opportunity cost of shifting more towards individual investments. As argued, increasing dependency and the need for cooperation between companies contribute positively to the hydrogen share, as shown in Figure 7.10, and reduce the unit system cost by 41%.

Table 7.4: Change in system cost per hydrogen consumption under different minimum subsidy capacity scenarios (500kw costs are taken as reference) for HydroControl case

	Change in system cost	
Minimum subsidy capacity limit (kw)	**Base**	**Collective**
300	-1.7%	14.2%
500	0.0%	0.0%
700	19.5%	-41.0%

The same experiment was conducted on three other sectoral configurations from the previous study. For the HydroLow and HydroModerate cases, where the share of hydrogen-dependent sectors is the lowest, the experiment resulted in behavior similar to a non-collective investment setting, as indicated by the blue line in Figure 7.12. As the minimum subsidy capacity increases, individual plans shift towards collective investment due to the increasing interdependence of companies. However, a detailed analysis revealed that efforts to form a community, even with high initial participation, often result in most potential members withdrawing due to high economic expectations. This confirms that the collective action has only a marginal contribution in the HydroLow and HydroModerate cases.

Therefore, despite the increase in interdependency with a higher subsidy limit, it is not economically viable for companies in these regions, which are less dependent on hydrogen and thus expect higher economic returns from such investments.

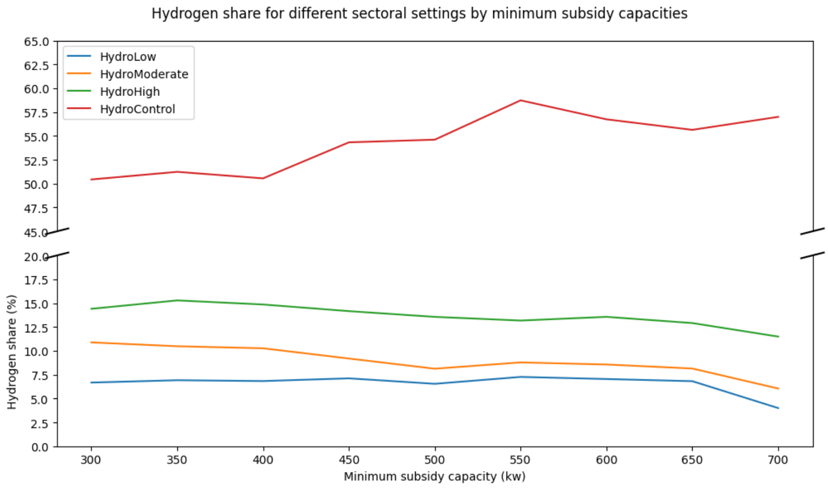


Figure 7.12: Effect of minimum subsidy capacities on average hydrogen share under collective investment of different sectoral configurations

Although the negative slope of the lines in Figure 7.12 was previously associated with the behavior in the baseline scenario for HydroControl, the collective scenario also exhibits this behavior in the HydroLow and HydroModerate cases, as it fails to generate significant added value compared to the baseline scenario. This negative slope is related to the sectoral settings in a region. As the share of hydrogen-dependent sectors in the region increases from HydroLow to Moderate, High, and Control, the negative slope of the lines in Figure 7.12 gradually shifts to a positive slope in the HydroControl case. This indicates that increasing the minimum subsidy capacity starts to yield more favorable results in terms of the regional hydrogen share as the proportion of hydrogen-dependent sectors increases in the region.

7.4. Validation of the model results

7.4.1. Validation by literature comparison

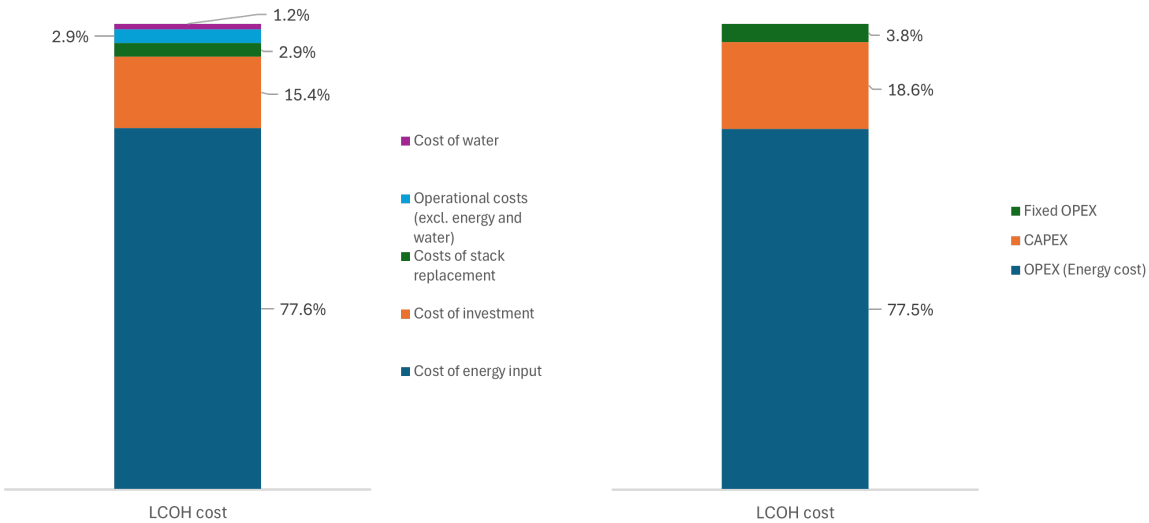
The academic literature can be reviewed to support the validation of a research. The confidence in the model outcomes is increased by the similar conclusions that have been reached through other types of research and models. An increase in model validity can be asserted when a course of action suggested by the built model is consistent with an existing theory or published case studies [82].

An important validation for the study is that the simulation model produces consistent results with the term "launching customers" referred in analysis of HyDelta national research programme [27]. The term describes either large industrial plants or groups of smaller plants that can act as accelerators for hydrogen uptake in a specific region. Launching customers are deemed essential for establishing hydrogen value chains and act as an intermediary for various end-users to access the infrastructure [118, 27]. Furthermore, techno-economic studies predict that launching customers will expedite the development of cost-efficient transport infrastructure at both national and local levels. Building on these insights, the concept of local collective pipeline users is regarded as promising and to be deserving significant policy consideration [39].

The results of the simulation model, particularly from the first and second experiment with the introduction of collective action and application to different sector configurations, demonstrate a similar impact as the launching customers. Although detailed in Chapter 7, the simulation model outcomes emphasize the significance of several small customers that operate in highly hydrogen-dependent sectors acting as launching customers in their region. This is accomplished by the primary off-taker sectors' more consistent participation on community formation process, thereby increasing the economic and technical feasibility of investments for all other end users. The contribution of collective investment to regional hydrogen off take performance is shown to increase non-linearly as the share of hydrogen-dependent companies with "launching" effect increases in the region.

Regarding the methodology used in building the conceptualized model, recently published HyRegions [31] study follows similar methodological steps in its investigation for the potential regional hydrogen infrastructure developments in the Netherlands. HyRegions study also focuses on Cluster 6 companies, however, only includes large gas consumers which have annual consumption of more than 1 million m3 in its scope. With a more comprehensive techno-economic analysis, [31] foresees a pipeline based roll-out for the hydrogen transportation for regional demand, and utilizes current natural gas consumption as proxy for the heat and hydrogen demand. Furthermore, the concept "sectoral hydrogen dependency" used in the thesis project directly matches with the term "virtual willingness to pay" used in [31] which is a sector categorization to reflect a sectors' potential to use hydrogen and categorization is similarly based on the process temperature requirements of the sectors to a large extent with an addition of sectoral expertise. This link established between temperature requirements and willingness to pay in [31] also validates the methodology used in thesis for determining company's expected return on their investments.

On the other hand, same study rules out the possibility that regional hydrogen production development can be a driving force for the infrastructure development and leaves stand alone production potential out of the scope. It draws attention to the fact that many standalone projects mentioned in [27] have not yet been realized, and views their likelihood of success as low. The main arguments for this reasoning are stated as grid congestion and the uncertainties about cost and subsidies, which are in line with the main pillars of the problem formulation in this research. Therefore, the insights from the thesis project becomes more relevant for the ongoing conflicting discussions on the topic.



(a) Breakdown of LCOH, adapted from [104] **(b)** Breakdown of LCOH, simulation model

Figure 7.13: Comparison of LCOH Breakdown

Secondly, the accurate representation of the hydrogen production cost breakdown is an important indicator of model's validity. In studies addressing the levelised cost of hydrogen (LCOH) [119, 120, 104, 121, 122, 123, 124], the fact that operational costs constitute the largest portion of the total cost and electricity price forecasts are external inputs to the studies makes cost calculations and consequently the economic feasibility of hydrogen investments sensitive to assigned values. Therefore, close representation of the cost breakdown is valuable for the study results. In Figure 7.13, examples from several agent's cost calculations for an individual electrolyzer investment (Figure 7.13b) demonstrated similar cost distribution analyzed in the literature (Figure 7.13a). In the study, the cost elements are detailed less, with more focus on the main contributors. However, when the cost components are grouped together to have the same rough breakdown as in the model, results become sufficiently close to each other. The contribution of OPEX from energy consumption is well reflected in the model, while the CAPEX cost share is slightly higher. This effect can be attributed to the smaller-sized electrolyzers used in the model, which have a more expensive unit capital investment cost, thereby increasing the share of CAPEX in the cost breakdown.

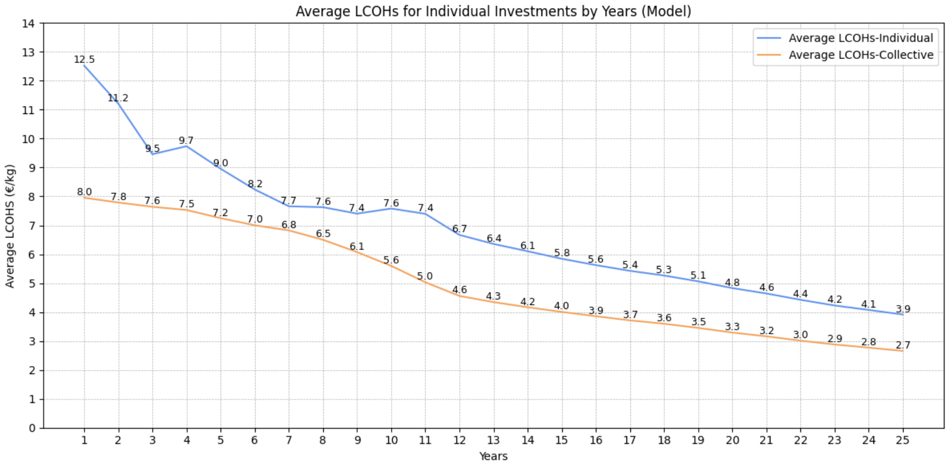


Figure 7.14: Average LCOH development in the simulation model over the years

Another validation is possible by comparing the average LCOH calculated in the model with figures from the literature. The average LCOH values calculated by agents in the simulation over the years are shown in Figure 7.14. As seen in Table 7.5, LCOH figures from publicly available sources show significant differences among themselves, possibly due to variations in electrolyzer capacity, cost of power source, location, and case-specific costs. TNO's most recent analysis [119] with the proposed electrolyzer projects in the Netherlands presents LCOH figures ranging between 9 and 16 €/kg. Therefore, it is reasonable to state that the average LCOH figures calculated by agents in the simulation model (see Figure 7.14) are consistent and within the ranges of the most recently published sources (see Table 7.5).

Table 7.5: Comparison of LCOH figures from publicly available sources with simulation model's LCOH calculation, adapted from [119]

Source	Reference year	Unit cost of capital (€/kwe)	LCOH (€/kgH2)
Simulation model	**2025**	**3676-4634**	**8 - 12.52**
TNO (2024) [119]	2023	3050	13.69 (9-16)
EU Hydrogen Observatory (2024) [122]	2022	1250	7.87
Berenschot & TNO (2023) [120]	2023	2200	12.14
Wood Mackenzie (2023) [121]	2023	1820	6.72
Umlaut & Agora Industry (2023) [124]	2023	1200	5.98
CE Delft & TNO (2023) [123]	2030	1710	8.3

As Table 7.5 shows, the resulting unit cost of capital figures in the simulation model are higher than those in other studies. However, it should be noted that the electrolyzer capacities used in the model are smaller compared to those in other studies. This is due to the smaller size of the companies and their demands, resulting in higher costs per kW for small-sized electrolyzer investments.

7.4.2. Expert validation

In agent-based modeling, expert validation is the most frequently employed method [82]. Collaboration with Stedin has provided access to expert opinions and supervision throughout the research. The participation from both technical and institutional experts during the model-building phase has enhanced the detailing of agent behaviors, system dynamics, and the model's suitability for its intended applications.

Regular discussions on the conceptual model helped to integrate different views and enhanced the model's applicability for the study. Among the numerous examples, expert validation meetings on the conceptual model in progress have contributed to the concepts such as:

- **Electrolyzer capacity calculation:** Initially, the approach to electrolyzer capacity calculations focused solely on hydrogen production during the power sources' available hours throughout the year, neglecting the higher hydrogen production needed during working shifts. Consequently, with more emphasis on companies' need for supply security, the methodology was revised to account for higher production capacity to meet the demand during working hours.
- **Effective capacity calculation for solar generation:** Discussions highlighted the need for a higher level of detail when incorporating installed solar capacities into the system. Peak power capacity figures were adjusted based on the availability of solar generation per month.
- **Gradual/modular growth of hydrogen demand:** Initially designed transition pathways for the companies were including either hydrogen blending into current natural gas consumption up to certain level or full conversion of the whole operations. However, experts' past experience revealed the possibility of more intermediate steps through the gradual conversion of production lines or modules in industrial applications, an approach not encountered in the reviewed articles which is likely due to the recent nature of these developments.

Furthermore, expert validations highlight the critical assumptions in the modeling process, where sound arguments and justifications are most needed when interpreting the results.

8 Conclusion

The research aims to bridge the knowledge gap in hydrogen adoption from the demand side, particularly focusing on its role as a natural gas substitute. It centers on the challenges encountered by smaller users, such as those in Cluster 6, who struggle to keep pace with infrastructural developments. It highlights the lack of understanding regarding collaborative efforts through clustering and the creation of hydrogen-based industrial community energy systems (CES). The distinct nature of these systems compared to existing CES formations, including differences in process heat requirements, higher asset specificity, investment costs, and evolving support mechanisms are touched upon in the study.

The research seeks to explore how collective action might overcome technical, economic, and institutional challenges for dispersed, smaller hydrogen users with varying sectoral dynamics, aiding their transition to hydrogen. Ultimately, it aims to provide insights into the necessary conditions for successful demand off-take and efficient regional infrastructure development.

Using a modeling approach and agent-based simulation, the research examines the emergent system behaviors among industrial actors as they interact, share resources, and plan collective investments in hydrogen production. The modeling effort seeks to identify and represent the key real-world concepts related to hydrogen off-take among industrial players. The simulation model enables a comparative analysis of system behaviors under different organizational principles, agent interactions, and government policy interventions, evaluating the relative impacts of these actions within the current technical and institutional constraints faced by industrial customers.

8.1. Answering the research questions

Which group of industries (actors) and purpose of hydrogen use should be the concern of the regional hydrogen off-take?

Based on desk research, two most prominent use of hydrogen among industries are identified to be for heating and as feed-stock. Chemical industry takes the lead in hydrogen use as feedstock, and especially for the projects involving stand alone production feedstock users become more prevalent due to the highest purity requirements. However, as far as regional development is of concern with Cluster 6 companies, such demand nearly does not exist.

For process heating, hydrogen substitutes the natural gas combustion and offers important emission savings to the companies. Furthermore, hydrogen purity requirement is low compared to feedstock or mobility use cases since the heat from hydrogen combustion is the main concern. This makes the hydrogen use for process heating also suitable for a future connection to nation-wide hydrogen network considering the purity level in pipeline will be at a determined standard and moderate value for all users.

Among many mentioned factor the temperature needs of the processes becomes the dominant factor for hydrogen use in heat applications. Although there is not a hard rule for categorization, based on reviewed literature, temperature ranges can be set for low, medium and high temperatures as 0-100, 100°C-500°C and >500°C, respectively. Technically, hydrogen technology is capable to offer zero-emission solutions for all temperature levels. However, competitive advantage of hydrogen use stands out for mainly medium and high temperature processes where decarbonization options stay limited to types of green gas. Whereas, low and parts of the medium temperature processes are offered by more variety of technologies that are not centered around hydrogen. Therefore, the suggested categorization is used in the study as a proxy for sector's willingness to take part in the development of regional hydrogen value chain.

It should be noted that the specifics of industrial hydrogen use potential can vary greatly depending on different processes in the same industry. This variance tends to increase as the temperature levels decrease. Nevertheless, a significant part of metal, cement, ceramic and glass industry processes operate with the high temperatures (more than 500°C) and this increases hydrogen's potential for the sectors, thereby making them important potential off-takers in their region. Chemical, food and paper sectors are the main players of medium heat temperature processes and agriculture, textile and wood industries operate with relatively lower temperatures for which hydrogen is not prioritized as a transition pathway.

Although certain sectors stand out to be main potential off-takers for hydrogen, the study followed more inclusive approach towards low and medium temperature sectors. As the recent government policy trends show, pressure for decarbonization grows for instance for agriculture with the removal of energy exemptions. For low and medium temperature sectors, this could create a push for decarbonization via electrification, however, availability of electricity grid capacity starts to become relevant in this case. Depending on the severity of the grid congestion, companies waiting for connections, and the need for operators to upgrade the grid could result in suboptimal societal costs. In terms of natural gas consumption volume, these sectors are still significant users of the natural gas grid and this makes them important stakeholder of a successful hydrogen infrastructure development in their region. Their participation can have a great influence on the regional hydrogen off-take by reaching to higher regional demand volumes and ultimately benefits their operations as well.

To summarize, hydrogen's competitive advantage in high temperature heating processes better addresses transition of sectors such as metal, cement, ceramic and glass which could be considered as off-takers in their regions. Sectors that are not typically expected to be actively involved in hydrogen plan due to the low-temperature requirements are also included in the study. Their reliance on natural gas and its infrastructure is substantial, and the feasibility of alternatives like electrification is under risk by infrastructural constraints. Consequently, these sectors are also included in the research and viewed as secondary off-takers in the regional hydrogen roll-out with their relatively lower motivation for hydrogen transition.

What are the limitations that collective action could address to scale up the regional hydrogen transition?

The literature review identified four main limitations that collective action can address, as summarized in Figure 8.1.

One factor affecting the technical feasibility of an electrolyzer investment plan is the power supply for hydrogen production. Considering the continuous need for heating in industry type applications, constant supply of the fuel is essential. Especially, cases of high reliance on intermittent renewable power sources puts the supply under risk or necessitates other precautions such as large storage capacities. Dependency on more stable power supply from electricity grid is often sought for by stand alone project initiatives in the Netherlands. The practices such as group-ATO contracts and cable pooling applications offer benefits for participating group of companies to more efficiently use the available grid capacity by pooling of individual connection capacities. In such applications, system operators act as independent party which only approves the technical feasibility of the request, however, the contractual agreements taking place between companies are the product of collaborative action and companies' initiatives. Companies which are under utilizing their contracted capacity during the year or have still room to grow in their physically allocated capacity by contracting for more capacity can offer the capacity to realize the planned collective investment. Furthermore, such collective action also benefits participants who are not allowed to feed-in their overproduction from their energy generation. Therefore collective action increases the net capacity that collaborating companies can act more flexibly with their power supply needs.

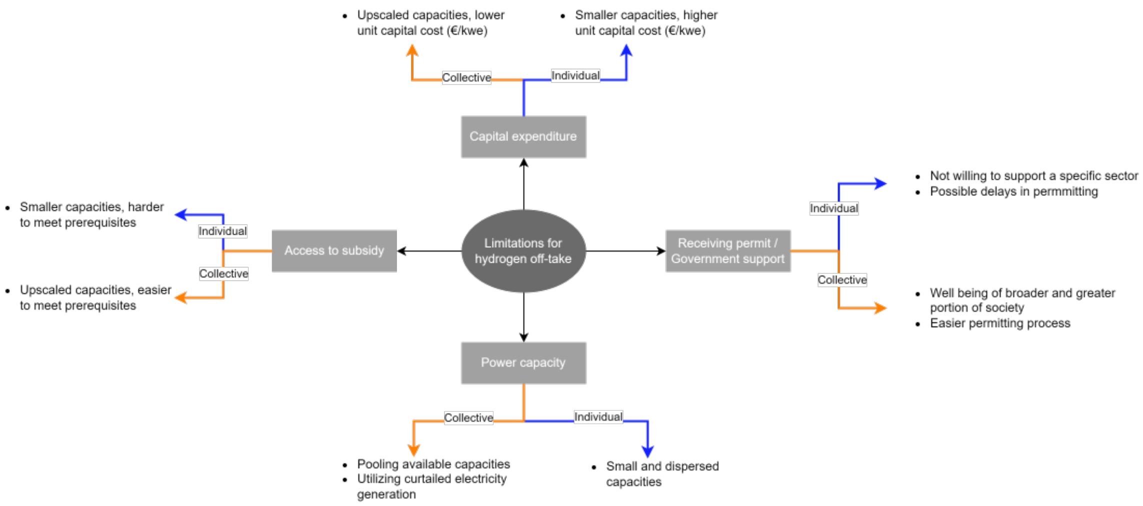


Figure 8.1: Limitations that collective action has potential to address

Based on realized projects and literature review, following the operational cost from energy consumption, capital cost of investment is reported to be constituting 15-18% of the LCOH in hydrogen production. The fact that downpayments are paid within shorter periods compared to longer operational period increases the financial risks on investor. The effect of economies of scale on the unit cost of capital and economic feasibility of electrolyzer investments is quite evident from the reviewed literature. Analysis of the most recent studies shows LCOH figures ranging between 6-14 €/kgH2. Together with the energy price, capacity of the investment is among the main reasons for this considerable variance in resulting LCOH of real projects or analysis. Doubling the electrolyzer size around 100 MW capacity levels is estimated to have around 14% saving on the cost per kwe installed. Furthermore, literature demonstrates a decrease in the marginal benefit of upscaling as the capacities get higher. Electrolyzer capacities considered for the smaller companies within the scope of the study ranges between 0.5-1.5MW and consequently offer higher marginal gains for a potential upscale in the capacity. Therefore, hydrogen demand of participating companies pooled under collective action could indeed make significant improvements in the economic feasibility of projects especially considering the smaller individual scales compared.

Another benefit of production capacity pooling is evident in the subsidy application process where the collective action can allow much smaller production plans to be realized by making them part of a larger final electrolyzer investment which is able to meet minimum capacity limits for subsidy application. This in fact could invite into collaboration the companies whose intention is only testing and experimenting with the hydrogen in their processes as an initial step, and realize it as part of a larger system. Furthermore, SDE subsidy scheme allows the application via partnerships and facilitates the procedural process for such actions.

The literature review showed that the number of companies participating in the project and the diversity of sectors involved are observed to be critical for developing strong relationships with local governments by spreading benefits to larger and more diverse parts of society. Therefore, while individual projects face the highest probability of delays due to their minimal societal benefit (involving only one company and sector), a formation where all companies join and maximum sectoral diversity is achieved would encounter the least barriers in terms of permitting and delays.

Final contribution of a collective action is anticipated to be in permit receiving phase. Cluster strategy reports and standalone initiatives highlight the importance of sectoral diversity and size of the participation for smooth permitting processes due to its expected contribution to create stronger relationships with local governments, better emphasize the larger societal benefit.

How can the key components of a system of regional hydrogen off-take among industrial actors be modeled?

The concepts for modeling regional hydrogen off-take by industrial actors' initiatives are organized into three main categories. During the project planning phase, the impact of sectoral hydrogen dependency and the progress of hydrogen transition in the region are considered when determining the volume of hydrogen production in project plans. Additionally, the modularity of companies' production processes is used to simulate a gradual transition to hydrogen. Moreover, the decision to rely on local production or to purchase hydrogen is incorporated into the model, linked to concerns about supply security and the initiation of expressions of interest within the region. The choices made during model conceptualization result with limitations in reflecting the variety of factors which are actually playing role in hydrogen transition plans. These are pointed out in the limitations and future work sections of the report.

Following, the feasibility of the planned project is checked from the perspective of three main painpoints which are power availability (technical), subsidy eligibility (institutional) and economic feasibility. Economic feasibility is examined more in depth with costs such as capex, opex for electrolyzer investment, hydrogen purchase and hydrogen equipment investment and benefits such as avoided cost of natural gas, CO2 tax and expected cash flow from subsidy.

Lastly, subsidy application process is included in the simulation model due to its critical role in project realization and problem situation. Furthermore, decision to give access to the national backbone is based on the hydrogen production volume reached in the region. Such concepts are established from the current outlook in hydrogen rollout and perspectives of companies who are the participants of current hydrogen initiatives.

Agent-based modelling facilitated suitable ground for simulating the interactions between agents and their environments based on main building blocks of the real life processes. Model building constituted the majority of the efforts in the research. Dynamic nature of the modelled environment and vast variety of factors influencing the decisions and processes were the most significant challenges complicating the modeling process. Furthermore, the fact that the spread of the technology being relatively limited results with the lack of understanding the decision rules of actors. The modeling effort in the research and the methodology used in representing real-life processes have laid an important foundation for future work in this field.

How does the availability of collective investment options affect the regional hydrogen off-take?

The simulation model results demonstrated that collective investment plays a crucial enabling role in achieving a full transition in the regional as a whole. Individual efforts by a few companies may prove insufficient, especially when the region is expected to meet a production volume as high as half of the total energy demand, as outlined in the model.

When we resemble the baseline scenario to the present situation where industrial players rely solely on their own capabilities without collective action, progress tends to plateau with the efforts of off-taker sectors and fail to trigger other players into transition. This current scenario not only hinders the region's overall decarbonization but also disrupts the full transition plans of off-taker sectors that rely on a backbone supply, which proves ineffective.

Collective investment has shown potential to break this deadlock, more than doubling the progress achieved by individual efforts. By leveraging economies of scale through upscaling electrolyzer capacities, the cost of transitioning one unit of the region's demand decreases by approximately 42%, and the utilization of available electricity grid capacity in the region increases by 68%. Therefore, collective investment not only facilitates a full regional transition to hydrogen but also accomplishes it with significantly lower societal costs and without disrupting power systems. In fact, it enhances the efficiency of existing redundancies in the electricity grid capacity, which is a critical resource in the Netherlands, making the transition smoother and more cost-effective.

Due to power capacity and subsidy access limitations, collective investments formed by companies working together account for approximately 70% of successful transitions. This community formation arises naturally from the interdependence of companies facing these constraints. When these efforts fall short of reaching the threshold as whole region, coordinating the plans of all companies in the region—whether individual or collective—under a unified strategy proves crucial for successful transitions. This highlights the importance of regional actors communicating and collaborating rather than working in isolation, contributing to 30% of successful transitions.

Simulation runs that achieved successful regional transitions in a more delayed manner compared to others reveal a common characteristic of having a higher prevalence of individual investments in hydrogen development. This indicates that achieving the desired regional performance becomes more challenging when growth trends are predominantly driven by individual investments. Conversely, growth scenarios dominated by collective investments yield earlier and more effective results. When the participation of sector groups with less willingness to transition is necessary to achieve the expected hydrogen development performance at the regional level, an investment environment driven by individual initiatives hinders the inclusion and participation of these other sector players in the transition process. Reaching the expected levels of regional hydrogen development with slow steps and delays results in the suboptimal growth of regional hydrogen infrastructure, as mentioned in the problem formulation, leading to investments being underutilized for a longer period.

What role does sectoral configuration in the region play in the performance of regional hydrogen off-take?

The simulation results showed that the regions where so called secondary off-taker sectors have the majority in regional energy consumption are more prone to showing insufficient hydrogen transition performance. Since majority of the companies hold variety of options to transition their processes, creating an attractive business case becomes a dominant factor in hydrogen investment decisions. Efforts of few first off-takers in such regions may remain well below for reaching a threshold and incentivizing secondary off-takers into transitioning.

Availability of collective action outperforms an individual pathway in every sectoral configuration, however, its enabling effect diminishes with the increasing dominance of less motivated sectors in the region. Results of the simulation showed a non linear relationship between the contribution of collective action and presence of highly dependent sectors in the region. When collective investment is an option for the companies, regional hydrogen development increases exponentially as the number of hydrogen-dependent companies in a region increases. When these companies hold a sufficient enough demand volumes, thereby a transformative power, they are able to exert influence on the hydrogen offtake by creating favorable investment conditions for companies in other sectors as well.

The study highlights the importance of hydrogen dependent sectors which can also be called as "launching customers" in shaping regions' transition pathway. They act as the initiators of the transition by breaking the cold-feet problem for others, being active participants of collective investment plans. Their transformative power, which increases non-linearly with their size in the region, gives them the potential to exacerbate the contribution of collective investment.

This result highlights an important region characteristics when trying to anticipate and plan for future infrastructure developments and also to identify in which settings incentivizing a collective action have potential to materialize into a successful regional development

How do changes in current government support settings, particularly regarding subsidy eligibility conditions, affect regional hydrogen off-take?

Access to the subsidy has a pivotal role in realization of the hydrogen investments with its contribution to the economic feasibility. Hence, this makes it an integral part of the strategy followed in national hydrogen roll out plans. Baseline scenario used in the model experiments is well reflective of the formulated problem with high shares of failing individual investment attempts due to subsidy limitations. With the larger upscaled project plan capacities, this issue becomes less significant for collective investment.

Experiment results revealed two sided effect of minimum capacity requirement of subsidy on regional hydrogen developments. The general expectation or interpretation of reducing the minimum capacity requirements in subsidy applications is that it fosters a more inclusive approach, making smaller projects viable and providing investment opportunities to a wider range of companies. This strategy is effective in scenarios that rely on individual investments, as in the baseline model, but it can never match the performance of collective investment scenarios.

On the other hand, the policy of relaxing subsidy access can have an adverse effect in cases where collective action is essential, leading to a decline in regional hydrogen development. While it is true that easing eligibility conditions encourages a wider array of individual efforts, it simultaneously decreases firms' reliance on one another and weakens regional cooperation. This situation overshadows the greater contribution that could be achieved through collective investment. Consequently, rather than relaxing the conditions, increasing the entry barriers could have potential to yield better results by indirectly promoting collective action.

The same analysis with different sectoral configurations shows that the magnitude of this adverse affect observed with the collective investment scenario increases as collective investment has lots to offer in a region setting. In other words, in the regions where hydrogen dependent sectors' presence is higher, policy change towards relaxing the subsidy conditions has negative effect on the hydrogen off-take in the region. On the other hand, for the region settings where majority of sectors are considered as secondary off-takers, same intervention on subsidy relaxation promises better outcomes for the regional hydrogen off-take performance.

Main research question: "To what extent can collective action facilitate hydrogen off-take in regions where small-sized companies operate in diverse sectors and are located far from the planned hydrogen backbone?"

For the prescribed group of companies which falls under Cluster 6 in the Netherlands, hydrogen has a growing potential for decarbonizing the industrial heat use by substituting natural gas consumption. The technology offers solutions for all temperature ranges and diverse sectors, however, hydrogen's competitive advantage stands out especially in higher temperature heat processes, thereby distinguishing some sectors as primary off-takers of hydrogen. In order to integrate hydrogen use into these processes, collective action has potential to resolve the technical, economical and institutional issues that small-sized industrial heat users are experiencing by upscaling the size of transition plans, exploiting economies of scale, pooling power sources, having a more effective application for subsidy and permit processes. With these offerings, analysis shows that collective action becomes the enabler of the regional hydrogen transition. Next to the collective formation due to dependencies among companies, facilitating a unified approach in regional hydrogen demand planning also show important potential. Earlier and more effective hydrogen off-take is shown to be dependent on collective-intensive hydrogen growth trend that takes place from the beginning. Importantly, the extent of contribution of the collective action is highly dependent on the sector configurations in the region where its potential grows exponentially with increasing hydrogen dependency in the region. Policy tools such as subsidy prerequisites can be used to further improve the potential that collective action offers. Analysis shows that, for the regions that collective action offers a distinctive potential, policy changes to increase the entry barrier for subsidies have a positive effect on top of its promised effect.

8.2. Implications for system operators

The individual and collective investments studied in this research involve local-level hydrogen production and consumption, with assets either owned by one party or, in collective scenarios, by multiple parties. These initiatives do not imply that a connection to a larger network is not being considered. On the contrary, they are anticipated to serve as a foundation for building a hydrogen demand and market and consequently for future regional network connections.

The readiness of hydrogen demand poses significant infrastructure utilization risks in regions of Cluster 6. In larger clusters, even if a few companies fail to make the expected progress in transitioning to hydrogen, the accumulated demand is substantial enough that the infrastructure utilization is not severely impacted. However, for the regions in Cluster 6, when not all companies are willing to switch to hydrogen, or some require dedicated pipelines, or if industries change their minds about transitioning to hydrogen, the infrastructure developments are much more vulnerable to becoming suboptimal. Therefore, the collective action investigated under various sectoral configurations and policy applications in this study has demonstrated a significant contribution to the development of regional hydrogen production and consumption, setting the stage for further expansion. This approach offers a solution for timely and efficient infrastructure development by reducing delays in regional hydrogen development and minimizing uncertainty for system operators and companies.

It has been shown that while hydrogen demand growth through individual and independent efforts may appear promising, it carries the risk of companies not fully completing the transition. This approach could lead to either an incomplete or significantly delayed full transition. For system operators, this results in unfinished and inefficient infrastructure development. In contrast, collaboration initiated in the early phases promises a quicker and more reliable switch to hydrogen, ensuring comprehensive adoption across the region.

By using the arguments and insights from this study, system operators can engage with gas-consuming customers as advocates and mediators of collective movement. Considering the responsibilities and capabilities of system operators in the Netherlands, it would be beneficial for future research to explore the roles they can assume and the practical steps they can take in this guidance.

8.3. Recommendations

Designing region specific policy instruments

The sectoral configuration of a region significantly influences the extent and effectiveness of collective action contributions on hydrogen development. It is recommended to assess regions' potential by their sectoral configurations, categorize and create zones depending on the presence of highly hydrogen dependent sectors in these regions. For the regions where collective action could create a considerable impact, eligibility criteria for electrolyzer subsidy applications could be set higher which indirectly encourages companies to start regional collaboration among themselves. Having the pressure from rising emission costs and urgency of decarbonization from one side and high entry barriers for the government support could lead companies to pool their resources and form larger, subsequently more economically viable projects. At the end this helps to avoid partial, tentative switching behaviour from the region spread over longer time periods. From the perspective of infrastructure development, this gives opportunity to the emergent behaviour of all at once switching, thereby decreases the exposure time of underutilization risk on the investment. Otherwise, such regions with higher hydrogen dependency have tendency to show individual and independent hydrogen development pathways. Although this situation may present itself as a positive and promising outlook, it might cause missed opportunities with more inclusive transition with collective action, causing delays and risk of not reaching full transition at region level.

Increasing awareness in the region regarding each other's transition plans

Realizing a collective action over a hydrogen production project requires much more meticulous steps and higher level of collaboration than forming a community energy systems for electricity generation and consumption. In case of electricity, negotiations and agreements take place on the already highly connected network open to use of all consumers of the network and asset specificity is at low levels. Meaning that already existing infrastructure does not become redundant in case of failing community formation, less demand realization or entry and there is high flexibility for participants' entry and leave to the agreed upon energy system. On the other hand, a hydrogen based community energy system presents highly asset specific characteristics. Since the existing gas pipeline infrastructure can not accommodate the flow of two different types of gas at the same time, decisions on switching to hydrogen by using existing pipelines shows dependency on other users of the same network. Building a new hydrogen pipeline network, on the other hand, dedicated for the use of community members is highly asset specific, specifically designed for a transportation purpose between fixed locations and carries the high risk of becoming obsolete. Therefore, the asset specificity arising from technical factors in forming a hydrogen based community energy system necessitates higher level of collaboration, communication and unified action. Creating platform/forums, and working groups via local governments where companies in the region, responsible system operators and hydrogen technology providers can communicate possible hydrogen investment plans is recommended to discover unnoticed potentials. The simulation results showed the success of collaboration arising from limitations but also pointed out to the effect of sharing and communicating plans with each other rather than following an individual and independent path.

From the perspective of transaction cost theory, the collaboration could give participants upper hand by reducing search and information, bargaining costs with technology providers. However, it should also be noted that the complex agreements, and governance structures or the risk of opportunistic behaviour potentially increases the transaction cost and requires attention in forming such collaborations.

Promoting collaboration and inclusiveness

The study results highlighted the significance of primary off-taker companies as launching customers in their region, but it also revealed the dependency on other sectors' participation to complete a full transition. Therefore strategic plans should not disregard the secondary off-takers but promote plans that includes more diverse set of sectors. Other than the subsidy tools given to the investments, advantageous support schemes for collective investments, support with transportation needs in collective pipelines, tax breaks, grants, or recognition programs could be conducted. Highlighting the societal benefit of following more inclusive approach for getting over the hump for future pipeline connections to the region can be an effective strategy.

8.4. Limitations and future work

As explained in detail, conceptualized model builds on several assumptions to represent the reality due to the time and scope limitations of the research. More detailed approach to increase the accuracy of the processes could enhance the validity of the results. While conducting cost benefit analysis, involving the cost of water and revenues from by-products of oxygen sale, the costs of increasing contracted capacity in electricity grid, financing cost of the investment, and transportation cost. One limitation of this study is the exclusion of the transportation cost from investment decisions due to its highly complex nature. Next to the agreements on developing the hydrogen demand, feasibility of existing pipelines, needed transportation capacity should be integral part of the investment decisions in the future research. Furthermore, supply options given to the companies are limited to production via electrolyzer investments and purchase from pipeline supply, when realized. However, other supply options via tube trailers, LOHC trucks are also possible and could serve as a temporary mean of transportation during transition period. Therefore, future research could investigate the effect of other procurement and transportation methods on the development of demand in the region.

Another important limitation of the research is the reliance on few number of factors in shaping agent's decisions into hydrogen transition determining economic expectations from an investment. Currently their processes' dependency on hydrogen and regional hydrogen transition performance factors are utilized to reflect technical and social perspectives of giving a decision. Further research into the other factors affecting hydrogen use across different sectors, such as the availability of hydrogen burners, compatibility with existing processes, investment cycles could improve the representation of the reality.

The research misses the important inputs that companies themselves can provide in planning for their transitions such as cultural, behavioral, inter-company dynamics, perception of risks, expectations of return etc. Especially regarding the electrolyzer capacity calculations, simulation model follows a simplistic approach. However, in reality companies could position themselves to strategically increase the electrolyzer capacity to be eligible for a subsidy application or utilize the electrolyzer capacity at different rates during the year depending on the availability of renewable power. Future research could expand the investigation via interviews with actors from different sectors and identify underlying driving forces for planning a transition. This approach could also pave the way for applying relevant theories from the literature about decision making of actors and better use of the academic body of knowledge.

Current study is devoted to an investigation about realization of a decarbonization pathway with hydrogen. With the estimated decrease in renewable electricity price, and improvements in the technology and efficiency, it considers a future with widespread use of hydrogen as optimal scenario and investigates a more efficient and convincing way to reach to that objective. However, future research could also investigate the relative value of collaboration on hydrogen-based solutions in a larger set of options with other alternative decarbonization pathways for low and medium-temperature processes and assess their comparative performance.

The study draws attention to the possible use of subsidy policies to steer companies into a collective action. Understanding the synergies and effects of other policy instruments, such as tax incentives, and regulatory measures on promoting collective action could be the topic of future research.

Furthermore, in the study, one region is selected as case study and model is calibrated accordingly. The different sectoral configurations used in the second experiment are applied on this calibrated model with same companies and conditions. This methodology still gives important insights by asking what if the sectoral configuration was different when all other conditions are same. However, different characteristics in terms of gas consumption and power capacity distribution among companies could affect the results. The future research could apply the same effort of model calibration and experimentation on each case study separately and reach more generalizable insights.

Moreover, permitting process is identified in the literature review as a limitation that collective action could contribute positively. However, due to increasing modelling complexity, it is not included in the conceptualized model. Its possible delaying effect on the project realization could be integrated in future research.

It should be noted that the study builds on many assumptions and simplification of the real decision making process of the companies and events occurring in the simulation environment. The effort is made to represent the most relevant concepts as accurate as possible. The methodology followed in the research that starts with a base model and builds the experiments on top of each other provides a suitable ground for comparative analysis and insight generation. Therefore, all inherited limitations being valid for every step, relative changes in the model outcomes with respect to different experiment conditions delivers the main message of the research.

8.5. Use of artificial intelligence in the research

The integration of artificial intelligence, particularly ChatGPT, in academic research has become increasingly valuable, offering researchers efficient tools to enhance various aspects of their work. In the context of this thesis project, AI was instrumental in optimizing the research process, enhancing the quality of the report, and assisting with the use of specialized software and platforms.

One of the primary ways ChatGPT contributed was by refining the flow of sentences and enhancing the clarity of the report. By providing more appropriate and academically sound vocabulary, it enabled to convey ideas more effectively. The interactive nature of the tool allowed for the explanation of the intended meaning, giving guidance to the rephrasing process and reducing the likelihood of misunderstandings. The tool also highlighted potential ambiguities in explanations, allowing for the correction of possible misunderstandings. Moreover, AI was used to paraphrase text from references, helping to integrate external information into the thesis with precision. With its holistic approach to paraphrase texts rather than word by word paraphrasing as in several other tools, artificial intelligence offers more effective results. By providing detailed, sentence-by-sentence and sometimes word-by-word guidance, it was effectively utilized to incorporate information from other sources with precision.

Additionally, ChatGPT was instrumental in assisting with the use of software and platforms such as Python and Overleaf, which were essential for visualizing data, presenting analysis results and formatting the report. While Python offers extensive options for data visualization, it can be challenging to learn the syntax and specific commands required for complex plots. Upon providing detailed descriptions of the envisioned plots, ChatGPT generated the code necessary to create those graphs. Although achieving the desired results required several hours of iterative refinement, the use of artificial intelligence significantly reduced the time required to learn the syntax of Python and its associated libraries, as well as the specific code needed for different types of plots. Similarly, ChatGPT facilitated adjustments in LaTeX formatting, enabling me to implement specific features in Overleaf that were otherwise difficult due to unfamiliar syntax.

The tool also proved invaluable in providing a quick grasp of a new analysis technique, including its applications, advantages, disadvantages, and appropriate conditions for their use. In the course of the thesis project, familiarizing oneself with new methodologies, frameworks, and analysis types and selecting the most suitable approach for the research can be time-consuming. ChatGPT significantly reduced this time, enabling faster decision-making and allowing focus on the most relevant parts of the literature, rather than spending excessive time skimming through and eliminating less significant options.

Approximately 95% of the AI's contributions fell within the realms of text refinement and technical support via software and platform use. Given that the core of this study focused on the conceptualization and application of agent-based modeling, ChatGPT's direct involvement in conducting research was minimal. Its methodological contributions were limited to a few instances since the methodological steps were straightforward and not dominated by novel frameworks. However, the AI's role in improving the text quality and enhancing the presentation of findings through clear language and effective visualizations was significant.

In conclusion, the use of artificial intelligence in this thesis project was instrumental in saving time, improving the quality of deliverable, and supporting the effective use of softwares and platforms. While the AI's role in the research itself was limited, its contribution to the overall presentation and clarity of the work was indispensable.

A wise integration of AI in academic research highlights how this rapidly expanding technology can effectively enhance and complement traditional research methods. By saving time and allowing scholars to focus on the more valuable aspects of the research process, AI makes complex tools more accessible, increasing efficiency and ultimately contributing to more impactful academic work.

9 Discussion

9.1. Perspective from transaction cost theory

Williamson's transaction cost theory focuses on the costs associated with economic transactions and the implications these costs have for the structure and organization of firms. The theory highlights understanding and managing the transaction costs, ensuring appropriate governance structures, addressing opportunism, and leveraging the collective expertise to mitigate bounded rationality and asset specificity challenges [125]. Besides collective action's contribution in principle to the limitations that companies are facing, better understanding of the economic rationale behind its organizational structures and the management of transactions is also highly critical conclude its economic efficiency. Discussing the possible implications of the theory's key elements in the context of community formation for hydrogen production enriches the outcomes of the research.

Transaction costs

Transaction costs are the costs associated with making an economic exchange and forming a community for hydrogen production involves various transaction costs:

- **Search and information costs**: These are the costs incurred in finding and gathering information about potential partners, market conditions, and technologies. In business contexts, these might include costs related to identifying suitable suppliers, researching market prices, and understanding technological capabilities. In the context of collective action for hydrogen production, these costs involve identifying companies willing to collaborate, understanding their technological needs and capabilities, and gathering information about subsidies and regulatory requirements. By pooling resources and sharing information, the community can significantly reduce these costs, making it easier for individual companies to participate without incurring high initial expenses. However, there can be challenges in aligning the diverse information needs and interests of various stakeholders, leading to potential conflicts and inefficiencies.
- **Bargaining costs**: These costs arise from the process of negotiating and reaching agreements with other parties. This includes the time and effort spent on drafting contracts, negotiating terms, and reaching mutually acceptable agreements. Effective collective action in hydrogen production requires clear and efficient bargaining processes to ensure that all parties feel their interests are protected and that agreements are fair and enforceable. Developing standardized contracts and negotiation frameworks can streamline these processes and reduce individual bargaining costs. Nevertheless, the negotiation process can become complex and time-consuming, especially when there are many parties with differing objectives and priorities.
- **Monitoring and enforcement costs**: These are the costs associated with ensuring that all parties adhere to the agreements. This includes costs related to monitoring compliance, enforcing contractual terms, and resolving disputes. In the context of hydrogen production, this could involve monitoring production levels, ensuring compliance with safety and environmental standards,

and managing disputes. Collective action can help distribute these costs among participants and establish shared monitoring and enforcement mechanisms, such as joint audits and third-party verification, to ensure compliance and minimize individual enforcement burdens. However, there is a risk that some members may not fully comply with agreed terms, requiring additional resources for enforcement and potentially causing friction within the group.

Bounded rationality

Individuals and organizations may not be able to foresee all future contingencies and may make decisions based on incomplete information. The contracts between companies in the hydrogen community might have risk to be incomplete. The members cannot anticipate all future events and conditions, which could lead to the need for renegotiations and adaptations over time. To address this, the community can develop flexible contract frameworks that allow for adjustments and renegotiations as conditions change, ensuring that agreements remain relevant and fair over time.

Furthermore, companies in the hydrogen production community must make decisions with limited information and under uncertainty. This includes uncertainty about future hydrogen demand, technological developments, and regulatory changes. By forming a community, companies can share information and resources, reducing individual uncertainty and improving collective decision-making. Joint scenario planning and risk assessments can help the community anticipate and respond to changes more effectively. On the other hand, group decision-making can sometimes lead to slower responses to market changes due to the need for consensus and the potential for conflicting interests.

Opportunism

Opportunism refers to the cases where companies act opportunistically, taking advantage of incomplete contracts or unforeseen contingencies. For example, a company might underinvest in shared infrastructure or overuse shared resources. To mitigate this risk, the community needs safeguards such as clear contracts, regular audits, and mechanisms for dispute resolution. Establishing trust and ensuring transparency through regular communication and shared governance structures can also help reduce the risk of opportunism.

Asset specificity

Asset specificity refers to the extent to which assets can be redeployed to alternative uses without loss of value. High asset specificity implies that assets are tailored to particular transactions and cannot be easily repurposed. Hydrogen production infrastructure, such as electrolyzers and pipelines, is highly specific to hydrogen production and cannot easily be repurposed for other uses. This increases the dependency among community members and raises the stakes for each participant. High asset specificity necessitates a high level of commitment from all parties involved, as the value of these assets is significantly tied to the success of the hydrogen production initiative.

High asset specificity also increases the risks of underutilization if the expected hydrogen demand does not materialize. Collective action helps mitigate this by pooling demand and resources, making the investments more viable. By sharing the investment burden and risks, companies can achieve economies of scale and make the venture more financially feasible. However, the high level of commitment required can also be a barrier, as companies may be reluctant to invest in highly specific assets without guaranteed returns.

Frequency of transactions

Frequency of transactions refers to how often transactions occur between parties. Hydrogen production involves ongoing transactions, such as the continuous supply of electricity for electrolysis, the production and distribution of hydrogen, and maintenance of infrastructure. Frequent transactions strengthen the case for a collaborative governance structure to manage these interactions efficiently. The regularity of these transactions fosters interdependence and encourages long-term relationships among community members.

Uncertainty

The hydrogen market and related technologies are evolving, creating uncertainty about future demand, prices, and technological advancements. This uncertainty complicates investment decisions and contract formulations. Collective action allows companies to share the risks associated with this uncertainty and to adapt more flexibly to changing conditions. However, shared risks also mean shared vulnerabilities, and the failure of one participant can impact the entire group. Community formation can also provide a collective voice to advocate for favorable policies and adapt more effectively to regulatory changes.

The concepts from transaction cost economics provide a broader perspective beyond just the investment costs, subsidy cash flows, or avoided CO2 taxes when evaluating the costs and benefits of an investment plan with or without a collective action. Although, the integration of these considerations can increase the accuracy of the simulation, they were not incorporated into this study due to time and scope limitations. Future work could explore these dimensions in greater detail, increasing validity of the results with the integration of transaction cost implications.

9.2. Reflection

9.2.1. Academic reflection

Knowledge gap

This study adds a niche layer to the existing body of knowledge on hydrogen energy systems, particularly by highlighting the importance of collective action in regional hydrogen infrastructure development. It extends existing techno-economic research on hydrogen energy systems with a socio-technical perspective with a specific focus on small-sized companies in diverse sectors, which are largely overlooked in the literature. By identifying the sectors that most likely to benefit from hydrogen adoption and formulating the specific factors influencing their decisions, this research suggests an approach to assess the feasibility and impact of hydrogen in an industrial setting.

Methodology

The use of ABM provides a sophisticated way to simulate interactions among companies, allowing researchers to observe emergent behaviors and outcomes in a complex system. This technique allows for a detailed exploration of interactions between various stakeholders and offers a robust tool for future research in energy transition studies. The research reinforced ABMs' potential contribution as valuable tool for academic research about energy systems by showing its ability to incorporate various parameters and scenarios and enabling the exploration of different policy and market conditions.

Especially in hydrogen based community energy systems which is largely underexplored in the literature, this research constitutes a base for the use of modelling approach in such research domain.

Multi-perspective approach

The research integrates insights about energy systems from technical, economic, and institutional perspectives to provide a holistic view. By combining techno-economic analysis with socio-technical perspectives, the study sets a precedent for future research aiming to address complex, multi-faceted problems in energy transitions. The research framework followed in this study can be adapted to investigate other renewable energy technologies, providing a blueprint for comprehensive, multi-perspective studies.

Policy implications

The findings underscore the need for policy frameworks that promote collective investment and provide flexible, region-specific subsidy schemes. By demonstrating the importance of collective action and tailored subsidies, the study provides evidence-based guidance for developing supportive policy frameworks. This contributes to the academic discourse on how policy instruments can be designed to effectively support the transition to sustainable energy systems.

9.2.2. Societal reflection

Environmental impact

By focusing on facilitating the transition to hydrogen, the study supports efforts to reduce greenhouse gas emissions, contributing to global climate goals. The findings highlight how strategic collective action can accelerate the decarbonization of industrial processes, offering significant environmental benefits. The study underscores the role of hydrogen in sustainable industrial development, promoting cleaner production methods that have long-term environmental benefits.

Economic impact

The study illustrates how collective investment can lower costs and make hydrogen projects more economically viable, thus optimizing societal costs of decarbonization. With its implications on increased efficiency of infrastructure development, it offers significant savings on tax-payer funds allocated for infrastructure development.

Community and stakeholder engagement

The research emphasizes the importance of community engagement and multi-stakeholder collaboration. By involving a diverse range of sectors and companies in hydrogen projects, the study fosters a sense of shared responsibility and collective benefit, which is crucial for sustainable development. This can lead to stronger, more resilient industrial ecosystems where stakeholders are more invested in mutual success.

Social equity

Larger companies have more capability to cope with the risks and uncertainty of decarbonization. On the other hand, ensuring that smaller companies and diverse sectors have access to hydrogen infrastructure can promote social equity. The study's recommendations for inclusive policies and collective action frameworks aim to facilitate access to hydrogen infrastructure and clean energy technologies for small-sized companies, benefiting a broader segment of society. The findings also highlight the critical role of supporting small businesses in their transition to hydrogen for the benefit of the larger system.

9.2.3. Managerial reflection

Strategic planning

Industry managements considering to adopt hydrogen technology can leverage the insights from this study to inform their strategic planning to develop long-term strategies for integrating hydrogen into their operations. Understanding the benefits of collective investment can help them make more informed decisions about partnerships and identifying potential partners early on. Understanding the benefits of collective action can help decision makers allocate resources more effectively, prioritizing investments that offer the greatest potential for cost savings and efficiency gains.

The study could also provide input to strategic gas network investment planning of system operators. Better anticipating future demand or identifying potential areas to steer into social optimal could improve strategic planning processes.

Risk management

The study highlights the risks associated with individual investment approaches and the benefits of collective action in mitigating these risks. Decision makers can use these insights to develop more resilient investment strategies that spread financial and operational risks across multiple stakeholders. Awareness about the risk that an individual transition attempt may not be sufficient to receive a pipeline connection and reach to a full transition could be a driver for managers to consider collaboration options to decrease this risk. The study draws attention to think way ahead in order to alleviate possible risks.

Furthermore, showing that collective action can mitigate uncertainties related to power supply, capital costs, demand development, it enables better risk management for both users and providers of the pipeline infrastructure.

Operational Efficiency

By participating in collective investments, companies can achieve greater operational efficiency through economies of scale and shared resources. Decision makers in the industry can leverage the study's findings on the economies of scale achievable through collective investments to reduce unit costs and improve the economic feasibility of hydrogen projects. On the other hand, managers of the system could reach to more efficient use of electricity grid capacity, curtailed renewable power, reducing operational bottlenecks and improving overall energy management.

Policy Advocacy

Industry leaders can use the findings of this study to advocate for the development of regulations that support collaborative approaches and reduce administrative burdens. By demonstrating the potential benefits of collective action and flexible subsidy schemes, managers can engage with policymakers to shape regulations that better support hydrogen infrastructure development.

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A

Appendix A

Table A.1: Distribution of temperature needs of certain industrial processes, adapted from [89]

Sector	**Process**	**15°C-75°C**	**75°C-100°C**	**100°C-125°C**	**125°C-150°C**	**150°C-200°C**	**200°C-500°C**	**500°C-1000°C**	**>1000°C**
Iron and steel	Blast Furnace						0.03	0.2	0.77
Iron and steel	Electric arc furnace							0.1	0.89
Non-ferrous metals	Aluminum, primary							1	
Non-ferrous metals	Aluminum foundries							1	
Non-ferrous metals	Copper, primary								1
Paper and printing	Chemical pulp			0.1	0.2	0.7			
Paper and printing	Mechnaical pulp		1						
Non-metallic mineral products	Container glass			0.06	0.06	0.08	0.19	0.3	0.3
Non-metallic mineral products	Clinker calcination-dry						0.1	0.6	0.3
Non-metallic mineral products	Bricks	0.1	0.1					0.6	0.2
Chemical industry	Ammonia							0.66	0.33
Chemical industry	Ethylene							1	
Chemical industry	Methanol							0.22	0.78
Food, drink and tobacco	Dairy	0.45	0.45	0.03	0.03	0.03			
Food, drink and tobacco	Brewing	0.28	0.28	0.15	0.15	0.15			
Food, drink and tobacco	Bread&Bakery	0.1	0.1	0.11	0.11	0.11	0.47		

Table A.2: Distribution of temperature needs of certain industrial processes, adapted from [90]

Sector	**Process**	**Low °C**	**High °C**
Dairy	Sterilization	99.85	119.85
Dairy	Drying	119.85	179.85
Canned food	Sterilization	109.85	119.85
Agricultural products	Drying	79.85	199.85
Textile	Drying	99.85	129.85
Textile	Degreasing	159.85	179.85
Paper	Bleach	129.85	149.85
Chemistry	Soaps	199.85	259.85
Chemistry	Synthetic rubber	149.85	199.85
Chemistry	Process heat	119.85	179.85
Chemistry	Petroleum	99.85	149.85
Wood products	Pulp preparation	119.85	169.85
Desalinization	Heat transfer fluid	99.85	249.85
Mining	Drying	99.85	399.85
Mining	Concentrate smelting	99.85	399.85
Mining	Heating solution	99.85	399.85
Mining	Washing	99.85	399.85
Plastics	Preparation	119.85	139.85
Plastics	Distillation	139.85	149.85
Plastics	Separation	199.85	219.85
Plastics	Extension	139.85	159.85
Plastics	Drying	179.85	199.85
Plastics	Mixing	119.85	139.85
Thermal treatment	Medium tempering	349.85	449.85
Refrigeration	Double effect solar chiller	119.85	189.85

B

Appendix B

Table B.1: All parameters used in the simulation model

Category	Parameter/Input	Source	Current value	Unit	Specificity
Demand	# of production lines	Randomized	[2, 5]	-	Company specific
Demand	Heat demand	Stedin	[10k, 1000k]	m3	Company specific
Investment	Expected ROI level	Sensitivity analysis	[-1, 0]	-	Company specific
Power availability	Rooftop solar installed capacity	Stedin	Depends per company	kwp	Company specific
Power availability	Unused grid capacity	Stedin	Depends per company	kw	Company specific
Capex- fixed opex calculation	Scale factor	Literature	(69, 90)	%	Environment
Capex- fixed opex calculation	Reference cost	Literature	[4850k - 1450k]	€	Environment
Capex- fixed opex calculation	Reference years	Literature	(2020, 2030, 2050)	-	Environment
Capex- fixed opex calculation	Fixed cost as % of Capex	Literature	(2.05, 2.10)	%	Environment
Conversion	CO2 emission of natural gas	Literature	0.000203966	ton CO2/kwh	Environment
Conversion	Natural gas m3 to kwh	Literature	9.909139178	kWh/m3	Environment
Conversion	Burner efficiency	Literature	80	%	Environment
Demand	Hydrogen blending percentage	Literature	~20	%	Environment
Determining electrolyzer cap	Electrolyzer efficiency	Literature	[60, 80]	%	Environment
Determining electrolyzer cap	Working days in year	Reality	260	days	Environment
Determining electrolyzer cap	Working hours in a day	Reality	20	hours	Environment
Investment	Discount rate	Literature	4.5	%	Environment
Investment plan validity	Start of EoI process	Randomized	[0 10]	Years	Environment
Investment plan validity	Percentage of regional demand as threshold	Sensitivity analysis	50	%	Environment
Motivation degree	Weight of sector's dependency on hydrogen	Sensitivity analysis	50	%	Environment
Motivation degree	Weight of region's hydrogen transition performance	Sensitivity analysis	50	%	Environment
Others	Construction duration	Literature	3	Years	Environment
Others	Operation duration	Literature	15	Years	Environment
Others	VAT	Public sources	19	%	Environment
Power availability	Monthly solar capacity factor	Literature	(9 16 26 37 40 41 40 37 30 20 11 8)	%	Environment
Price	Grid electricity price	Eurostat, PBL	-	€/kWh	Environment
Price	Natural gas price	Eurostat, PBL	-	€/kWh	Environment
Price	CO2 tax	PBL	-	€/ton CO2	Environment
Price	Solar electricity price (PPA)	Public sources	-	€/kWh	Environment
Price	RES electricity price (PPA)	Public sources	-	€/kWh	Environment
Price	Hydrogen purchase price	TERI	-	€/kWh	Environment
Process investment	Payment duration	Literature	3	Years	Environment
Process investment	Process investment subsidy rate	Subsidy documents	40	%	Environment
Subsidy	Ceiling probability (highest bid's winning probability)	Sensitivity analysis	90	%	Environment
Subsidy	Floor probability (lowest bid's winning probability)	Sensitivity analysis	10	%	Environment
Subsidy	Minimum capacity of subsidy	SDE documents	500	kw	Environment
Subsidy	Minimum price to ask	SDE documents	0.0634	€/kWh	Environment
Subsidy	Maximum price to ask	SDE documents	0.155	€/kWh	Environment
Power availability	Total regional RES capacity	Stedin	Depends per region	kw	Region specific
Sectoral data	Sectors	Literature	(Metal, Glass, Food, Agriculture, Ceramic, Cement, Chemical, Paper, Textile, Wood)	-	Sector specific
Sectoral data	Sectoral hydrogen dependency~Energy intensity	Literature	(10, 8, 5, 3, 8, 9, 6, 5, 4, 3)	-	Sector specific
Sectoral data	Process investment cost	Literature	(393 649 1259 700 1416 944 1259 1259 1259 1259)	€/kW	Sector specific
Sectoral data	Process efficiency	Literature	(45 75 50 50 40 75 70 60 60 60)	%	Sector specific

C

Appendix C

Table C.1: Price forecasts used in the model

Years	Electricity price /kwh[1]	Natural gas price /kwh[2]	Solar & PPA price /kwh[3]	Hydrogen price /kwh[4]	CO2 tax /ton[5]
2025	0.245	0.174	0.284	0.133	87
2026	0.222	0.156	0.263	0.129	100
2027	0.199	0.138	0.229	0.125	112
2028	0.177	0.120	0.203	0.121	147
2029	0.154	0.103	0.203	0.117	182
2030	0.132	0.085	0.203	0.114	216
2031	0.132	0.085	0.203	0.112	216
2032	0.132	0.085	0.203	0.111	216
2033	0.132	0.085	0.172	0.110	216
2034	0.132	0.085	0.172	0.109	216
2035	0.132	0.085	0.172	0.107	216
2036	0.132	0.085	0.172	0.106	216
2037	0.132	0.085	0.172	0.105	216
2038	0.132	0.085	0.172	0.104	216
2039	0.132	0.085	0.172	0.102	216
2040	0.132	0.085	0.172	0.101	216
2041	0.132	0.085	0.172	0.100	216
2042	0.132	0.085	0.172	0.099	216
2043	0.132	0.085	0.172	0.097	216
2044	0.132	0.085	0.172	0.096	216
2045	0.132	0.085	0.172	0.095	216
2046	0.132	0.085	0.172	0.094	216
2047	0.132	0.085	0.172	0.092	216
2048	0.132	0.085	0.172	0.091	216
2049	0.132	0.085	0.172	0.090	216
2050	0.132	0.085	0.172	0.089	216

[1] *Adapted from [126]. 2025, 2030 were given, other years are interpolated, years after 2030 are assumed constant*
[2] *Adapted from [126]. 2025, 2030 were given, other years are interpolated, years after 2030 are assumed constant*
[3] *First 4 years are taken from [127] forecast, 2033 forecast is from [128]. Rest is assumed constant*
[4] *Adapted from [129]. 2020, 2030 and 2050 were given, other years are interpolated*
[5] *Adapted from [109]. Forecast is available until 2030, rest is assumed constant*