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# **The Impact of the Thermal Transition** in the Built Environment **on Gasunie's Infrastructure**


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# THE IMPACT OF THE THERMAL TRANSITION IN THE BUILT ENVIRONMENT ON GASUNIE'S INFRASTRUCTURE

Master thesis submitted to Delft University of Technology in partial fulfilment of the requirements for the degree of

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by

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# PREFACE

Dear reader,

You are about to read a tangible result of - so far - surviving a pandemic well-spent: my master thesis. The past eight months have not always been easy as a result of combining writing this thesis, while not really being able to do something else than writing this thesis. Nonetheless, I am proud of where this journey has ended and would like to extend my gratitude to the people that I could not have done this project without.

Trivik. As my second supervisor, you were drawn into the project as an expert on the field of data. However, I think that your most valuable contributions were actually to the design of the conceptual model. In the early stages of the project when we met, you were able to ask challenging questions as an outsider of the agent-based paradigm that helped me rethink some things that seemed so logical to me. Thank you for your contribution to my project and I think it is a shame that you only started teaching your EPA data and visualization course the year after I started in the EPA program!

Igor. As my first supervisor and chair, you were very frequently involved in my project. During the many sessions we had, you were an excellent guide to my journey. Every time I was stuck or lost you provided me with the right words that this was completely normal in such a process. In hindsight, I respect how you are able to within just a matter of seconds, you can understand what is going on in someone's mind and how you can best help someone find the right way. Apart from your unquestionable expertise in the field of ABM and energy systems, this is a quality I admire.
I remember coming to your office the first time when I wanted to do a project combining ABM and *impact investing*. You were not really interested in helping me with such a topic, but you did propose the project that I ended up working on. I am very grateful for the opportunity you gave me to work on a project for Gasunie. I found that having a stakeholder that needed a real problem solved is a great motivator.

Jarig. I had many (wrong) expectations before starting my final phase as a student with this master thesis. But what I expected the least was having such an involved external advisor to my project. As my Gasunie advisor and mentor, you were a great source of information, motivation and inspiration. Our Friday afternoon meetings every other week to show you my progress were moments of real moments of gratification to me. I hope that my project can contribute to the very important work you do at Gasunie.

I want to thank all my dear friends for making my time as a student in Delft, above all, a fun journey. Emma, the final phase of this project was challenging for me, I am incredibly grateful for your distractions when I needed it the most and which required a lot of your flexibility in your time. Also, thank you for your beautiful cover design (:. And finally, my parents. Marjolijn and Teddy, while I never really call you by your first names, you truly deserve an honorable mention by helping me write down this story to my best ability. I could not have done this much work in the final two weeks without your support.

This thesis marks the end of an incredible journey as a student, I had an amazing time. I am looking forward to what is to come on my next adventure!

Jaromir

# ABSTRACT

The residential built environment in the Netherlands is on the verge of a transition of its thermal system. The Climate Agreement has suggested that municipalities will have to play a leading role in transitioning their neighborhoods' currently natural gas-driven heating systems towards sustainable alternatives. But changing the thermal systems of these neighborhoods will have consequences for the gas transmission system operator: Gasunie. Currently, no model captures this transition from the perspective of municipalities as key instigators while studying its implications on a transmission system operator. Therefore, this thesis presents a data-driven agent-based model representing the Dutch built environment consisting of municipalities, neighborhoods and energy sources to study the effect of municipal decisions in this transition on Gasunie's infrastructure. A novel municipal decision-making framework is designed that hypothesizes various factors contributing to municipal decisions in this transition. Aggregating peak gas demand to the level of Metering and Regulation stations in Gasunie's network captures the emergent behavior of interest from an infrastructural point of view. Simulation results show that the decisions of municipalities matter for the regionally required capacity in Gasunie's infrastructure, depending on the regional built environment characteristics, national transition goal, unfolding scenario, and municipal strategies. But the limited availability of renewable gas is a significant model driver and limits municipalities in what they can decide. It can be concluded that insight in the supply-side availability of the renewable gasses for the built environment in combination with multi-stakeholder coordination with the national policymaker and municipalities on the thermal transition can contribute to unraveling the uncertain character of this system and its implications for Gasunie's infrastructure. The agent-based model can expose the formulated theory of municipal decision-making and its effect on Gasunie's infrastructure while exploring and discovering what-if scenarios of interest for Gasunie and other stakeholders. It can potentially be used as a decision-support or debate starting tool by the involved stakeholders to show how their interests, characteristics, and decisions shape the change of this thermal system towards its sustainable future.

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# 1 INTRODUCTION

Climate change is a *wicked problem* that has encouraged many (long) existing energy-related systems to start transitioning towards more sustainable solutions. The *'problem'* part in *wicked problem* suggests that we are aware of the necessity to act on this highly undesirable situation. However, the problem being of *wicked* nature, suggests that solving this undesirable situation is all but straightforward. Wicked problems are described by characteristics such as being *intangible, impossible or compromised* among others. This thesis is a story on interpreting such wickedness of a large-scale, multi-stakeholder energy system currently on the verge of a transition. And by doing so, enabling decision-makers to jointly move this transition forward in the best interest to all.

## 1.1 THE THERMAL TRANSITION AS AN UNCERTAIN WICKED PROBLEM

In 2015 the world's largest united response to anthropogenic climate change yet was drafted during the Paris Climate Conference. 195 participating countries committed themselves to the reduction of greenhouse gas emissions to limit global warming to a rise of 2 degrees Celsius (United Nations, 2015). Following the United Nations (United Nations, 2015) and the European Union (European Commission; EuropeanCouncil, 2018; European Commission, 2018), the Netherlands presented its Climate Agreement in 2019 in which they outline the national strategy for reducing greenhouse gas emissions with 49% by 2030 and 95% by 2050 compared to 1990 levels (Klimaatberaad, 2019).

One of the main pillars of this national strategy is transitioning the built environment towards a sustainably heated and energy-efficient sector (Klimaatberaad, 2019). Consisting of 7,5 million dwellings (CBS, 2019), heating this sector is responsible for 350 PJ of energy consumption, which is equal to 17% of total final energy consumption in the Netherlands (van Leeuwen et al., 2017). The greenhouse gas-producing energy source for the thermal system in the built environment is predominantly natural gas (Menkveld et al., 2015). While natural gas demand for heating purposes by dwellings has declined by 25% since 2000 due to improved insulation (ECN et al., 2016), transitioning the built environment towards becoming fully energy neutral and less reliant on natural gas still is a necessity, but yet a great challenge. Therefore this study will focus on the required change of thermal systems within the residential built environment.

Improving energy efficiency and implementing sustainable thermal systems in the built environment may seem like straightforward strategies to achieve our climate goals, but stating this dismisses the wickedness this challenge constitutes. As with any large-scale transition, its path towards the end, and the outcome itself are uncertain to predict (Kwakkel and Yücel, 2014), slow, and expose many challenges (Verbong and Geels, 2007). Meanwhile, the large potential solution space for its technical design (Menkveld et al., 2015), multi-actor environment (Leeuw and Groenleer, 2018), and heterogeneity of the building stock (Klip, 2017) further establish the complexity of this socio-technical system.

These uncertainties and complexities result in that we do not know how this transition will develop and what end states are likely, while many stakeholders are involved by either shaping the system or being affected by its outcomes.

## 1.2 MUNICIPALITIES AS OBLIVIOUS KEY INSTIGATORS

Municipalities in the Netherlands are one of the key stakeholders, playing a significant role in shaping the sustainable thermal system of the built environment in the future through their neighborhood-driven approach. Policy frameworks have started to trickle down from high-level international programs (e.g. United Nations (2015) and European Commission (2018)) to lower national levels (e.g. Klimaatberaad (2019)). This trend is further illustrated by Castán Broto (2017), who identifies the international trend of the institutionalization of climate change governance to municipalities. This is also the case for the Netherlands, where the national strategic approach is centered around municipalities having to make decisions for the transition per neighborhood (Klimaatberaad, 2019; Programma Aardgasvrije Wijken, 2020).

While municipalities are positioned as the key instigators for determining when, and how their neighborhoods are to be transitioned (Klimaatberaad, 2019), it is not clear what their approach will be. It is widely recognized that municipalities are best enabled to reflect on the specific needs of their neighborhoods (Klimaatberaad, 2019; Castán Broto, 2017; Hoppe and Miedema, 2020; Hawkey et al., 2013; Leeuw and Groenleer, 2018). And those regional and national institutions are created to enable multi-level interaction to support decision-making through information sharing and resource provision (Markantoni, 2016; Geels, 2018). But as municipalities face a new challenge, mismatches in their stated ambition and operational approach are observed (van Leeuwen et al., 2017), they are simply not aware of their role (Diran et al., 2020) while the national climate agreement remains imprecise on the implementation of their neighborhood-driven approach. Not knowing how and what the impact of the municipal-led neighborhood-driven is, concerns stakeholders in the energy system, especially Gasunie.

## 1.3 GASUNIE AND THEIR ADAPTATION TO THE ENERGY SYSTEM OF THE FUTURE

Gasunie is the Transmission System Operator (TSO) for the Netherlands and the northern part of Germany. The state-owned company has a public objective of ensuring maintenance and operations of the transportation infrastructure of gasses. This is achieved by steering for safe, reliable, affordable and sustainable gas infrastructure. They play a pivotal role in the energy transition as TSO and aim to facilitate the road to a sustainable energy system by providing various infrastructural services, hence their interest and involvement in this research. Their vision is that the energy system of the future will contain a hybrid mix of various energy sources, with renewable gasses playing a vital role (Gasunie, 2019). The significance of their role in the energy system is characterized by the required maximum capacity of their network, which is around 100 GW. In 2017, just 74 GW of peak demand was generated. Contrasting with the required peak electricity demand, which only fluctuates between 9 and 18 GW on a given day (Klip, 2017).

Following the transition strategy as laid out by the Klimaatberaad (2019), the built environment phasing out the use of natural gas as its primary source of heat will have consequences for Gasunie (Rijksoverheid). The national goal of transitioning and refitting 250,000 dwellings a year towards sustainable thermal systems by 2030 will set in motion local decisions by municipalities, neighborhoods and households that will impact strategic network decisions of TSO's. There are no "one-size-fits all solutions" for the thermal system of the built environment. Heterogeneity of the built environment implicates that preferable solutions for efficiency and type of thermal system will differ per region, municipality and even within neighborhoods (Schepers and Aarnink, 2014). With the question not only being to what thermal systems the built environment will shift but also when (Klip, 2017).

Even though Gasunie has traditionally been an energy infrastructure institution whose main reason for existence has been the facilitation of fossil fuel, they understand their role is changing towards an energy transition facilitator (Gasunie Transport Services, 2017; Gasunie and TenneT, 2019). Sustainably produced electricity is considered to be the most promising carrier for the energy system of the future, but gas will likely remain an important technology to be used complementary where electricity is not sufficient. For example, hydrogen can be produced from electricity to meet the demand for industrial appliances and other difficult to electrify appliances. Bio-methane can be used to replace traditional methane in areas where it is available (Gasunie and TenneT, 2019). Overall, demand for natural gas is expected to decrease as its role changes from a primary energy source, to a variable one that will support renewable sources.

Gasunie is interested in how this uncertain shift of thermal systems in the built environment will impact their infrastructure. Infrastructures can be studied on their reliability, sustainability, affordability and cost (Gasunie, 2019). This study focuses on the required capacity needed for their network as a result of these uncertain changes in the built environment. Gasunie is an infrastructure facilitator between suppliers and consumers of gas. Understanding the supply and demand side of their network yields insights on how they might have to adapt or position themselves to accomplish their mission in the future. Just as with energy infrastructures in general, gas infrastructures are constructed and planned according to thermal peak loads of the system (Liu et al., 2019; Blokhuis et al., 2011).

Therefore, the key question for Gasunie is how local changes in the built environment as a result of this transition might impact their gas infrastructure.

## 1.4 MODELLING THE THERMAL TRANSITION

Instead of focusing on specific elements or subsystems of this transition, Gasunie is interested in how the behavior and resulting changes on a local level have an impact on their national infrastructure system. The complexities and uncertainties at this level prevent Gasunie from overseeing how this transition might impact their infrastructure. Simulation modeling approaches can provide insights into developments of energy systems that are expected to transform in the future and do not yet currently exist (Kwakkel and Yücel, 2014). Therefore, this thesis aims to study a suitable model-based methodology for addressing such infrastructural problems in this particular case.

Different model-based approaches have been used to study different aspects of the energy transition, and more specifically, the thermal transition of the residential built environment. Either serving the interest of local (Schepers et al., 2019) or national policymakers for different countries (Sopha et al., 2011, 2013). Or focusing on the lowest level of aggregation by studying household adoption of thermal technologies. While some specifically focus on estimating total system costs estimations for different scenario's (Menkveld et al., 2015).

The most commonly used methodologies that have studied this transition are techno-economic and agent-based models. Techno-economic models that studied this transition are models that have focused on providing cost-optimal evaluations for policymakers. By using different scenario's and highly data-driven input, these models have the intention to provide policymakers with which solutions are optimal for their neighborhoods (Schepers et al., 2019, 2015; Menkveld et al., 2015; CE Delft, 2019). While they can provide such evaluations for given end-states under different scenarios, they do not explain what the transition pathways to these solutions could be.

In agent-based models, agents are software representations of entities that can perform actions or independent decisions on other agents or their environment. Agents can represent any actor that functions in a social network, from birds in a flock, or municipalities interacting with other municipalities and their stakeholders. The system behavior can then be studied as a result of the emerging behavior of the lowest level agents (van Dam et al., 2012). However, agent-based models that have studied thermal transitions have lacked a focus on the perspective of transmission system operator energy infrastructures and the use of real-world data.

The currently developed models provide insights on various uncertainties concerning this transition, but a model intended to study the impact of municipal decision-making in this transition on Gasunie's network and their interdependencies are currently missing.

Existing models have indicated that studying inherently uncertain systems with such models can be worthwhile. They provide a tool for societal debates, decision-making support and might also provide insights on Gasunie's future gas facilitating role.

Therefore, this research intends to study whether agent-based models can be used to explore the uncertainties of the thermal transition in the built environment and provide insights on what future gas capacity requirements might be necessary.

## 1.5 THIS THESIS

The thermal system of the residential built environment has for long been a natural-gas driven system. Section 1.1 illustrated that as a result of climate change and the institutionalization of climate strategies, transitions in various segments of society will disrupt our energy system, one of which is the built environment. Section 1.3 argued that Gasunie is aware that they will have to adapt their role for a thermal system that will use a mix of sustainable energy sources. How the future of the thermal system in the residential built environment will be shaped, is largely dependent on the approach by municipalities, as reasoned in section 1.2. Therefore, section 1.4 suggests studying how a data-driven agent-based methodology can be used to study the context of this transition and its impact on Gasunie's gas infrastructure.

The remainder of the thesis' is structured as follows. Chapter 2 describes the identified research gap and research questions. Chapter 3 describes what methodological approach is applied for this thesis. Chapter 4 describes the socio-technical elements relevant for designing a model of this system, presents the conceptual design and a formalized data-driven agent-based model. Chapter 5 presents the methodological result, the experimental setup and the model outcomes. Chapter 6 describes the process of validating the model and its results. And finally, chapters 7 and 8 conclude on the findings of this thesis, discuss its implications and present its recommendations.

# 2 RESEARCH FORMULATION

In the introduction, the context, complexity and uncertainty of the relation between the thermal transition of the built environment and Gasunie were illustrated. Simulation models have been introduced as a methodology to address this complexity and uncertainty within the context of this transition. This chapter aims to formulate the research as introduced in the previous chapter. The research gap is made explicit in section 2.1. The objective of this study is presented in section 2.2. The research questions are presented in section 2.3 and the chapter concludes with the scope of the research in section 2.4.

## 2.1 GAP

The research gap for this thesis consists of a case gap, a stakeholder gap and a methodological gap. Firstly, as described in the introduction, the goal for 2050 is to create a fully sustainable residential built environment by increasing the energy efficiency of dwellings and replacing natural-gas driven thermal systems with sustainable alternatives. Meanwhile, municipalities are given the role of key instigators in transitioning their neighborhoods to this sustainable goal. Therefore, the case gap is how we arrive at this sustainable goal in 2050 is uncertain and we don't know how municipal decision-making in this transition might work.

Secondly the stakeholder gap. We know that the built environment constitutes a large part of gas demand in the energy system. And that Gasunie has to consider the supply and demand of various gasses over time to comply with their mission. The stakeholder gap is therefore that it is not known how the shift in energy demand of the residential built environment will develop as a result of this transition.

And thirdly, the methodological gap. We know that different modeling methodologies have been used to study various aspects of the transition. However, we don't know how a data-driven agent-based model can capture energy demand developments of the built environment as a result of municipal decision-making in this transition. Also, it is not known how such a methodology can be used by Gasunie to support their role.

## 2.2 OBJECTIVE

The research objective of this thesis is twofold. The first goal is to provide Gasunie with a scientifically sound data-driven agent-based methodology of this transition from the perspective of municipalities as key instigators as a tool to study required gas infrastructure capacity needs. The second goal is to determine whether this methodology can be used for such problems.

## 2.3 RESEARCH QUESTIONS

The main research question that is synthesized from the research gap and objective is as follows:

> **How can a data-driven agent-based model be used to study the impact of the thermal transition in the built environment from the perspective of municipalities as key demand instigators on Gasunie's infrastructure?**

The main research question intends to assess how a data-driven agent-based methodology can be used for studying the impact of this transition on Gasunie's infrastructure. The central hypothesis to this research question is that municipal decisions are conclusive for the thermal transition of the built environment, meaning that they make decisions over time which neighborhoods shall transition to what thermal systems, driving change in their energy demand. The data-driven agent-based methodology implicates that the designed model is initialized using relevant real-world datasets while combined with the agent-based modeling paradigm. Gasunie's physical infrastructure is not included in this research, but effects on it are deduced from changing gas capacity requirements of the built environment.

The sub-questions formulated to support answering the research question are as follows:

1. ***How can the municipal-driven neighborhood-approach in the context of the thermal transition in the built environment be captured in a data-driven agent-based model?***

The first sub-question is aimed towards finding a way how a data-driven agent-based model can be designed that includes the municipal decision-making driving the thermal transition of the built environment. The process of municipal decision-making is defined as municipalities determining when and what thermal systems are implemented in their neighborhoods.

2. ***What insights can such a data-driven agent-based model provide to support the strategy and role of Gasunie?***

The second sub-question is aimed towards synthesizing what information such a model can provide, both methodologically as its outcomes. What insights could be extracted from this model to support Gasunie in formulating their strategy and adapting role given the transition it intends to capture. This sub-question does not have the ambition to shape specific decisions for Gasunie through the application of the model, but rather its competences of interest for Gasunie.

## 2.4 SCOPE

The scope of this research is delineated by what is included in this research and what is not included. Aspects that are included in the scope is the development of a novel framework that explains municipal decision-making in the context of this transition. As conceptualization of decisions can include a large number of factors, the Theory of Planned behavior is used as a foundation to form this framework. It does include decision-making based on socio-demographic and building characteristics but excludes financial evaluation and political preferences.

The second scoping aspect is that this research includes the design and actual implementation of a simulation model using the identified concepts and several open-source datasets. This model is novel and includes the residential built environment and its resulting thermal energy demand. Industrial gas consumers are excluded from the model. The datasets used are static, but the model simulates the transition between 2020 and 2050. Electricity infrastructure limitations are excluded as well.

The third scoping aspect concerns the synthesizing the aggregation and interpretability results. While thermal energy demand is generated by households heating their dwellings, it is assumed that the most interesting insights related to Gasunie's network capacity can be found on a higher level of aggregation. The level Metering and Regulation station level of aggregation is chosen as an appropriate level for studying this system. The mapping of neighborhoods, municipalities and Metering and Regulation stations is the author's interpretation of the network. The physical infrastructure limitations, such as piping, are not considered in this research.

The fourth scoping aspect concerns how thermal demand is categorized and measured in this research. The sources of heat for thermal systems in this thesis are delineated as natural gas, green gas, hydrogen, electricity and heat. Green gas, hydrogen, electricity and heat are not primary energy sources, but rather thermal energy carriers instead of primary energy sources. How these forms of energy are generated is considered out of scope for this research. The author is aware that hydrogen, for example, can be synthesized by using natural gas or electrolysis. When writing about energy sources, this research implicates energy sources fed into the thermal systems, not their primary energy sources.

# 3 METHODOLOGY

The previous chapters described the context of the transition and Gasunie's need for a novel data-driven agent-based modeling approach. In this chapter, the methodology to answer the related research question is presented. Section 3.1 describes the high-level methodological approach and theoretical lens used for studying the system. Then section 3.2 describes the qualitative and quantitative methods of data collection. Section 3.3 describes the method for the design of the data-driven agent-based model and section 3.4 illustrates the methods of analysis. Section 3.5 concludes with the flow of the research process.

## 3.1 METHODOLOGICAL APPROACH

### 3.1.1 A Model-Based Approach

To answer the research question as presented in section 2.3, a model-based approach is used as the main methodology. Before it can be determined whether a data-driven agent-based model can be used to study this case for Gasunie, such a model is to be designed through this approach. Supporting methods that are used for the model-based approach are a literature study, unstructured interviews, desk research and data analytical methods.

### 3.1.2 The Socio-Technical Systems and Complex Adaptive Systems lens

To come to a conceptual understanding of the thermal system of the built environment and its complexity, the theoretical lenses of Socio-Technical Systems (STS) and Complex Adaptive Systems (CAS) is applied throughout this thesis. Socio-Technical Systems are systems that combine the interaction of social networks of actors (e.g. of individuals or organizations), physical technical systems (e.g. energy systems) and institutions (e.g. regulations and rules that bind the characterize their interactions) (Chappin et al., 2007). The interaction between the social networks, technical systems and its institutions manifests both physical and social complexity (Herder et al., 2008).

The notion of Complex Adaptive Systems (CAS) is used as the second theoretical lens through which the thermal system is translated into a conceptual design. Complex Adaptive Systems are defined as systems where structures, patterns and behavior emerge from interactions by bottom-up, highly dispersed, decentralized, individual agents (Waldrop and Stein, 1992). The CAS perspective is in sharp contrast to a top-down system-dynamics approach where systems are viewed from a central point of control.

In light of these two definitions, this research views the thermal transition of the built environment as such a system consisting of interactions between a network of agents, a technical system and a set of institutions. Many different layers of this system can be included or excluded, depending on the perspective of the research (Moncada et al., 2017). This research, however, defines the thermal transition of the built environment as Dutch municipalities and their respective neighborhoods interacting with each other as a network of agents. The configuration of thermal systems used by neighborhoods and available energy sources being the technical system. While the institutions can be regarded as the basis for interaction between all the systems elements, such as rules and regulations. The emerging change of interest in this system is the configuration of thermal systems and resulting energy demand change within the built environment.

## 3.2 METHODS OF DATA COLLECTION

The term 'data-driven' hints that this research has a strong foundation in using external data sources. This section will explain how the data is collected throughout the research and for what purposes. First, the qualitative data is discussed, then the quantitative data collection.

### 3.2.1 Qualitative Data Collection

The qualitative data used for this research entails written literature, unstructured interviews and a workshop. The main literature used consists of academic papers from journals covering aspects of the thermal transition, municipal governance, agent-based modeling, energy infrastructure and theories on how behavior is formed. Engineering reports by several research institutions were used for specific knowledge on the gas infrastructure, the thermal system in the Netherlands and the built environment. By combining scientific journals with engineering reports specific on the case of this thermal transition in the Netherlands, it was possible to tailor the model specifically towards the Dutch thermal system, because of the lacking academic literature on this topic. The most recently available literature on the necessary topics was used. Refer to the end of this thesis for the used bibliography.

The second qualitative method was the unstructured interviews with municipalities and Gasunie. Two subject experts on the thermal transition within municipalities were interviewed for this research. The interviews were used as expert validation of the conceptual design of municipal decision-making. Gasunie experts were also interviewed for expert validation of the conceptual design of the model. As no previous models or literature existed on how municipalities form their decisions in this transition, these interviews provided a way to validate the constructed conceptual design with the closest stakeholders to this process. Refer to appendix D for more details on the interviews.

The third qualitative method used was a workshop organized for Gasunie experts. This workshop was organized to formalize assumptions on the *Relative Advantage* concept as included in the municipal decision-making framework of this thesis. During this session, assumptions on which sustainable thermal systems were most fitting to what kind of neighborhood characteristics were formed and validated. Stakeholder expert input on these assumptions provides a sound validation method (van Dam et al., 2012).

### 3.2.2 Quantitative Data Collection

The quantitative data used for this research include external data sources, model parameters extracted from literature, and data generated from the model's experiments. First, the use of externally sourced datasets is explained. The 'data-driven' aspect of the data-driven agent-based model derives from using externally sourced data sources to create, initialize and parametrize the model. Data sources from CBS, PBL, RVO and Gasunie were used in this research. These raw data sources were manipulated using several Python scripts and various packages. The intention of using these datasets is that building large-scale real-world simulation models is a very time consuming and complex process. By leveraging data sets representing the system under study, the initialization and parametrization of such systems can for a large part of the modeling process be automated (Huang, 2013). Appendix D describes the use of data sources in more detail of their use, composition, preparation and use.

The second quantitative data collection sources were academic literature, engineering reports and desk research. Many parts or processes of the model design are grounded in model parameters found in other literature or engineering reports. These data points were used in calculations that are necessary for the simulation model. While it is difficult to one-on-one copy data points from other sources to the applications in the model designed for this thesis, they provide a better starting point than point-blank guessing the numbers. Examples of such data points are the duration of the transition of a neighborhood, which is parametrized at 2 years based on multiple pilot projects and estimations of new projects.

The third quantitative data collection sources are the experiments from the model as designed in this thesis. By simulating over the designed experiments, large datasets were generated. These datasets provide the input for the data analysis used for determining the validation and effectiveness of the data-driven agent-based methodology.

## 3.3 METHODS OF MODEL DESIGN

One of the main objectives of this thesis is to develop a data-driven agent-based model. The model-based approach for designing this model is strongly based on the agent-based paradigm as described by van Dam et al. (2012) and Epstein and Axtell (1996). The modeling cycle as described in van Dam et al. (2012) was used iteratively and as a backbone during the process of this research. During the modeling process, the designed concepts, formalizations and implementations were iteratively validated by stakeholder involvement.

### 3.3.1 The Agent-Based Modeling Paradigm

Agent-based models are models that have the interactions of agents with one another and the environment at the core of their functionality. Agents are software representations of social entities, which can constitute individuals, but also organizations of individuals or institutions, such as municipalities and neighborhoods. Agents can interact with technical (sub)systems in the model, therefore making it a suitable methodology to use when studying a socio-technical system (van Dam et al., 2012). The outcome of interest is the emerging holistic behavior of the agents on a whole system level.

### 3.3.2 Considerations for Agent-Based Models

#### *Advantages*

There are many advantages of using an agent-based approach for modeling a transition system where the behavior of municipalities instigates change to a technical system. The first advantage for modeling such problems is that agent-based models allow for an ex-ante hypothesis and exploration of municipalities' behavior in a system that is to transition in the future. We do not know how municipalities decide, but by hypothesizing their behavior and implementing this on an agent level, we can study its holistic implications on a system level. This ex-ante hypothesis also allows for exploring the adoption of non-existent technologies, such as large-scale hydrogen-powered thermal systems.

The second advantage is that this modeling paradigm both captures the social interactions and its interaction and effect on the technical subsystem. The effect on the technical system being of most interest to Gasunie.

The third advantage is that through modeling such a system with its hypothesized behavior, we can simulate scenarios of the model and study the effects of a not yet existing system. Scenario simulations provide a strong analysis method of exploring *what if* in the model.

Fourth, as agent-based models include agents representing real-world entities, they can be effectively used to look like an accurate appearance of the Dutch thermal system consisting of municipalities and neighborhoods. This characteristic is especially powerful for model validation and stakeholder communication. Also, by combining data-driven parameterization of the model, heterogeneity of the agents can be exploited in its emergent behavior. Different elements of the system have different characteristics and will therefore behave differently over time.

#### *Limitations*

Using agent-based models also has limitations to its use. The first major drawback of modeling large-scale complex socio-technical systems is that it can be very time-consuming. The model as designed for this research took quite some time to design and implement, even though large data sets were used for its automatic generation. The second limitation of agent-based models, especially with larger ones, is that they can become increasingly slow to simulate. The model designed in this thesis contains around 13,000 agents each with an instruction set, which has resulted in a simulation time of around 1 minute on the computer used by the author. Fast quick manual testing was therefore difficult. The third limitation is that they can become increasingly difficult to understand when they contain many agents each with complex behavior. Especially when the model is analyzed on various aggregation levels. And finally, the validation of agent-based models representing non-existent systems is limited to comparison to other authors or validation by experts (van Dam et al., 2012; Chappin et al., 2020).

### 3.3.3 NetLogo as Agent-Based Simulation Tool

The computer tool used for the implementation of the designed agent-based model is NetLogo. NetLogo is an open-source agent-based simulation environment developed for and widely used by academic scholars. It is a programmable computer environment, based on its own high-level Java compiled programming language (Wilensky, 1999).

There were multiple reasons for the author to use NetLogo as a tool of choice. The first is that NetLogo is a very user-friendly GUI-driven environment using it's own easy to understand programming language. The author *was* not very proficient with writing code, thus making an entry-level syntax preferable. The second advantage of NetLogo is that it can be used with useful extensions, such as GIS and CSV, allowing to include external data sources. And the third advantage is the built-in experimentation environment which can be used to simulate different experiments or scenarios with the model.

The downsides of using NetLogo were limited but present. The first downside is that for a deeper understanding of what is happening inside the model, external processing of the data is necessary. The visualization of experiments is very limited inside the NetLogo environment itself. The second downside is the format in which data is exported for external processing. This results in time-consuming post-processing of the experiments.

## 3.4 METHODS OF ANALYSIS

To study the use of the designed data-driven agent-based model two methods of analysis have been used. This section will explain what methods have been used to analyze the use of the model. First, the methods of simulation experiments are discussed, then the post-processing of the resulting data.

### 3.4.1 Simulation Experiments

A set of experiments is simulated to gain insight into how the model behaves and what kind of outcomes it can generate. The experiments are aimed towards insights on the model assumptions, its general behavior, the influence of municipal-decisions and exploring Gasunie generated scenarios. The original intention was to use this model in combination with the EMA workbench (Kwakkel and Pruyt, 2013) to study its behavior under deep uncertainty. However, coupling the agent-based model with the workbench turned out to be very time consuming due to issues with the workbench connector and the model as designed in this thesis. Therefore for this research scenario-driven experiments and not parameter sweeping, open exploration experiments are designed.

Simulation of the experiments was performed on a loaned computer fitted with 12-processor cores (Intel Core i7-9750H). The experiments were replicated with 100 runs to account for the stochasticity of agent-iteration and random methods in the municipal decision-making strategies. The seeds of the random number generator were fixed at seed 222 in NetLogo.

### 3.4.2 Data Analysis of Experiments

As the NetLogo environment provides no analysis tool for the experiments, the data generated in the experiments have been analyzed using Python scripts. In every simulation run, the data at every timestep at the aggregation of Gasunie's Metering and Regulation stations and the national level were saved. The outcomes of the model are interpreted in kilowatts of peak energy demand. The data is presented using line graphs, boxplots and choropleth maps which describe statistical trends of the model outcomes.

## 3.5 RESEARCH FLOW

The research as presented in this thesis has been done through an iterative process that was initiated with a thorough literature study and concluded with synthesizing the results in the conclusions. This research started with a stakeholder question from Gasunie on the applicability of data-driven agent-based models for the thermal transition of the built environment. A thorough literature review on previous applications of agent-based models with comparable problems in combination with case-specific literature formed the foundation for the knowledge gaps as identified in section 2.1. The reviewed literature in combination with using a socio-technical systems engineering lens was applied to form an understanding of the thermal transition system as studied in this thesis. Socio-demographic and building characteristic datasets collected from public data sources were collected during the design of the model. The design of the model was done through a conceptualization and implementation phase by converging the insights from understanding the system and what data was available. The experimental setup designed after completion of the model was used as a basis for the analysis of the data and synthesis of results. The results of the thesis were validated after the analysis of the data. And finally, conclusions of this research were formed in the final phase of this research.

# 4 MODEL DESIGN

In this chapter, the design of the model is formulated. By describing the perception, logic, steps and results it is argued how the thermal system from the perspective of municipal decisions for studying implications on Gasunie's network can be captured in a model. The model design as presented in this chapter is the result of combining the STS and CAS lens, dynamics found in literature, the modeler's perception and available data resources. Section 4.1 presents the perception of the system from the perspective of the author using an STS and CAS lens. Section 4.2 presents the conceptual design of the model elements included and section 4.3 describes the formalization of the design into a data-driven agent-based model. Section 4.4 concludes the chapter.

This chapter intends to find a way to translate these dynamics into a model. It intends to answers the following sub-question:

1. ***How can the municipal-driven neighborhood-approach in the context of the thermal transition in the built environment be captured in a data-driven agent-based model?***

## 4.1 THE SYSTEM THROUGH THE THEORETICAL STS AND CAS LENS

In the introduction of this thesis, the uncertainty of the transition of this large-scale system was illustrated. The uncertainty about the transition paths, outcomes, multi-actor environment, and many potential solutions for its technical design implicate the complexity of describing this system in one formalization. Therefore, the perception of the system is delineated by using the author's perception, research intention, STS and CAS lens. By synthesizing a literature review of the social and technical context of this case, a formalization of the system used in this study is described. First, the STS lens is used, then the CAS lens. Further elaboration and justification of the system context can be found in appendix A.

### 4.1.1 The Social Network

The social network consists of municipalities and neighborhoods. Municipalities are considered governmental actors capable of making decisions on the implementation of thermal systems in neighborhoods. Whereas neighborhoods are considered aggregations of the households that they are made up of. This implicates that the characteristics of individual households are inherited by the neighborhood that they are aggregated in.

Neighborhoods, as a collection of households, have a combined demand for energy as a result of heating its dwellings and can only have one kind of thermal system at the same time. Its energy demand therefore only consists of the need generated for heating, therefore excluding other energy-consuming appliances. The thermal energy demand generated by these neighborhoods is the result of a unique combination of insulation level, dwelling characteristics and its currently installed thermal system.

### 4.1.2 The Technical System

The technical system consists of the installed thermal systems in neighborhoods, the energy sources and Gasunie's gas infrastructure. Thermal systems are systems used by neighborhoods to satisfy their thermal demand. Six different thermal system alternatives can be implemented in neighborhoods. All neighborhoods initially start with a natural-gas-fired boiler system. The sustainable alternatives consist of all-electric heat pumps, green gas hybrid heat pumps, hydrogen hybrid heat pumps, high/medium temperature district heating networks, and low-temperature district heating networks. Each of these systems has different energy efficiencies to translate the neighborhoods' thermal energy demand into an energy source-specific demand.

The different energy sources included in this perspective consist of natural gas, green gas, hydrogen gas, electricity and heat. Every thermal system requires its system unique energy source, while the hybrid heat pumps combine the use of gas and electricity as they combine a gas-fired boiler with electric heat pumps.

Gasunie's gas infrastructure is not included as a physical network in the model, but rather as an abstract aggregation level at which a gas capacity is required for the thermal system. This level of aggregations is chosen to be the Metering and Regulation stations that connect Gasunie's main national grid to the regional gas distribution network. It is assumed that the gas demand of the neighborhoods can always be met by the Metering and Regulation stations.

### 4.1.3 The Institutions

The institutions included in the model are the national transition goal and the mandate for municipalities that they are the key instigators for the transition of neighborhoods as formulated in the Climate Agreement Klimaatberaad (2019).

### 4.1.4 Complexity, Adaptivity and the Bottom-Up Holistic Perspective

The author is aware that socio-technical systems can not be captured in one formalism, therefore the design has to account for different parametrizations and formalisms. As discussed in the introduction, it is not known what approach municipalities will adopt for transitioning their neighborhoods. The decision-making is complex, therefore municipalities are not assumed to have one formalism of decision-making in the design of the model.

The social network consisting of municipalities and neighborhoods are improving their states over time by their actions. They aim for a more sustainable built environment through positive improvements of their characteristics and thermal systems, thus contributing to transitioning the system as a whole. The system is characterized by adaptivity as the transition described by municipalities and neighborhoods is driven in response to stimuli from their environment.

While the perspective of the system described in this section does not include the lowest level social actors in the system (which can be argued as households or even individuals), it does incorporate a bottom-up perspective. The perspective implicates that the interactions and decisions of the social network with the technical system on the lowest level result in the desired outcome on the level of the system as a whole. In this light, the description case is viewed through a Socio-Technical and Complex Adaptive Systems lens.

## 4.2 MODEL CONCEPTUALIZATION

Having constructed a perspective of the system under study by using the theoretical STS and CAS lens, the next step is to formalize the key concepts of the model. In the design of the model, several concepts are used that derive from the perspective in this thesis that municipalities are the key instigators for transitioning their neighborhoods to sustainable thermal systems. By making these main concepts explicit, a foundation is made for how the model will explain the dynamic of the thermal transition in the built environment.

First, subsection 4.2.1 describes a brief conceptual design overview of the included model elements and their interaction. Subsection 4.2.2 describes the concept of how a thermal transition of a neighborhood is defined in the model. Then subsection 4.2.3 describes how municipalities make decisions for when and how their neighborhoods should transition. And finally, subsection 4.2.4 describes the agents, their environment and interactions included in the model.

### 4.2.1 Design Overview

The conceptual model design is based on the social, technical and institutional elements of the systems perspective described in 4.1. The design of the conceptual model consists of municipalities, neighborhoods, energy sources and the model environment interacting with one another through two main concepts resulting in an emerging transition phenomenon. The emerging transition of the model is municipalities driving change in neighborhoods of their thermal systems. This results in a subsequent emerging change in the required thermal energy capacity of the residential built environment. The first main concept describes what a thermal transition is in the model. The second main concept describes the approach for municipal decision-making in the model. Subsections 4.2.2 and 4.2.3 describe these main concepts in further detail.

Municipalities are playing a central role in the model as a key instigator of the thermal transition of their neighborhoods. Their intended purpose is that every simulated year from 2020 until 2050, they have to make decisions concerning which neighborhoods are to transition to what sustainable thermal system. Their decisions are formed based on their decision-making strategy, their characteristics, characteristics of their neighborhoods, the energy sources available, activity by other municipalities and the environment. Neighborhoods change their thermal system based on the decisions of their municipalities. Based on their characteristics and currently used thermal systems every neighborhood demands a certain amount of thermal energy. Figure 4.1 describes the above mentioned model elements and their basic relations.

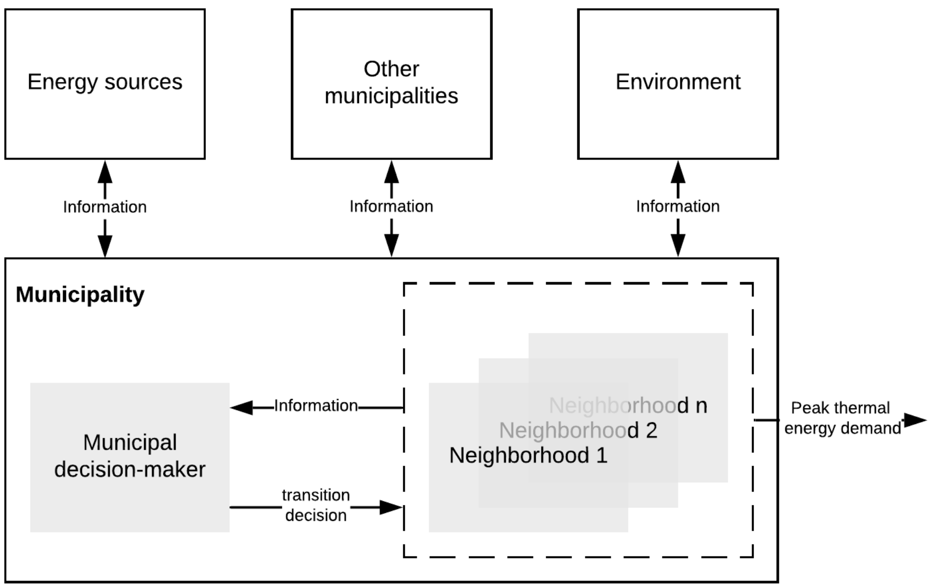


Figure 4.1: *Schematic overview of model design.*

### 4.2.2 The Thermal Transition of a Neighborhood

In the introduction of this thesis, it was stressed that reaching the goal of a fully sustainable built environment, it has to undergo a thermal transition. In chapter 1, it was described that for this to happen, the currently used natural gas-driven thermal systems in neighborhoods need to be replaced by sustainable alternatives. In reality, the process of a thermal transition involves a lot more stakeholders than included in this model. Therefore, a concept that explains the actual resulting change at the lowest level within the design of this model is necessary.

The concept of a neighborhood's thermal transition is conceptualized as: *'a certain moment in time where a neighborhood transforms from using one thermal system to a sustainable thermal system'*. This moment in time for this event to happen is instigated by the neighborhood's municipality and finished after a specific duration. Three states of the thermal transition can be distinguished for a neighborhood: 1) *before the transition has started*, 2) *during the transition*, 3) *after the transition*. It is assumed that the neighborhood switches from a natural gas-driven thermal system to one of the sustainable thermal systems during the second transition phase. When a neighborhood is considered *in-transition*, the municipality uses some resources for this process equal to the neighborhood's number of households. These resources can not be spent on transitioning other neighborhoods as long as they are used on neighborhoods in this state.

### 4.2.3 The Municipal Decision-Making Framework

The event of a neighborhood transitioning to a sustainable thermal system is triggered by a decision of its municipality. However, as the introduction explained, no existing theory or framework exists in the academic literature (to our current knowledge). It is also difficult to empirically assess the approach for such decisions by municipalities as the thermal transition has just merely begun while ambition and execution within governmental institutions diverge (Leeuw and Groenleer, 2018). While the Climate Agreement suggests the leading role for municipalities in these decisions, consensus on their approach is lacking (Klimaatberaad, 2019).

Therefore, a conceptual framework of how municipalities decide on the thermal transition of their neighborhoods is developed based on insights from existing theories, availability of data and expert input. The designed municipal decision-making framework hypothesizes that decisions by municipalities are characterized by a *who, when and what* question. Based on multiple factors, it provides an explanation for *which* municipalities are transitioned to *what* thermal system and *when*. The framework is designed by combining constructs from the Theory of Planned Behavior (Ajzen, 2012) with literature focusing on the thermal system adoption behavior of households (Michelsen and Madlener, 2012a,b; Hecher et al., 2017). Appendix E describes and justifies the framework in more detail. The factors contributing to the decision of municipalities are briefly explained for their essence and relevance below.

**AVAILABILITY OF RESOURCES:** This factor explains the maximum number of neighborhood transitions a municipality can manage at the same time. It includes both the abstractions of human as financial capital necessary to perform certain actions. Hence it limits the maximum number of decisions a municipality can make within a given period.

**TECHNICAL CONSTRAINTS:** This factor includes the technical limitations that bound the possible decisions by municipalities. It includes limitations such as the availability of (nearby) energy sources necessary for certain thermal systems. As such, it limits the choice between possible thermal systems for municipalities at a certain moment in time.

**RELATIVE ADVANTAGE:** This factor determines the relative advantage one sustainable thermal system comprises over another for a given neighborhood. It includes the abstractions of economic advantage, environmental aspects and the security of energy supplies, based on assumptions of specific neighborhood types and thermal system advantages or limitations with such neighborhoods. Thus this factor contributes to determining the preferability of sustainable thermal systems for neighborhoods that ought to be transitioned.

**NEIGHBORHOOD LIKELIHOOD:** This factor determines how a municipality prefers to transition one neighborhood over the other, given that they can both be transitioned. It assumes that based on the socio-demographic characteristics of neighborhoods, municipalities can prefer transitioning one neighborhood over another.

**TRANSITION ACTIVITY BY OTHERS:** This factor captures the influence municipalities have on each others' decisions based on their own historic decisions. The construct includes the abstraction of governance diffusion (Hakelberg, 2014), which states that municipalities share information on implemented strategies with their network. As such, the factor contributes to determining which thermal systems are implemented in neighborhoods by municipalities.

**PERCEIVED PRESSURE:** The final factor of the framework determines how much external pressure municipalities perceive to make a decision. The construct assumes that municipalities need external pressure, for example from the national policymaker, to take action transitioning their neighborhoods towards sustainable systems. As such, the factor contributes to the volume of transitions started by municipalities.

### 4.2.4 Agents, The Environment and their Interaction

The socio-technical elements as abstracted through the STS and CAS lens in 4.1 and included in the model design in 4.2.1 are characterized as model agents, model objects, the environment and their interaction in between. Doing so creates understandable formalisms of agents and objects of the municipalities, neighborhoods, energy sources and the environment. Municipalities are considered as agents, which are capable of independent decision-making in the model. The neighborhoods and energy sources are considered as model objects. These are not capable of independent decision-making in the model. The model environment is defined as the remainder of the observed system that is of influence in the conceptualized model (van Dam et al., 2012).

**MUNICIPALITIES:** They are the main agents in the model driving the transitions of their neighborhoods through their decisions (refer to subsection 4.2.2 for this concept). During the simulation, municipalities interact with their neighborhoods and other municipalities to retrieve the information necessary to form decisions on changing the states of their neighborhoods. Consequently, municipalities use the conceptual factors of the municipal decision-making framework (refer subsection 4.2.3 for the framework) to determine the volume of their decisions, who they make decisions for and what is chosen for them every year in the model.

**NEIGHBORHOODS:** They are the main objects in this model, as their currently used thermal system, level of insulation, size and dwelling characteristics determine the emerging required thermal energy capacity of the residential built environment. During the course of the simulation, neighborhoods change their current state of transition, being either *to-start-transition*, *in-transition*, or *transition-finished*. This change in transition states is instigated by their municipality. All neighborhoods have a natural-gas driven thermal system before they start their transition. When their transition is instigated, they can transition to either an all-electric heat pump, green gas hybrid heat pump, hydrogen heat pump, low-temperature district heating network, or high/medium temperature district heating network (refer to A for further descriptions of these systems). Neighborhoods are only able to transition to a thermal system that is within its neighborhood-specific technical boundaries. After they have transitioned, they can not transition again to a different system.

Neighborhoods have a certain level of insulation which determines how thermally efficient they are. This level of insulation is assumed to increase yearly according to a nationally established amount. Their current level of insulation, size, and dwelling type composition determine how much peak thermal energy is required. This level of required peak thermal energy is translated into a peak energy demand per energy source depending on the installed thermal system. Further detailed conceptualization of the neighborhood's insulation levels and peak thermal energy demand is described in appendix H.6.

**ENERGY SOURCES:** They provide the boundaries which thermal systems are technically possible to implement in neighborhoods. For every type of sustainable energy source (electricity, green gas, hydrogen gas and heat) they provide information on whether a particular neighborhood has access to its resources. These boundaries can be resource, time and location dependent. When its resources are depleted, neighborhoods are no longer able to transition to the thermal system corresponding to this source. For example, when the green gas capacity is fully utilized (which is a national capacity (Stedin, 2020)), none of the neighborhoods in the model can transition towards green gas-powered heat pumps until new capacity is added. A second example is the high/medium temperature heat capacity, which is dependent on a nearby heat source for neighborhoods to use, if these are depleted or non-existent neighborhoods are not able to transition to the corresponding sustainable thermal system. Energy capacity per neighborhood for electricity, heat, green gas and hydrogen is included in the concept.

**THE ENVIRONMENT:** It consists of three abstractions: **information**, **structure** and **time**. **Information** provided to the agents through the environment includes the pressure from the national policymaker on municipalities, the speed at which neighborhoods increase their insulation and the duration of a transition. The first abstraction is the national transition goal as the national policy driver in the model. When the Climate Agreement was presented, it included national goal targets in the form of the number of households that need to be transitioned every year to reach the goals set in 2030 and 2050. The higher the yearly goal, the more neighborhoods the municipalities have to transition accordingly (Klimaatberaad, 2019). There are currently no other suitable data points or formalizations to our knowledge available that can be logically used in the model to drive the decision-making by municipalities (Programma Aardgasvrije Wijken, 2020). Therefore, the national policy goal is assumed to be the driver for the perceived pressure on the municipalities.

Similarly, the speed at which neighborhoods increase their insulation is conceptualized. While authors have studied the adoption of thermal efficiency measures by households (Ameli and Brandt, 2015; Wittmann, 2008; Moglia et al., 2017; Tronchin et al., 2018; Hesselink and Chappin, 2019), the increase of insulation in neighborhoods is assumed to be a homogeneous process in this conceptual design. Therefore, the environment dictates the strategy which influences how neighborhoods increase their insulation levels.

The final information abstraction of the environment is the duration of a neighborhood's transition. A neighborhoods transition is conceptualized as being three separate stages with a beginning and an ending (refer to subsection 4.2.2 and paragraph 4.2.4). Inherent to this conceptualization of multiple phases is that each phase is characterized by a duration. Therefore the duration of a neighborhood's transition is defined as the time between the start and the ending. The conceptualization of heterogeneous transition durations for neighborhoods is not included in the model design. Hence this parameter is considered homogeneous over the neighborhoods.

The **structure** of the environment is the topology of the model itself. The model is intended to be a representation of the residential built environment of the Netherlands. Therefore the topology of the model follows an accurate representation of municipalities and their neighborhoods in the Netherlands, with its inherent municipal structures and relative distances.

The final concept in the environment of the model is **time**. As any transition is a phenomenon that occurs over time, time is of the essence in this concept. Every tick or simulation step represents one year. The result is that any model run takes 30 ticks to complete for simulating the transition from 2020 to 2050. Within one simulated year, municipalities can make multiple decisions as they seem fit.

## 4.3 MODEL FORMALIZATION

In this step, the designed model concepts from section 4.2 are translated into computer understandable formalisms. The conceptualized agents, objects, the environment and their interactions are captured in a description of who does what and when in the model.

First, subsection 4.3.1 describes the rationale for the KPI's of interest in the model. Second, subsection 4.3.2 describes the sequence of agent processes as implemented in the model. Then, subsection 4.3.2 describes how the municipal decision-making framework, as introduced in section 4.2.3, is formalized in five different municipal decision strategies. Subsection 4.3.2 describes the process of how the required thermal energy capacity is calculated in the model. Subsection 4.3.3 describes the data-driven approach for parametrization and initialization of the agent-based model. This section concludes with the verification procedure of the formalized model in subsection 4.3.4.

### 4.3.1 Key Performance Indicators

The model design overview described that the essence of the model is to capture emerging change in required energy capacity as a consequence of the thermal transition. To observe this emergent system behavior of interest, Key Performance Indicators (KPI's) are formulated that measure the thermal energy demand of the residential built environment in the model. As this research is aimed towards a model applicable for Gasunie, the indicators of most interest to their network are specifically focused on.

Energy infrastructure networks, including gas infrastructures, are commonly designed with the requirements needed for operation under extreme conditions in mind (Liu et al., 2019; Blokhuis et al., 2011; Menkveld et al., 2015). During these extreme conditions, networks have to accommodate their peak supply. Assuming that peak demand can be met by peak supply at all times in the model, peak thermal energy demand from neighborhoods will provide a sound proxy for estimating gas the infrastructure capacity needed for the residential built environment. Peak thermal energy demand is measured as average peak power over an hour.

The KPI's are categorized per energy source as not all are of equal interest. Different thermal systems require different energy sources to provide heat for the dwellings in neighborhoods. This research includes natural gas, green gas, hydrogen gas, heat and electricity as forms of thermal energy. Of special interest for Gasunie are the gasses. They are aggregated in methane gas (natural gas and green gas) and all gas (natural gas, green gas and hydrogen). These are aggregated separately as methane gas is technically one gas that does not differentiate between natural gas green gas and can be combined into Gasunie's infrastructure. Hydrogen gas is a different gas altogether. Indicating them separately allows for more detailed insight in required capacity insights at the infrastructure level. The KPI's are measured in kW's as this is how Gasunie tracks the required capacity in their network.

The KPI's are categorized as follows:

**Main Model KPI's:**

- Peak methane gas demand (natural gas + green gas) [kW]
- Peak all gas demand (hydrogen + green gas + natural gas) [kW]

**Secondary Model KPI's:**

- Peak natural gas demand [kW]
- Peak green gas demand [kW]
- Peak hydrogen gas demand [kW]
- Peak heat demand [kW]
- Peak electricity demand [kW]

The KPI's are measured at an aggregation level of interest conducive to Gasunie's TSO role. In the model design, the neighborhoods are the lowest level entities generating the peak energy demand metric of interest. However, Gasunie's network does not include the regional distribution grid which is directly connected to the gas consumers. Gasunie's network is the national network connecting the regional grids through Metering and Regulation stations. Hence, this level of aggregation for peak gas demand is found to be useful for Gasunie. This is done through mapping municipalities with Metering and Regulation stations by applying a shortest distance method on all municipalities to the regional distribution networks. Refer to appendix C and B for Gasunie's network topology and the resulting mapping. The resulting aggregation of household peak demand to the MR-stations is assumed as in figure 4.2.

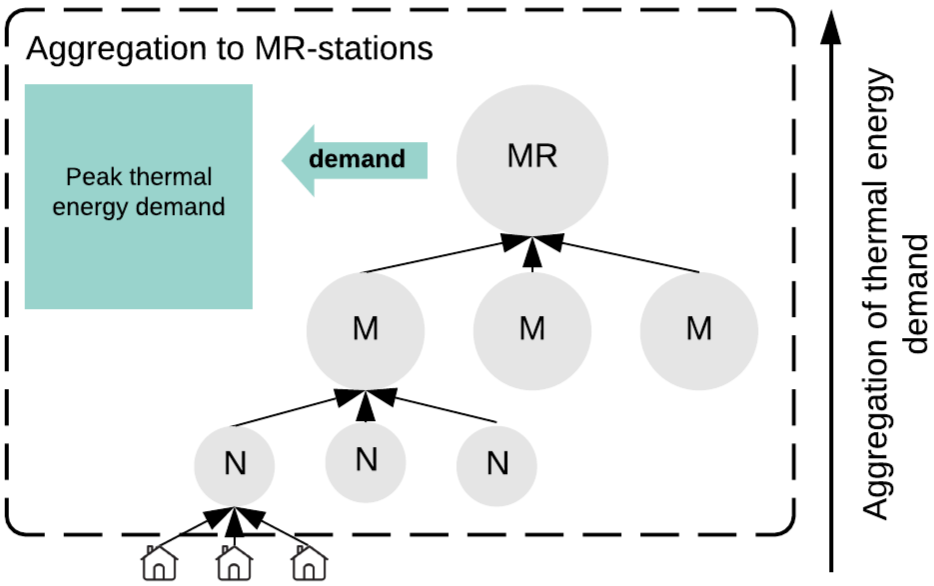


Figure 4.2: *Visual representation of aggregating peak thermal demand of neighborhoods to Gasunie's Metering and Regulation stations. MR = Metering and Regulation-station, M = Municipality, N = Neighborhood.*

Peak thermal energy demand for the gasses included in the model is analyzed using relative change and overcapacity. This metric is used to compare MR-stations based on their change relative to the peak gas demand in the year 2020. By using relative change, the change among MR-stations can be compared. While overcapacity is used to gain insight into the absolute change in peak gas demand over time. This metric can be used to compare the different MR-stations in terms of absolute required capacity change. As no actual capacity values are included in the model, the MR-stations capacities are assumed equal to peak demand in 2020.

The KPI's selected are merely used as indicators of the emerging behavior of interest to the stakeholder: Gasunie. No value judgments are made on either increasing or decreasing developments of the KPI's.

### 4.3.2 Schematic Overview of Formalized Model Processes

To understand how the actions of the agents are included in the model, their actions are to be translated in sequential tasks. The formalization of the processes in the model can be roughly separated into two main processes. The first main process is the formalized process of municipal decision making by using different strategies. The second main process is the calculation of peak energy demand by neighborhoods. First the order of who does what in the model is described in section 4.3.2. Then the concept of the municipal-decision framework is formalized into different municipal strategies in section 4.3.2. Section 4.3.2 describes how the model is formalized to output a certain peak energy demand.

#### *Model Sequence*

The concepts and elements defined in 4.2 are to be translated to agent tasks in an appropriate order. This formalization step is described using a Business Process Model and Notation diagram (BPMN) in figure 4.3. This diagram describes which agent does what in the model and when by describing the order of tasks performed in the model between the start of a tick and the end. The four swim lanes contain the different agents included in the model and their performed tasks. The arrows describe the sequence of the tasks.

The actions in the model can roughly be separated into two groups: 1) the updating of transition states and 2) the municipal transition decision cycle. During the updating of the transition states, neighborhoods advance their transition state if necessary and calculate their thermal energy demand (see subsection 4.3.2). In the municipal transition decision cycle, the municipalities are starting the transitions of a subset of neighborhoods to sustainable thermal systems according to their strategies. It is not the intention to capture the elements in their strictest form in this diagram, but rather to provide a clear and understandable overview of the processes to the reader. A detailed description of the process can be found in the model narrative in Appendix G.

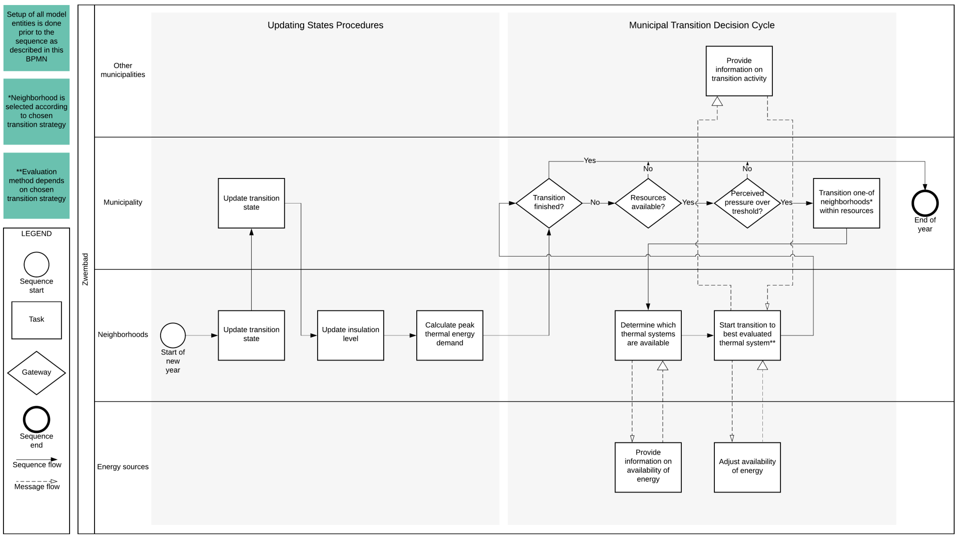


**Figure 4.3:** *High-level BPMN overview of the model sequence. A larger version can be found in appendix F.*

### *Municipal Decision-Making Strategies*

The factors of influence as hypothesized in the municipal decision-making framework (see subsection 4.2.3) are formalized in the municipal model agents as different strategies. The rationale for designing the framework was that no current theory or framework for such decisions existed to our current knowledge. As the framework itself does not suggest an implementation approach for the agents, multiple different implementations are formalized as decision strategies for the agents. Modeling different strategies does not provide an answer or direction on what is the right or actual empirical observed approach by municipalities, but rather what the influence of municipal decisions can be in such a model and what its boundaries of influence are.

The formalized strategies use different combinations of the factors of the framework for the decisions regarding which neighborhoods are to be transitioned, and to what sustainable thermal system. Some factors are present in all strategies, while other factors are either excluded, included or combined. The factors of resource availability, perceived pressure and technical limitations are always included. While variations in the use of relative advantage, neighborhood likelihood and transition activity constitute the different strategies. When a neither of the factors is used for either neighborhood selection or thermal system selection, a randomness is assumed to be the method for selection. The formalizations of how the factors are used for neighborhood and thermal system selection are described in the next paragraphs. The five strategies included are presented table 4.1 below:

| | Neighborhood Selection | Thermal System Selection |
|---|---|---|
| *Strategy 0* | Random | Random |
| *Strategy 1* | Random | Highest Relative Advantage |
| *Strategy 2* | Highest Relative Advantage | Highest Relative Advantage |
| *Strategy 3* | Highest Neighborhood Likelihood | Highest Relative Advantage |
| *Strategy 4* | Highest Neighborhood Likelihood | Highest (Relative Advantage + Transition Activity) |

Table 4.1: *Formalization of five different municipal decision strategies.*

**RELATIVE ADVANTAGE:** This is the factor of the municipality decision-making framework that explains what type of thermal system is the best fitting for a particular type of neighborhood. The thermal systems that neighborhoods can implement have characteristics that make them either suitable or less suitable for particular neighborhoods. Whether a thermal system has a relative advantage over another thermal system is explained by looking at a neighborhood's urban density in combination with the neighborhood's insulation level. These two neighborhood characteristics were found to be of most influence when predicting what thermal system has the most relative advantage over the other systems. Different combinations of urban density and insulation levels for neighborhoods yield different orders of relative advantage scores for thermal systems.

Table 4.2 presents the used relative advantage scores, which were derived from an expert workshop session with Gasunie. When using this factor for thermal system selection, municipalities transition their neighborhoods to their highest-scoring thermal system, considering the technical constraints in place for this neighborhood. When this factor is used for neighborhood selection, municipalities prefer to first transition neighborhoods that have their highest scoring thermal system alternative still available, given the technical constraints in place for this neighborhood. Appendix E.1.1 describes the concept of relative advantage and its assumptions in more detail.

| **Type** | **Insulation Level** | **Urban Density** | AE | HT/MT | LT | GG | H2 |
|---|---|---|---|---|---|---|---|
| 0 | Low | High | 5 | 1 | 3 | 2 | 4 |
| 1 | Medium | High | 5 | 1 | 4 | 2 | 3 |
| 2 | High | High | 2 | 3 | 1 | 4 | 5 |
| 3 | Low | Medium | 5 | 1 | 4 | 2 | 3 |
| 4 | Medium | Medium | 5 | 1 | 4 | 2 | 3 |
| 5 | High | Medium | 2 | 3 | 1 | 4 | 5 |
| 6 | Low | Low | 4 | 3 | 5 | 1 | 2 |
| 7 | Medium | Low | 3 | 4 | 5 | 1 | 2 |
| 8 | High | Low | 1 | 5 | 4 | 2 | 3 |
| 9 | Low | None | 3 | 4 | 5 | 1 | 2 |
| 10 | Medium | None | 3 | 4 | 5 | 1 | 2 |
| 11 | High | None | 1 | 5 | 4 | 2 | 3 |

Table 4.2: *Relative advantage scores for the different neighborhood types and thermal systems. A score of 1 means that a thermal system is most preferable in comparison to the other thermal systems for this neighborhood type. 5 is the least preferable. AE = All-Electric Heat Pump, HT/MT DHC = High/Medium Temperature district heating network, LT DHC = Low Temperature district heating network, GG HP = Green Gas hybrid heat pump, H2 HP = Hydrogen hybrid heat pump.*

**NEIGHBORHOOD LIKELIHOOD:** This is the factor from the municipality decision-making framework that ranks the order of which neighborhoods are more likely to be transitioned first based on several neighborhood characteristics. This method concept assumes that based on neighborhood characteristics, one can say that one neighborhood is more likely to be transitioned earlier than another neighborhood. The neighborhood characteristics used are the share of housing corporation ownership, the share of households using district heating networks, the share of newly built homes in a neighborhood and the average property value of a neighborhood. A score can be calculated for every neighborhood based on these characteristics which creates an order between the neighborhoods. When this factor is used for neighborhood selection, municipalities prefer to transition the neighborhoods with the highest score first. The parametrization of these characteristics is derived from the CBS dataset. Appendix E.1.1 describes the concept of neighborhood likelihood its argumentation and calculation in more detail.

**TRANSITION ACTIVITY BY OTHERS:** This is the factor from the framework that hypothesizes that municipalities diffuse their governance decisions amongst their network. Based on using the theory of Gravity Models, it is hypothesized that the distance and relative size between municipalities determines the volume of information shared between them. This volume of information containing historic decisions then influences the decisions of others. Appendix E.1.1 describes the concept of transition activity by others in more detail.

***Thermal Energy Demand per Energy Source***

Neighborhoods are dependent on the decisions of their municipalities for when they start their transition and what thermal system they adopt but are not dependent on them for their thermal energy demand. By formalizing the calculation of how neighborhoods generate their thermal energy demand, the emergent transition phenomenon of the model can be captured in the model's KPI's. Every neighborhood is different in size, composition and level of insulation. Consequently, every neighborhood generates a thermal energy demand per energy source unique to their composition type of thermal system implemented. Using the number of households per dwelling type and the average insulation level of a neighborhood, heat profiles (see figure 4.4 for the profiles used as calculated in a study of Menkveld et al. (2015) are used to estimate peak thermal energy demand per neighborhood.

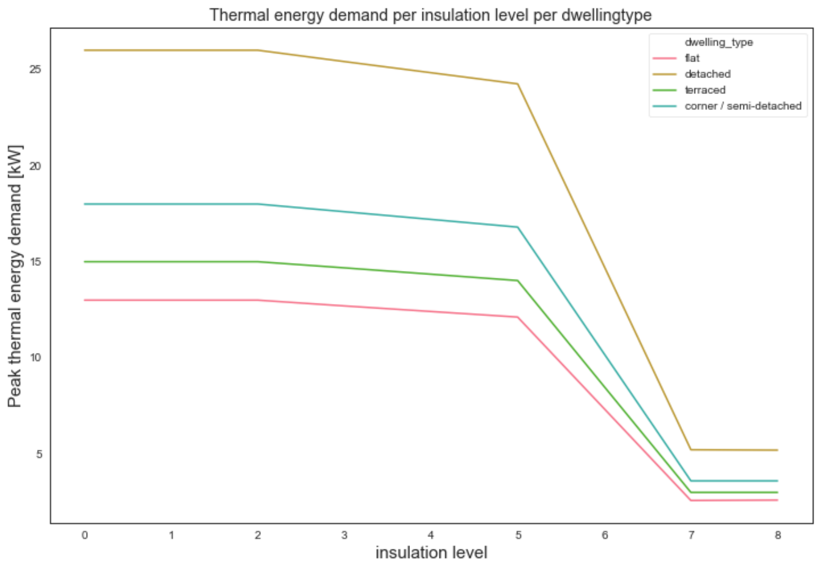


**Figure 4.4:** *The formalized heat profiles per insulation level and dwelling type as calculated by Menkveld et al. (2015).*

By using the neighborhood's calculated peak thermal demand and their currently installed thermal system, the peak thermal energy demand per energy source can be estimated. Each thermal system is assumed to have certain energy efficiency and distribution of energy source use. Appendix H.3 describes the parametrization, logic and calculations of peak energy demand in more detail.

### 4.3.3 Data-Driven Initialization and Model Parametrization

Having discussed the formalization and parametrization of the peak thermal energy calculations in the previous sector, this section will discuss how the agents in the model are initialized using a data-driven approach and how the used model parameters are found. Data-driven initialization is the process of using real-world external data sources to set up the agent structures in the model as described by this data. While the process of parametrization is finding the appropriate parameter values for the municipal, neighborhood and heat source agents in the model.

Datasets from four different sources are used for initializing this model, allowing us to make a data-driven real-world representation of the designed model. The first and main dataset used in the model is the CBS dataset. This dataset includes all data variables for the initialization of the municipality and neighborhood agents. Both these agents require location and socio-demographic characteristic variables unique per municipality and neighborhood. The second dataset is the PBL dataset. This dataset is used to parametrize the local heat source agents with their location and capacity variables. Thirdly, the dataset from RVO is used for parametrizing the insulation levels of all neighborhood agents. The fourth and final dataset is sourced from Gasunie. This dataset is used to link all municipality agents with their corresponding MR-stations. All these datasets are representations of the Dutch built environment.

By using these datasets, every municipality, neighborhood and heat source in the model inherits empirically observed data which creates a heterogeneous environment. While the data in the model does not say anything about the formalized behavior of its agents, the agents can react differently if they are confronted with different data. Different agent characteristics mean different agent capabilities. The resources and pressure municipalities experience to perform actions during a simulation depend on their number of households. While the different characteristics of neighborhoods determine how they are treated by municipalities and what peak thermal demand they deliver. In appendix D the mentioned datasets, their composition, preparation and use are discussed in more detail. Table 4.3 contains the reference parameters for the model. Appendix H describes the parameters in more detail.

| **Parameter Name** | **Default Value** |
|---|---|
| mp-transition-strategy | 2 |
| national-transition-goal | 250000 |
| nh-transition-duration | 2 |
| mp-top-n | 10 |
| mp-resource-percentage | 10 |
| nh-low-ins-transition? | TRUE |
| nh-ins-strategy1 | 20 |
| national-gg-potential-PJ | 60 |
| max-distance-heatsource | 15 |
| hs-limited | TRUE |
| national-h2-availability | TRUE |
| national-h2-availability-ticks | 15 |
| nh-cost-par | 50 |

**Table 4.3:** *Reference parametrization of the model.*

### 4.3.4 Verification

Before the model can be used for analysis, verification is necessary. Verifying the model is necessary to make sure that the conceptual model as designed in chapter 4.2 is translated correctly into its simulation modeling environment and free of errors (van Dam et al., 2012).

Various verification procedures have been performed to make sure the model can be used as intended. First, static verification has been performed to make sure the model code was free of errors. Second, the behavior of the model was observed both on the lowest agent level of municipalities and neighborhoods, on the MR-region and national level. In this step, the observed behavior is compared to the desired behavior of the conceptual design. Third, the model's behavior is tested under extreme conditions of the input parameters to check for unexpected errors. And finally, the model variability is tested to determine how many replications of the model are necessary to prevent interaction-order artifacts of the simulation.

After having performed these verification tests iteratively during the modeling process and after completion, the modeler is confident that the simulation model is implemented correctly. In appendix J the detailed steps of the verification procedure are described.

## 4.4 CHAPTER INSIGHTS

In this chapter, an approach for designing a data-driven agent-based model for this study is found and discussed. The main elements of the system could be determined by using an STS and CAS theoretical lens on the perspective of the system under study. Two main concepts are found to be of the essence for describing the behavior of this conceptual model. The first designed concept is the transition of neighborhoods and the second the municipal decision-making framework, which is used to explain the decision making of municipalities. Municipalities are the main agents in the model, while neighborhoods and energy sources are the objects of interest.

By formalizing and implementing the model using data-driven initialization, an agent-based model can be designed to study the impact of this transition on Gasunie's gas infrastructure. The main KPIs of interest are found to be the peak energy demand for natural, green and hydrogen gas on the aggregation level of Gasunie's MR-stations. The model can be formalized through a model sequence consisting of two phases: 1) the updating of transition states and 2) the municipal transition decision cycle. By formalizing the municipal decision framework in five different strategies, different factors of the framework can be combined for describing the municipalities' behavior.

The transition behavior of municipalities and neighborhoods can be translated towards KPIs of interest for Gasunie's network by using heat profiles and aggregating to an infrastructural level relevant to Gasunie. It is found that peak demand is a commonly used metric for determining the required network capacity in energy systems. Therefore, peak thermal energy demand is estimated for all neighborhoods by using peak heat demand profiles unique to each level of insulation, the composition of dwelling types, neighborhood size and neighborhoods' implemented thermal system. Aggregating this demand to the level of Metering and Regulation stations results in KPI's of interest for Gasunie's infrastructure.

By using a data-driven approach, the model can be initialized to represent the residential Dutch built environment. this allows for a heterogeneous representation of the neighborhoods and municipalities in the model. As the used data is of the same level of aggregation, no statistical representations had to be used. The data-driven initialization allows for an efficient generation of this large-scale model.

# 5 RESULTS

In this chapter, the results of this study are presented. The goal of this chapter is to demonstrate the developed data-driven agent-based model and then present its output. The output of the designed model will provide the foundation for determining whether the methodology can be used to study such problems.

First, section 5.1 will present the model as implemented in the NetLogo environment. Then, section 5.2 will illustrate the output the model is capable of. This is done by first providing insights on the models general behavior and assumptions (subsection 5.2.1), then discussing the influence of the municipal decision-making (subsection 5.2.2) and concluding with a scenario-driven analysis (subsection 5.2.3). This chapter intends to provide insights for answering the second sub-question:

2. ***What insights can such a data-driven agent-based model provide to support the strategy and role of Gasunie?***

## 5.1 THE AGENT-BASED MODEL

This section will briefly describe the in NetLogo developed simulation model. First, the resulting transition visualization of the model is described on the national and municipal levels. Then, the interface with which the model can be operated is discussed. And finally, the resulting output of the model is described.

The transition dynamics as a result of the municipal decision-making in the model are captured with dynamic visualizations of the neighborhoods in the built environment. Figure 5.1 illustrates three simulation screen captures of the visualization from NetLogo. From left to right the transition is visualized for 2020, 2035 and 2050. The neighborhoods are represented by houses. The houses are initially grey, which indicates the use of a natural-gas driven thermal system. Through the simulation, the colors change according to the implemented sustainable thermal system. Yellow indicates an all-electric heat pump, green indicates green gas hybrid heat pumps, blue indicates hydrogen gas hybrid heat pumps, red indicates high/medium temperature DHC systems and orange indicates low-temperature DHC systems. Neighborhoods still in transition are colored white.

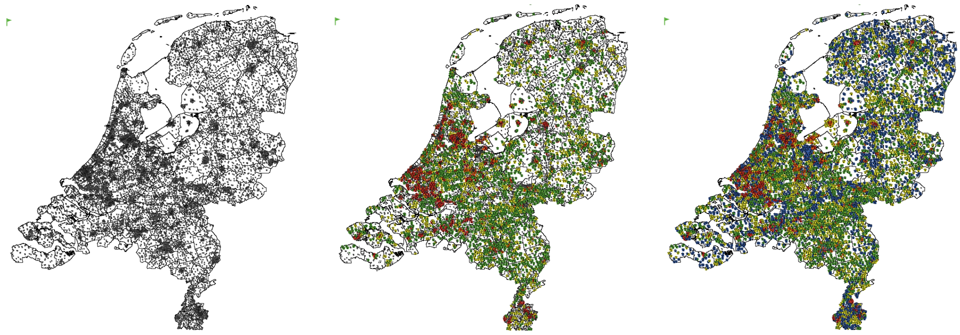

**Figure 5.1:** *Three model simulation screen captures of the model on national level for the reference scenario. Left represents 2020, the middle 2035 and right 2050.*

Zooming in on the municipality of Groningen, the transition dynamics in the model can be captured on a local scale of the built environment. Figure 5.2 presents three simulation screen captures for the municipality of Groningen in NetLogo. The behavior simulated with this scenario yields that first the neighborhoods outside of the old city center transition to various thermal systems. And towards 2050, the city center itself is also transitioned.

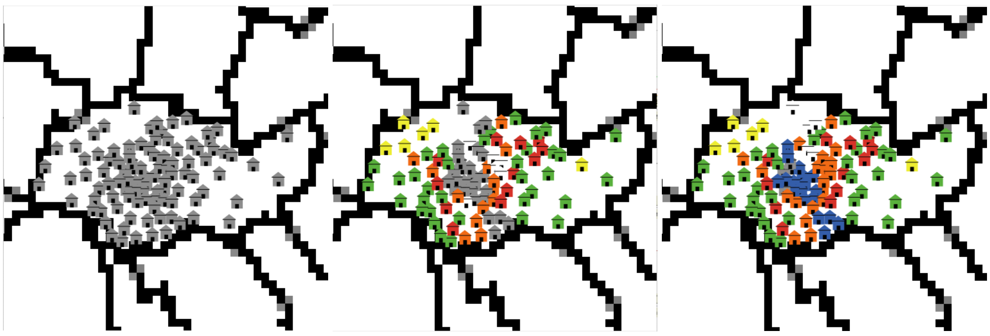

**Figure 5.2:** *Three model simulation screen captures of the model zoomed in on the local level showing the municipality of Groningen. Left represents 2020, the middle 2035 and right 2050.*

The interface of the model serves as the control and monitor dashboard for single simulation runs. Figure 5.3 shows the model interface in NetLogo. The model can be operated through the setup, reset and go buttons on the bottom left of the interface. The sliders in the green boxes can be used to set the parameter values in the model. The plots on the right side of the interface can be used to monitor the global behavior of the model during a simulation run. The black visualization on the top left side of the interface describes the yearly progression of the interface through color changes of the neighborhoods.

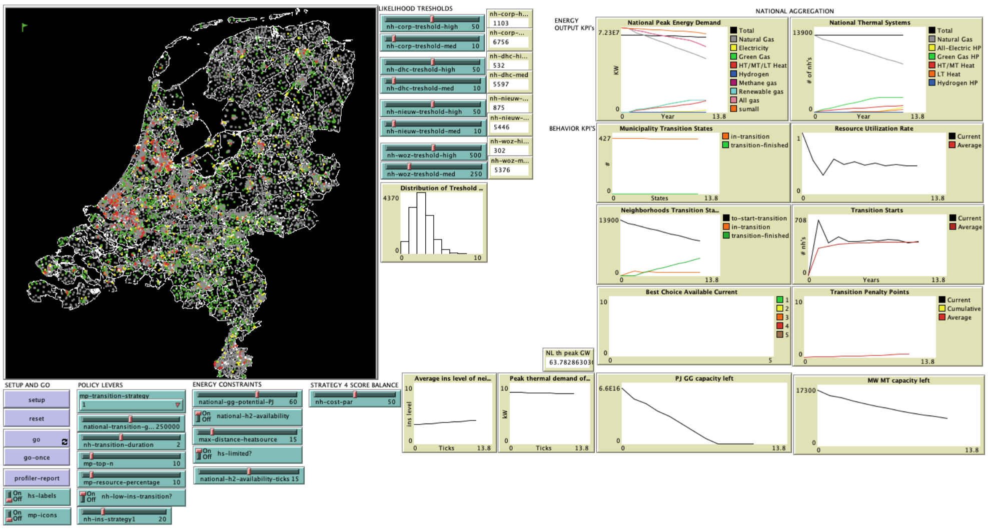

**Figure 5.3:** *Screen capture of the models interface in NetLogo.*

To further analyze the behavior of the model as implemented in NetLogo, post-processing of the experimentation runs is necessary. The results of the experiments performed with the model are presented in the next section.

## 5.2 MODEL OUTPUT

In this section, the output of this model is capable of is presented. The model's behavior, the influence of its assumptions, the effect of the decision-making by municipalities in the model and an exploration of its uncertainty space with a scenario approach are presented. The goal of this section is to present the ingredients to conclude on what kind of insights for Gasunie the model is capable of providing.

First, the model behavior and its assumptions are presented and discussed in subsection 5.2.1. Then, subsection 5.2.2 describes the influence of the municipalities' behavior in the model. And finally, subsection 5.2.3 concludes with a the scenario analysis of the model.

### 5.2.1 General Model Behavior and Assumptions

The first set of experiments is aimed towards finding insights on the general model behavior and the underlying assumptions in its parameters on the national model level. By varying the parameters underneath the assumptions, the sensitivity and resulting behavior can be extracted. The analysis of the model behavior and assumptions is presented by first discussing the neighborhood insulation assumptions, then the heat source assumptions and finally the availability of renewable gasses. The observations are synthesized in the key insights paragraph at the end of this subsection.

In the experimental setup the parameter of interest is varied in its uncertainty space with the reference parametrization (refer to table 4.3 for the parametrization) of the model. The design of the experiments is presented in table 5.1 as follows:

| **Experiment** | **Variable** | **Values** |
|---|---|---|
| *Low insulated neighborhoods cannot transition* | nh-low-ins-transition? | TRUE / FALSE |
| *Insulation strategy for neighborhoods* | nh-ins-strategy1 | [0 10 80] |
| *Limitation to HT/MT heatsources* | hs-limited? | TRUE / FALSE |
| *Maximum distance to heatsource* | max-distance-heatsource | [1 3 30] |
| *National Green Gas potential* | national-gg-potential-PJ | [0 10 120] |
| *Hydrogen availability year* | national-h2-availability-ticks | [0 1 30] |

Table 5.1: *The design of experiments for analyzing the models behavior and assumptions.*

#### *Insulation Assumptions*

It is found that the model parameters that relate to insulating the built environment affect the selection of which neighborhoods are transitioned, the total volume of peak energy demand and the distribution of peak energy demand per energy source.

The two parameters that relate to insulating the neighborhoods in the built environment are *nh-low-ins-transition?* and *nh-ins-strategy*. The first parameter controls the assumption in the model whether neighborhoods with a poor insulation level (below 3.5 or label D) are not eligible for a transition, the second parameter influences the speed at which neighborhoods advance their insulation level.

The assumption that poorly insulated neighborhoods cannot transition until they reach a sufficient level of insulation does not significantly impact the overall transition, but creates a small allocation of resource inefficiencies in the model (refer to appendix figure L.4). Having the assumption included limits old, poorly insulated city centers to not transition to a sustainable thermal system in the reference scenario. This is illustrated by showing the difference in transitioned neighborhoods with the assumption on (left) and off (right) in figure 5.4 for Amsterdam in 2050. Amsterdam has a lot of very poorly insulated neighborhoods in its city center, who do not achieve the threshold insulation level by 2050 with the reference insulation speed while this insulation is included.

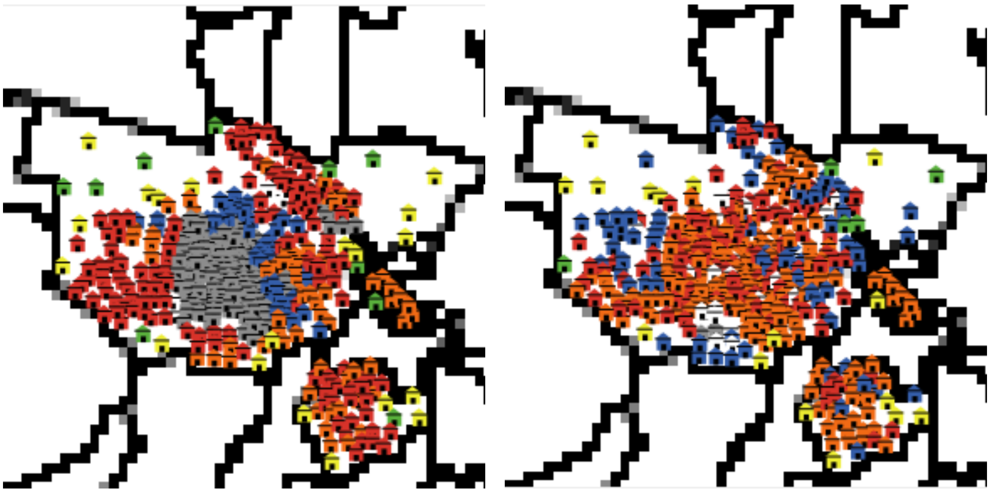

**Figure 5.4:** *Comparison of simulation snapshots of Amsterdam in 2050 with the reference parametrization that show the effect of the assumption that poorly insulated neighborhoods are not eligible for a transition.*

The speed of insulation in the built environment not only changes the overall volume of demand as a result of increased energy efficiency (refer to appendix L.5) but also the configuration of the renewable energy sources. Figure 5.5 shows how increasing the speed of insulation with the model parameter influences the distribution of renewable energy sources in 2050. This plot shows the multivariate relationship between the insulation strategy and the fractions of renewable energy sources in the total volume of renewable energy. The color change indicates the level of the speed of insulating the built environment. Analyzing the plot shows the nonlinear relationships between increasing the insulation speed and in what direction the energy demand develops towards 2050. This implicates that different speeds of insulating the built environment result in not only influencing the total volume due to thermal energy efficiency change but also the transition paths towards different distributions of peak thermal energy demand. An increase of a neighborhood's insulation level changes its neighborhood type, thus changing its relative advantage order (refer to table 4.2 for the different neighhorhood types and relative advantages).

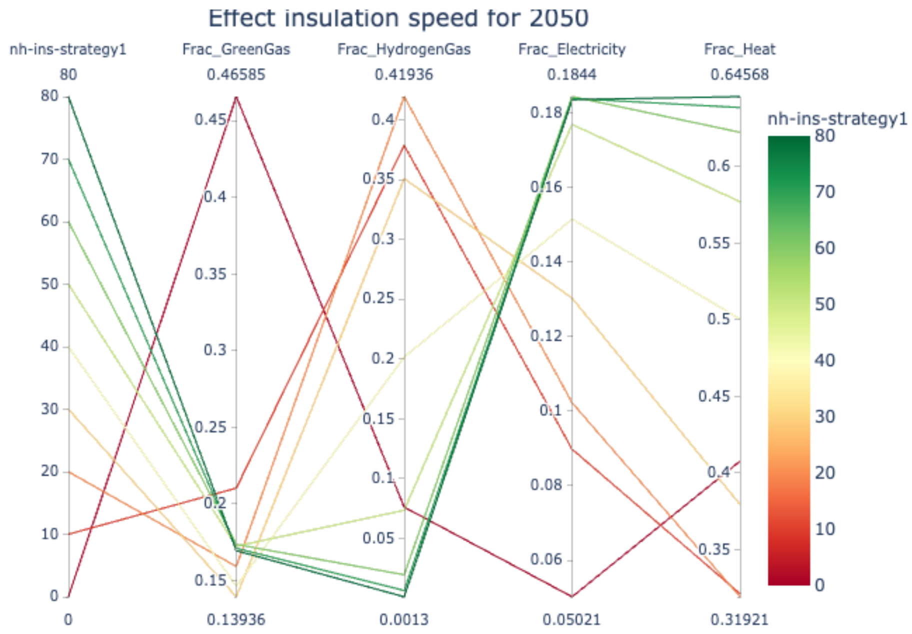


Figure 5.5: *Parallel coordinates plot showing the relation between different levels insulation strategies for the built environment and the fractions of renewable energy sources in the total volume of renewable energy sources. This plot shows this relation for 2050.*

### *Heat source Assumptions*

The model parameters that have an impact on the adoption of district heating network thermal systems are found to significantly affect the peak thermal energy demand. The two parameters that relate to the heat source assumptions are *hs-limited?* and *max-distance-heatsource*. The *hs-limited?* parameter controls the assumption in the model whether neighborhoods must connect to a nearby high- or medium temperature heat source to be able to transition to a high- or medium temperature district heating system. The parameter *max-distance-heatsource* consequently controls the model parameter that dictates the radius in which neighborhoods need to have an available heat source available to connect to.

The assumption that neighborhoods must have a nearby existing heat source significantly influences the model behavior. It is found that a lot more neighborhoods transition towards DHC's if they can do this without any heat source to connect to (refer to appendix figure L.7). When neighborhoods can transition to a high or medium temperature DHC without any of such boundaries, the model indicates more peak heat demand and less electricity and hydrogen peak demand. Green gas peak demand is only impacted marginally by reaching its maximum capacity a few years later.

The second assumption that dictates the radius in which the heat source must be available also influences the model's behavior, but to a lesser extent (refer to appendix figure L.8). A more detailed explanation is provided in appendix L.3.2. Green gas is only limitedly influenced by the changing radius, while hydrogen gas peak demand is not impacted. Electricity is significantly less used when the radius of distance to a heat source is increased.

### *Renewable Gas Availability*

It is found that the availability of renewable gasses is very strongly influencing the model's behavior. The two parameters influencing the assumptions on the availability of green gas and hydrogen are *national-gg-potential-PJ* and *national-h2-availability-ticks*. *national-gg-potential-PJ* is the parameter that controls how much national green gas capacity is available for use in neighborhoods, whereas *national-h2-availability-ticks* controls at what point in time during the simulation hydrogen becomes available as a technology.

The availability of green gas is found to strongly influence the model's behavior as it is a scarce resource. Figure 5.6 shows the effect of varying the national potential of green gas between 0 and 120 PJ on the national peak energy demand per energy source. The most prevalent insight of this figure is how linear the relationship between increasing the green gas potential and green gas demand, electricity demand and heat demand seems. The model shows that every bit of extra green gas available is used by the thermal systems of neighborhoods, indicating significant scarcity in the residential built environment of this source. This is the result of the neighborhoods that are asked to transition when green gas is still available, prefer a transition to green gas driven systems. In the early phases of the transition, the share of neighborhoods that have characteristics leading to a preference for green gas is larger than the share of how much green gas can be provided.

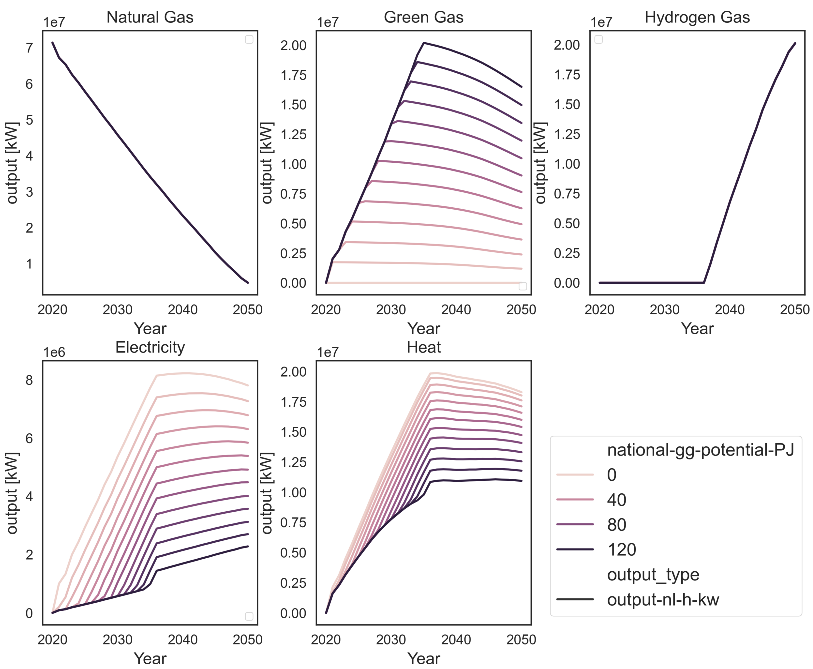


**Figure 5.6:** *Peak energy demand per energy source in the reference scenario while varying the availability of green gas.*

This linearity is confirmed in figure 5.7. In the parallel coordinates plot, the multivariate relation between increasing the potential (illustrated with the color change) and its effect on the fractions of renewable energy sources in the total volume of renewable energy is described. It shows that the increase in green gas potential is positively related to green gas and inversely related to hydrogen gas, electricity and heat. This confirms the strong influence of the availability of green gas on the model's behavior. Green gas is found a scarce resource of which its availability is strongly influencing how the other sustainable alternatives are implemented.

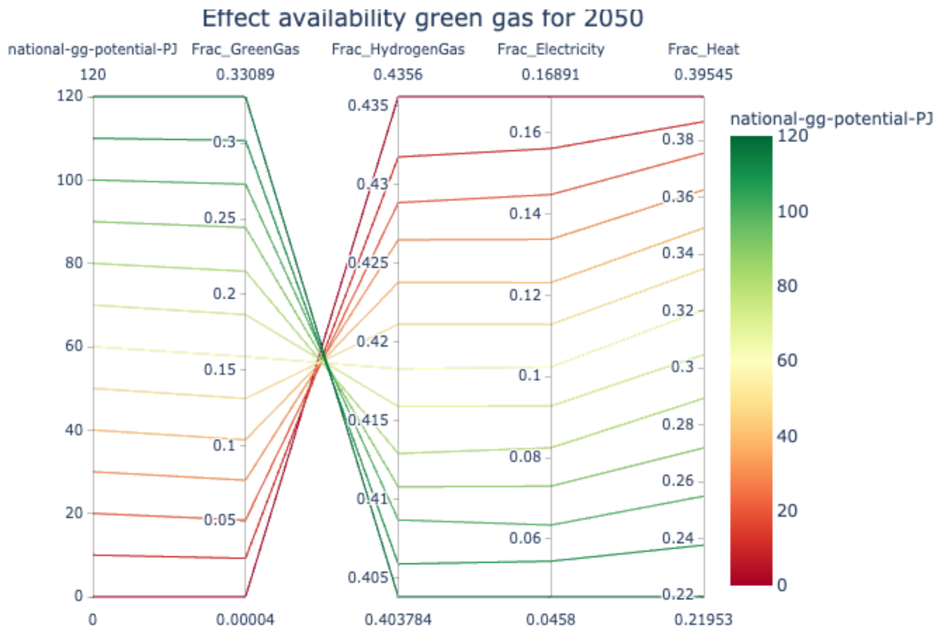


**Figure 5.7:** *Parallel coordinates plot showing the relation between different levels of green gas availability in PJ and the fractions of renewable energy sources in the total volume of renewable energy sources. This plot shows the this effect for 2050.*

Similarly, the availability of hydrogen is also found to strongly influence the model's behavior, but in the later stages of the transition. Figure 5.8 illustrates the influence of the point in time that hydrogen becomes an available technology on the national peak energy demand per energy source.

Three important insights can be drawn from this figure. The first is that at the point in time that hydrogen becomes an available technology, an almost linear increase of its demand is observed (top right plot in figure 5.8). The second insight is that when hydrogen becomes available and starts increasing, both electricity and heat demand significantly flatten their demand curve over time (bottom left and bottom middle plot in 5.8). And the third important insight is that green gas does not seem to be affected at all by varying the time at which hydrogen becomes available, as a consequence of hydrogen always being less preferred by than green gas when both of them are available. This indicates that hydrogen is strongly preferred over electricity and heat when available in the model.

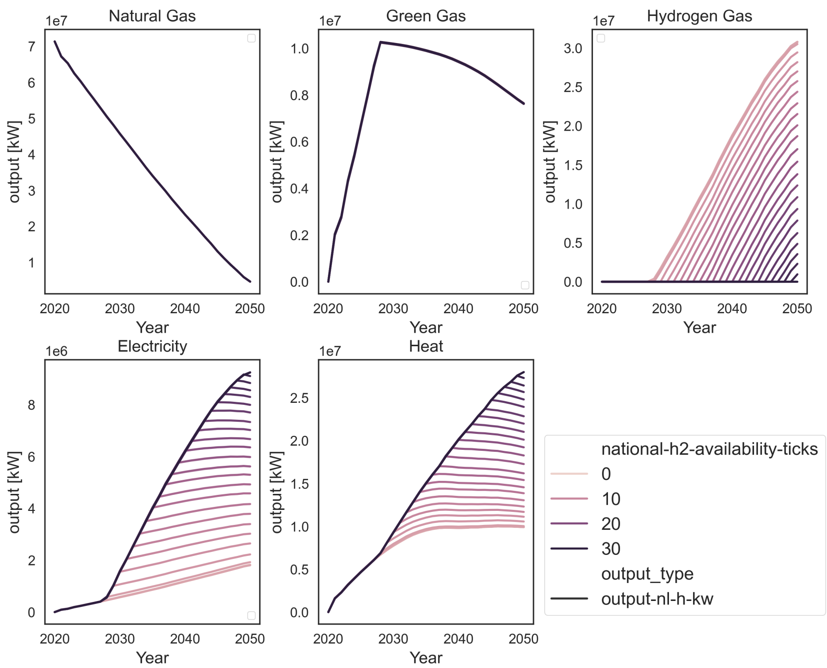


**Figure 5.8:** *Peak energy demand per energy source in the reference scenario while varying the point in time of the simulation that hydrogen technology becomes available.*

The same linear seeming behavior is observed when inspecting a parallel plot of this experiment. Figure 5.9 shows the relation between the time at which hydrogen becomes available in the model (indicated by the color change) and the fractions of renewable energy demand per energy source in the total volume of renewable energy. The figure shows that the later hydrogen becomes available (greener), green gas, electricity and heat will have a larger share and hydrogen a smaller share. This observation can be interpreted as the later hydrogen becomes available, the more neighborhoods have already adopted thermal system alternatives that are less preferred than the hydrogen hybrid heat pumps. Timing the transition of a neighborhood can therefore mean the difference between a sub-optimal or optimal solution. This indicates a similar observation that when hydrogen becomes available it is a significantly preferred energy source in the model.

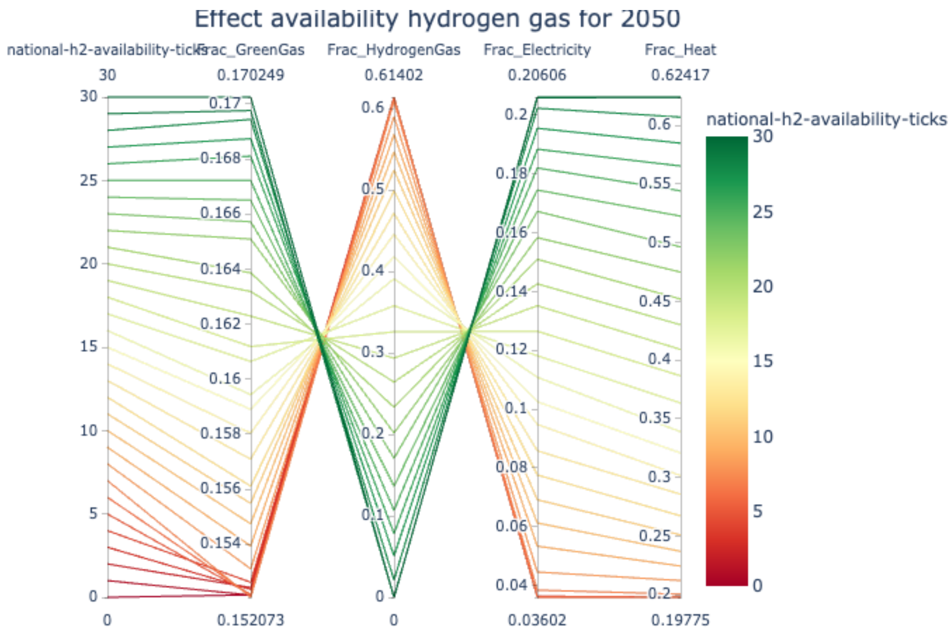


**Figure 5.9:** *Parallel coordinates plot showing the relation between different points in time hydrogen becomes available as a technology for neighborhoods and the fractions of renewable energy sources in the total volume of renewable energy sources. Tick 0 corresponds to 2020, while tick 30 corresponds to 2050. This plot shows this effect for 2050.*

#### *Key Findings*

This subsection discussed the results of the experiments focusing on the model assumptions and general behaviors. By analyzing the results of the experiments, several observations on the model behaviors can be made. The first insight is that the model tends to show a decreasing peak natural gas demand pattern which is translated into a distributed increase of the different renewable energy sources. And second, the model is found to be very sensitive to the availability of renewable gasses, as they are scarce energy sources for the built environment.

### 5.2.2 Influence Municipal Decision Strategies

To understand the influence of decision-making by municipalities in the model, the factors influencing their decision are further analyzed. The factors influencing municipal decision-making are the national transition goal, the municipality's resource percentage and the different formalized strategies. Four different sets of experiments are run in this subsection. First, the influence of the national transition goal and the municipality's resource percentage on the models KPI's are considered in the paragraph on transition speed driving assumptions. Then, the five initially formulated strategies are compared on their national and MR-region behavior in the paragraph hereafter. The experiments are simulated with the reference parameterization of the model. The design of the experiments is presented in table 5.2 below.

| Experiment | Variable | Values |
| --- | --- | --- |
| *National transition goal* | national-transition-goal | [50000 50000 500000] |
| *Municipal resource percentage* | mp-resource-percentage | [2 2 20] |
| *Municipality decision strategy* | mp-transition-strategy | 0, 1, 2, 3, 4 |
| *Neighborhood transition duration* | nh-transition-duration | [1 1 5] |
| *Importance of governance diffusion* | nh-cost-par | [0 10 100] |

Table 5.2: *The design of experiments for analyzing the different implemented municipal decision strategies.*

### *Transition Speed Driving Assumptions*

It is found that the model parameters influencing the speed at which municipalities can drive the transition forward changes the total volume of peak demand for all energy sources included in the model and their distribution.

The parameters that influence the speed at which municipalities can instigate transitions of their neighborhoods are the *national-transition-goal*, *mp-resource-percentage* and the *nh-transition-duration*. The combination of these three determine the speed, but are bounded by each others limiting effects (refer to appendix L.3.2).

Figure 5.10 shows the effect of varying the national transition goal between 50,000 and 500,000 households per year on the national peak energy demand per energy source. The most prevalent behavior that is to be noted is the decrease in peak natural gas demand and a varying increase in renewable sources. Increasing the goal results in a steeper downward slope of natural gas peak demand over time (top left graph in 5.10), suggesting an acceleration of the transition if the transition goal is higher. Increasing the transition goal results in a stronger increase of renewable energy sources over time, suggested by the peak energy demand of green gas, hydrogen gas, electricity and heat. However, the development of hydrogen gas suggests that increasing the national transition goal over a certain threshold results in an inverting effect over time (top right graph in 5.10).

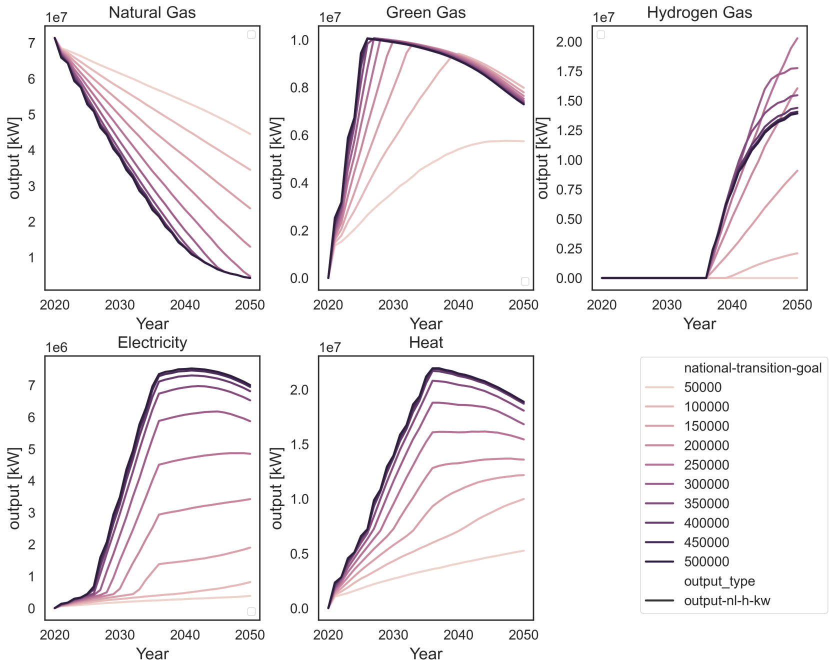


**Figure 5.10:** *Peak energy demand per energy source in the reference scenario while varying the national transition goal.*

Having noticed and further analyzed this inverted effect over time with hydrogen gas development, it is found that changing the speed at which the transition occurs in the model also shifts the distribution towards which renewable energy sources the transition develops. Figure 5.11 shows how increasing the national transition goal influences the distribution of renewable energy sources. This plot shows the multivariate relationship between the national transition goal and the fractions of renewable energy sources in the total volume of renewable energy sources. The color change indicates how the relationship changes by varying the national transition goal. Looking at this plot suggests that a nonlinear relation exists in the model between increasing the national transition goal and the fraction of hydrogen gas and heat use in by the residential built environment.

This relation can be explained by the phenomenon of deciding for a transition in a particular neighborhood now, instead of in 10 years, changes the circumstances that have to be chosen in. Two particular circumstances change for neighborhoods in the model. First, as insulation of neighborhoods' is decoupled from transitioning their thermal system, a transition of this neighborhood in 10 years implicates that the neighborhoods level of insulation might have improved. This increase in insulation results in the neighborhood being eligible for different thermal systems that require higher levels of insulation. The second changing circumstance is the availability of renewable gasses. As mentioned, the availability of renewable gasses is a significant driver of the model. For example, transitioning a neighborhood now instead of in 10 years might implicate the difference between being able to implement green gas, hydrogen gas, or neither of these energy sources.

This suggests that in the model, the configuration of the transition in the built environment is dependent on the speed at which the transition will occur.

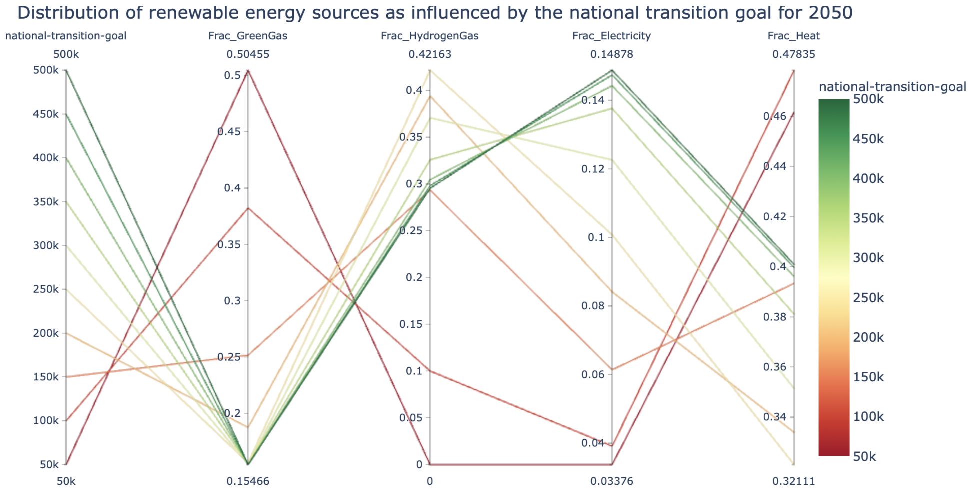


**Figure 5.11:** *Parallel coordinates plot showing the relation between different national transition goals and the fractions of renewable energy sources in the total volume of renewable energy sources. This plot shows the this effect for 2050.*

### *Municipal Decision Strategies*

By analyzing the differences between the municipal decision-making strategies, it is found that the neighborhood selection method has a regionally differing but limited influence, while the thermal system selection method is of significant importance. The five strategies, as formalized in table 4.1, are compared on their influence on the peak energy demand per energy source in the reference parameterization. Figure 5.12 describes the different national trends for the included energy sources.

First, it can be observed that they do not result in a significant difference in transition speed, as shown by the equal downward slope of peak natural gas demand (top left plot 5.12).

Second, comparing the strategies on how they influence the distribution of renewable sources, it can be observed that strategies 1, 2 and 3 perform very similar in contrast to strategies 0 and 4. Strategies 1, 2 and 3 differ in their neighborhood selection method but are similar in the thermal system selection method. This implicates that the neighborhood selection method does not have a significant influence on the national peak energy demand level in the model.

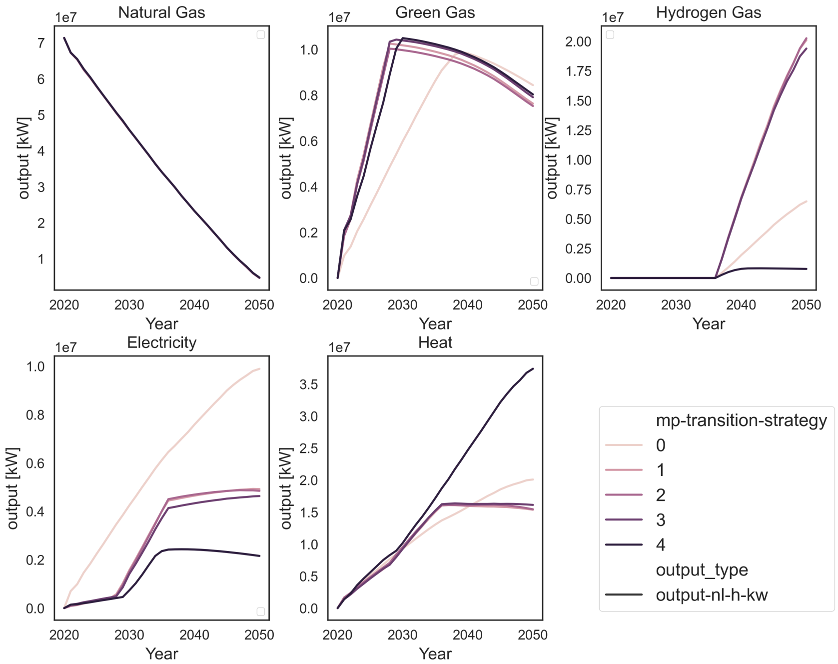


**Figure 5.12:** *Peak energy demand per energy source in the reference scenario while varying the 5 formalized municipal-decision strategies.*

The effect on the MR-region level is found to be similar to the national level but provides more detail on the dynamics of the strategies with four observations. Figure 5.13 presents the influence of the different strategies on the MR-region level per energy source for 2035 and 2050.

The first observation is that the strategies seem to have the least effect on green gas peak demand (see the top left graph of figure 5.13). This is the result of all the strategies reaching the limits of green gas availability (see the top left graph of figure 5.12), thus not being able to differentiate at this energy source.

The second observation is the different effects of the strategies on peak hydrogen gas development (top right graph figure 5.13). Strategies 1, 2 and 3 seem to be grouping together in 2050, while strategies 0 and 4, which have different thermal system selection methods, behave significantly differently. The third observation is the many outliers for strategy 0 with peak electricity demand (bottom left 5.13). This indicates that when a non-random thermal system selection method is used (strategy 1, 2, 3 and 4), neighborhoods with a high volume of thermal demand do not prefer electrically driven thermal systems.

And the final observation concerns the significantly higher peak heat demand for strategy 4 in 2050 (bottom right graph of figure 5.13). This indicates that when neighborhoods include governance diffusion in their decision-making, peak heat demand will be higher as a result of more district heating networks implemented. Overall, strategies 1, 2 and 3 seem to behave similarly as a result of the same thermal system selection method, while strategies 0 and 4 are significantly different.

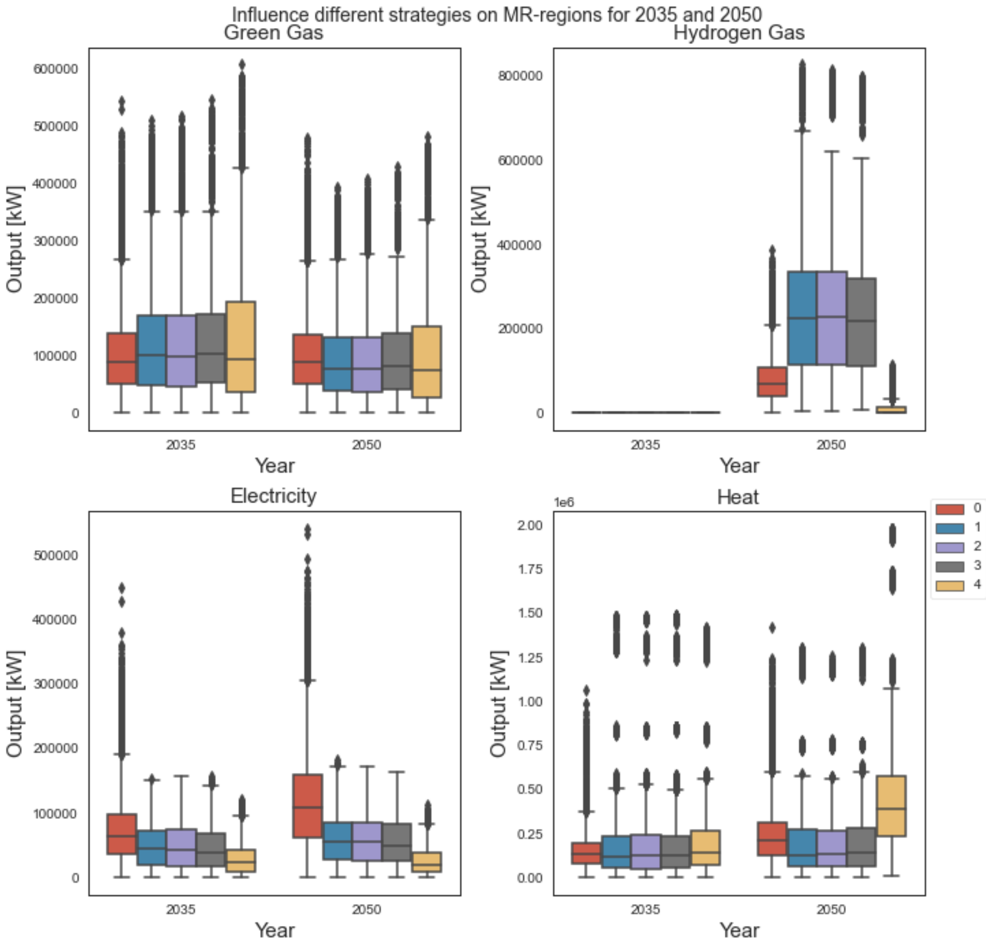


**Figure 5.13:** *Peak energy demand per energy source in the reference scenario on the MR-regions.*

The most interesting observation is that the MR-stations regions are to a different degree sensitive to the different strategies considering peak gas demand. Figure 5.14 presents the coefficients of variation for all MR-stations on the difference in peak methane or all gas demand as a result of the different implemented strategies. With the coefficient of variation, the amount of variability relative to a sample mean can be described by dividing a sample's standard deviation by its mean. This allows for comparing the variability between regions of different total gas demand volumes.

Two insights can be drawn from figure 5.14. First, it suggests that the MR-stations are not equally sensitive to different municipal strategies. Even when all model parameters are kept constant and the only variable that changes is the homogeneous strategy of municipalities, MR-stations are differently sensitive. The only difference between the MR-stations is their underlying characteristics, suggesting that MR-stations might respond with different sensitivity to how municipalities will approach their transition. This is illustrated in the figure by the spread of the methane gas and all coefficient of variation. If there were no differences in sensitivity, no spread would have been visible in this figure.

The second insight is that when hydrogen is considered in the aggregation with the All Gas peak demand, MR-stations seem to have fewer sensitivity differences among themselves. This can be observed in the smaller spread among the outliers in figure 5.14.

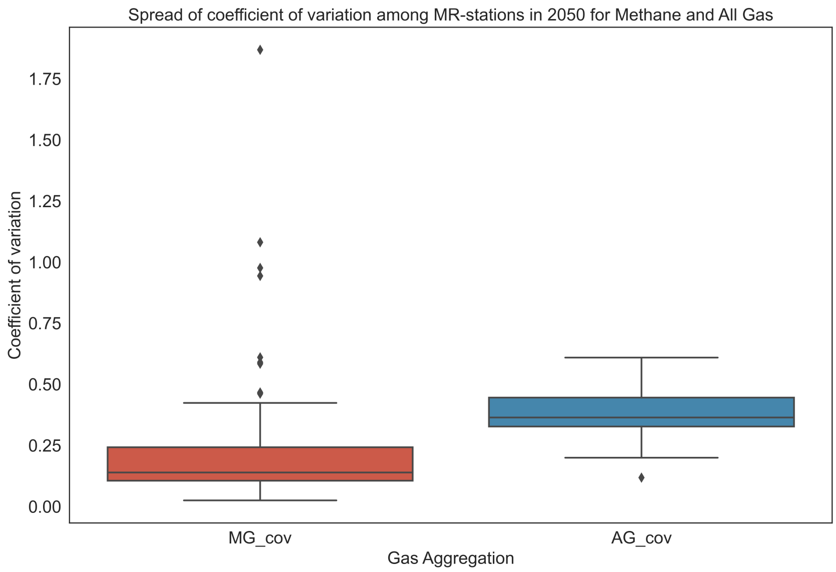


**Figure 5.14:** *Comparing the coefficients of variation spread resulting from differing the municipal strategies for all MR-stations for methane and all gas in 2050.*

This difference in sensitivity is illustrated by figures 5.15 and 5.16 showing the peak demand development for green and hydrogen gas of a highly sensitive and a limitedly sensitive MR-station. The MR-station Weesp is used as an example of a region highly sensitive to different strategies, while Scheemda is used as an example of a limitedly sensitive MR-region. A clear difference in trends is observable for green and hydrogen gas.

Figure 5.15 describes a region that has limited sensitivity to the municipals strategies. This does not implicate that there is no sensitivity, but it is less sensitive compared to Weesp. This can be observed in how peak green and hydrogen gas demand develops over time. Green gas is seen to develop relatively close to each other, with only strategy 0 drifting until after 2035. Hydrogen also has different trajectories, with strategy 0 and 4 being significantly different. By comparing Scheemda to Weesp in figure 5.16 the difference in sensitivity becomes more clear.

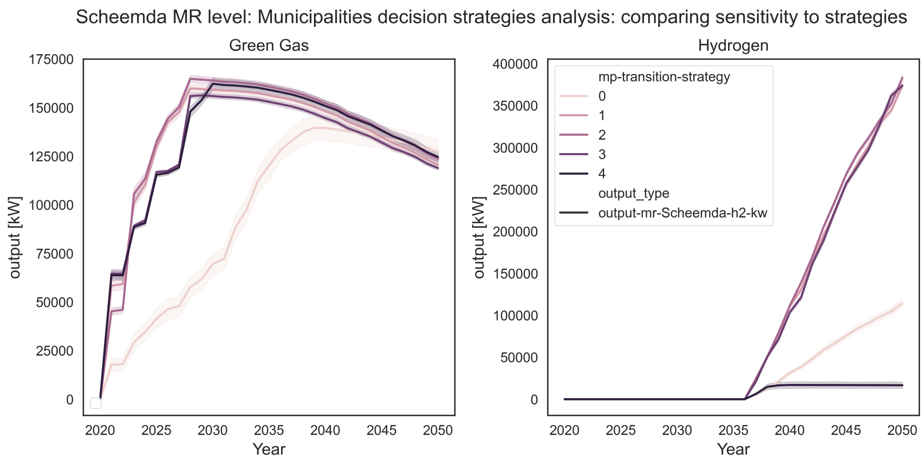


**Figure 5.15:** *Example of limited sensitivity for different strategies in the Scheemda MR-region.*

Figure 5.16 describes an example of an MR-region that is more sensitive to the implemented strategy. For green gas, it can be observed that the spread for peak green gas demand towards 2050 is significantly different. The peak hydrogen gas demand trajectories are also highly sensitive to different strategies. Comparing the examples of Weesp to Scheemda, it can be concluded that MR-regions are different in their sensitivity to municipal decision-making strategies, dependent on their characteristics in the built environment.

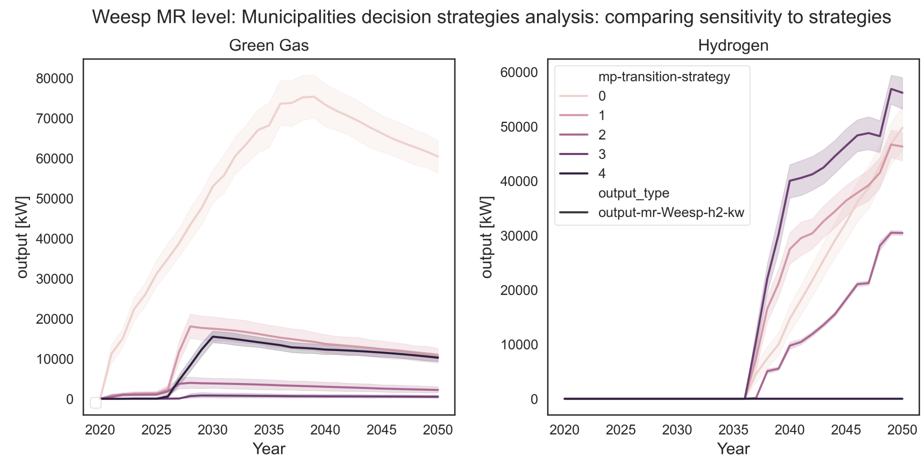


**Figure 5.16:** *Example of high sensitivity for different strategies in the Weesp MR-region.*

This implicates that the regional allocation of required gas capacity is dependent on the speed of the transition, the municipal decision-strategies and the regional characteristics of the built environment.

### *Governance Diffusion Assumptions*

It is found that increasing the amounts of governance diffusion in the model increases the model's preferability towards peak heat demand significantly.

The factor influencing the governance diffusion concept in the model is *transition activity by others* and implicates how much the decisions municipalities in one's network contributes to its own decisions. The more governance diffusion, the more municipalities are looking at each other for their own decisions. This is translated in the *nh-cost-par*. A lower value of this parameter indicates *more* governance diffusion, corresponding with the red color in the parallel coordinates plot in figure 5.17. More governance diffusion leads to a significant bias towards peak heat demand in the model for the reference scenario.

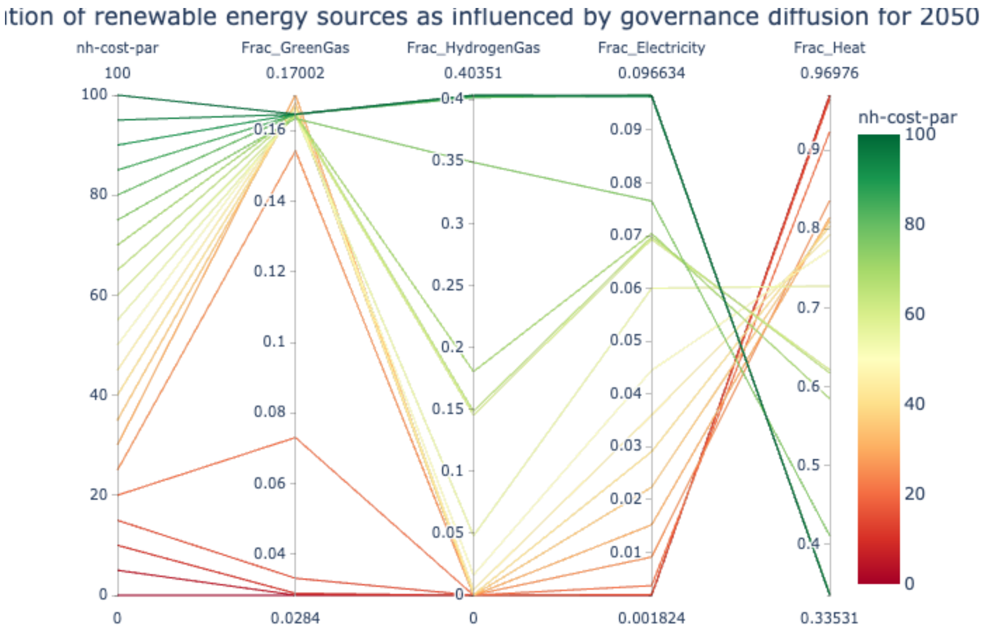


Figure 5.17: *Parallel coordinates plot showing the relation between the levels of governance diffusion and the fractions of renewable energy sources in the total volume of renewable energy sources. This plot shows the this effect for 2050.*

### *Key Findings*

This subsection discussed the results of the experiments concerning the factors contributing to the dynamics of the municipalities' decisions: the speed driving assumptions and the different municipal strategies. By analyzing the results of the experiments, several observations on the municipal's behavior in the model can be made. The first key insight is that the assumptions influencing the volume of decisions by municipalities drive the transition forward as a whole, while also influencing the distribution of renewable energy sources. The slope at which natural gas peak demand declines is dependent on the volume of the decisions, while the increase of the renewable sources is dividedly increased over time depending on the speed. The second key insight is that the selection method for selecting which neighborhood's transition first is of limited influence to the peak energy demand in the model. Third, it is found that the selection method for determining which thermal system is to be installed is of significant influence in the strategies. Fourth, MR-station regions are found to be differently sensitive to changing municipal decision strategies. And the final insight is that more governance diffusion in the model leads to a strong bias towards peak heat demand.

### 5.2.3 Gasunie Scenario's

To understand how the model responds to different scenarios and what its competencies are in terms of outcome representation, eight different scenarios are developed. By studying the scenario's, their visualizations and their implication on the model outcomes, observations necessary to conclude on its usability are provided. The outcomes are discussed from the national perspective, the MR-stations perspective and the MR-stations with a geographical perspective. The different perspectives are described for their use and insights based on the scenario's are extracted.

To focus the scenario's towards the stakeholder's interest, the scenarios were developed in collaboration with Gasunie. First, the most relevant model parameters were identified, then their varying values were determined. The scenario outcomes are analyzed on the national system level and the MR-region level.

The identified model parameters of interest that make up the different scenarios are *1) hydrogen availability, 2) green gas potential and 3) insulation speed*. The scenarios are simulated with the reference parameterization of the model. First, the design of the experiments is presented below in table 5.3, then the scenarios are briefly discussed for their characteristics.

| Scenario | H2 availability [year] | Green gas potential [PJ] | Insulation speed |
|---|---|---|---|
| *G1: Hydrogen Focus* | 2035 | 60 | 20 |
| *G2: Hydrogen Insulation* | 2035 | 60 | 40 |
| *G3: Hydrogen All Renewables In* | 2035 | 120 | 20 |
| *G4: Hydrogen All Technologies In* | 2035 | 120 | 40 |
| *G5: No Focus* | 2050 | 60 | 20 |
| *G6: Efficiency Focus* | 2050 | 60 | 40 |
| *G7: Cow Fart Driven* | 2050 | 120 | 20 |
| *G8: Keep Cow Fart Inside* | 2050 | 120 | 40 |

**Table 5.3:** *Design of experiments for Gasunie's scenarios.*

**G1: HYDROGEN FOCUS** This scenario can be considered as the reference scenario. It is characterized by hydrogen availability in 2035 while having a modest availability of green gas and a relatively slow insulation progression of the built environment. The only bright side of this scenario is that efforts are focused on the development of making hydrogen work as a thermal technology in the built environment.

**G2: HYDROGEN INSULATION** This scenario builds upon the *Hydrogen Focus* scenario, but efforts to step up the game for insulating the built environment are included. Hydrogen becomes available as a technology in 2035, green gas is available to a limited degree, but insulating is progressing rapidly. This scenario focuses on hydrogen and insulation efforts to move the transition forward.

**G3: HYDROGEN ALL RENEWABLES IN** This scenario is characterized as the best-case scenario in terms of renewable gas availability. Hydrogen is available from 2035, green gas availability is doubled to 120PJ nationally, but insulation efforts remain behind. This scenario is all-in for renewable gasses.

**G4: HYDROGEN ALL TECHNOLOGIES IN** This scenario represents the best-case in terms of all parameters. Hydrogen is available from 2035, green gas availability stands at 120PJ, while insulation efforts are big for the built environment. This scenario is all-in for everything we have got.

**G5: NO FOCUS** This scenario is comparable to the *Hydrogen Focus* scenario, except that there is no focus at all. All the model parameters are at their worst-case values. Hydrogen does not become available before 2050, green gas is only limitedly available with 60PJ and insulation efforts are just mediocre. There is no focus on the thermal transition of the built environment at all.

**G6: EFFICIENCY FOCUS** This scenario builds upon the *No Focus* scenario, except for an increased effort on insulating the built environment. Hydrogen is not available before 2050, 60PJ of green gas is available yearly, but we do focus our efforts at insulating the neighborhoods. The thermal transition is not supported by renewable gasses but merely focused on improving efficiency.

**G7: COW FART DRIVEN** This scenario is arguably the most carbon driven scenario of the bunch. Hydrogen is not expected to play a role before 2050, insulation efforts will be low, but 120PJ of green gas will be available to the built environment yearly. The thermal transition of the built environment will be largely driven by methane gas such as extracted from composted plant material, or cow farts.

**G8: KEEP COW FART INSIDE** This scenario is similar to the *Cow Fart Driven* scenario, but includes a stronger effort to insulate the built environment. Hydrogen is not expected to play any role before 2050, but 120 PJ of green gas will be available and insulation efforts will be high. By improving the insulation levels of the built environment, the cow farts will be kept inside.

### *National Results*

The first aggregation level of interest is the national level. By observing peak energy demand development trends on the national level, the resulting emergent behavior of the municipal driven transition can be captured compactly. By aggregating these KPI's, the high-level implications of the scenario can quickly be compared to one another. However, local developments of relevance for capacity implications are not observable. Figure 5.18 presents an overview of the absolute peak thermal demand development on the national level for all scenarios. And figure 5.19 illustrates the statistical spread amongst the scenarios for the national level and respective model KPI's.

The stacked and grouped bar chart presented in 5.18 can quickly translate absolute peak energy demand developments per energy source, while effectively comparing scenarios. It translates high-level trends of volume development per energy source. Such a visualization does lack any form of statistical trends, except for describing means of the underlying data. And inherent to the aggregation, it cannot describe regional trends, which would be necessary for pinpointing local capacity implications in Gasunie's infrastructure.

From this figure, it can be concluded that under these scenarios, the built environment as a whole will reduce its peak thermal energy demand and that the distributions of renewable demand vary. Three observations on the scenarios in terms of peak gas development can be extracted. The first insight is that the eight scenarios result in only two different trajectories for natural gas decline as a result of the difference in insulation speed. The high insulation speed results in a slightly faster decline of natural gas. The second insight is that green gas development knows four trajectories, as a result of varying the availability of green gas and insulation speed. The scenarios *Hydrogen Insulation* and *Efficiency Focus* result in the least green gas peak demand, while the scenario's *Hydrogen All Renewables In* and *Cow Fart Driven* result in the most green gas peak demand. The third observation concerns hydrogen gas. Hydrogen development comes in three varying patterns, namely a lot (scenario's *Hydrogen Focus* and *Hydrogen All In Renewables*), a small amount in scenarios' *Hydrogen Insulation* and *Hydrogen All Technologies In*.

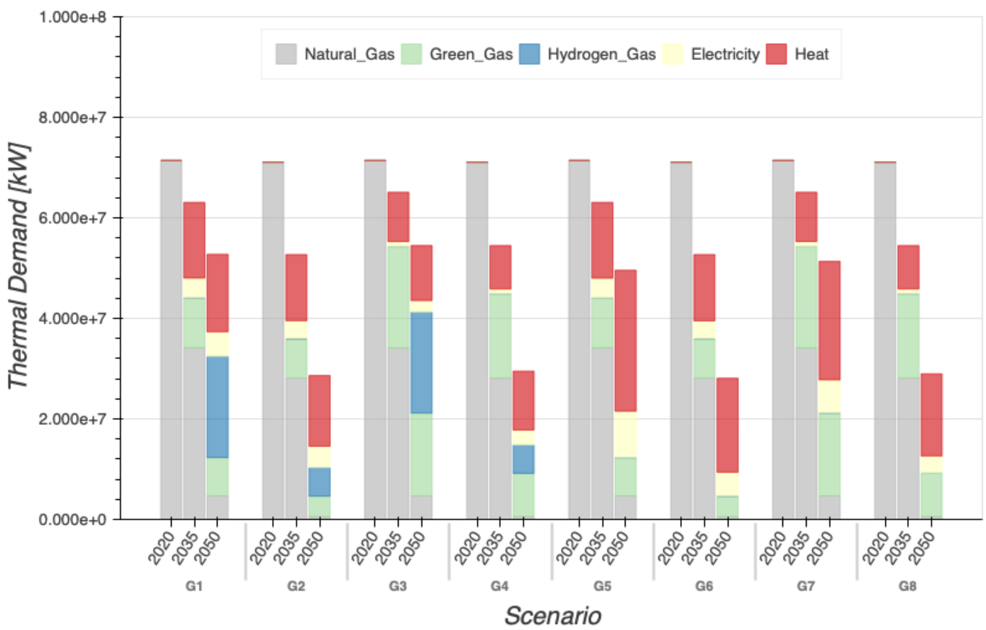


**Figure 5.18:** *The absolute peak thermal energy demand developments on national scale for the 8 scenario's simulated in this study.*

Comparing statistical trends for the main and secondary energy KPI's for the formulated scenario's reveals different patterns. Figure 5.19 compares the statistical trends over the scenario's for the years 2035 and 2050. Comparing the all gas and methane gas KPI's (left plot), the decreasing peak gas demand is confirmed in the model for the all gas and methane gas KPI's. However, when including all gas in the aggregation, peak gas demand decline is more dispersed than when only including natural gas and green gas. Comparing statistical trends with the secondary energy KPI's suggests that towards 2050, heat will play the most prominent role in terms of absolute peak thermal demand. Peak green gas and natural gas peak demand decline between 2035 and 2050. Electricity peak demand suggests the least spread over the scenarios, while hydrogen and heat have a significant spread in 2050.

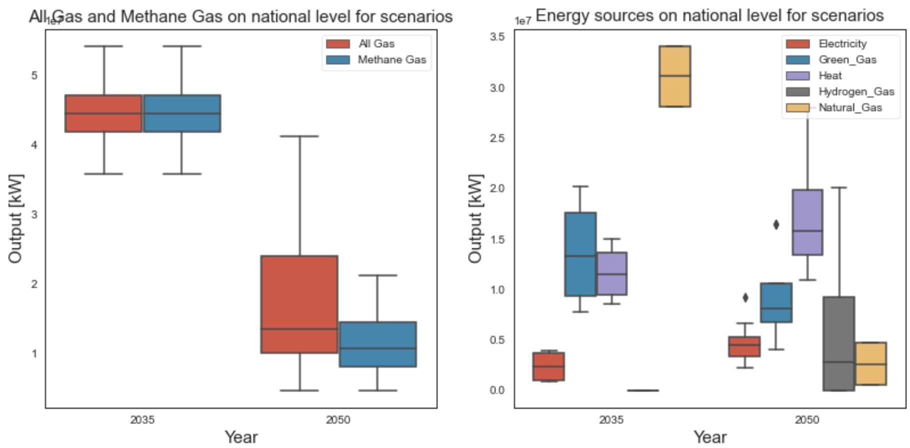


**Figure 5.19:** *Statistical analysis for 2035 and 2050 between the scenario's for the KPI's.*

#### *MR-Station Results*

The second aggregation level of interest for understanding the model is the MR-stations. While national-level aggregations are interesting to quickly understand the different implications of system-wide effects, the aggregation at MR-stations is more insightful for infrastructure capacity related conclusions. Observing the emergent behavior at this level can provide insights on the required peak demand at the regional MR-stations of Gasunie. These in turn could provide a proxy for the required capacity at the respective MR-stations.

The boxplots in figure 5.20 and 5.21 provide statistical metrics on the aggregation level of MR-stations for all gasses. The figures 5.22 and 5.23 present trends on average change per MR-station. Multiple scenarios can be captured in these visualizations. As these boxplots include natural gas, green gas and hydrogen gas, they provide insights into the total gas demand on Gasunie's network. No differentiation is made between methane gas and hydrogen gas, which are probably not physically combined in the network. For the separate methane gas aggregation, refer to appendix L.3.2.

Figure 5.20 describes the average change from 2020 to 2050 per MR-station for all scenarios. This is particularly useful for concluding which MR-regions will see large or small changes in their peak demand for gas over the length of the transition. As all scenarios indicate a decline in gas demand, one can conclude based on this figure which regions will remain fairly gas-driven and which ones not in the model, given these scenarios. For example, we can deduct which three regions will change their peak gas demand the most or least. Hence, Oostum, Lingewaal and Nijland change their peak all gas demand the least, while Gilze, Rijswijk and Weeesp will see the sharpest decline of peak all gas demand in the simulated scenarios'.

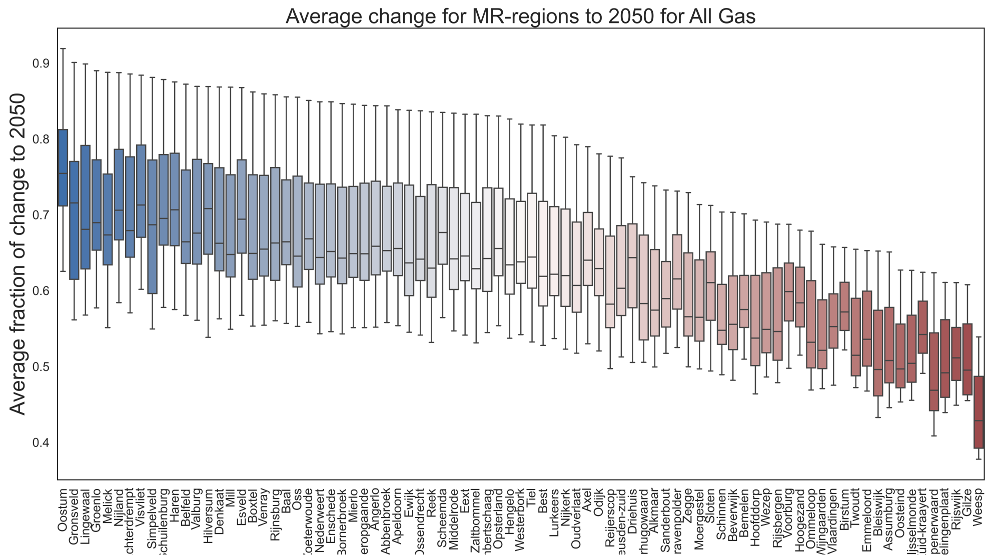


**Figure 5.20:** *Average fraction of change for MR-regions from 2020 to 2050, sorted by change. Red indicates MR's averagely diverging further from all gas demand, blue indicates less divergence from all gas demand than red.*

Figure 5.21 shows the average overcapacity from 2020 to 2050 per MR-station for all scenarios. Such analyses can be used for insights into which regions will have the most or least overcapacity installed in terms of absolute capacity. The scenarios all indicate a decline of gas use, as such, the analyses will not indicate any capacity limitations. For example, it can be concluded from this figure that the two metropolitan areas in the Netherlands, the Vlaardingen (Rotterdam area) and Sloten MR-region (Amsterdam) area, will contribute the most to the installed overcapacity at the MR-station level in Gasunie's infrastructure.

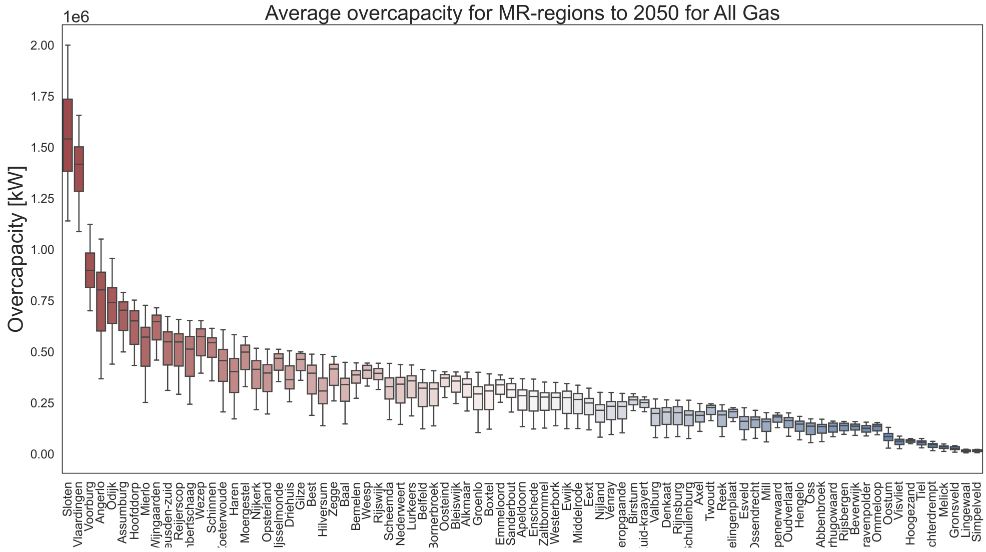


**Figure 5.21:** *Average all gas overcapacity bandwidths for the scenario's. Red implicates more overcapacity in terms of absolute kW's, blue less overcapacity.*

### *MR-station Regional Results*

The third aggregation level of interest for understanding the model is the national geographic representation of the MR-stations. This perspective combines the advantages of the national and detailed regional perspective. It provides detail on the regional differences between MR-stations in a map while displaying national trends in one visual representation. The downside of this perspective is that it is limited in the statistical dimensions it can display. Only one statistical metric per region can be displayed.

The chloropleths presented in figure 5.22 and 5.23 describe their statistical change of peak gas demand from 2020 to 2050 per MR-station averaged for all scenarios. This is exceptionally useful for capturing regional differences and trends in how regions respond differently and might require different attention by Gasunie. The drawback of using such chloropleths is that they lose statistical value by averaging the scenario's to a single mean, while not being able to display trends over time. The figures 5.22 and 5.23 describe the all gas KPI, for methane gas, refer to appendix L.3.2.

Figure 5.22 describes the regionally different change of peak gas demand. The greener the region, the less change over time is simulated by the scenarios. A more red region indicates that more change is observed over the scenarios. Hence, more change relative to 2020 implicates that a region will be less gas-driven towards 2050. The insights of interest from this figure are the differences between the urban and rural areas. A clear difference can be observed between the eastern rural parts and the more urban Randstad. This implicates that according to the simulated scenarios, the Randstad will be less gas-driven towards 2050, while the rural areas remain fairly gas-driven.

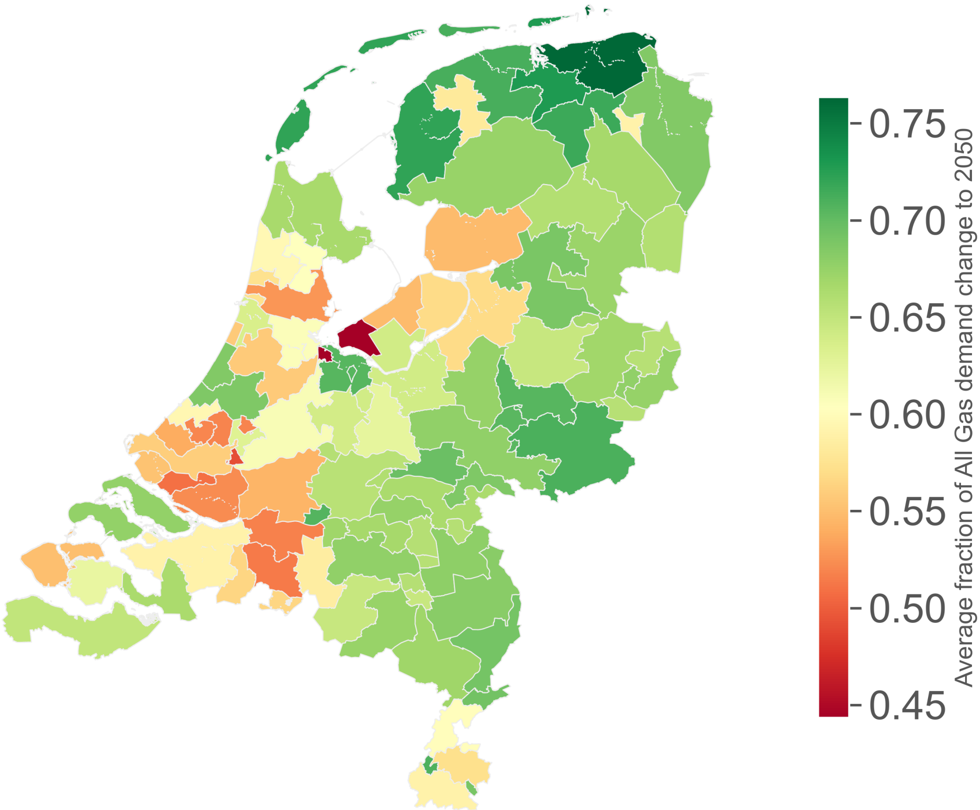


**Figure 5.22:** *Map of MR-regions in the Netherlands showing the average fraction of All Gas demand change to 2050.*

Figure 5.23 characterizes the regional overcapacity of peak gas demand. Green indicates less overcapacity, while red indicates more overcapacity. Therefore, the main insight from this figure is the significant absolute overcapacity by the Rotterdam and Amsterdam regions.

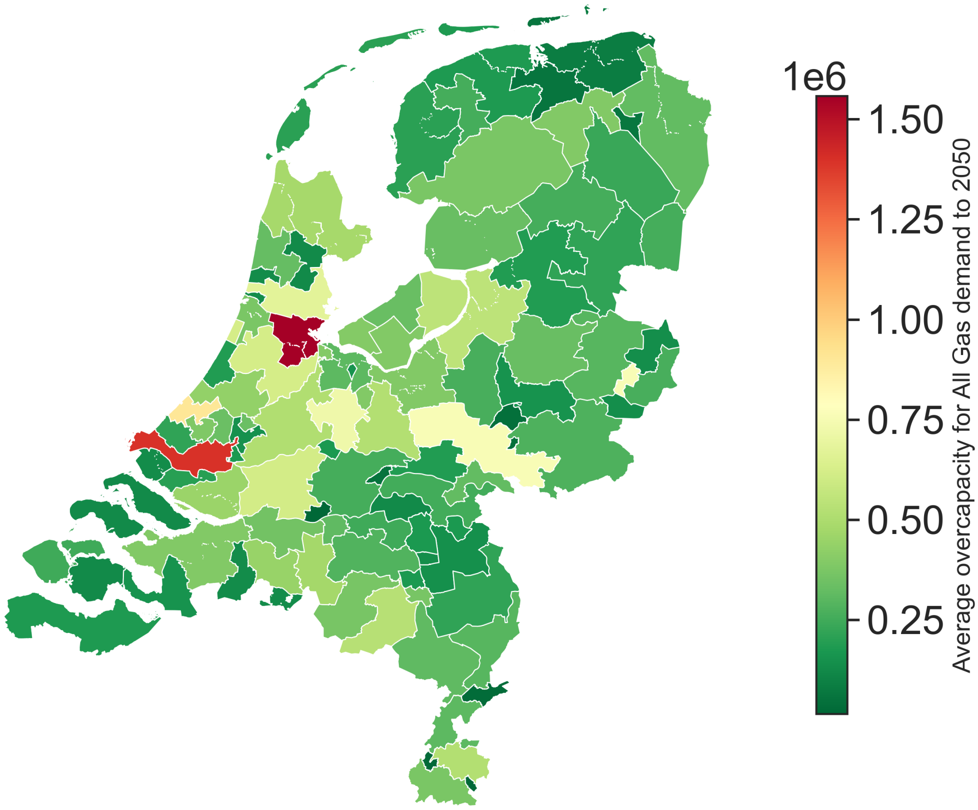


**Figure 5.23:** *Map of MR-regions in the Netherlands showing the average overcapacity for all gas demand change.*

### *Key Findings*

This subsection discussed the behavior of the model under eight different scenarios and how the results can be used to extract insights of relevance for Gasunie. The eight scenarios of interest were developed in conjunction with Gasunie and varied the model parameters concerning hydrogen availability, green gas availability and the speed of insulation. The outcomes of the scenarios were considered from the national, MR-station and regional MR-station perspectives. First, it was found that the model can provide insights on comparing national peak energy demand trends. Second, it was found that the model can provide insights on differences in change among MR-stations concerning their peak gas demand. Third, it was found that the model can provide insight into the bandwidths for absolute overcapacities for MR-regions. And finally, it was found that the model can provide insights into regional trends using chloropleths for these statistics.

## 5.3 CHAPTER INSIGHTS

This chapter has presented the results of this study. This chapter intended to introduce the implemented data-driven agent-based model, what kind of results it produces and how it could be used to provide insights relevant for Gasunie. First, the developed agent-based model was demonstrated by describing the national and regional visualizations of the model's transition dynamic as a result of the municipal decision-making. Then the model interface and its output were briefly discussed.

The second part of this chapter is concerned with describing the output of the model and what relevant insights it can produce. This was done by first discussing the general model behavior and assumptions, the influence of municipal-decisions and finally a scenario-driven analysis. When analyzing the model's behavior, it was found that the model is very sensitive to the availability of renewable gasses.

Then, studying the influence of municipal decision strategies yielded that the volume of the decisions by municipalities not only drives the transition forward but also changes the distribution of peak renewable energy sources over time. It was also found that the method that determines in which order neighborhoods are transitioned by municipalities does not significantly influence the national outcome, and is being of regionally varying influence. The method determining the selection of thermal systems was found to be of significant influence in the model. And MR-station regions are found to be differently sensitive to the implemented municipal decision-strategies.

And finally, studying eight scenarios from different perspectives concluded that the model was able to provide various insights of interest for Gasunie on the regionally different development of the required gas capacity for the residential built environment.

# 6 MODEL VALIDATION

This chapter is aimed towards validating the conceptual model design, its results and its purpose. Validating its design and its results are required to determine whether the right model is built for this study (van Dam et al., 2012).

The conceptual model design and its results are validated through consulting experts and a literature comparison. Traditionally, model design and results validation is concerned with comparing the model results with real-world empirical observations. However, as the model designed for this study describes a system that describes future change from a perspective that has not been extensively studied, it is not possible to validate the design and the results through comparison with the real world. The empirical observations necessary do not exist yet. Therefore, expert validation and literature comparison is used to determine whether the model is useful and convincing (van Dam et al., 2012).

## 6.1 EXPERT VALIDATION

Expert validation has been applied to the conceptual design and model results through unstructured interviews with multiple Gasunie experts and two municipality experts. The interviews with the municipalities mainly focused on the conceptual design of the municipal decision-making mechanics. The knowledge of the Gasunie experts is leveraged to validate model assumptions and results.

### 6.1.1 Conceptual Design Validation

The conceptual model design has been validated in unstructured interviews with two municipality domain experts. Both the experts were field managers for the thermal transition in their respective municipalities and were tasked to manage the neighborhood approach.

During the interviews, the municipal perspective that includes the neighborhood-based decision-making was confirmed to some extent. While municipalities indeed make plans per neighborhood, the dynamic of the transition can be more 'fluid' than is suggested in the model for this thesis. While they recognize that dwelling characteristics inside neighborhoods are quite homogeneous, this does not implicate that a transition will occur at once over a given set of years for the neighborhood. Especially with the individual based thermal systems, such as heat pumps, a more household-based transition might be more fitting. However, on a macro level for their municipality, the development of the transition through all the neighborhoods seems familiar.

The factors contributing to municipal decisions, as described in appendix E.1, were discussed with the experts and recognized as being of importance for their decision. In the interviews, it was stressed that the contribution of all the factors combined is of importance to the final decision. All factors were perceived as important for the decision. The only factor that was mentioned that is not present in this conceptualization is the factor of politicization of decisions.

The assumption that the approach for every neighborhood is different and requires different decisions by municipalities, is strongly confirmed in their data-driven approach. The municipalities confirmed that their approach for every one of their neighborhoods is different based on the specific characteristics of the neighborhood. An important driver for initial exploration of their neighborhoods for when and to what thermal system they might transition are data-points. Based on data-points, such as the ones used for this model, and local knowledge, preliminary and final decisions are made within the context of this transition. However, they stressed the importance of infrastructural data, such when sewer systems or streets have to be maintained. This infrastructural work was found to be an important driver for the transition time path of their neighborhoods. This data could not be included in the model due to universal unavailability.

### 6.1.2 Stakeholder Validation

The model as presented in chapter 5 was developed in close cooperation with Gasunie as key stakeholder. As such, the original research objective was closely followed during this process, namely designing a model that captures the emergent phenomenon of municipal decision making in this transition. The stakeholder validated that the original research objective was met and that the model indeed captures the original intention behavior of interest.

Also, the designed model intends to capture the emergent behavior of interest through the aggregation of peak energy demand to a level of interest for Gasunie: the Metering and Regulation stations. This approach does not include the physical limitations of the gas transportation pipes and can therefore not be validated for such purposes. However, the stakeholder confirmed that aggregation of neighborhood peak demand to the level of MR-stations as network nodes is a viable method for capacity requirement estimations at this level in the network. The method of aggregation in this thesis is done with the interpretation of the Gasunie's infrastructure of the author (refer to appendix C for the mapping). Gasunie has confirmed that this interpretation is an approximation, and not completely accurate. The methodology of aggregation is therefore validated, but not the resulting outcomes.

It can be argued that by modeling socio-technical systems that do not yet exist in cooperation with the stakeholder, its results are inherently invalid as the stakeholder can alter its behavior (Chappin et al., 2020). However, the model designed in this thesis does not contain any agents representing the behavior of the stakeholder. The stakeholder is included as a passive entity of the demand driven conceptual design. Therefore, the model does not lose validity by being designed in participation with the stakeholder.

## 6.2 LITERATURE COMPARISON

The model's results are validated through comparison with other literature and reports studying the case of this transition. As no similarly agent-based models studying municipal decision-making was found to be comparable, the conceptual design is only validated through expert face review. First, the results on a national level are validated. Then, the local level is validated.

### 6.2.1 National Results Validation

Comparing national projections for the energy demand in various reports, it can be concluded that consensus on the future trends toward 2050 is varying significantly. The Rijksoverheid understands that many scenarios towards 2050 might unfold and considers many variants of the energy mix. The only consistent factors in their projections are that fossil fuels in the form of green gas or natural gas will play a significant role in the share towards 2050. For all other energy sources, the boundaries within the projections are wide and considered uncertain (Netherlands Ministry of Economic Affairs, 2016).

A study by Berenschot den Ouden et al. (2020) on the potential energy scenarios for the Netherlands designed as input for the Integrale Infrastructuurverkenning yields four varying scenarios. The four projected scenarios are different but less so than the Rijksoverheid scenarios. Noteworthy in their scenarios is the inclusion of green gas and natural gas in the energy mix for the built environment for 2030, but their exclusion in 2050. A significant share of the green gas demand is transferred to electricity and heat, whereas the results of this study suggest that the coexistence of gasses will remain an important driver in the transition towards 2050.

A study towards the applicability of hydrogen by Stedin van Groot Battavé et al. (2020) confirms that the projections for the energy demand of hydrogen in this thesis fall within the boundaries of what is projected by the energy system operators. The report shows a minimal increase of around 50 PJ towards 2030 and a maximum increase of 300 PJ over different sectors. This falls within the projected Gasunie boundaries of Gasunie's scenario's

Studies by DNV-GL (van den Noort et al., 2017) and Gasunie (Gasunie Transport Services, 2017) project a decline in required gas capacity, as is also indicated by the model in this thesis. Projections of national required capacity are projected to decline between 16 and 47% by 2035 by DNV-GL and Gasunie, whereas the projected scenario's for this study indicate a required gas capacity decline between 25 and 50% by 2035. Therefore, the projected boundaries overlap to an extent.

### 6.2.2 Local Results Validation

The validation of results on a local level has been done by comparing the outcomes of comparative studies with the results presented in this research. The local results for three municipalities have been compared for validity purposes. Validation results for the Amstelveen municipality have been presented in this section. The supplementary validation results for Amsterdam and Drechtsteden can be found in appendix K.

*Amstelveen Municipality*

The reference parameter simulation results for the Amstelveen municipal region have been compared to a meta-study by CE Delft who compared three different models on the transition configurations for Amstelveen (CE Delft, 2020). CE Delft compares the model results from the VESTA-MAIS model by PBL (Schepers et al., 2019), the Caldomus model of Innoforte Innoforte (2017) and their model. Figure 6.1 describes the comparison and analysis between the three models and combines their results in the bottom right graph. These model results exclude hydrogen as a viable thermal system. Figure 6.2 illustrates three reference scenario model simulation stills for this study for the Amstelveen region for 2035 (left) and 2050 (middle and right). The middle and right model simulation stills differ in the availability of hydrogen technology, as the results compared by CE Delft do not include hydrogen.

Comparing the results of CE Delft's meta-analysis with the simulation model results for the reference scenario yields very similar results with slightly varying alterations between the configuration of electric heat pumps and green gas heat pumps. The distinction between heat networks and heat pumps is very clearly observable in all of the illustrated results, with some slight configuration variations between the models. While the configuration of electric versus green gas heat pumps is sometimes slightly different. While the results are not one-on-one comparable, the similarity of the end-states suggests the validity of the results to some extent.

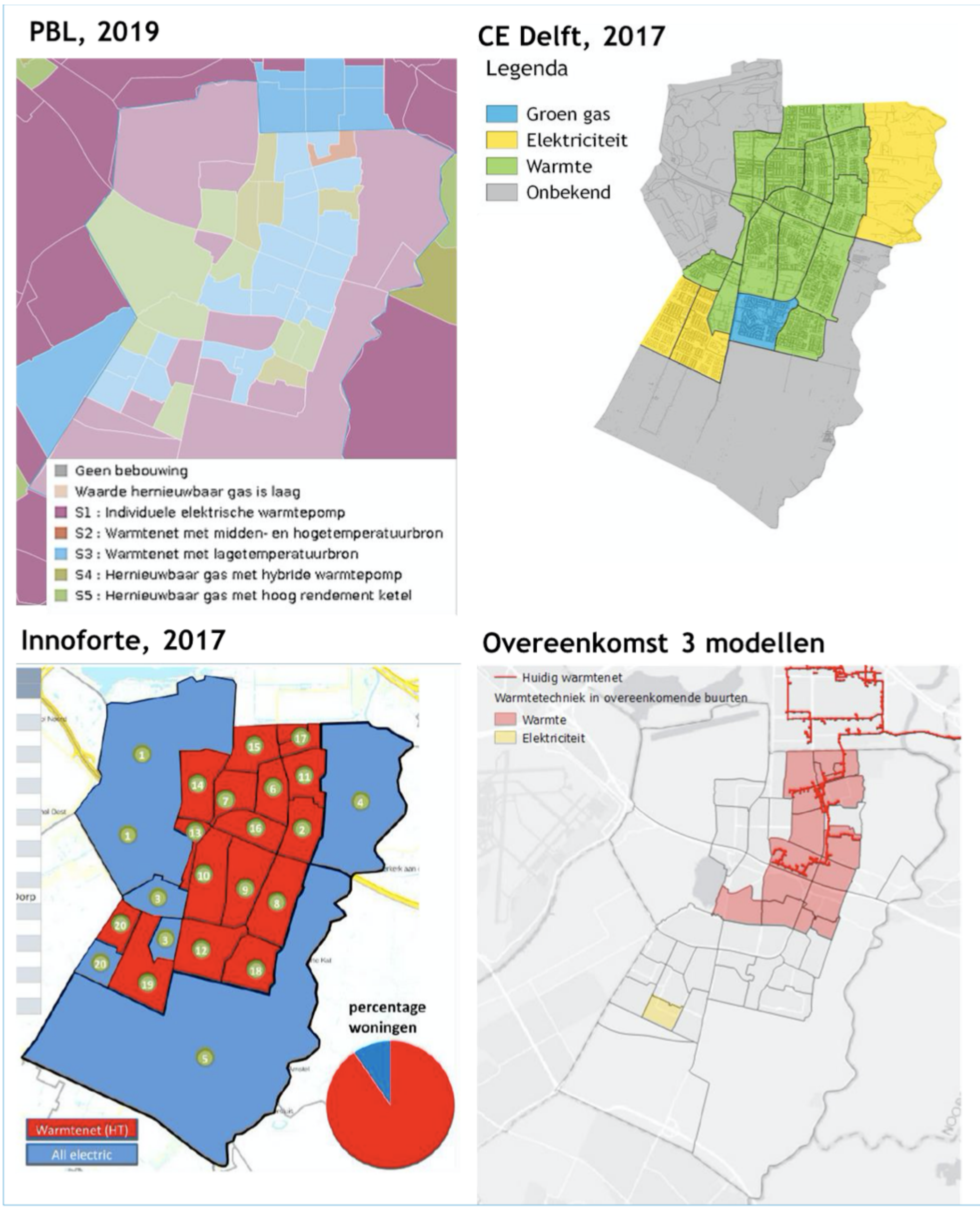


**Figure 6.1:** *Meta-analysis of thermal system distribution in Amstelveen municipal region for four different models. Copied from CE DELFT report, page 25 (CE Delft, 2020).*

**Figure 6.2:** *Three model simulation screen captures of the Amstelveen municipal region.*

## 6.3 CHAPTER INSIGHTS

The methods used for validation of the designed model are face validation by experts and comparing local and national results with comparable studies. Other objective validation methods are not possible as the designed model in this thesis describes a not existing system transition for the future. The lack of comparable agent-based studies from this thesis' perspective has made it impossible for this research to validate the model with similar agent-based studies. As such, studies projecting future scenarios for the energy demand in the built environment are used for validation purposes. For the local configuration of thermal systems in neighborhoods, other (scientific) models and municipal visions are used for validation purposes.

The model is considered valid to a limited degree. No significant objections by experts were found in the conceptual design and model results during the interviews. And comparing results with other studies suggests that the boundaries of the projected scenarios overlap with the results of this model, but that results are to a high degree sensitive to parametrization. The uncertainty in all aspects of the model implicates the difficulty of the validation, which has to be considered when concluding on this model. But comparing the configuration of thermal systems in neighborhoods with comparable models and municipal visions yields very comparable results. The confirmation of the stakeholder that the designed model is fit for purpose indicates that the designed model can be considered valid for reaching its objective.

# 7 DISCUSSION

This chapter is intended to set the reach of the conclusions that are drawn in the next chapter. By discussing the limitations of the study, the used approach and other authors, one can get a better perspective on how this study fits in a broader context. Section 7.1 discusses the limitations of this study, section 7.2 discusses the suitability of agent-based modeling as an approach for such a research problem, section 7.3 discusses the methods and results of other authors and reports that support providing context for this' research conclusions and section 7.4 summarizes this chapter.

## 7.1 LIMITATIONS OF THE MODEL DESIGN

For discussing the limitations of model design, first, the system scoping assumptions are discussed. Then the design of the model is considered. And finally, the results of the model are debated.

### 7.1.1 System Scoping

The first set of limitations discussed is the author's perspective of the thermal transition of the built environment system. Figure A.1 provides a schematic overview of the elements included in the author's system perspective. As one can imagine, a complete picture of a socio-technical energy system is much broader than this. Elements such as the physical production of energy, it's transportation, distribution, storage and final end-user behavior are all significantly simplified for this study. The assumptions for where to focus on and what elements not is critical in the perspective of the system. Hence, the model can not be used to conclude the whole energy chain.

An example of one such consequence of this scoping is that this study considers 'heat' as an energy source. As figure A.2 describes, heat, in reality, is a transportable medium to store energy in and not a primary source. This study includes a dataset of potential heat sources in the Netherlands but excludes the fact that this heat is either generated by burning fossil fuel or by the use of renewable energy. The same applies to 'electricity'. Electricity can have many different sources, as figure A.3 describes. However, for this study, all these sources are combined in the physical transportable medium that enters the thermal system of the end-user.

The second critical scoping assumption concerns the sole inclusion of the residential built environment in the model while excluding the utility and industrial sectors. The design of the study inherently implicates that the essence of the model is that it is a demand-side driven model for only a part of total demand influencing the energy infrastructure. Gas infrastructure capacity is based on the requirements for all the gas-consuming sectors, which include the industrial and utility building sector. This model excludes these sectors. As such, the model is not able to conclude on the system-wide required capacity as a result of this transition, but only on what is required for the residential built environment. Hence, only being able to provide insight into *what infrastructure is needed for the residential built environment*. Therefore, collective infrastructure development decisions should also include projections of these two sectors and not just the model designed in this study.

### 7.1.2 Model Design

The second category of study limitations derives from the design of the model. Chapter 4 describes the design of the model and the reasoning for the choices made. But with each decision, assumptions are implicated. The decisions and implications of several model design decisions are discussed.

#### *The Aggregation in MR-Stations*

This model intends to capture infrastructure insights at a level relevant to Gasunie. This is done by aggregating peak energy demand to a higher level the Metering of Regulation stations of Gasunie's network. To do this, a manual shortest distance approach was applied to the network topology of Gasunie. An additional analysis comparing Gasunie's confidential capacities at this level with my estimated required capacities in 2020 yielded a slight mismatch in these estimations. This is likely the result of my mapping not being accurate enough and the strong assumption that this is how peak energy demand *can* be aggregated in the first place. As such, the insights related to the required capacity always have to consider that they are simplified aggregated estimations.

#### *The Multi-Actor Nature of this Transition*

The aggregation of information also concerns the identified social network in the design. Only the neighborhoods and municipalities as stakeholders are included and municipalities are assumed to be the key instigators of demand-driven change. In reality and as described by the Climate Agreement Klimaatberaad (2019), the decision-making includes many more stakeholders on various levels. But for scalability reasons, this study has chosen to include the stakeholders that could be scaled easily from a municipal to a national level. The inclusion of more stakeholders can make the model much more complex, but more tailored towards regionally different characteristics. For example, regional coordination is excluded from the model design. In reality, the Regional Energy Strategies are a regional institutional organization that coordinates energy-related decision-making between municipalities.

The second group of stakeholders that could be included in the decision-making is the transmission and distribution system operators in their role of safeguarding the functional development of their systems. This model is strongly bottom-up orientated, whereas, in reality, it is a combination of bottom-up emerging behavior and top-down implied or suggested strategy, while regional coordination exists between these layers.

### *The Implementable Thermal Systems and Peak Thermal Demand*

Municipalities are also simplified in their selection of implementable solutions. The design of the model limits the available thermal systems to a selected few. In reality, many thermal systems exist that vary in their efficiency specifications. In the future, we might also see new technologies that are currently not available. However, as the main goal of this study was to study the peak gas demand development, a selection was made that covered all the currently possible technologies by simplifying each technology.

Where assumptions are made on the available systems, the calculations to derive a peak thermal demand are simplified as well. The development of peak energy demand per energy source is strongly influenced by the current level of insulation of a neighborhood and the thermal heat demand profile. Both factors are strongly simplified in the design of the model. While the current level of insulation of a neighborhood is derived from real-world data, its development is assumed to be a homogeneous national linear improvement over time, instead of a hypothesized adoption mechanic. In reality, this development is likely to be much more locally driven and probably differing per household. It is not trivial to make predictions about the development of insulation levels for neighborhoods, which other scholars could devote an entire thesis.

### *The Municipal Decision-Making*

Furthermore, the municipal decision-making is strongly hypothesized in this study, only providing for testing of its hypothesized behavior with limited validity. One of the reasons for using theory and expert input to create the framework is that it allowed for an explanation of how external data could be interpreted for decision-making. The framework designed did not by any means suggest the formalization of it in municipal agent behavior. Hence, multiple formalizations were established resulting in different strategies. Many more formalizations of the hypothesized framework are possible, which could result in very different behaviors in the model.

One such consequence of these municipal behavior formalizations is the conceptual choice to decouple the transition of the thermal system with an increase of insulation levels. This choice has consequences for its impact on the model insight that the speed of the transition influences the distribution of renewable energy sources. This insight is generated by varying the speed of the transition through the national transition goal parameter and observing different distributions of energy towards 2050. But in reality, a transition is likely to be a combined effort of insulating a neighborhood to a certain standard while at the same time implementing the most suitable thermal system. Hence, this is a model insight that is difficult to generalize.

This design of the model suggests that municipalities do not differentiate in their method of determining the most appropriate thermal system for a neighborhood. Meanwhile, the results show that the understanding of municipalities what thermal system they should pick for a particular neighborhood type is a strong driver of the model's output. This implicates that the assumptions that are at the core of the Relative Advantage factor table are largely generating the outcome of the model for the Gasunie scenarios. It is shown that changing the understanding of what neighborhood type fits best with which thermal system is a critical assumption. While this model assumes that all municipalities have the same understanding of this table, in reality, there might be different interpretations of Relative Advantage among municipalities.

Another core assumption in the formalized municipal strategies is how municipalities are driven to perform any action at all. If the national transition policy goal is pushing municipalities towards transitioning, transitions will occur no matter what. First, the need for a transition is confirmed, then the order of neighborhoods is determined and finally, the thermal system is selected for a particular neighborhood. This order for the decision-mechanic sequence is fixed. However, as the experts pointed out that were consulted for this thesis, decision-making is rarely this linear. In reality, it might happen that first a solution is found, then the need for a transition is assessed and only the last step explains where the solution is implemented. This thesis assumes that first, a problem has to be found and then the most appropriate solution for this problem is evaluated but excludes the possibility of solutions seeking problems. This also touches upon the fact that these decisions can be strongly influenced by local or national politics. The decision-mechanic is also constant over time, while it is the same for all municipalities, not allowing different or adaptive strategies throughout of a simulation.

One of the results while studying the different municipal strategies is that the neighborhood order method does not seem to matter that much. This insight is to be taken with an important precaution. It was found that on the national level, the order of the neighborhoods as dictated by the strategies is not changing peak energy demand significantly. However, it was found that on the lower levels of aggregation, this impact varied. While the result might still hold, it was found that this difference in variability among MR-stations was the result of three model implications. The first implication is a consequence of small fractions being more susceptible to varying methods dictating the distribution of probability than larger fractions. The second implication is that some municipalities are more homogeneous than others based on the factors and data used in this model. Municipalities that are more homogeneous are less susceptible to different municipalities as there is no particular suggested order in the first place. And the third implication is the way how the conceptual design suggests that municipalities are somewhat forced to make decisions until they are out of resources. This results in that municipalities also transition neighborhoods that they initially did not want to *inside the model tick* because they have to deplete their resources until no more pressure is perceived. A more detailed explanation is provided in appendix L.2.3.

#### *The Static Built Environment*

The last conceptual design limitation concerns the exclusion of development in the built environment. While the neighborhoods can change their level of insulation and choice of thermal system, development in terms of new dwellings or demolishment of old dwellings is not included. Newly built dwellings have to comply with the highest insulation standards nowadays, whereas old dwellings are mostly poorly insulated. Including this turnover effect in the built environment might introduce additional behavioral effects in terms of energy demand development. Transition paths might be altered causing different results. However, it is expected that it will not contribute to more peak gas demand, as newly built dwellings are most often constructed without a connection to the gas grid.

### 7.1.3 Model Results

The third category of study limitations concerns the model results. The outcomes of the model in terms of the developed model, how it behaves and what kind of results it produces are discussed in chapter 5. The way how the results of the model are extracted comes with some limitations which are discussed here.

First, the limitation of the experimental setup is discussed. The angle for the development of the model designed in this thesis was partly proof of concept for such a case with the agent-based modeling paradigm. As a result, a lot of time was spent on the conceptual design of the model. Initially, the idea was to study the models use with the EMA-workbench (Kwakkel, 2017). However, due to the use of the workbench not being as straightforward with NetLogo as originally anticipated, it was not possible to conduct this study within the given time.

Due to the real-world resemblance to the built environment of the Netherlands and the complexity of the procedures, the model is scaling quite badly in terms of computational time. Running a single experiment on the main machine used for writing this thesis takes around 60 seconds in the fastest settings. During programming, the model in the NetLogo environment, a lot of coding inefficiencies were already addressed. The reason for the long computational time solely derives from the replication of the decision-making cycles for around 15000 agents in the model. As the model requires around 100 replications for a solid experiment, extensive experimentation, such as with exploration under deep uncertainty, is difficult and requires a cluster of processing cores.

As such, a limited experimental setup was designed targeting the model's behavior and its general assumptions, the influence of municipal strategies within the model and a stakeholder-driven scenario study. A lot of parameters in the model are uncertain but were considered fixed in these experiments. The result is that the outcomes of the model are yet unexplored under deep uncertainty. It is strongly encouraged for future scholars to study the use of such a data-driven agent-based model with the EMA-workbench.

The stakeholder-driven scenario exploration is the closest resemblance of the results in this study for studying the model insights under uncertainty. By analyzing the Gasunie scenario's, only three parameters were varied. The results and conclusions based on these analyses therefore are limited to one strong assumption: that the transition of the built environment will develop at the pace that is suggested by the government. Thus these scenarios are about *if* the transition occurs at a given pace, *where* does it take us and what can insights does it produce for Gasunie? Given this pace, how does the transition distribute over the different regions? The model is limited in explaining the pace of the transition in itself, which might be explained in a different thesis completely. Because of this, a lot of uncertainty space that the model can generate is therefore left unexplored. Doing so can increase the robustness of the insights such a model generates. This again suggests that it can be of value to explore this model under deep uncertainty.

## 7.2 AGENT-BASED AS MODELLING APPROACH

This study has been conducted through a model-based approach. Specifically, the agent-based modelling paradigm was studied for its use as an insight generating methodology for such problems, not necessarily solving an optimization problem. The initial idea of using data-driven agent-based modeling was grounded in a few arguments. The first argument was that agent-based models for this particular casus were not particularly common to use. The second reason was to investigate whether using such a bottom-up modeling approach made any sense for this case. The third reason was that by using this method, an extensive open data source could be leveraged by using this model. This section will further elaborate on its benefits, drawbacks and whether using this data-driven agent-based approach has made sense and should be used in the future for this kind of research.

### 7.2.1 Benefits

The first benefit discussed is that this approach enabled the implementation of a bottom-up perspective in a model and model hypothesized behavior of a system that does not exist. By coming to a conceptual understanding of how single entities might behave in this system, the multiplication of such entities generated emergent behavior on the system level which might not have been possible with, for example, a system dynamics approach. Also, it was possible to study the adoption of technologies that do not exist yet on a large scale. By including hydrogen gas hybrid heat pump systems with several assumptions, the model suggests the important role hydrogen might play in the thermal system of the future.

The second benefit is that the model can be relatively easily be extended, both on its technical system as its social behavioral side. Its technical side consists of the energy system limitations, such as the exhaustive green gas stock. It was also found that the model is significantly driven by the availability of renewable gasses. Adding additional or different formalizations of limitations to these renewable gasses can significantly broaden the *what if* insights of this system in terms of distribution and allocation of required gas capacity. Such potential formalizations of additional technical limitations of the energy system can be coupled on a neighborhood level to the current model. A highly suggested example is the extension of the electricity grid limitations in the model. While developing the model, including this limitation was included in the conceptual design, therefore leaving room open for such an addition. The social side of the model can be further developed by introducing and exploring different formalizations of municipal behavior. This can be done by adding different formalizations of the current strategies, or a whole different mechanic altogether.

The third benefit of this approach is that by the NetLogo environment with external datasets, the model of the built environment can be generated automatically to resemble the built environment of the Netherlands. Based on geographical, social and technical data large-scale models such as this model can be created in a limited time frame. The relative ease of using large real-world representing datasets also enables for automatic generation of heterogeneity agents, instead of using homogeneous or randomly generated agents. By creating a model that has a strong resemblance to the actual system that we are studying, visualization, verification and validation is easier for the modeler and stakeholder.

### 7.2.2 Drawbacks

Some drawbacks of this method were also found during this thesis. The first disadvantage was that the sheer size of the model, consisting of around 15000 agents, significantly slowed the computational time down. Powerful computational machines are a must when experimenting with similar or bigger models over larger uncertainty spaces. This resulted in constraints for the experimental setup. While we have seen glimpses of very interesting behavior down to the lowest level of neighborhoods, due to the time constraints and scoping of this thesis it was not possible to show it all, even if I could.

The second drawback is that we have to remember that we model behavior from a perspective that we do not even know if it exists making validation very difficult. While established theories, state-of-the-art literature and expert insights were used to design this model, it is still just a model of a system that does not exist and is difficult to validate. All the data frames that are used for this model are based on empirical observations, thus implicating reality. However, how is decided on these real datapoints is merely an educated guess. It only tells us what might, not what is or will be. All models are wrong, but some are useful, they say...

**DOES IT MAKE SENSE?** So does a data-driven agent-based make sense for studying such systems? The answer is, it depends on what the purpose of the study is.

The agent-based paradigm as applied in this study does by no means try to predict or optimize how the thermal system of the built environment will develop and what its implications will be for Gasunie. It is simply not possible to build such a model due to data-unavailability, structural behavior uncertainty and the intractable nature of evolutionary problems (which a transition inherently is) (van Dam et al., 2012).

For 'what-if' questions from a socio-technical perspective where decisions of individual entities are of importance for generating systemwide emergent behavior, it is proven to be a useful method. It was possible to implement bottom-up hypothesized behavior in the system and provide insights relevant for studying the infrastructure implications for Gasunie. While there are significant limitations to what conclusions and insights such a model can provide, the hypothesized behavior, limitedly included technical subsystems and a relatively constrained scenario study can be considered just a start of what is possible to study the what-if implications of this transition on the energy system.

## 7.3 THIS STUDY IN THE CONTEXT OF OTHER LITERATURE AND REPORTS

Placing this study in the context of previously mentioned studies and reports yields new conclusions, but novel questions as well. Chapter 1 introduced a selection of authors and reports that were reviewed for establishing the context for this study. The review concluded that both academic authors as (scientific) reports have covered the context of the thermal transition in the built environment to a certain extent. The academic literature consists of both (agent-based) modelling studies ((Nava Guerrero et al., 2019; Sopha et al., 2011, 2013; Michelsen and Madlener, 2012a,b; Hecher et al., 2017; Chappin and Dijkema, 2010; Schwarz and Ernst, 2008; Busch et al., 2017)) and non-modelling literature (van Leeuwen et al., 2017; Geels and Schot, 2007; Diran et al., 2020; Faber and Hoppe, 2013). While the (scientific) reports focuses on energy mix scenario projections (Netherlands Ministry of Economic Affairs, 2016; Gasunie Transport Services, 2017; den Ouden et al., 2020), system descriptive studies (Klip, 2017; Gasunie and TenneT, 2019) or cost-projecting modelling studies (Schepers et al., 2019; CE Delft, 2019; Menkveld et al., 2015; Schepers and Aarnink, 2014).

### 7.3.1 Similarities and Differences in Scope

While the casus of the thermal transition is overlapping with many of the mentioned authors, comparison between the studies in terms of setup is difficult. Agent-based modeling studies for this case exist, but are significantly different in their scope and perspective, making a comparison of conclusions difficult. All the studies mentioned were intended for very different purposes in the first place. This study did not intend to estimate costs, which has been studied by multiple actors. It might be useful to include cost variables in the designed model and compare such results, as these conclusions are absent in this research. Other modeling studies, on the other hand, lack variables that might indicate local peak energy demand development. Combining the constructs as presented in their studies with this thesis could therefore be a potentially interesting route.

### 7.3.2 Similarities and Differences in Results

Whereas the combination of system perspective, methodology and modeling objective are different for this thesis than any of the mentioned authors, similarities and differences in conclusions surface. This study found that the energy availability boundaries will strongly influence the available transition pathways towards a sustainable environment and configuration of the energy infrastructure. This conclusion has generally been acknowledged mostly in scientific reports covering the system from a descriptive perspective. But some modeling studies completely ignore the importance of the availability in their design. These differences in conclusions also show in the non-consensus on future projections of the energy mix for the built environment. While some trends do overlap, such as a declining gas demand trend and an increase in electricity and heat use, others do not. Assumptions on whether hydrogen heat pumps will be a technology to consider, or whether green gas will be allocated to the built environment strongly vary amongst authors. While such important core assumptions are not further researched, such projections will remain ambiguous.

Noteworthy is that some models are extremely detailed and complex, such as the VESTA-MAIS model (Schepers et al., 2019), and produce similar *end-states* of the transition in the built environment. Their model is intended to be used by local policymakers to estimate costs, but municipalities indicate that their assumptions can be deceiving. It does not matter how complex or elaborative the model is, when you are scaling assumptions to a national scale to estimate local effects, the model loses inherent accuracy in its results. Parameters used on a national level may strongly vary per neighborhood, and even per household, which may significantly alter results. Comparing transition pathways of the VESTA-MAIS model (see chapter 6) with the model designed for this thesis also indicates that with relatively simple and few assumptions, similar *end-states* can be generated. The purposes of both models are very different, but in essence, they both are models that can be either useful or very deceiving in their results.

## 7.4 CHAPTER INSIGHTS

This chapter is aimed at discussing this study's results. First, the limitations of the study are discussed, then the suitability of the methodology and lastly its context in the context of other reports and literature. While the model provides clear distinguishable results that are not too difficult to interpret, they have to be strongly bounded by the limitations of the study. Assumptions regarding the system scoping, conceptual design and parametrization have to be considered before acting on its conclusions.

The methodology of a data-driven agent-based model to study the thermal transition of the built environment is to be found useful for this particular thesis. The results indicated that regional differences in behavior emerge that could not have been uncovered with some other methodologies. However, disadvantages in the used data, sheer size, complexity and the inherent uncertainty in the conceptual design implicate that validity of the model is difficult to determine.

Comparing the results of this study in the context of other works shows significant differences in research goal, model perspective, but also overlap in conclusions. The thermal transition of the built environment has been studied by various (academic) authors. This thesis underlines the necessity of studying the potential availability of energy sources for this system.

# 8 CONCLUSION AND RECOMMENDATIONS

In this chapter, the main findings are synthesized, recommendations based on these findings are presented and the research relevance is discussed. First, the main motivation for conducting this study is reformulated. Then, the findings are synthesized by answering the research and sub-questions as introduced in chapter 2. The presented recommendations are directed towards both Gasunie and future scholars or academics involved in studying the thermal transition of the built environment. Finally, the societal and academic contribution of this research is discussed.

## 8.1 RESEARCH MOTIVATION SYNOPSIS

In light of climate change, many sectors are facing a transition towards sustainable solutions. One of these sectors is the natural gas-driven residential built environment in the Netherlands. Enacted national climate policy frameworks tend to put the urban operationalization in the hands of their respective local governments. In the Netherlands, municipalities are put forward as key instigators to transition their neighborhoods towards more sustainable thermal systems. But how their decision-making will shape the thermal system of the built environment towards 2050 is not known. The Gas Transmission System Operator, Gasunie, is particularly interested in how this transition will unfold as it will have consequences for their infrastructure. Currently, no (modelling) studies focus on this transition from the municipal-driven neighborhood-approach perspective, while capturing the emerging influence of the transition on Gasunie's network. The objective of this study is therefore to provide Gasunie with a scientifically sound data-driven agent-based methodology from this perspective that can provide insights of interest to their role and strategy. The second objective is to determine whether this methodology can be used for such problems.

## 8.2 ANSWERING THE SUB-QUESTIONS

Before the main research question can be answered in section 8.3, the sub-questions as presented in chapter 2.3 are answered.

***1) How can the municipal-driven neighborhood-approach in the context of the thermal transition in the built environment be captured in a data-driven agent-based model?***

It can be concluded that by using a socio-technical and complex adaptive systems lens, the system relevant concepts can be captured in a model of disaggregate elements and their interaction resulting in a theory of this transition. These concepts can be translated into an agent-based model that can be initialized using a data-driven approach.

The foundation of the conceptual model design benefited from using the theoretical lenses in combination with existing literature and expert input. A design consisting of municipalities as change instigators, neighborhoods as energy demand generators and energy sources as energy system limiting elements were established as a starting point. These elements and their interaction were found sensibly capable of describing the social, technical and institutional context of this transition as proposed by the Climate Agreement while incorporating the relevant aspects for Gasunie's gas infrastructure.

Two main concepts describing the transition of neighborhoods and a hypothesized framework of municipal decisions could adequately form the conceptual glue between the model elements. The concept of the transition of a neighborhood as a whole allowed for an explanation of the change in the thermal system at a higher level of aggregation than households. By using existing behavioral theories in combination with existing literature and expert input, a municipal decision-making framework could be established. This framework was found useful to hypothesize a theory of how municipalities might decide even if their behavior is not known ex-ante, based on what is known from various sources of information. Lastly, different formalizations of this framework could be implemented as different municipal strategies to study the sensitivity of the model to formalizations thereof.

By using real-world open-source datasets characterizing the built environment, a heterogeneous representation of the built environment could be implemented in the agent-based model. Data sets describing the socio-demographic nature of municipalities and neighborhoods were found useful in initializing heterogeneous agents. These data sets were aggregated at the same level as the conceptualized municipalities and neighborhoods, therefore being relatively straightforward to use. As the built environment is characterized by its diversity in dwellings, a data set containing descriptions of characteristics provided to be useful in generating such differences in the neighborhood agents. These differences in dwelling characteristics provided useful for estimating unique energy demand patterns per neighborhood. The resulting data-driven initialization was found efficient for the generation of a large-scale representation of the Dutch built environment in a simulation model.

Combining these concepts in a data-driven agent-based model, the model was found able to describe a theoretic relation between the top-down national institutions and policies, the disaggregated character of the transition and the emerging behavior of interest: municipalities adapting to this transition by making decisions on the thermal systems of their neighborhoods.

***2) What insights can such a data-driven agent-based model provide to support the strategy and role of Gasunie?***

The model can provide insights on the relation between national policy institutions and resulting disaggregated theoretical behavior influencing regional required capacity in Gasunie's network for the residential built environment.

By coupling the transition dynamics in the model to KPI's capturing emergent behavior of interest for Gasunie, the model can provide insights on what kind of infrastructure might be necessary to facilitate the built environment through this transition with their required gas capacity. The KPI's found relevant in capturing such insights are peak gas demand for natural, green and hydrogen gas resulting from the changing thermal energy demand and implemented thermal systems of neighborhoods. By aggregating peak gas demand from the neighborhoods to the Metering and Regulation station level, regional emerging behavior of interest for Gasunie's infrastructure can be observed.

The main findings are that both the supply side, with the availability of renewable gasses, and the demand side, with municipalities deciding *when, who, what and how many* transitions for their neighborhoods, matter for the development of regionally varying required capacity. It is found that the limited availability of the renewable gasses and the decrease of natural gas demand leads to a system-wide decline in required gas capacity for the residential built environment. This decline is also shown to vary regionally over the MR-stations. Thus concluding that if municipalities are expected to solve the thermal transition of the built environment bottom-up while availability of the renewable gasses is limited, Gasunie is dependent on their decisions to anticipate on the regional change of required capacity for the residential built environment.

And how they decide is found to matter for its allocation. The variation in their decisions is dependent on the different characteristics of municipalities, the strategies of municipalities, the national transition goal and the enfolding scenario's. Their resulting decisions influence regionally required gas capacity from Gasunie's infrastructure for the residential built environment.

As formulated in the introduction, Gasunie's role is to maintain and operate the national gas infrastructure system in the Netherlands. Their strategy to fulfill this role is to steer for a safe, reliable, affordable and sustainable gas infrastructure. As such, insights into how the required gas capacity for the residential built environment might change as a result of this transition can contribute to fulfilling their role and strategy.

For Gasunie to fulfill its strategy as the transmission system operator in the best possible way, participating in the decision-making process of municipalities can support their role and strategy. If Gasunie becomes involved in this disaggregate decision-making process, which they are not in this model design, allocation coordination could be improved to adapt its infrastructure in the best possible way for all stakeholders, including Gasunie. As such, the safety, reliability, affordability and sustainability strategy from Gasunie's network perspective can be included in the debate of this thermal transition.

## 8.3 ANSWERING THE MAIN RESEARCH QUESTION

Given the motivation for this research and the foundation of the answers to the sub-questions, the research question for this thesis can be answered. Reformulating from chapter 2, the question reads:

> **How can a data-driven agent-based model be used to study the impact of the thermal transition in the built environment from the perspective of municipalities as key demand instigators on Gasunie's infrastructure?**

Having designed, tested and validated a data-driven agent-based model in line with the research objective, the conclusion is that a data-driven agent-based model can be used to expose a theory about the yet to unfold thermal transition-related uncertainties while exploring and discovering *what if* scenarios of interest to Gasunie and other stakeholders as a tool for decision-support.

The methodology proved that it can be used to combine the proposed municipal-driven neighborhood-approach of the transition, with hypothesized bottom-up municipal behavior, while including real-world data describing this system to study the impact of emergent change on Gasunie's infrastructure. The system under study does not yet exist, but by combining new concepts based on the context of the case with existing data, it is possible to combine what is known about the system with its inherent uncertainty into a model. By leveraging the agent-based modelling paradigm, the multi-level interaction of the national policy framework, municipal behavior and its impact on Gasunie's infrastructure can be captured. Agent-based modeling allows for exposure of this formulated theory of the system while studying implications relevant for Gasunie.

Having captured this theory of the thermal transition system in a model, a scenario-driven approach can be used to explore and discover interesting states of this model over time. The thermal transition of the built environment is a complex and uncertain challenge. By using the designed model, the formulated theory can be explored under various scenarios of interest. This research used a stakeholder-driven scenario approach to study the model under different scenarios of interest. This approach allowed for uncovering insights concerning the regionally varying impact on Gasunie's infrastructure.

This methodology can be used as a tool to support decisions, and contribute to the debate, regarding this transition by the stakeholders - the municipalities, the national policymakers and Gasunie - by showing their relations and interdependencies exposed in this model.

Municipalities can be shown that their decisions influence their peers and Gasunie, and that there are limitations to what they can decide, caused by the scarcity of renewable gasses and the characteristics of their neighborhoods. Suggesting that coordination between municipalities could be beneficial for all in dealing with the limited availability of the renewable gasses.

National policymakers can be shown that their push for moving the transition forward not only increases the speed at which natural-gas demand is being reduced but that it might also change the paths of the transition. Also, as the limited availability of the renewable gasses is found to be a significant model driver, national policymakers can be shown that their efforts in determining its availability nationally, its allocation between sectors, and allocation regionally, could reduce uncertainty on the potential configuration of this transition. This can improve informed decision-making with municipalities on the transition of their neighborhoods and consequently its resulting impact on Gasunie infrastructure.

And to conclude with Gasunie. They can be shown how local decisions of municipalities, driven by the national policymaker, shape the regional required capacity in their infrastructure. And that uncoordinated decision-making can result in different requirements depending on the scenarios for their infrastructure. However, as the importance of scarcity in the model suggests, studying emerging behavior on the demand-side of their infrastructure is only part of this story. Therefore, insight in the availability of the renewable gasses for the residential built environment on the supply-side could significantly contribute to unraveling the uncertain character of this system and its implications for Gasunie's infrastructure.

But all of the involved stakeholders can be shown that their interests, characteristics and decisions will collectively shape the change of this thermal system towards its sustainable future. As wicked as this problem is and will always remain, the only thing that is known for sure is that together going forward is the only way.

## 8.4 scientific contribution

The thermal transition of the built environment has been covered in different modelling studies from a different perspective and for different purposes. Models covering this transition are found to provide insights on techno-economic best-case studies and behavioral what-if studies. Agent-based models predominantly fall in the latter category while studying energy domain-related systems (Chappin et al., 2020).

This study has addressed the use of the agent-based modelling paradigm for studying the effect of such a transition on a national infrastructure network. Instead of modeling the adoption behavior of individual households, this study approached the system from the perspective that municipalities are the key instigators of change in energy demand. A novel framework hypothesizing the behavior of these municipalities is constructed and implemented in various strategies. The aggregation of this change in demand to a level of interest for the energy system is found to provide insights relevant to the transmission system operator. It, therefore, contributes to the field of agent-based modeling related to the energy infrastructural domain by providing a demand-driven perspective of local governments while studying TSO relevant insights.

This study is merely intended as a starting point for studying such a wicked problem with this methodology. Other scholars are encouraged to build upon this research using this agent-based approach for studying the impact of the transition on the energy system.

## 8.5 GASUNIE CONTRIBUTION

The initial goal for this research as formulated by Gasunie was to show that there are limitations to what municipalities can realize in terms of the thermal transition in the built environment and that the energy infrastructure and other factors are key in realizing the goals of the Climate Agreement. However, the goal of this research shifted a bit towards finding a way how to use agent-based models that are of interest to Gasunie given this context. This resulted in not only uncovering the effect of this transition on Gasunie's network but also the limitations and consequences of municipal decisions.

The model in this research indicates that the required capacity for gas in the residential built environment is largely determined by much of the renewable gasses that will be available and allocated for use in this sector. The perspective of the model in this research is that municipalities are the key instigators of changing peak energy demand, thus capacity requirements, for the residential built environment. The different strategies do show different behavior, but also that availability of renewable gasses in the model is a significant driver in the transition paths they are able to choose, no matter how they choose (refer to figures 5.7, 5.6, 5.8, 5.9 and 5.18).

A second significant observation on the model's behavior indicates that peak gas demand will decline over time everywhere as a result of municipal decisions, even when considering the use of renewable gasses. This is a logical result, as the model implicates that 1 reduction of natural gas is to be replaced over 4 other replacing sustainable energy sources. However, the model also strongly suggests that this decline in peak gas demand will be regionally different (refer to figures 5.20, 5.21, 5.22 and 5.21). A clear trend between the less gas-driven urban versus rural is observed. This implies that Gasunie's strategy will have to consider strong regional differentiation in its approach. Which is further amplified by the availability and allocation challenge with renewable gasses.

In light of these observations, it can be confirmed that there are limitations to what municipalities can realize in the context of this transition. These limitations are driven by uncertainties in the system that are caused by the supply side of the system. It is simply not yet known when, and how much of the renewable gasses will become available. And even if they become available, how it will be allocated between the industrial, utility and transport. Consequently, these uncertainties and allocation decisions will shape the use of renewable gasses in the residential built environment. Further exploring their potential and uncertainties is highly suggested as a result of this research. Investments in these technologies and increasing awareness with national policymakers on the significance of their allocation decisions are crucial in fulfilling Gasunie's role and strategy towards a sustainable transmission system operator.

## 8.6 SOCIETAL CONTRIBUTION

The main motivation for all the questions asked and answers given in this thesis is maybe the most pressing grand challenge society is facing today: climate change. As mentioned in the introduction, what makes this challenge so complex is the lacking of a turn-key solution. While certain directions for solutions are obvious, such as the use of solar energy and renewable gasses, they all come with consequences and limitations. This thesis intended to provide insights into these consequences and limitations through a socio-technical and complex adaptive systems lens.

While it can be argued whether municipalities have this much influence in shaping the transition as modeled in this thesis, it does provide insights on their decisions if they are uncoordinated. Municipal decisions do matter in this transition. Their policy decisions may shape the configuration and speed at which the transition of the built environment may occur. The unawareness about their role and the consequences of their decisions are made explicit in this thesis. It is therefore highly suggested to have a debate with municipalities discussing the emerging consequences of their disaggregated decisions. While this may seem trivial, it is not.

Decisions municipalities make for transitioning their neighborhoods now or shortly may limit what we can do in the future. The model in this research suggests that the speed of the transition, as determined by the volume of municipal transition decisions, does not only alter the decreasing use of natural gas in the built environment but also the distribution of energy sources that are adopted in the future (refer to figure 5.11). A fast transition might indeed be preferred, but the decision-makers have to be aware of the impact it might have on future decisions. Significantly better solutions might be available in the future. The timing of decisions might be the key to an efficient sustainable thermal system for the future. Increasing awareness with policymakers that such trade-offs exist can increase the robustness of their decision-making over time.

The significance of the speed of this transition cannot be separated from the concept of timing. The results of the model suggested that the order in which neighborhoods are transitioned does not matter all that much for its impact on Gasunie's infrastructure. And while in the discussion it was mentioned that this result can largely be attributed to probability, data bias and an inherent implication of the conceptual model design, it is a thought starter. Deciding which neighborhood transitions when is a decision that cannot be separated from politics. Also, even if the order in which neighborhoods are transitioned is found to being not of significant impact to Gasunie, it is always influencing stakeholders directly involved with this neighborhood which have not been mentioned once in this thesis: its residents.

Through the theoretical lenses used in this research, the emphasis has always been put on municipalities, neighborhoods and their interaction impacting an energy system. But it must not be forgotten that the real implications of this transition will be for the residents living in the neighborhoods. By aggregating them, this research has not emphasized the implications for them.

However, the model does show that if this transition is about to happen, we may expect change for everyone, impacting real people. Not only through a change in what technology is used in their dwellings, but also the urban planning and retrofitting of dwellings to accommodate for its necessary infrastructure. Change will be observed through the whole supply chain of the thermal system, inherent to the complexity of this grand challenge.

## 8.7 RELEVANCE TO THE EPA PROGRAM

The Engineering and Policy Analysis program of the Technology, Policy and Management faculty at the TU Delft is centered around solving complex and wicked problems that are of political and policy nature using a data analytical, modeling and simulation approach. This study touches upon all of the core contents of the EPA program.

As discussed in the introduction (refer section 1.1), the thermal transition of the built environment is an inherently complex, uncertain and wicked problem that will impact many. Climate change requires that we move towards a less carbon-intensive energy system. One of the five sectors identified in the Climate Agreement to have to significantly contribute to this goal is the built environment. The approach in this study intends to address insights on the *what-if* question concerning the impact of this transition on multiple stakeholders.

While the model as designed in this thesis is not directly aimed towards public policymakers, its policy nature is rooted in its behavior. The municipal-driven neighborhood-approach is conceptualized as at the core of driving this transition forward. And the developed framework hypothesizes that the speed at which this transition is driven forward is a direct implication of the institutionalization of the Dutch Climate Agreement. Therefore making the policy and political context of this transition one of the foundations of this study. Its results and conclusions on the systemwide implications of this transition are very well relevant for them.

And finally, the part where TPM, and specifically the EPA program, is differentiating itself from peer programs: their focus on approaching such challenges from an analytical, modelling and simulation approach. The designed model in this concept leverages on the of combining the paradigm of agent-based modeling with socio-demographic and building characteristic data. It is found that the model designed in this thesis can be used for its intended purpose. A significant portion of the knowledge acquired during the time spent in this program was converged into this single thesis.

To conclude. The EPA approach of solving grand challenges through modeling and simulation is found to be a relevant combination. As such, this research has provided insights that can contribute to coming one step closer to unraveling the complexity of climate change and its implications.

## 8.8 SUGGESTED FUTURE RESEARCH

This study has shown an approach for how the agent-based modelling paradigm can be used to study the thermal transition in the built environment and its effect on an energy system. The benefits and limitations of this approach can be leveraged by taking this modeling exercise in directions currently unexplored in this study. Directions for extension of this model, conceptual additions, different experimentation methods, theory identification and exposition are suggested. The following directions for future research have been identified.

### 8.8.1 Extending the Current Model

The model presented in this research is intended as a showcase or first step of how an agent-based model might be constructed for studying the thermal system of the built environment and its effect on an energy system. A lot of time for this thesis has been spent on building the conceptual model and decision-flow of the municipalities. The implication is that elements of energy system constraints can be further developed. Only the energy sources of green gas, hydrogen and high or medium temperature heat are constrained to some extent in this design. Studying this model has revealed that the boundaries of renewable gasses play a significant effect on its outcomes. Therefore, it is highly suggested to build upon the energy system limitations to further explore the model's capabilities.

The ABM as implemented for this research leaves room for further implementation of local energy system constraints on the neighborhood level. Each neighborhood can evaluate for each of the five implemented thermal systems whether local, regional, or national constraints are present regarding the choice for this system. As such, the model can be relatively easily be extended with additional data sources and other thermal systems that might include more detailed limitations. Datasets comparable to the heat source data set, but for electricity and low temperature heat, can greatly contribute to this purpose.

Examples one might look at are adding electricity or hydrogen network constraints on a neighborhood level. Many authors discussed in this thesis have suggested that fully transitioning the built environment towards electrical powered systems is not possible due to the necessary expensive grid expansions (Klip, 2017; Menkveld et al., 2015). Also, while still a lot is uncertain about how hydrogen might be implemented as a thermal system driver in the future, one can explore how assumptions about hydrogen network limitations might affect the configurations of the thermal transition. It can be that opting for hydrogen in one particular neighborhood might have network consequences that also affect surrounding neighborhoods.

And more specifically, the model designed in this thesis could be extended to study the capacity implications on TenneT's electricity network. While this study focuses on modelling the thermal transition in the built environment from Gasunie's point of interest, the same research question can be imposed on the electricity transmission system operator, or even at a distribution operator level. The model as designed can include (dynamic) limitations in the energy infrastructure at the level of neighborhoods. However, this study has imposed no limitations at this level for the electricity network. While the national electricity output does increase as a result of this transition, it only does so by a limited amount of around 10GW (see figure **??**). But congestion might occur at the level of regional or trans-regional transmission. With different methods of aggregating peak demand, such insights could be studied.

It is argued that multi-modeling can contribute to combining different levels of resolution, both vertically as horizontally (Camus and Bourjot, 2015). An example of a horizontal extension with a multi-model for Gasunie might be combining agent-based models of the other gas-consuming sectors, such as the industrial and transportation sector, to extract a wider view of the required capacity on its infrastructure. An example of vertically multi-modeling such a system might be the combination of the model designed in this thesis with the household adoption agent-based model of Nava Guerrero et al. (2019). Combining the municipal-driven neighborhood-approach with models including household adoption behavior might be especially interesting.

### 8.8.2 Exploring the Model Under Deep Uncertainty

It is highly suggested to further explore the behavior of the model under the vast deep uncertainty space it is capable of entering. The behavior of the model is currently studied under various experiments that vary either the model variables one at a time, or for a limited set of scenario's which only vary three parameters. However, the results of the model have hinted towards scenarios that might generate emerging phenomena not yet fully explored, especially under extreme conditions. Combining the effects of model parameters in various degrees can yield results now still unexplored.

The suggested approach is to test the model with an open explorative or scenario discovery approach. The EMA workbench might provide the tool to couple this model with for further exploration. As discussed in chapter 3, the initial intention for this thesis was to include an analysis to study its deep uncertainty space, but time constraints and programming issues limited this approach.

#### *Addition of the Conceptual Design*

The conceptual perspective through which this system is modeled (as described in section 4.1) implicates that required infrastructural change is the result of the independent change in peak energy demand. Causality driving the change is therefore assumed to run from change in demand to required change of energy infrastructure. This assumes that transmission system operators are the subject of change and not the actors participating in or driving the change in this perspective. While in the real world, they are important stakeholders participating in all levels of decision making for such an energy transition.

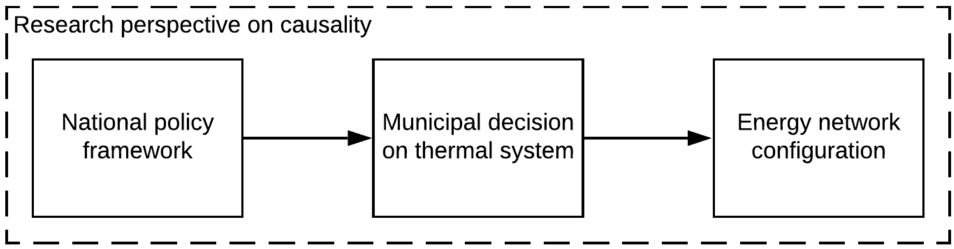


**Figure 8.1:** *Causality of change in this study.*

A new perspective is therefore suggested in a future model, that incorporates feedback loops from the transmission system operator and even the municipalities. Figure 8.2 describes the conceptual design which might provide for such an approach. With such a perspective, the two-way interaction between national policymakers, municipalities and the transmission system operator might provide less demand-driven results. How this multi-layered dynamic interaction might look like and what it implicates, is a suggested question for future research.

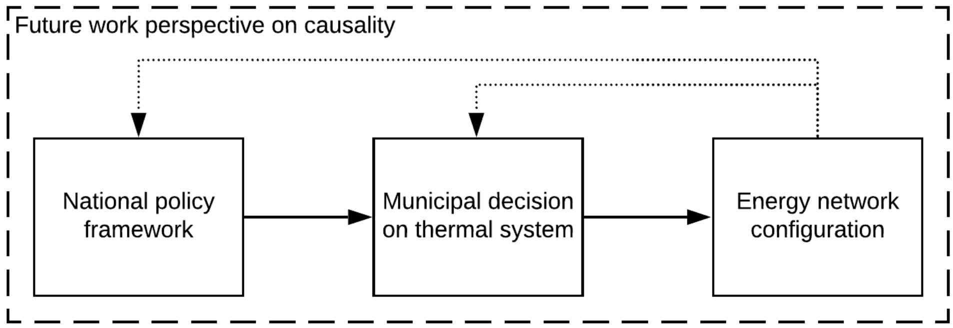


**Figure 8.2:** *Causality of change in suggested future studies.*

***Theory Identification and Exposition of the Municipal Decision-Making***

The direct cause of this study was to clarify the effect of municipal decision-making within the context of the thermal transition on Gasunie's infrastructure. By studying various documents and literature, it was found that policy ambitions on a national and municipal level are clear, but how these ambitions are to be transformed into theory, not Diran et al. (2020); Leeuw and Groenleer (2018) . A new conceptual design for municipal decision-making was therefore designed, but the validation of this design is only possible to a limited extent.

As such, a new study towards the decision-making context is therefore suggested. Some municipalities have cautiously started with pilot programs for their neighborhoods (Programma Aardgasvrije Wijken), which may provide useful empirical information. Arising questions therefore are: what drives municipal decisions in the first place except for a national policy goal and how do municipalities differ in their approach? What is their view on the implementation of specific thermal systems in neighborhoods? And finally, what determines when they will transition neighborhoods. These are all questions that can be linked to the drivers found to be of most influence on the output of the model. Combining the insights of such a study into an improved formalization of the municipal decision-strategies could improve the validity and usefulness of the agent-based model designed in this thesis.

# 9 PERSONAL REFLECTION

This is the end of my thesis. I hope that by coming this far you have somewhat understood what this project is all about: change, uncertainty and interdependency, but above all, that going forward is the only thing not uncertain about solving this wicked challenge. In this final section, I will reflect on my endured challenges during this journey and what learnings I will take on my next adventure.

First, I would like to reflect on why I wanted to use the agent-based methodology for my thesis. Ever since my first encounter with this modeling paradigm, I was grasped by its ability to be able to expose complexity in a very approachable way. It is not about how difficult or extensive the model can be (which it can be), but rather its ability to capture and explore a theory or perspective of a seemingly endless complex system with relatively simple assumptions. Agent-based modeling is not about finding an optimal solution in an energy system, which I only *really* understood in the final phase of writing this thesis.

Second, it is in my nature to work hard while trying to make the best possible model. However, this turned out to be not the most fruitful combination for this project. For ABM, and scientific research in general, it is not necessarily about the final design, but rather at finding out what is in the uncertainty space in the first place, why and how this knowledge can contribute. The reason that this project took longer than anticipated is that I kept perfecting things that did not need perfecting in the first place. Not having a reference of what is good or bad while exploring this uncertainty with an apparent structure in the project missing is something that I have found to be very difficult, but have improved at. But still, I keep the urge in perfecting the work that I have delivered now.

Third, I found working on this project from home, without being able to face-to-face spar with peers or mentors, is difficult. While we have to make the best out of working from home with digital ways of communication, I found it difficult to not being able to just walk in or talk to my neighbor about this project. I found that being able to reflect on your work by just randomly talking about it with others is extremely helpful in moving forward and unraveling my thoughts.

These challenges, amongst others, also learned me many new valuable things about being a scientific researcher and, above all, myself. First, I found that I can be extremely enthusiastic and over-optimistic about ideas that spark my mind. While I think this is not a bad thing in the first place, I have to wary that I first need to realistically assess their feasibility and added value. For example, some graphs and parts of the model took me days, maybe even weeks, to fully work out. However, if I reflect on some time vs added value contributions, I would have decided and planned many things differently. But during the project, I kept improving my efficiency with such challenges. This perfecting of initial ideas also made it hard for me to throw away stuff and start over. Sometimes this felt like starting over, whereas in reality I then started over *with experience*.

Second, I learned that many times doing some things better means doing them simpler and more elegantly. I started this project off with many ideas for the designed model. In hindsight, while I still believe in the applicability and usability of the model, I could have done things so much simpler and still extract the same or even better insights. Great models start with great simple ideas, and not necessarily with added complicated stuff which makes them ambiguous.

Third, I learned that asking for help is not a sign of weakness and of great value in improving your thoughts. I started this project off with really wanting to show what *I* could achieve, without realizing that it might be others that are necessary for showing you how to get there. This is a lesson learned the hard way. I am grateful for everyone involved in the project who showed me this. I could not have done it without you.

And finally, I learned to code! In hindsight, I literally had 0,01 % skill in how to write either Python or NetLogo code. It took me many days and introductory course recaps to get myself up to speed with writing the model and data analytical scripts necessary for this project. I really enjoyed solving these small problems, maybe even so much that I spent too much time on perfecting insignificant details in the project related to this code. Now I can confidently state that I have 0.1 % skill in writing code!

I have hated and loved this project. Having finished it gives me a double feeling. One the one hand, I am confident that I can do so much better given the experience this project has brought me, but on the other hand I am genuinely happy that it is over now. It has been an invaluable experience and only now I grasp the value of everyone saying that it is a process that everyone has to go through themselves.

Thank you for reading my thesis,

Jaromir

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# A RESEARCH CONTEXT

This appendix is aimed towards describing the research context and literature on the thermal transition of the built environment in the Netherlands. Information from this appendix is used to define the conceptual model design. First the Dutch transition of the built environment is described in sectin A.1. Then in section A.1.1 the sustainable alternatives included in this thesis are introduced. The considered energy sources and their explanation is described in section A.2. How insulating the built environment contributes to a more energy efficient sector is described in A.3. The role of municipalities is detailed in section A.4 and Gasunie's significance and their network in section A.5.

## A.1 THE DUTCH THERMAL SYSTEM OF THE BUILT ENVIRONMENT

The historic development of the current thermal system of the built environment in the Netherlands originates from 1948, the year when natural gas was first found near Coevoorden in the province of Drenthe and 1959, when the Slochteren gas field in Groningen was discovered. Up and till this period, most dwellings were heated by using coal, town gas and oil. By 1968 all municipalities on the mainland were connected to the national gas grid. These large gas field findings enabled the Dutch government to exploit a relatively cheap, stable and clean energy source for the heating of its built environment. As gas-based thermal solutions are less-carbon intensive compared to the other by then usual thermal solutions, the Dutch built environment maintained a reputation of being fairly $CO_2$ efficient in comparison to other EU countries whom were less dependent on natural gas (Klip, 2017; Correljé et al., 2003; van Leeuwen et al., 2017).

The collective national gas thermal system contributes a significant share to the yearly final energy consumption balance. Primary energy consumption in the Netherlands consists of 3060 PJ in total, of which 1366 PJ is natural gas. Households then use 350 PJ of energy for their heating purposes (van Leeuwen et al., 2017). Heating of dwellings accounts for the majority of their natural gas use (79%), while hot water (19%) and especially cooking (2%) contribute a lot less to the natural gas demand (ECN et al., 2016). Natural gas is used to fuel boilers which in turn heats water for use as tap water or as heat exchangers in radiators. In the current building stock, over 90% of the dwellings are heated with natural gas fired boilers. But alternative thermal system are increasing their share as newly built homes can not be connected to the natural gas grid as of 2018 (Dutch Ministry of Internal Affairs, 2018).

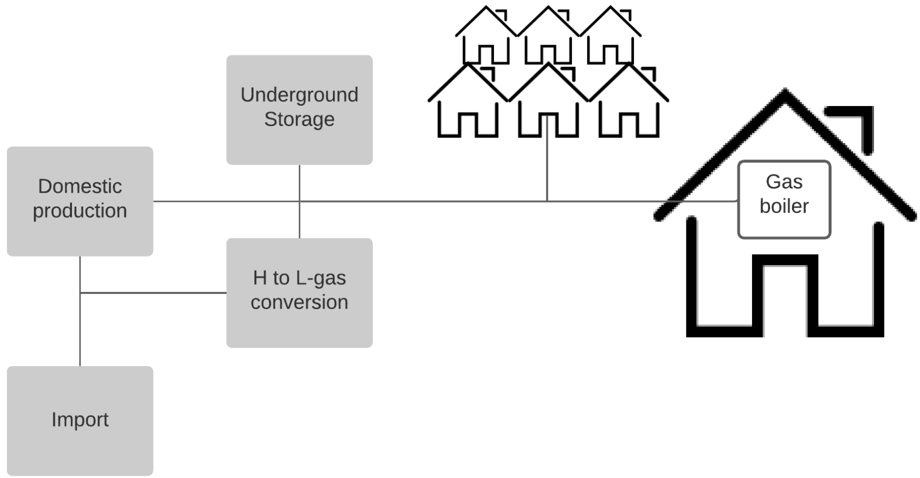



**Figure A.1:** *Schematic overview of the natural gas supply chain for typical neighborhoods in the Netherlands, inspired by (Klip, 2017).*

The increase of newly built dwellings, installation of modern, more efficient boilers and retrofitting of existing buildings (Faber and Hoppe, 2013) has resulted in an overall decline of natural gas use in the average dwelling by 25% from 2000 to 2015 (ECN et al., 2016). But the thermal system in the built environment remains a large consumer of natural gas. Figure X represents a schematic overview of the current natural-gas driven thermal system of a dwelling.

Figure A.1 represents a schematic overview of the current natural-gas driven thermal system of a typical Dutch dwelling. Natural gas is produced in either the Netherlands itself or imported from other countries. Depending on the quality specification of the natural gas, it has to be converted to low-calorific gas that is used as the standard for heating appliances in dwellings. The flexibility in natural gas supply is derived from flexible production underground gas storages and varying imports. As mentioned before, space heating uses the majority of gas consumption in dwellings by the use of in-house gas boilers (Correljé et al., 2003; Klip, 2017).

### A.1.1 The sustainable thermal alternatives

The future sustainable thermal alternatives for the built environment are facing a great challenge to replace the current natural gas-driven system. While big steps towards sustainability can be achieved in the sector that includes 7 million gas consuming households, it is a well functioning and efficient system that will be difficult to compete with (Schepers et al., 2015). The most promising subset of thermal systems for the built environment are therefore included in this study. Reviewing the literature and reports of various authors (Schepers et al., 2015; Klip, 2017; Diran et al., 2020; Menkveld et al., 2015; Lund et al., 2014; Nava Guerrero et al., 2019; Klimaatberaad, 2019; Kreijkes, 2017; Schepers et al., 2019; ECN et al., 2016; Stedin, 2020; Gasunie Transport Services, 2017; Gasunie and TenneT, 2019; Lund et al., 2018; Busch et al., 2017; Persson and Werner, 2011), it can be concluded that the future sustainable thermal systems can be categorized in two groups: collective systems and individual systems. Collective systems are centered around the principle of a collectively shared thermal system, whereas individual systems only produce heat for a single dwelling. District heating networks (DHC) fall in the first category, while heat pumps come in the latter (van Leeuwen et al., 2017). One has to note that more technologies are available or currently in development, but for scoping purposes this study is limited to just the systems described below.

### A.1.2 District heating and cooling as a collective solution

Collective systems, in the form of District Heating and Cooling (DHC) are centered around the principle of connecting buildings in a neighborhood, district or even a complete city with pipes that distribute heat from one or multiple sources to the end user (Lund et al., 2014). This heat is transported in the form of water to households, and used for space heating or hot tap water through the use of heat exchangers. DHC's are expected to play a key role in the transition towards sustainable thermal systems throughout Europe (Lund et al., 2014; Connolly et al., 2014). As they are capital-intensive energy networks and have to deal with heat losses during transportation, they are a economically viable option in denser populated areas where heat demand is high (Klip, 2017; Reidhav and Werner, 2008). Due to the scale of such a network, a wide range of energy sources can be used to produce the heat.

District heating thermal systems are 'technology neutral', meaning that it does not matter what energy source is used for heating the water in the infrastructure. This can either be a fossil fuel, but also residual heat from industrial processes or other heat producers. The second implication or opportunity for being 'technology neutral' is that the source of the heat may change over time. For example, an initial heat network can be fueled by coal, but over time switch to a sustainable energy source thus making it carbon neutral (Klip, 2017; Lund et al., 2014). Currently, most existing heat networks are supplied by waste incineration or natural gas-fired plants (ECN et al., 2016). Sustainable energy sources, such as biogas/greengas, solar thermal and especially geothermal sources have been found to provide potential to further reduce carbon emissions of these networks. Another solution being explored is using residual heat from industrial processes as a heat source for these networks (van Leeuwen et al., 2017; Persson and Werner, 2011). For simplicity reasons, this study assumes DHC systems as being sustainable and their energy source as out of scope.

DHC's can operate at different temperature levels depending on different heat sources and dwelling characteristics. Three main distinctions are made between temperature levels of the grid: High Temperature (HT, above 70 degrees Celsius), Medium Temperature (MT, above 50 degrees Celsius) and Low Temperature (LT, below 50 degrees Celsius). Lower supply temperatures in heat grids result in higher energy efficiencies of the dwelling thus making the grid more sustainable. However, lower supply temperatures require higher levels of dwelling insulation, making only high temperature supply temperatures suitable for all dwelling insulation levels (Diran et al., 2020; Menkveld et al., 2015; Lund et al., 2014).

Figure A.2 describes the schematic supply chain of a typical Dutch dwelling connected to a district heating network. The heat necessary for heating the dwelling can be produced by various sources, either sustainable (i.e. waste CHP, industrial heat surplus, solar thermal, bio-CHP or large heat-pump facilities) or through fossil fuels (i.e. coal or natural gas) due to being 'technology neutral'.

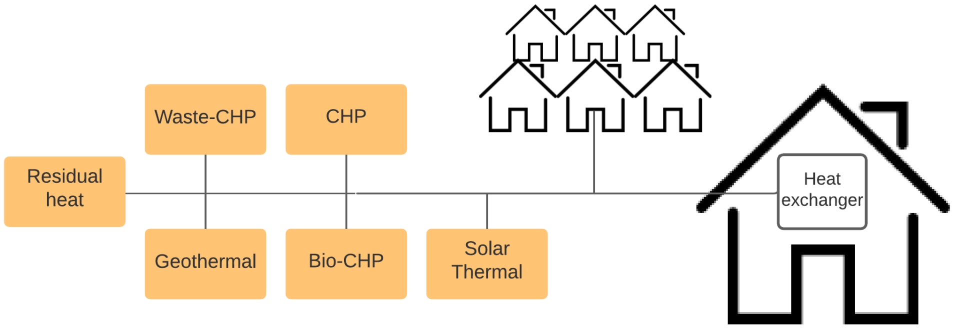



**Figure A.2:** *Schematic overview of DHC supply chain for a typical Dutch dwelling, inspired by Klip (2017).*

### A.1.3 Heat pumps as an individual solution

Individual systems are centered around the principle of using home-installed heat pumps with or without support of a gas-fired boiler as the only source of heat in a dwelling. There are many variations of the heat pump as technical installation to heat a dwelling. The main distinction can be made between the pumps being fully electric, also known as all-electric heat pumps, or partly gas-driven, known as hybrid heat pumps. For electric heat pumps to be fully sustainable, their electricity source has to be completely renewably generated. For the hybrid heat pumps to be sustainable they have to use a renewable gas such as green gas (Klip, 2017) or hydrogen (Stedin, 2020). Both these variations use the core principle of a vapour compression cycle that extracts heat from an external source and feeding it into the heating system of the building. The higher the temperature difference that has to be bridged between outside and inside, the lower the efficiency. Both the hybrid heat pump and al-electric heat pump can be an air sourced or ground sourced system. The main difference being where the heat is sourced from. Air sourced systems are cheaper, less complex, but also less efficient. Ground sourced heat pumps are more efficient, but also more complex and expensive systems. Figure A.3 includes all different schematic heat pump configurations.

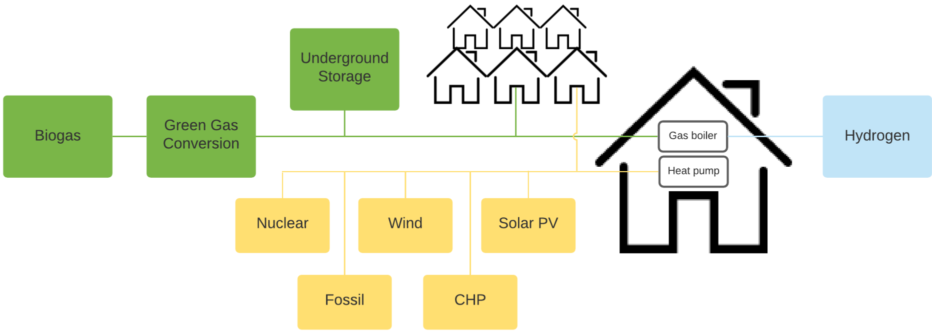



Figure A.3: *Schematic supply chain overview of hybrid or all-electric heat pump application in typical Dutch dwelling. In all-electric configurations the gas boiler and gas connection is not present, inspired by Klip (2017).*

Hybrid systems are a combination of a gas powered heat system and an electrical heat pump. They represent an attractive transition alternative in comparison to the all-electric heat pumps as they can provide higher heat power output than electric pumps, therefore being more suitable for dwellings which are poorly isolated. When the electrical power output of a heat pump is not sufficient during peak thermal demand, the gas-fired boiler is able to cover for the (substantial) extra needed power. The all-elecric solutions are more suitable for newly built, well insulated dwellings which require lower peak thermal demand (Netherlands Ministry of Economic Affairs, 2016). Whereas hybrid heat pump systems are a suitable solution for dwellings which are already using gas systems and are not extremely well insulated (Committee on Climate Change, 2018). Both the all-electric and hybrid heat pumps require their energy source to be renewable to be renewable thermal systems of themselves. However, this is not considered within the scope of this research.

## A.2 THE ENERGY SOURCES FOR THE SUSTAINABLE THERMAL SYSTEM

Replacing the current thermal systems in the built environment to a configuration of the before mentioned sustainable alternatives is just the means to the end of the thermal transition. The main reason for replacing the current systems is to replace natural gas as its main energy source by a mix of sustainable (or 'technology neutral') alternatives. The selected four sustainable thermal system alternatives are driven by electricity, heat, green gas and hydrogen. In the following sections, each of these energy sources are briefly discussed.

### A.2.1 Electricity

Using electricity in dwellings for thermal heating seems an obvious route to sustainable energy use, but is yet to be widely implemented. Currently, electricity is mostly used in dwellings for powering appliances other than thermal systems. In the current system, electricity is largely generated by dedicated fossil power plants or renewable sources such as wind farms or solar PV systems. The term 'technology neutral' also applies for electricity, as the carrier of energy does not care from what source it originates. This implicates that electricity can only be considered renewable when generated as such.

The availability of electricity itself is not so much of the main issue as it being renewable or having the capacity for transportation. Currently, peak load of the electricity system is measured at swinging between 9 and 18GW during the day, with around 28GW of capacity being installed. While the total peak gas demand is estimated at around 100GW of capacity. This extra capacity in the electricity network does not exist and is expensive to build (Veldman et al., 2011). Even if it did, most of the electricity production would originate from fossil sources anyway (Klip, 2017).

### A.2.2 Heat

Just as with electricity, heat is not the original source of energy, but rather a carrier of energy and thus 'technology neutral'. It can be extracted from a wide variety of sources, as described in figure A.2, and transported through a network of pipes containing to neighborhoods in the form of hot water. Historically, heat has had a minor role in the energy system of the Netherlands, bit interest due to the energy transition is gaining. Around 400.000 households are currently connected to an external source. As the sustainability of the system is dependent on the source for production, this form energy carrier is a promising solution for the built environment (Niessink and Rösler, 2015).

The availability of heat is dependent on what primary energy source is used for its production, whether the source of production is nearby and what the desired level of temperature for its end-users is. The source of heat is also a large contributor to what output heat temperatures can be achieved for the DHC network. Upgrading low temperature heat to higher temperatures is possible but requires additional energy. Of all heatsources depicted in A.2, a wide variety of possible heat output temperatures is possible (Niessink and Rösler, 2015).

### A.2.3 Green gas as renewable gas

In recent years in the Netherlands, green gas is considered a promising renewable energy source for multiple purposes. Green gas is the final conversion product originating from biological anaerobical codigestion of natural products. These natural sources, such as from sewer systems, landfills, or fermentation plants, yield a methane gas called biogas. In the Netherlands this gas is commonly upgraded to natural gas quality in order to inject it into the national gas grid. This upgraded biogas is called green gas (Hoppe and Sanders, 2014). This renewable energy source does produce greenhouse gas emissions, but is sourced from a biological origin, making it renewable.

Various estimations have been made over the years of how much green gas potential might exist in the Netherlands. Hoppe et al. estimate the potential in the Netherlands at around 30PJ per annum (Hoppe and Sanders, 2014), while the national green gas institution estimates the potential for 2020 at 25PJ, increasing to 75PJ in 2030 (Groen Gas Forum, 2014). Distribution network operator Stedin estimates the potential for 2030 at 60PJ (Stedin, 2020). Future production of green gas is highly dependendent on the investment climate and government support schemes (Gasunie Transport Services, 2017). What is clear however, is that there is a lot of uncertainty on the availability of green gas, let alone what sectors might consume this estimated potential in the future.

Green gas can be used as a relatively easy substitute for the currently dominating natural gas in the built environment. As green gas is of the same quality of natural gas, current thermal systems in theory do not have to be replaced or adjusted in order to use this energy source. However, the outlook is that hybrid heat pumps will be fueled by green gas instead of natural gas (Gasunie Transport Services, 2017). The existing gas infrastructure will require little modifications in order to support a green gas driven system. While green gas will mostly be produced on a local scale and injected in the regional gas intrastructure, gas boosters are able to transport the green gas from the local infrastructure networks to the national grid (Netbeheer Nederland, 2019).

Green gas is a highly regarded alternative to natural gas for the built environment, but also faces barriers to its widespread implementation. Its main advantages are that it offers the flexibility and relatively high energy density of natural gas, but the source in itself is renewable. Therefore, the existing gas infrastructure of Gasunie and the local distribution network operators are usable without large investments. Another advantage is that while green gas is not yet available on the same scale as natural gas, the share of green gas can be increased gradually as it does not differ in quality from natural gas. This is currently demonstrated by 140.000 households in the Netherlands already using a share of green gas in their thermal energy consumption (Groen Gas Forum, 2014).

Currently, barriers are preventing green gas from being already adopted and used on a national scale across all natural gas consuming sectors. First of all, the potential is unknown and severely limited by the availability of profitable biogas production plants. This implicates that green gas is obviously more expensive than natural gas if it is not subsidized by government aid. The second barrier is the allocation challenge. As green gas is limited in its availability, and many sectors require reduction of fossil fuel use, the allocation of to which sectors green gas is distributed is of importance to the casus in this thesis (Groen Gas Forum, 2014).

### A.2.4 Hydrogen as renewable gas

The second renewable gas alternative that could be a part of the transition puzzle is hydrogen. Hydrogen is an energy carrying gas that can be produced by reforming methane, which is not considered renewable, or by electrolysis of water, which is considered the renewable method when the electricity is produced in a low carbon chain. Currently, almost all production of hydrogen occurs through the traditional method of reforming methane (Committee on Climate Change, 2018). The future promising electrolysis technology is still very much a promising technology for the future.

Currently, hydrogen is a widely available energy source for the industrial sector with around 175PJ of production (van Groot Battavé et al., 2020; van den Noort et al., 2017). However, its use in the built environment is limited as it requires different thermal systems to the currently installed ones. Hydrogen can either be used as a fuel that is used as a direct replacement for natural gas by burning it in boilers, or by converting it to electricity in fuel cells. Also, as renewable hydrogen production and consumption in the built environment is limited, its future development is still very much a question mark. Several pilots currently exist in the Netherlands that test the applicability of hydrogen use in neighborhoods (van Groot Battavé et al., 2020).

While hydrogen is still a technology that has to continue its development before widespread use in neighborhoods as thermal energy carrier, some clear advantages exist. Research suggests that hydrogen can be used in the current existing gas infrastructure network with minor adjustments (Committee on Climate Change, 2018; van den Noort et al., 2017). It is either possible to add small portions of hydrogen to the existing methane gas flow, or gradually increase the proportion from 0 to 100 %. More research however is being conducted on the use of hydrogen as possible future replacement in the gas infrastructure. What kind of configurations might be possible in the future for hydrogen is therefore dependent on production and demand development of this gas (Dodds et al., 2015). A combined study by Gasunie and TenneT marks sustainably produced hydrogen as 'the most promising technology to convert renewable electricity into a physical product" (Gasunie and TenneT, 2019)

Barriers, however, are that the technology is still not available and it is uncertain when it will become available. Even if the developments for a hydrogen economy turn out to be positive, the same allocation problem as with green gas applies for hydrogen. Also, transforming parts of the gas infrastructure to a hydrogen based network may result in lock-in of certain regions of the gas infrastructure. Careful regional planning of this development is necessary (van den Noort et al., 2017).

## A.3 INSULATING THE BUILT ENVIRONMENT

The final energy demand as a result of heating the built environment is an equation that includes the type of thermal system, what kind of dwellings are included and their insulation level (Itard and Meijer, 2008). Higher insulation levels result in lower thermal energy demand as heat losses are reduced. Newly built dwellings in the Netherlands typically are very well insulated (Menkveld et al., 2015), but as Filippidou et al. (2016) points out, the currently existing building stock will dominate the stock for the upcoming 50 years. This existing stock is not always insulated up to the levels required or wanted for the thermal transition and retrofitting existing buildings to higher levels of insulation can be costly. Insulation measures that increase dwelling efficiency include roof, wall and floow insulation or replacing single layer glass panels with double layer glass panels. Higher levels of insulation implicate lower peak thermal demand energy for equal consumption.

## A.4 MUNICIPALITIES: THEIR ROLE AND AMBIGUITY IN CLIMATE GOVERNANCE

With the Paris Climate Agreement as the overaching global sustainability framework (United Nations, 2015), policy frameworks have started to trickle down from top-level policymakers to the lowest levels. On an European level, several strategies have been presented targeting 2020 (European Commission), 2030 (EuropeanCouncil, 2018) and 2050 (European Commission, 2018) as time horizons for achieving their goals. As mentioned in the introduction, the Dutch policy framework for this transition is the Climate Agreement (Klimaatberaad, 2019).

The Climate Agreement outlines considers the built environment as one of the five key strategic sectors for accelerating this transition (the others being mobility, industry, agriculture and electricity). Clear goals are mentioned in this agreement, such as: completely transforming the built environment to a sustainable heated and powered sector; diminish the use of Groningen aardgas as quickly as possible; keep the transition affordable. And all this has to be achieved by 2050.

And by no surprise, the national government shifts the responsibility of the transition further downwards to municipalities. The proposed approach for the transition in the built environment has to be initiated by the municipalities targeting each of its neighborhoods separately. This municipality-neighborhood approach is at the core of the Dutch thermal transition of the built environment. Main reason for the local approach is that by municipalities targeting neighborhoods, the local circumstances can be captured at the best granularity (Netherlands Ministry of Economic Affairs, 2016).

Academic scholars have emphasized effectiveness and barriers for such a localized approach. Broto (Castán Broto, 2017) stresses the international trend of the institutionalization of climate change governance to cities and regional governments entities as the better reflect on the specific needs in urban areas. Cross-institutional and international climate change policies are more often shared among peers to further advance the practical field of addressing this transition through network governance (Castán Broto, 2017) or governance diffusion (Hakelberg, 2014). Meanwhile, Castán Broto (2017) recognizes that these regional or local entities are facing completely new challenges which require experimentation. The thermal transition of the built environment is such an example, as several pilot projects in neighborhoods exist (Programma Aardgasvrije Wijken).

Markantoni (2016) adds to this observation by Broto Castán Broto (2017) as she emphasizes the interplay between local climate action and necessary top-down support. She concludes that in the current paradigm of low carbon governance, local action is at the core of climate policy, but is highly dependent on multi-level interaction with other institutions. This is also the case for this transition which has neighborhoods and municipalities at its core. Regional and national institutions are established to support local transition action by means of information sharing and resource provision. The Regional Energy Strategies is a fine example of such an institution created. This institution is tasked with playing the regional connecting role between municipalities in order to coordinate the allocation of renewable energy, including urban heating, in the region (Interprovinciaal Overleg et al., 2018). And Hoppe et al. Hoppe and Miedema (2020) stress the effectiveness of such multi-level interconnectednes through institutions as 75% of municipalities state that intermunicipal collaboration results in benefits for all.

While consensus exists on the theoretical effectiveness of local governance for climate change, empirical observations conclude that operationalization of policy frameworks often falls behind by their intentions. The Climate Agreement (Klimaatberaad, 2019) for example is a very broad policy documenet outlining the neighborhood approach and central role for municipalities, but fails to present clear protocols or instructions for municipalities. While Groenleer et al. van Leeuwen et al. (2017) study several Dutch regions on their governance implementation, they recognize the sustainable ambitions within their case studies, but observe a high variety in actual implementation. Diran Diran et al. (2020) explains this ambition and implementation mismatch by stakeholders as unawareness of individual roles in this transition.

To summarize, municipalities play a (given) central coordinating role downwards to their local neighborhoods while they have a connecting role to the higher level institutions upwards. Meanwhile, actual implementation of these roles and ambitions remains difficult as uncertainty operational policies exist.

## A.5 THE ROLE OF GASUNIE

Where municipalities play a leading role locally, Gasunie has to adapt and steer the transition from their gas network perspective. If the global energy transition has made one thing clear, it is that fossil fuels like natural gas will be playing a decreasingly important role in our energy system (Gasunie and TenneT, 2019). Since its establishment in 1963, Gasunie's main task has been to operate and maintain the national gas infrastructure network, which transports natural gas. The thermal transition will have a profound effect on what thermal systems and thus what energy sources we will be using to heat our dwellings. Consequently, Gasunie's role in the national energy system will change as they have to accommodate for decreasing natural gas use and increasing use of sustainable gasses like green gas and hydrogen. The key strategic question for Gasunie therefore arises how their current market will be developing as a result of the energy transition and what adaptations they will have to make (Gasunie Transport Services, 2017).

Gasunie's gas infrastructure is the national backbone of a more fine mazed regional gas distriburtion network. The main infrastructure (HTL) transports gas from Dutch and international gas connections through the country. This HTL network is then connected to regional networks (RTL) and distribution networks. The national HTL network consists of two seperate networks, one for high-calorific gas and the other for low-calorific gas. All these networks together constitute the gas infrastructure, resulting in a redundant network. In total, the Dutch gas grid consists of 136.000 km of pipelines (Netbeheer Nederland, 2019; Correljé et al., 2003).

A simplified schematic overview is presented in figure A.4. Natural gas enters Gasunie's network in the HTL network and is transported at 40-67 bar to Metering and Regulation stations, where the gas pressure is lowered and injected in the RTL network at 16-40 bar. From the MR stations, the gas is transported to end-users. Biogas is produced locally, where it is converted to greengas before it can be boosted into the RTL network for national transportation. The Metering and Regulation stations are the physical stations which are closest to the gas consumers in Gasunie's network.

Gasunie has the legal responsibility to ensure its consumers have access to sufficient gas during extreme conditions. Therefore capacity of the network is configured based on peak demand figures. Peak demand is the extra capacity of gas needed in extreme conditions during a short period of the day. Under normal circumstances, peak demand is nowhere near maximum capacity of the network (Gasunie Transport Services, 2017). It is common practice for energy infrastructure networks to be designed for extreme conditions in which they deliver peak supply (Liu et al., 2019).

Gasunie understands that the energy transition will impact how their network will operated and developed in the future. The transition of the built environment from natural gas towards sustainable alternatives will change the content and distribution of how energy will flow through their infrastructure (Gasunie and TenneT, 2019). Currently, investment decisions and future outlooks already pick up on developments such as green gas boosting and hydrogen (Gasunie Transport Services, 2017). However, the foreseen change as a result of the thermal transition in the built environment might drastically change consumption behavior of end-users. This change will impact the upstream national gas grid of Gasunie. Anticipation to these changes are necessary for reliable operation and strategic investment decisions.

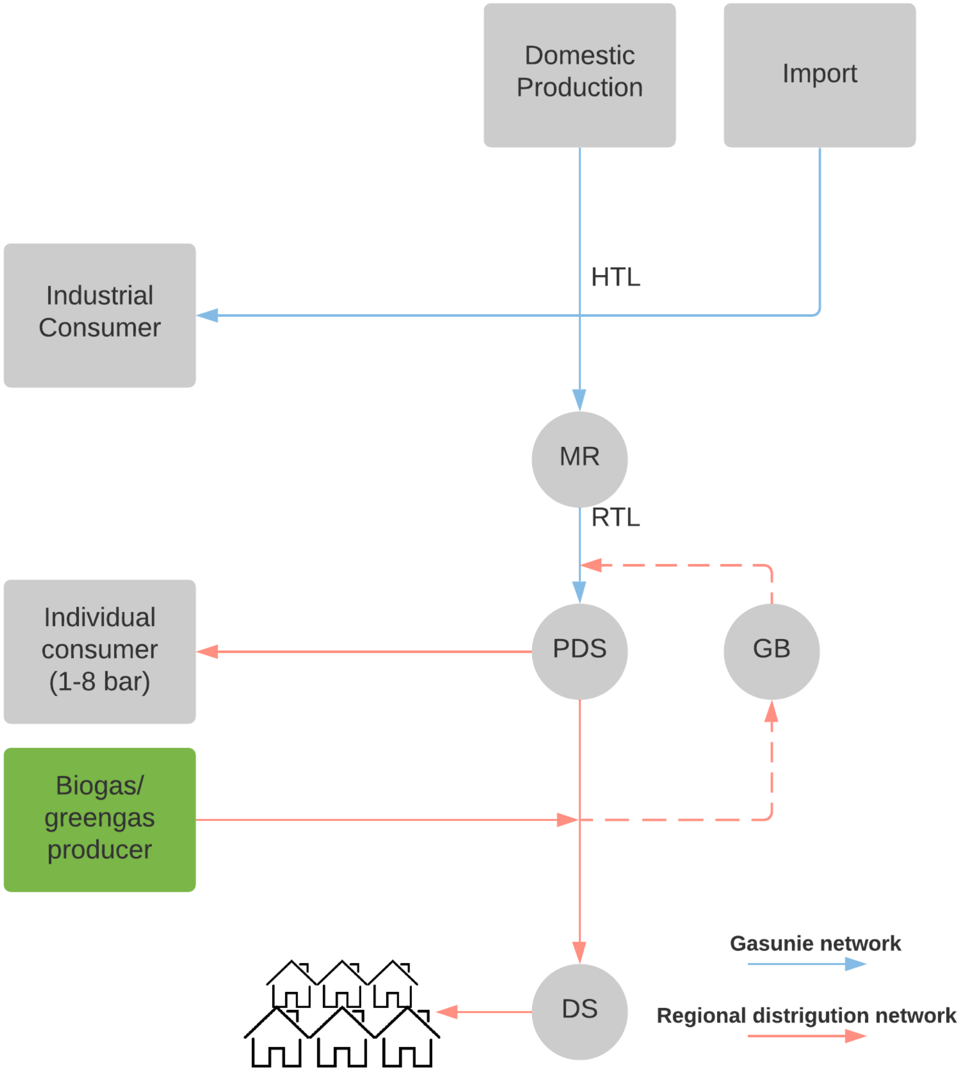



**Figure A.4:** *Simplified schematic overview of gas network configuration. MR = Metering and Regulation stations, PDS = Public Distribution System, GB = Gas Booster, DS = Distribution Station. Inspired by (Netbeheer Nederland, 2019), own adaption.*

# B | GASUNIE'S DUTCH TRANSPORT SYSTEM

gasunie
crossing borders in energy

# Gasunie's Dutch Transport System

21th Edition status January 2015

# C | MUNICIPALITY MR-STATION MAPPING

| GM_NAAM | MR_STATION | GM_NAAM | MR_STATION | GM_NAAM | MR_STATION | GM_NAAM | MR_STATION |
|---|---|---|---|---|---|---|---|
| *Appingedam* | Scheemda | *Zaltbommel* | Zaltbommel | *Schiedam* | Vlaardingen | *Voerendaal* | Schinnen |
| *Bedum* | Oostum | *Zevenaar* | Angerlo | *Sliedrecht* | Wijngaarden | *Weert* | Nederweert |
| *Bellingwedde* | Scheemda | *Zutphen* | Esveld | *Cromstrijen* | Ijsselmonde | *Valkenburg aan de Geul* | Bemelen |
| *Ten Boer* | Oostum | *Nunspeet* | Wezep | *Albrandswaard* | Vondelingenplaat | *Lelystad* | Emmeloord |
| *Delfzijl* | Scheemda | *Dronten* | Wezep | *Westvoorne* | Ommeloop | *Horst aan de Maas* | Venray |
| *Groningen* | Haren | *Neerijnen* | Zaltbommel | *Strijen* | Ijsselmonde | *Oude IJsselstreek* | Groenlo |
| *Grootegast* | Visvliet | *Amersfoort* | Leusden-Zuid | *Vianen* | Reek | *Teylingen* | Rijnsburg |
| *Haren* | Haren | *Baarn* | Hilversum | *Vlaardingen* | Vlaardingen | *Utrechtse Heuvelrug* | Leusden-Zuid |
| *Hoogezand-Sappemeer* | Hoogezand | *De Bilt* | Odijk | *Voorschoten* | Zoeterwoude | *Oost Gelre* | Groenlo |
| *Leek* | Haren | *Bunnik* | Odijk | *Waddinxveen* | Bleiswijk | *Koggenland* | Heerhugowaard |
| *Loppersum* | Oostum | *Bunschoten* | Nijkerk | *Wassenaar* | Zoeterwoude | *Lansingerland* | Bleiswijk |
| *Marum* | Haren | *Eemnes* | Hilversum | *Woerden* | Reijerscop | *Leudal* | Nederweert |
| *Almere* | Weesp | *Houten* | Odijk | *Zoetermeer* | Bleiswijk | *Maasgouw* | Nederweert |
| *Stadskanaal* | Scheemda | *Leusden* | Leusden-Zuid | *Zoeterwoude* | Zoeterwoude | *Eemsmond* | Oostum |
| *Slochteren* | Scheemda | *Lopik* | Reijerscop | *Zwijndrecht* | Ijsselmonde | *Gemert-Bakel* | Mill |
| *Veendam* | Scheemda | *Montfoort* | Reijerscop | *Borsele* | Gravenpolder | *Halderberge* | Zegge |
| *Vlagtwedde* | Scheemda | *Renswoude* | Leusden-Zuid | *Goes* | Gravenpolder | *Heeze-Leende* | Mierlo |
| *Zeewolde* | Nijkerk | *Rhenen* | Leusden-Zuid | *West Maas en Waal* | Ewijk | *Laarbeek* | Reek |
| *Winsum* | Oostum | *Soest* | Nijkerk | *Hulst* | Axel | *De Marne* | Oostum |
| *Zuidhorn* | Visvliet | *Utrecht* | Odijk | *Kapelle* | Gravenpolder | *Reusel-De Mierden* | Best |
| *Dongeradeel* | Schuilenburg | *Veenendaal* | Leusden-Zuid | *Middelburg* | Zuid-Kraayert | *Roerdalen* | Melick |
| *Achtkarspelen* | Schuilenburg | *Woudenberg* | Leusden-Zuid | *Giessenlanden* | Wijngaarden | *Roosendaal* | Zegge |
| *Ameland* | Schuilenburg | *Wijk bij Duurstede* | Leusden-Zuid | *Reimerswaal* | Ossendrecht | *Schouwen-Duiveland* | Abbenbroek |
| *het Bildt* | Schuilenburg | *IJsselstein* | Reijerscop | *Zederik* | Wijngaarden | *Aa en Hunze* | Eext |
| *Franekeradeel* | Nijland | *Zeist* | Odijk | *Terneuzen* | Axel | *Borger-Odoorn* | Eext |
| *Harlingen* | Nijland | *Nieuwegein* | Reijerscop | *Tholen* | Zegge | *Cuijk* | Reek |
| *Heerenveen* | Opsterland | *Aalsmeer* | Hoofddorp | *Veere* | Zuid-Kraayert | *Landerd* | Reek |
| *Kollumerland en Nieuwkruisland* | Visvliet | *Alkmaar* | Alkmaar | *Vlissingen* | Zuid-Kraayert | *De Wolden* | Den Kaat |
| *Leeuwarden* | Birstum | *Amstelveen* | Sloten | *Lingewaal* | Zaltbommel | *Noord-Beveland* | Zuid-Kraayert |
| *Leeuwarderadeel* | Birstum | *Amsterdam* | Sloten | *De Ronde Venen* | Hoofddorp | *Wijdemeren* | Hilversum |
| *Ooststellingwerf* | Opsterland | *Beemster* | Heerhugowaard | *Tytsjerksteradiel* | Schuilenburg | *Noordenveld* | Haren |
| *Opsterland* | Opsterland | *Bergen (NH.)* | Alkmaar | *Aalburg* | Lingewaal | *Twenterand* | Bornerbroek |
| *Schiermonnikoog* | Visvliet | *Beverwijk* | Beverwijk | *Asten* | Venray | *Westerveld* | Westerbork |
| *Smallingerland* | Opsterland | *Blaricum* | Hilversum | *Baarle-Nassau* | Rijsbergen | *Sint Anthonis* | Mill |
| *Terschelling* | Nijland | *Bloemendaal* | Driehuis | *Bergen op Zoom* | Ossendrecht | *Lingewaard* | Baal |
| *Vlieland* | Nijland | *Castricum* | Beverwijk | *Best* | Best | *Cranendonck* | Nederweert |
| *Weststellingwerf* | Opsterland | *Diemen* | Sloten | *Boekel* | Hengelo | *Steenwijkerland* | Emmeloord |
| *Assen* | Eext | *Edam-Volendam* | Assumburg | *Boxmeer* | Mill | *Moerdijk* | Zegge |
| *Coevorden* | Zuideropgaande | *Enkhuizen* | Lambertschaag | *Boxtel* | Boxtel | *Echt-Susteren* | Sanderbout |
| *Emmen* | Westerbork | *Haarlem* | Driehuis | *Breda* | Gilze | *Sluis* | Axel |
| *Hoogeveen* | Zuideropgaande | *Haarlemmerliede en Spaarnwoude* | Driehuis | *Deurne* | Venray | *Drimmelen* | Oosteind |
| *Meppel* | Den Kaat | *Haarlemmermeer* | Hoofddorp | *Pekela* | Scheemda | *Bernheze* | Middelrode |
| *Littenseradiel* | Nijland | *Heemskerk* | Assumburg | *Dongen* | Oosteind | *Ferwerderadiel* | Schuilenburg |
| *Almelo* | Bornerbroek | *Heemstede* | Hoofddorp | *Eersel* | Best | *Alphen-Chaam* | Gilze |
| *Borne* | Bornerbroek | *Heerhugowaard* | Heerhugowaard | *Eindhoven* | Mierlo | *Bergeijk* | Mierlo |
| *Dalfsen* | Den Kaat | *Heiloo* | Alkmaar | *Etten-Leur* | Rijsbergen | *Bladel* | Best |
| *Deventer* | Lurkeers | *Den Helder* | Lambertschaag | *Geertruidenberg* | Oosteind | *Gulpen-Wittem* | Bemelen |
| *Enschede* | Enschede | *Hilversum* | Hilversum | *Gilze en Rijen* | Gilze | *Tynaarlo* | Eext |
| *Haaksbergen* | Hengelo | *Hoorn* | Lambertschaag | *Goirle* | Moergestel | *Midden-Drenthe* | Westerbork |
| *Hardenberg* | Zuideropgaande | *Huizen* | Hilversum | *Grave* | Ewijk | *Overbetuwe* | Valburg |
| *Hellendoorn* | Lurkeers | *Landsmeer* | Assumburg | *Haaren* | Boxtel | *Hof van Twente* | Bornerbroek |
| *Hengelo* | Angerlo | *Langedijk* | Alkmaar | *Helmond* | Best | *Neder-Betuwe* | Valburg |
| *Kampen* | Wezep | *Laren* | Esveld | *'s-Hertogenbosch* | Middelrode | *Rijssen-Holten* | Lurkeers |
| *Losser* | Enschede | *Medemblik* | Lambertschaag | *Heusden* | Nederweert | *Geldrop-Mierlo* | Mierlo |
| *Noordoostpolder* | Emmeloord | *Oostzaan* | Assumburg | *Hilvarenbeek* | Moergestel | *Olst-Wijhe* | Lurkeers |
| *Oldenzaal* | Hengelo | *Opmeer* | Lambertschaag | *Loon op Zand* | Moergestel | *Dinkelland* | Hengelo |
| *Ommen* | Den Kaat | *Ouder-Amstel* | Sloten | *Mill en Sint Hubert* | Mill | *Westland* | t Woudt |
| *Raalte* | Lurkeers | *Purmerend* | Assumburg | *Nuenen, Gerwen en Nederwetten* | Mierlo | *Midden-Delfland* | t Woudt |
| *Staphorst* | Den Kaat | *Schagen* | Lambertschaag | *Oirschot* | Best | *Berkelland* | Groenlo |
| *Tubbergen* | Bornerbroek | *Texel* | Nijland | *Oisterwijk* | Boxtel | *Bronckhorst* | Groenlo |
| *Urk* | Emmeloord | *Uitgeest* | Assumburg | *Oosterhout* | Oosteind | *Sittard-Geleen* | Sanderbout |
| *Wierden* | Bornerbroek | *Uithoorn* | Hoofddorp | *Oss* | Oss | *Kaag en Braassem* | Zoeterwoude |
| *Zwolle* | Wezep | *Velsen* | Driehuis | *Rucphen* | Zegge | *Dantumadiel* | Schuilenburg |
| *Rijnwaarden* | Baal | *Weesp* | Weesp | *Sint-Michielsgestel* | Boxtel | *Zuidplas* | Oudverlaat |
| *Aalten* | Groenlo | *Zandvoort* | Hoofddorp | *Someren* | Nederweert | *Peel en Maas* | Belfeld |
| *Apeldoorn* | Apeldoorn | *Zaanstad* | Assumburg | *Son en Breugel* | Best | *Oldambt* | Scheemda |
| *Arnhem* | Angerlo | *Alblasserdam* | Wijngaarden | *Steenbergen* | Zegge | *Zwartewaterland* | Den Kaat |
| *Barneveld* | Nijkerk | *Alphen aan den Rijn* | Zoeterwoude | *Waterland* | Assumburg | *Súdwest-Fryslân* | Nijland |
| *Beuningen* | Ewijk | *Barendrecht* | Ijsselmonde | *Tilburg* | Moergestel | *Bodegraven-Reeuwijk* | Reijerscop |
| *Brummen* | Achterdrempt | *Drechterland* | Lambertschaag | *Uden* | Reek | *Eijsden-Margraten* | Bemelen |
| *Buren* | Zaltbommel | *Brielle* | Ommeloop | *Valkenswaard* | Mierlo | *Stichtse Vecht* | Reijerscop |
| *Culemborg* | Zaltbommel | *Capelle aan den IJssel* | Krimpenerwaard | *Veldhoven* | Best | *Menameradiel* | Birstum |
| *Doesburg* | Achterdrempt | *Delft* | Rijswijk | *Vught* | Boxtel | *Hollands Kroon* | Lambertschaag |
| *Doetinchem* | Angerlo | *Dordrecht* | Wijngaarden | *Waalre* | Mierlo | *Leidschendam-Voorburg* | Voorburg |
| *Druten* | Ewijk | *Gorinchem* | Wijngaarden | *Waalwijk* | Oosteind | *Goeree-Overflakkee* | Abbenbroek |
| *Duiven* | Angerlo | *Gouda* | Oudverlaat | *Werkendam* | Wijngaarden | *Pijnacker-Nootdorp* | Rijswijk |
| *Ede* | Angerlo | *'s-Gravenhage* | Voorburg | *Woensdrecht* | Ossendrecht | *Molenwaard* | Wijngaarden |
| *Elburg* | Wezep | *Hardinxveld-Giessendam* | Wijngaarden | *Woudrichem* | Wijngaarden | *Nissewaard* | Vondelingenplaat |
| *Epe* | Apeldoorn | *Hellevoetsluis* | Ommeloop | *Zundert* | Rijsbergen | *Krimpenerwaard* | Reijerscop |
| *Ermelo* | Nijkerk | *Hendrik-Ido-Ambacht* | Ijsselmonde | *Wormerland* | Assumburg | *De Fryske Marren* | Opsterland |
| *Geldermalsen* | Zaltbommel | *Stede Broec* | Lambertschaag | *Onderbanken* | Sanderbout | *Gooise Meren* | Hilversum |
| *Harderwijk* | Nijkerk | *Hillegom* | Hoofddorp | *Landgraaf* | Schinnen | *Berg en Dal* | Ewijk |
| *Hattem* | Wezep | *Katwijk* | Rijnsburg | *Beek* | Schinnen | *Meierijstad* | Boxtel |
| *Heerde* | Wezep | *Krimpen aan den IJssel* | Krimpenerwaard | *Beesel* | Belfeld | *Montferland* | Angerlo |
| *Heumen* | Ewijk | *Leerdam* | Zaltbommel | *Bergen (L.)* | Venray | *Menterwolde* | Scheemda |
| *Lochem* | Esveld | *Leiden* | Zoeterwoude | *Brunssum* | Schinnen | | |
| *Maasdriel* | Zaltbommel | *Leiderdorp* | Zoeterwoude | *Gennep* | Mill | | |
| *Nijkerk* | Nijkerk | *Lisse* | Hoofddorp | *Heerlen* | Schinnen | | |
| *Nijmegen* | Baal | *Maassluis* | Vlaardingen | *Kerkrade* | Schinnen | | |
| *Oldebroek* | Wezep | *Nieuwkoop* | Hoofddorp | *Maastricht* | Bemelen | | |
| *Putten* | Nijkerk | *Noordwijk* | Rijnsburg | *Meerssen* | Gronsveld | | |
| *Renkum* | Valburg | *Noordwijkerhout* | Rijnsburg | *Mook en Middelaar* | Ewijk | | |
| *Rheden* | Angerlo | *Oegstgeest* | Rijnsburg | *Nederweert* | Nederweert | | |
| *Rozendaal* | Angerlo | *Oud-Beijerland* | Ijsselmonde | *Nuth* | Schinnen | | |
| *Scherpenzeel* | Leusden-Zuid | *Binnenmaas* | Ijsselmonde | *Roermond* | Belfeld | | |
| *Tiel* | Tiel | *Korendijk* | Ijsselmonde | *Schinnen* | Schinnen | | |
| *Voorst* | Esveld | *Oudewater* | Reijerscop | *Simpelveld* | Simpelveld | | |
| *Wageningen* | Valburg | *Papendrecht* | Wijngaarden | *Stein* | Sanderbout | | |
| *Westervoort* | Angerlo | *Ridderkerk* | Ijsselmonde | *Vaals* | Bemelen | | |
| *Winterswijk* | Groenlo | *Rotterdam* | Vlaardingen | *Venlo* | Belfeld | | |
| *Wijchen* | Ewijk | *Rijswijk* | Rijswijk | *Venray* | Venray | | |

**Table C.1**

# D DATA

The purpose of this appendix is to present the data used in the model for this study. By discussing the sources, composition and preparation of the data we aim to make this research reproducible and transparant. In the first section the various sources are discussed, then the composition of the datasets is described and finally a brief description of the data preperation is given.

As described in the research formulation, one of the goals for this research is to incorporate publicly available data for the design of a data-driven model. The starting point for data use is the Centraal Bureau voor de Statistiek (CBS). The governmental supplementary datasources used originate from the Planbureau voor de Leefomgeving (PBL) and Rijksdienst voor Ondernemend Nederland. While Gasunie provided the data for the final two datasets. The following paragraphs describe the datasets used per originating source.

## D.1 CENTRAAL BUREAU VOOR DE STATISTIEK

**SOURCE** The CBS is the Dutch governmental organization tasked with the collection, processing and publishing of independent social relevant data. Their databases are incredibly diverse and detailed. As such, a collective, preprocessed dataset containing socio-economical combined with geographic information is used as a starting point for this thesis: the Wijk- en Buurtkaart (district and neighborhoodmap) of 2017. The 2017 edition of this dataset is preferred over the 2019 dataset as the latter is missing a majority of the datapoints that are present in the 2017 edition.
Link to dataset: `https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/wijk-en-buurtkaart-2019`

**COMPOSITION** The Wijk- en Buurtkaart is a detailed geometrical database of municipal borders from the Dutch cadastre (Basisregistratie Kadaster) and CBS drawn borders of districts and neighborhoods. In this dataset these geometrical features containing municipalities, districts and neighborhoods are combined with all their relevant societal datapoints from the CBS database. The dataset itself is a ESRI-Shape file and its geometrical projection system is according to the Rijksdriehoeksmeting.

**PREPARATION** Before the CBS data is used for modelling purposes, it is prepared for suitable use. This is done through the use of two pyhon scripts which separate the datasets in one file containing all Dutch municipalities and the other containing all the Dutch neighborhoods. Only the variables that are used in the agent-based model are kept. The geometrical projection system is changed from the original Rijksdriehoeksmeting to the conventional WGS84 (EPSG 32632) format for compatability reasons with NetLogo.

The municipality dataset is the first dataframe extracted from the Wijk- en Buurtkaart. Only minor other cleaning and other processing steps have to be done, such as calculating the distances between all municipalities and removing water objects. The second extracted dataframe is the neighborhood dataset. This dataset requires a little bit more effort as it has to contain more variables that are eventually used in the model. Just as with the municipality dataset all entries that are water locations where removed. Secondly, some variables contained non-sensible or missing values. Some variables contained large negative values when they seemed to be zero. Many other neighborhood entries had missing values. These missing values are addressed by taking the average value for that variable of all its surrounding neighborhoods. The final preparation step for the neighborhood dataset is merged with the RVO dataset which will be disclosed below.

**USE** The municipality and neighborhood dataframes which are extracted from the Wijk- en Buurtkaart are used to automatically generate the Agent-Based Model in combination with its GIS extension. As the municipality and neighborhood entries in the dataset contain geographical information on their borders, a real-world like simulation model can be generated and visualized.

| | AANTAL_HH | STED | P_STADVERW | WOZ | P_HUURCORP | P_WONV2000 |
|---|---|---|---|---|---|---|
| count | 12603.000000 | 12603.000000 | 12603.000000 | 12603.000000 | 12603.000000 | 12603.000000 |
| mean | 616.886852 | 3.593589 | 13.155662 | 250.613512 | 18.242060 | 15.349301 |
| std | 831.307088 | 1.487139 | 17.569534 | 109.757676 | 20.657545 | 21.328644 |
| min | 5.000000 | 1.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| 25% | 80.000000 | 2.000000 | 0.000000 | 182.000000 | 0.000000 | 3.000000 |
| 50% | 320.000000 | 4.000000 | 8.000000 | 234.000000 | 13.000000 | 9.000000 |
| 75% | 840.000000 | 5.000000 | 18.613103 | 298.000000 | 29.000000 | 17.000000 |
| max | 13950.000000 | 5.000000 | 100.000000 | 1633.000000 | 100.000000 | 100.000000 |

Table D.1: *Descriptive statistics of the used variables in the neighborhoods data set from CBS (1/2).*

| | LABELCAT | FLAT_APP | VRIJ | RIJHOEK | RIJTUSSEN | TWEE_KAP |
|---|---|---|---|---|---|---|
| count | 12603.000000 | 12603.000000 | 12603.000000 | 12603.000000 | 12603.000000 | 12603.000000 |
| mean | 3.143605 | 0.240946 | 0.270399 | 0.114703 | 0.219623 | 0.148651 |
| std | 0.952924 | 0.231412 | 0.243845 | 0.060932 | 0.144292 | 0.103272 |
| min | 0.048780 | 0.000000 | 0.000000 | 0.000000 | 0.000000 | 0.000000 |
| 25% | 2.580533 | 0.078404 | 0.066082 | 0.071375 | 0.099008 | 0.062913 |
| 50% | 3.174914 | 0.163522 | 0.205607 | 0.121745 | 0.208448 | 0.142857 |
| 75% | 3.668157 | 0.324902 | 0.421887 | 0.160648 | 0.329387 | 0.221936 |
| max | 6.000000 | 1.000000 | 1.000000 | 0.500000 | 0.800407 | 0.823529 |

Table D.2: *Descriptive statistics of the used variables in the neighborhoods data set from CBS (2/2).*

| | AANTAL_HH |
|---|---|
| count | 388.000000 |
| mean | 20087.822165 |
| std | 35522.701497 |
| min | 509.000000 |
| 25% | 7465.250000 |
| 50% | 11291.500000 |
| 75% | 19398.000000 |
| max | 462329.000000 |

Table D.3: *Descriptive statistics of the used variables in the municipalities data set from CBS.*

## D.2 PLANBUREAU VOOR DE LEEFOMGEVING

**SOURCE** The PBL is the national institute for strategic policy analysis for the Dutch (built) environment. The dataset used from PBL originates from their VESTA MAIS model, which is a model aimed towards calculating costs for the thermal energy transition. The specific dataset contains the geographical locations and capacities for high and medium temperature heatsources that can be used for district heating networks. It is extracted from the github page related to the model.
Link to dataset: https://github.com/RuudvandenWijngaart/VestaDV

**COMPOSITION** The heatsources dataset is a relatively standard CSV file containing the names, geographical locations and capacities for identified heatsources. The entries in the dataset not all have a specified capacity when this is unknown.

**PREPARATION** This dataset is not edited for further use.

**USE** The heatsources dataset is used to automatically generate heatsource agents in the Agent-Based model through the CSV extension in NetLogo. As the heatsource entries in the dataset contain coordinates, a real-world like representation of the heatsources can be simulated.

| | X | Y | MWcapacite |
|---|---|---|---|
| count | 604.000000 | 604.000000 | 604.000000 |
| mean | 153579.753311 | 452678.384106 | 25.970166 |
| std | 58429.836916 | 66692.505690 | 127.735194 |
| min | 27500.000000 | 308751.000000 | 0.000000 |
| 25% | 102100.250000 | 412482.500000 | 0.000000 |
| 50% | 158505.000000 | 439587.000000 | 0.000000 |
| 75% | 196133.250000 | 487580.750000 | 0.452500 |
| max | 276380.000000 | 608511.000000 | 1625.250000 |

Table D.4: *Descriptive statistics of the used variables in the heatsources dataset from PBL.*

## D.3 RIJKSDIENST VOOR ONDERNEMEND NEDERLAND

**SOURCE** The RVO is a governmental organization aimed towards supporting Dutch business owners and policy advisors on the subjects of sustainability, business abroad, agriculture and innovation. The dataset used from RVO contains the energylabels for all residential dwellings in the Netherlands. This dataset is used as a proxy for the insulation levels and building type composition of neighborhoods in the Netherlands. It is extracted from their webpage.
Link to dataset: https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels/bestaande-bouw/energielabel-woningen

**COMPOSITION** The energy labels dataset is a relatively straightforward CSV file containing information on every dwelling in the Netherlands. Per dwelling, its postal code, date of construction, dwelling type and energy label is disclosed.

**PREPARATION** This dataset is first prepared for merging with the neighborhoods dataset. All entries that are classified as non-residential buildings are dropped from the dataset. Then the labels (specified from G to A) are transformed to integers ranging from 0 to 8. Finally the dataset is grouped on the 4 digits of the postal codes in order to be able to merge it on the postal codes of the neighborhoods dataset.

**USE** The energy labels dataset is used to merge with the neighborhoods dataset. The main information deducted from this dataset are the average insulation levels for all postal codes and the distribution of dwelling types per postal code. These variables are used in the model to specify the insulation and energy demand profiles in the Agent-Based model.

| | POSTCODE_WONING | WONING_TYPE | VOORL_BEREKEND |
|---|---|---|---|
| count | 9070197 | 9070197 | 8317556 |
| unique | 459632 | 9 | 8 |
| top | 1033SC | Flat/appartement | C |
| freq | 1107 | 2857292 | 2283250 |

Table D.5: *Descriptive statistics of the used variables in the insulation levels dataset from RVO.*

## D.4 GASUNIE

**SOURCE** Two sources of data are used from Gasunie, a geographical map deduced mapping of municipalities with Gasunie's MR-stations and a workshop generated dataframe of relative advantage of thermal systems per neighborhood type.

The workshops goal was to come up with a methodology to categorize neighborhood types based on their urban density and insulation levels and connect this to the likelihood a particular thermal system is fitting for this neighborhood. Three experts of Gasunie were involved in the meeting. A suggestion of assumptions was made for the neighborhood types and thermalsystem after wich a discussion started on the configuration of the dataframe. The dataframe containing the likelihoods was validated by the experts in a follow-up session.

**COMPOSITION** The geographical map describes the topology of Gasunie's pipelines and regulation stations on a detailed level. It shows where Gasunies transport network is connected to regional gas distribution networks. A preview of the map is presented in appendix B. The workshop generated dataframe contents is further discussed in section E.0.1.

**PREPARATION** The purpose of the geographical topology data is to map the municipalities to their corresponding closest Metering and Regulation stations (MR). This was done manually by applying the shortest distance method. All municipalities of interest (that are included in the Wijk- en Buurtkaart 2017) were looked up on the map. Then the closest corresponding regional pipeline system was traced (green lines). These pipelines where traced back to the closest MR stations, of which 84 were actively used. A new dataframe was created which mapped all 387 municipalities to the best fitting MR station according to the shortest distance method. Refer to appendix C for the mapping of all municipalities and MR stations.

**USE** The municipality MR mapping dataframe is used in the NetLogo model to link the municipalities to their corresponding MR station. The output of the municipalities is then aggregated to these 84 MR stations which are used to generate the output of the model. This aggregation method is chosen in order to approach a Gasunie relevant output level.

## D.5 GITHUB

The NetLogo and Python scripts used for this research are uploaded to a GitHub repository, which can be accessed through the following link:
`https://github.com/JBogdanovski/GasunieThesis`

## D.6 INTERVIEWS

| Function | Organization |
| --- | --- |
| Strategic Advisor Thermal Transition | Municipality of Rotterdam |
| Project Manager Energy Transition | Municipality of The Hague |
| Senior Advisor Energy Transition | Gasunie |
| Senior Advisor Energy Transition | Gasunie |
| Strategic Advisor System Integration | Gasunie |

**Table D.6:** *Table with interviewees by function and organization.*

In the context of this research, several domain experts have been interviewed. All these interviews were executed in an unstructured format and held during the literature and initial model conceptualization phase of the project. Their expertise was used in forming the perspective and conceptual design of the model, as well as validate its design. Their names and the notes for these interview sessions are available upon request with the author of this thesis.

# E MUNICIPAL DECISION-MAKING FRAMEWORK

The purpose of this appendix is to present the Municipal Decision-Making Framework as designed for this research. By discussing the initial need, concepts and final formalization in different strategies and formulas, a more torough explanation and justification of the used concepts is presented.

### E.0.1 The municipal decision-making framework

As to our knowledge no existing or comparable decision framework exists for municipalities deciding on such matters as presented in this thesis. Therefore a novel decision-framework is to be developed for use in this concept. Each year, municipalities have to evaluate their own state and the states of their neighborhoods. Based on this information and the information it extracts from its environment a transition decision on which neighborhood is transitioned first and to what alternative is formed. The decisions of the municipalities are dependent on the availability of their resources, whether they perceive pressure to take action and some evaluation strategy that determines which neighborhood they transition and to what thermal system. Available resources, perceived pressure and energy source limitations for neighborhoods constitute the boundaries of the decision space of municipalities. While relative advantage of thermal systems, the neighborhood likelihood and activity by other municipalities form the inner mechanics of the decision strategies of the municipalities. Figure E.1 describes the factors influencing the municipal transition decision as they are further described below.

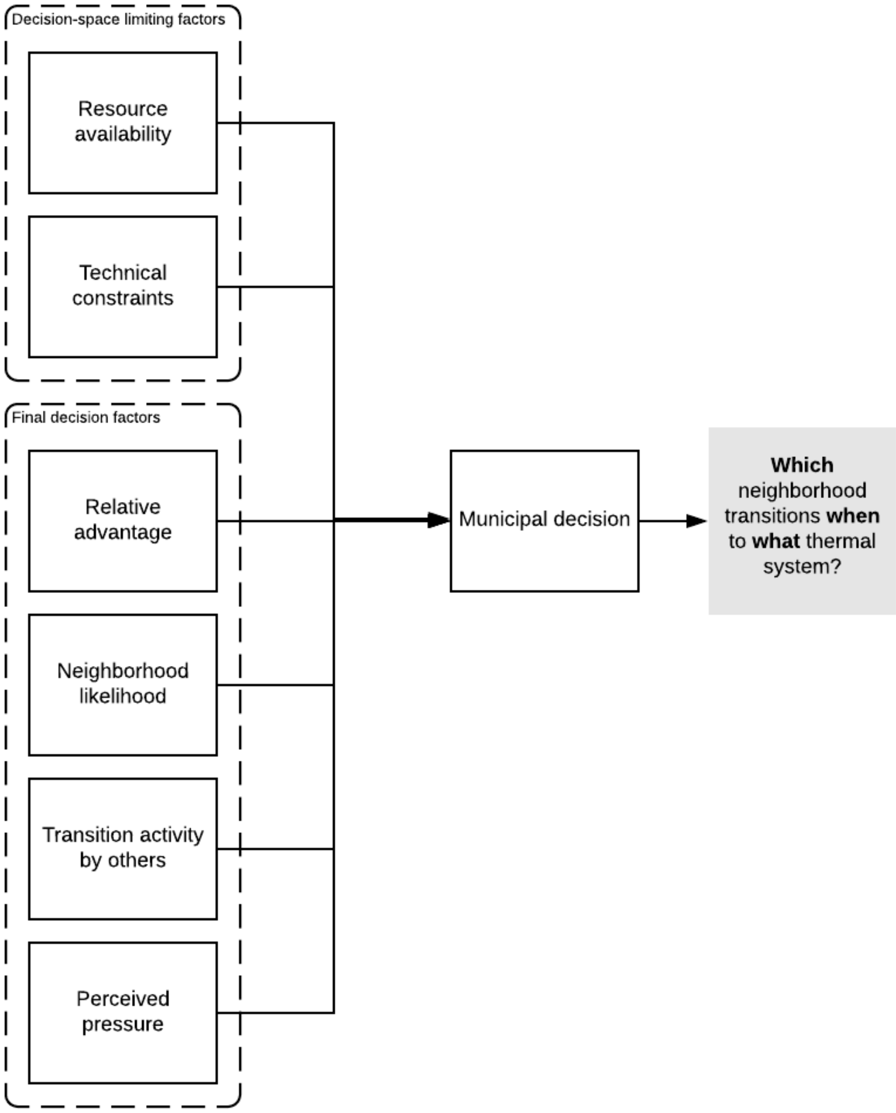



**Figure E.1:** *Conceptualization of factors leading to the municipal transition-decision.*

The factors hypothesized to be of influence on what decision is made are based on the Theory of Planned Behavior (Ajzen, 2012) and thermal system adoption specific literature (Michelsen and Madlener, 2012a,b; Hecher et al., 2017). The Theory of Planned Behavior by Ajzen (2012) states that an intention to behavior is shaped by three constructs: Attitude (AT), a Subjective Norm (SN) and Perceived Behavioral Control (PBC). Knowledge on how these three constructs are formed for any decision provides a proxy for the decision that is to be taken. Michelsen and Madlener (2012a) have developed a theoretical framework on how households approach approach the decision of adopting a new thermal system by combining the work of Ajzen (2012) and Rogers (2004) diffusion of innovations theory.

Rationale for using their framework as a starting point for the decision factors in this model is fourfold: 1) to our knowledge, there is no existing theory of framework that applies to such municipal decisions from this perspective; 2) the behavior influencing factors in the framework fit in the narrative of the Climate Agreement (Klimaatberaad, 2019) and are validated in stakeholder interviews; 3) the framework is use in the literature as an adoption decision mechanic, in a way this is similar to how the municipalities are perceived as the decision-makers in an adoption process of thermal systems and 4) the Theory of Planned Behavior leaves room for open interpretation of how behavior is formed and is not bound to any specific narrative or application.

**DECISION-SPACE LIMITING FACTORS** The decision factors that are included in the framework used in this thesis can be divided in two categories, as illustrated in figure E.1. The first category are the decision-space limiting factors. These factors set the boundaries for the available decisions a municipality can make. The first factor concerns the *available resources* of a municipality to transition one or multiple of its neighborhoods. It can be interpreted as a combination of the available capacity a municipality to execute a transition of a neighborhood and available financial resources. This factor limits municipalities in how many neighbourhoods a municipality can have in transition at the same time. It is derived from the concepts of 'financial resources' and 'authorization' by Michelsen and Madlener (2012a) and the construct Perceived Behavioral Control of the TPB (Ajzen, 2012).

The second factor in the category of decision-space limiting factors are the *technical constraints*. One can imagine that in an energy system no energy source or technical implementation is infinite, which is at the core of this factor. It corresponds to the concept of compatibility with infrastructure' of Michelsen and Madlener (2012a) and Perceived Behavioral Control of Ajzen (2012).

**FINAL DECISION FACTORS** The second category of factors shape the decision of which neighborhoods are to be transitioned and to what thermal system. The first factor in this category is *relative advantage* which is an abstract combination of economic advantage, environmental aspects and the security of energy supplies. With this factor, one can quantify a difference between desirability of thermal systems in a specific neighborhood. By using relative advantage, one can differentiate on the basis of cost, sustainability and reliability without having to accurately calculate each of these components per neighborhood per thermal system a every time step. The concept of relative advantage is developed by Michelsen and Madlener (2012a) and applied in a similar fashion to their household case. In the TPB by Ajzen (2012) it can be attributed to the construct of Attitude.

The second factor in this category is *neighborhood likelihood*, which is used to determine the preferability to transition one neighborhood over the other. The Climate Agreement (Klimaatberaad, 2019) and inherent to the concept of a transition, which says that a transition is not a phenomenon of an end state, but rather the dynamic towards it, it is not only of interest *what* happens, but also *when* and *who*. The Climate Agreement, other studies and experts suggest that there will be differences in favorability between neighborhoods based on their characteristics. Thus the neighborhood likelihood is a factor that will influence the municipalities decision of which neighborhoods it will transition first over the others, if a choice is applicable. Its concept is derived from Michelsen's (Michelsen and Madlener, 2012a) 'ease of use' and 'image' constructs and corresponds to both the Subjective Norm and Attitude constructs of the TPB (Ajzen, 2012).

The third factor of this category is *transition activity by others*. According to Hakelberg (2014) municipalities are increasingly important in developing climate change strategies by the forming of municipal networks in which information on successful implemented strategies is being shared. Research on this specific transition case in the Netherlands by Leeuw and Groenleer (2018) also suggests the existence of regional governance structures involving municipalities aimed at accelerating efforts to increase efficiency within the built environment. The Climate Agreement also stresses the use of new and existing institutions which are aimed towards sharing knowledge (Klimaatberaad, 2019). Combining this with the constructs of 'image' by Michelsen and Madlener (2012a) and Subjective Norm of (Ajzen, 2012), this factor is aimed towards municipalities sharing their historic transition activity with one another and adjusting their future decisions upon it.

The fourth and final factor in this category is *perceived pressure*. This factor, together with the availability of resources, is the models main driver of how fast the thermal transition of the built environment will occur. Municipalities need to have a reason in the first place to take any kind of decision, which can either be intrinsic or external. While municipalities all have their individual agendas in terms of policy decisions, it is assumed that pressure for municipalities to take some sort of action is external. This concept of external pressure is conceptualized in the factor perceived pressure. It is a concept that is rather dispersed in how it is conceptualized by Ajzen (2012) or Michelsen and Madlener (2012a). Pressure can be an Attribute (internal motivation) and a Subjective Norm (external motivation). Michelsen describes the concept of pressure in the concepts of complying with regulations (external) or being compabible with your own norms (internal).

As multiple implementations are possible of the municipal decision-making framework and no current knowledge exists on its effects, 5 different strategies combining some or all decision factors are implemented and tested. The different formalization's are described below:

**STRATEGY 0: RANDOM NEIGHBORHOOD, RANDOM THERMAL SYSTEM** The first strategy, strategy 0, is the strategy of transitioning neighborhoods in a random order to a random thermal system that is for them available to use. It is called strategy 0 as it only relies on the municipalities available resources and perceived pressure to take action. No deliberate decision-mechanic is used to determine what its final outcome should be, therefore it can be classified as a somewhat non-strategy or strategy 0 as it is named in the concept formalization.

**STRATEGY 1: RANDOM NEIGHBORHOOD, HIGHEST RELATIVE ADVANTAGE THERMAL SYSTEM** The strategy 1 is a little bit more deliberate than strategy 0 in a sense that it adds more sophisticated behavior to what thermal system is chosen for the neighborhood to be transitioned. Using the factor of relative advantage, the order of the neighborhoods is still randomly chosen, but the decision for which thermal system is based on the highest relative advantage for the randomly chosen neighborhood (if this is an available option for this neighborhood).

**strategy 2: neighborhood with highest relative advantage, highest relative advantage thermal system** Strategy 2 is comparable to strategy 1, but adds some preferable order between neighborhoods. It uses the factor relative advantage for two purposes in this strategy. The first purpose is determining which neighborhoods are preferred to transition first (strategy 1 selected neighborhoods randomly) , the second purpose is determining to which thermal system this selected neighborhood should transition (same as strategy 1). Neighborhoods are preferred over other neighborhoods in their order if they are able to transition to a thermal system with a higher score for relative advantage.

**strategy 3: neighborhood with highest likelihood, highest relative advantage thermal system** Strategy 3 differs from strategy 1 and 2 in how the preferable order between neighborhoods is determined. In this strategy, the preferred order is determined by using empirically derived neighborhood characteristics [will be an appendix section] that might indicate the likelihood of them being transitioned over others. The factor in which these characteristics are aggregated is the neighborhood likelihood.

**strategy 4: neighborhood with highest likelihood, highest relative advantage combined with transition activity** Strategy 4 combines the neighborhood preferability order of strategy 3 with the most extensive thermal system selection decision. While all previous strategies used the relative advantage as the final decision-factor for which thermal system is chosen for a neighborhood, this strategy expands the metric with the transition activity factor. By observing what decisions other municipalities make, the municipality forms a decision based on this activity combined with the relative advantage factor.

## E.1 FORMALIZATION OF FRAMEWORK IN MUNICIPAL TRANSITION DECISION CYCLE

### E.1.1 Municipal Transition Decision Cycle

After all states and energy calculations have been updated accordingly, the model sequence enters the Municipal Transition Decision Cycle. The purpose of this cycle is that the municipalities initiate transitions in their neighborhoods as long as the necessary conditions are satisfied. After each iteration of the cycle the conditions are reevaluated accordingly. When the conditions satisfied, the municipality exits its cycle for this year and hands over the turn to another, not yet evaluated municipality in this tick. The implication of formalising the cycle in this manner, is that there is a distinct random order between the start times the municipalities initiate their cycle every year. Only when one municipality has exhausted its cycle, the next (random) municipality may start his.

#### *Cycle conditions*

The conditions that have to be met in order to start or keep the cycle continuing are whether a municipality has any neighborhoods left to start their transition of, whether it has enough resources left to transition any of its neighborhoods and whether the municipality perceives threshold exceeding pressure. All of these conditions have to be met for the cycle to continue.

**MUNICIPAL TRANSITION STATE** The first condition that is evaluated is whether there are any neighborhoods within the municipality that require a decision of the municipality. This is done by the municipality checking their current states, that are updated previously in the model tick. The condition is not met when there are only neighborhoods left with the state that they are still in transition or have finished.

**AVAILABILITY OF RESOURCES** The second condition is whether the municipality has enough resources available to transition any of its neighborhoods that still require a transition decision. The maximum available resources of a municipality are calculated based on a percentage of their total households. The currently available resources of a municipality are the maximum resources minus the amount of households that are currently being transitioned as neighborhoods.

**PERCEIVED PRESSURE** The third condition is about whether the municipality perceives enough pressure by comparing its past actions to its transition goal. The past actions of a municipality is characterized by how many households they have made a transition decision for. While the transition goal of a municipality is directly proportional to the national transition goal for the Netherlands. Thus the third condition of perceived pressure is being met when the municipalities current transition speed (defined by its past actions), is lower than the intended municipal transition goal.

| | **Neighborhood selection** | **Thermal system selection** |
|---|---|---|
| *Strategy 0* | Random | Random |
| *Strategy 1* | Random | Highest Relative Advantage |
| *Strategy 2* | Highest Relative Advantage | Highest Relative Advantage |
| *Strategy 3* | Highest Neighborhood Likelihood | Highest Relative Advantage |
| *Strategy 4* | Highest Neighborhood Likelihood | Highest (Relative Advantage + Transition Activity) |

**Table E.1:** Formalization of the five municipal decision strategies.

#### *Neighborhood and thermal system selection*

When these three conditions are satisfied, the municipality will determine which of its neighborhoods will start a transition and to what thermal system. The procedure how each of these two steps is executed is dependent on the chosen strategy, as described in table **??**. For all of the formalised strategies, first the neighborhood is selected and then a thermal system is considered. Next the concepts of random, relative advantage, neighborhood likelihood and transition activity are specified:

**RANDOM SELECTION** The concept of random in the strategies implies that no sophisticated evaluation criteria are used for determining a choice. For the neighborhood selection this implies that a municipality may pick any of its neighborhoods as long as the neighborhood is within the available resources and still requires a transition decision. When the thermal system decision occurs through random selection, any of the thermal systems that are within available reach of that particular neighborhood may be chosen.

**HIGHEST RELATIVE ADVANTAGE** The concept of relative advantage, as introduced in chapter , allows us to quantify a difference between thermal systems for a specified neighborhood on the basis of economic advantage, environmental aspects and the security of energy supplies without having to accurately calculate each of these (Michelsen and Madlener, 2012b). To come to such a construct, the neighborhoods in the model have to be placed in different 'buckets' to differentiate between typical archetypes. Previous studies have done similar distinctions between neighborhoods in order to link them with thermal systems (Menkveld et al., 2015; Schepers et al., 2015).

The two determinants chosen to differentiate between the neighborhood types are a neighborhoods average insulation level and their level of urban density. The choice for the number determinants has been kept limited to two neighborhood characteristics in order to keep the construct simple and transparent, while retaining the two most important drivers according to various studies. Average insulation is an important driver for thermal system choice because not all thermal systems are suited for poorer insulated dwellings.

Insulation is an important driver because it is an indicator what heat supply temperatures are necessary to comfortably heat neighborhoods (Gasunie Transport Services, 2017) and resulting stress on energy infrastructures. Low temperature supply thermal systems, such as all-electric (Veldman et al., 2011), low-temperature DHC networks (Pirouti et al., 2013; Lund et al., 2014) and partly the hybrid systems (Klip, 2017), have difficulties properly heating poor and medium insulated dwellings as they can not provide enough heat. Also, as insulation implicates the reduction of thermal energy demand, the stress on energy infrastructures is reduced, resulting in lower capital costs for potential capacity expansions (Menkveld et al., 2005; Klip, 2017). Therefore, insulation levels of a neighborhood significantly contribute to the favourability of one thermal system over the other.

Urban density is the second important driver for determining the archetypes for the neighborhoods, mostly because its importance for the feasibility of DHC networks. Many studies indicate that the construction and operation of DHC networks involves high capital and operational costs up front. Persson and Werner (2011) identifies the most important factor for economic feasibility of DHC networks to be the distribution of heat. As a new, non-existing infrastructure network has to be constructed, the investment costs for such infrastructures have to be distributed among as many as possible to keep the project profitable. This is only the case in areas where there are sufficient customers with sufficient heat demand, which is in higher populated areas (Busch et al., 2017; Klip, 2017; Lund et al., 2014).

| Type | Insulation Level | Urban Density | AE | HT/MT | LT | GG | H2 |
|---|---|---|---|---|---|---|---|
| 0 | Low | High | 5 | 1 | 3 | 2 | 4 |
| 1 | Medium | High | 5 | 1 | 4 | 2 | 3 |
| 2 | High | High | 2 | 3 | 1 | 4 | 5 |
| 3 | Low | Medium | 5 | 1 | 4 | 2 | 3 |
| 4 | Medium | Medium | 5 | 1 | 4 | 2 | 3 |
| 5 | High | Medium | 2 | 3 | 1 | 4 | 5 |
| 6 | Low | Low | 4 | 3 | 5 | 1 | 2 |
| 7 | Medium | Low | 3 | 4 | 5 | 1 | 2 |
| 8 | High | Low | 1 | 5 | 4 | 2 | 3 |
| 9 | Low | None | 3 | 4 | 5 | 1 | 2 |
| 10 | Medium | None | 3 | 4 | 5 | 1 | 2 |
| 11 | High | None | 1 | 5 | 4 | 2 | 3 |

Table E.2: *Relative advantage scores for the different neighborhood types and thermal systems. A score of 1 means that a thermal system is most preferable in comparison to the other thermal systems for this neighorhood type. 5 is the least preferable. AE = All-Electric Heat Pump, HT/MT DHC = High/Medium Temperature district heating network, LT DHC = Low Temperature district heating network, GG HP = Green Gas hybrid heat pump, H2 HP = Hydrogen hybrid heat pump.*

Table E.2 specifies how the relative advantage per neighborhood type is formalized. The neighborhood types are specified in the rows and the thermal systems they are able to transition to in the columns. Every neighborhood type has a specified order of relative advantage, ranging from 1 (most advantage) to 5 (least advantage), resulting from insights from literature and verified in a workshop with experts of the stakeholder Gasunie.

The table is filled in with a few core assumptions based on these insights per thermal system, insulation level and urban density. The core assumptions itemized per thermal system are:

- All-Electric Heat Pump
  - Highly urban areas are less attractive for All-Electric thermal systems due to the expansive grid expansion within city centers, space limitations of groundsource heatpumps and noise generation.
  - Highly insulated neighborhoods are strongly preferred for All-Electric thermal systems due to the low supply temperature of such systems.
- High/Medium Temperature DHC

  - Highly urban areas are very attractive for HT/MT DHC networks due to their high heat density resulting in lower distributed costs. Very unlikely in none urban neighborhoods.
  - HT/MT DHC networks are applicable in poorer insulated neighborhoods due to their higher supply temperatures .
- Low Temperature DHC
  - Have similar characteristics and assumptions to HT/MT networks, with the main difference for the relative advantage being that they strongly prefer highly insulated neighborhoods.
- Green Gas Heat Pumps
  - Are especially favorable in neighborhoods where All-Electric or DHC's are not likely. Can be implemented in neighborhoods with poorer insulation.
- Hydrogen Heat Pumps
  - Are comparable to Green Gas Heat Pumps, except for that they are dependent on the timefactor of when the technology becomes available.
  - The Green Gas option is always considered before the hydrogen option.

The scores of the highest relative advantage can be applied for either the neighborhood selection or the thermal system selection. When the highest relative advantage is the decision procedure for the neighborhoods (Strategy 2, see **??**), all neighborhoods have to evaluate what the best still available thermal system is according to their neighborhood type. This yields a number for all neighborhoods considered in the selection (1 = best thermal system for my neighborhood type is still available, 5 = only worst thermal system for my neighborhood type is still available). The municipality then randomly selects a neighborhood out of the subset of neighborhoods that have the highest relative advantage. If the highest relative advantage is the selection procedure for the thermal system (Strategy 1, 2, 3 and partly 4), neighborhoods also first have to determine what thermal systems are still available to them. Then the neighborhood transitions to the thermal system with the highest relative advantage score that is still available.

**HIGHEST NEIGHBORHOOD LIKELIHOOD** The construct of neighborhood likelihood, as conceptualized in chapter , allows us to approximate the preferability of transitioning one neighborhood over the other based on observable characteristics of neighborhoods. Based on characteristics derived from the data, the likelihood of a neighborhood can be scored and compared to others.

The four datapoints used to score this neighborhood likelihood are based on what has been found in literature, policy reports and expert input. The first neighborhood datapoint used is the the percentage of households in a neighborhood owned by housing corporations. Housing corporations have been identified as suitable partners to accelerate the thermal energy transition in the Netherlands (Klimaatberaad, 2019; Gemeente Den Haag, 2020; Aedes, 2020). They are easier to communicate with than directly with the households and they tend to be more pragmatic with energy efficiency measures and other cost saving investments. The second datapoint is the percentage of household currently connected to an existing DHC network. Neighborhoods where already some form of a DHC network is present could indicate an opportunity that can be seized by extending the current network for the entire neighborhood (Schoof et al., 2018; Gemeente Den Haag, 2020; Aedes, 2020). The third datapoint used is the percentage of newly built homes in a neighborhood. The Climate Agreement specifies a section (C1.9) to addressing the stimulation of building new dwellings without a connection to the gas grid and switching recently built dwellings with a natural gas connection to a sustainable thermal system. The fourth and last used datapoint to score the neighborhood likelihood is the average property value in a neighborhood. Based on literature of Ameli and Brandt (2015) and Brounen et al. (2013) we find that income is an important driver of investment in thermal systems and energy efficiency measures. Given that correlations are found between income and and property values (Capozza et al., 2002), we use the property value average for neighborhoods as a proxy for the propensity to invest in thermal systems for neighborhoods.

For every datapoint, a neighborhood can exceed two thresholds that will yield in one or two points for the neighborhood likelihood score which is then used by municipalities to select the transition order of neighborhoods (for Strategy 3 and 4). Two tresholds, a medium and high threshold, are chosen because this will result in being able to differentiate between scoring a small amount (i.e. 5% of households is connected to a DHC, which is better than 0%) on a datapoint or scoring a proportional amount (i.e. 50% of households is connected to a DHC, which is considerably better). The neighborhood likelihood score is constant and calculated once in the setup of the model because the data input is also fixed. Municipalities then randomly select one of their neighborhoods in the subset of neighborhoods with the highest neighborhood likelihood to transition.

**TRANSITION ACTIVITY BY OTHER MUNICIPALITIES** The influence of other municipalities' decisions on each other was conceptualized as governance diffusion was found to be a potential factor contributing to the decisions of municipalities. The interaction between municipalities can take many complex forms and is poorly understood (Leeuw and Groenleer, 2018), therefore the formalisation of this construct is kept rather simple by using the theory of Gravity Model of (information) Trade Sen and Smith (1995). By using this theory as a foundation, networks between municipalities are established which represent the information sharing of their transition activity.

According to the Gravity Model (Sen and Smith, 1995), the volume of trade or information sharing between to municipalities, can be predicted based on the economic size (number of households assumed as proxy) and distance between two municipalities. In its essence, the dynamic of the model implicates the greater the distance between two municipalities, the lower the volume of information trade and the larger the number of households of the other municipality, the higher the information trade volume. A basic interpretation of the formula is used for this purpose:

$$F_{i,j} = G * \frac{M_i * M_j}{D_{i,j}} \tag{E.1}$$

Where $F_{i,j}$ represents the information trade volume between municipalities $i$ and $j$, G is a unknown but irrelevant constant for our purposes, $M_i$ is the number of households in municipality $i$ and $D_{i,j}$ is the distance between municipality $i$ and $j$. One has to note that the number $F_{i,j}$ itself has no meaning outside the context of comparing trade volumes between municipalities.

After having calculated all $F_{i,j}$, municipalities add the top $n$ (selectable through the model variable mp-top-n) municipalities to the network that they interact with. The interaction then consists of the municipalities' neighborhoods asking these other municipalities in the network for their past history on transition decisions. The activity received per municipality is multiplied by its information volume $F_{i,j}$ to derive a weighted score for the municipalities activity per thermal system. The sum of all weighted transition activities per thermal system of other municipalities is then normalized on a scale of 1 to 5 in order to add it up with the relative advantage score of the same thermal system. Both the relative advantage and transition activity by others score have been given an equal weight of 1 in this formula. The combined scores are finally used by the neighborhoods to determine to what thermal system they should transition (if the thermal system is available). The formulas for calculating the combined scores is presented below, with explanations of abbreviations in table E.3:

$$CS_{i,j} = TAS_{i,j} * \omega_{TAS} + RAS_{i,j} * \omega_{RAS} \tag{E.2}$$

$$TAS_{i,j} = 1 + \frac{(WNA_{m,j} - min(WNA_{m,j}) * (5 - 1)}{max(WNA_{m,j} - min(WNA_{m,j})} \tag{E.3}$$

$$WNA_{m,j} = \sum_{y=municipality-in-network}^{n} nhs_{y,j} * F_{y,m} \tag{E.4}$$

| Abbreviations | Explanation |
|---|---|
| $CS_{i,j}$ | Combined score for neighborhood \textit{i} and thermal system \textit{j} |
| $TAS_{i,j}$ | Normalized (1, 5) calculated transition activity as observed by neighborhood \textit{i} for thermal system \textit{j} |
| $RAS_{i,j}$ | Relative advantage for a neighborhood type per thermal system as presented in table \ref{tab:rel_adv} |
| $\omega_{TAS}$, $\omega_{RAS}$ | Weights for the individual scores TAS and RAS, assumed to be 1 |
| *$WNA_{m,j) =* | Information volume weighted transition activity as observed by municipality \textit{m} for thermal system \textit{j} |
| $nhs_{y,j}$ | Number of neighborhoods observed in municipality \textit{y} with thermal system \textit{j} |
| $F_{y,m}$ | Information volume between municipality \textit{y} and \textit{j} |

**Table E.3:** *Explanation of abbreviations in formulas used for calculating transition activity scores.*

After the $CS_{i,j}$ scores have been calculated by the neighborhood that is up for a transition, it selects the thermal system with the most favorable score that is still available to transition to. Note that it is conceptualized that the municipality makes a transition decision (who, where and when to transition) for a neighborhood, but this calculation is made also by the neighborhood. This is done for pragmatical programming reasons and can still be considered in line with the conceptualization of the decision mechanic by municipalities.

The final procedure before the Municipal Transition Decision Cycle either starts over or finishes, is the start of the neighborhoods transition and the adjustment of energy source stock. Depending on the selected Strategy (table **??**), a specific neighborhood and thermal system are chosen to transition towards. As energy supplies re not unlimited, the stock of the respective energy source has to be updated.

For electricity, it is assumed in this thesis that electricity generation and network capacity will grow proportional to demand. Underlying this assumption is that in the factor relative advantage, capital expenditure for electricity networks as a result of transitioning towards electrically driven systems is already included. Growth of supply and grid capacity is therefore in theory unlimited as it can be expanded, but at a high cost.

For the two DHC network options, High/Medium temperature (HT/MT) and Low temperature (LT), two different assumptions are made. For the HT/MT thermal system option, a large heat source with at least medium temperature heat should be in near proximity. While High/Medium temperature DHC networks can technically be heated with geothermal sources, costs are expected to be high in comparsion to lower temperature geothermal sources. Therefore, the technical energy limitation for HT/MT thermal systems is assumed to be the capacity of identified (residual) heat sources in the Netherlands and the distance to these sources. The LT DHC networks are fed by a much lower temperature heat. In comparison the the higher temperature geothermal sources, low temperature geothermal heat is expected to be possible to utilize in most parts of the Netherlands, research has indicated (Steffens et al., 2018). Therefore it is assumed that LT thermal systems are not limited by capacity or technical constraints.

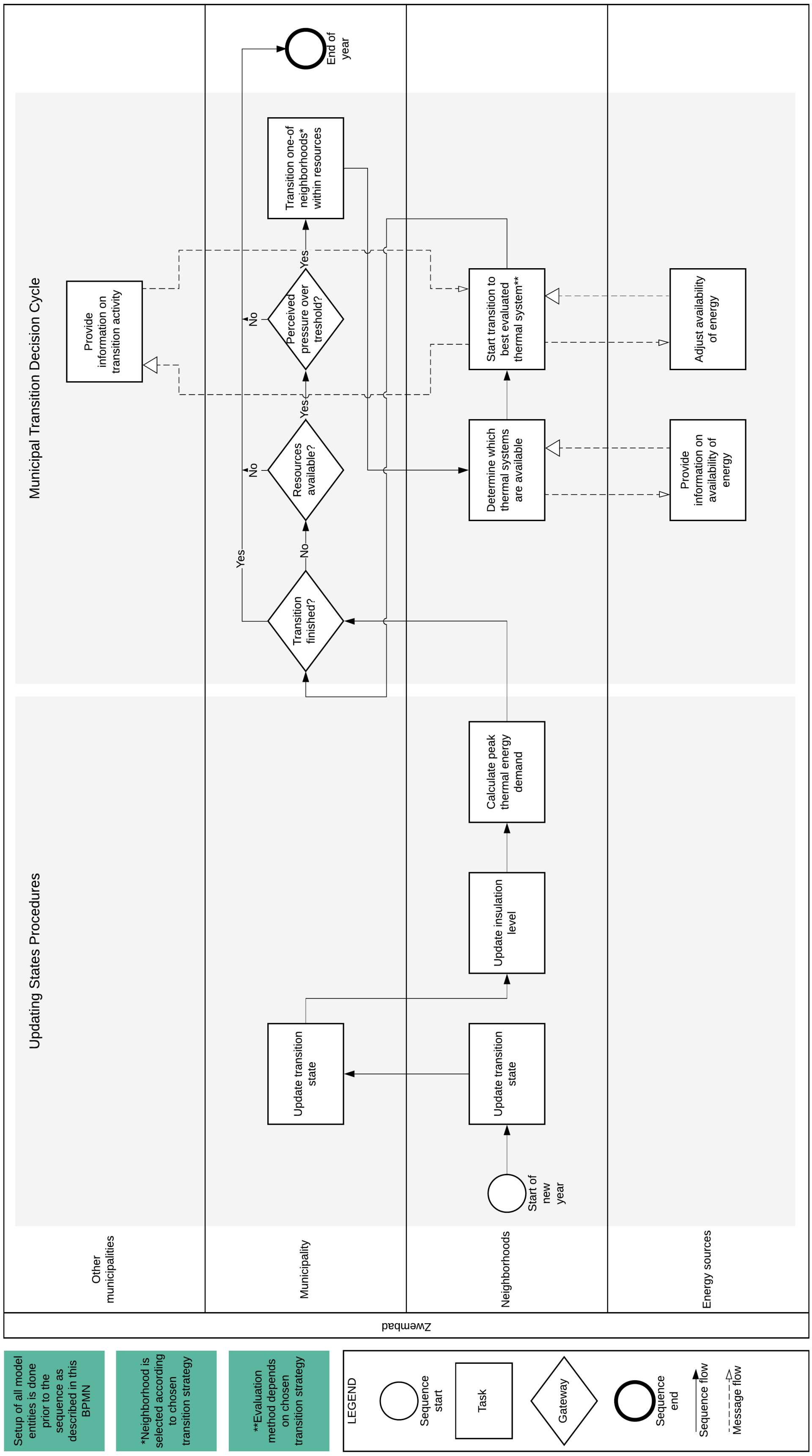
Green gas heat pump thermal systems are fed by electricity and green gas. We just noted that this thesis does not include limitations on the use of electricity. Green gas however, is limited in its capacity as it is to be extracted from exhausting sources. According to estimations by Stedin (Stedin, 2020), the national green gas potential equals roughly 1,7 billion m3 every year. This can be converted to roughly 60 PJ of green gas energy every year.

The last energy source of interest for this thesis is hydrogen. Hydrogen is considered an energy carrier surrounded with many uncertainties (van Groot Battavé et al., 2020). For hydrogen to be considered sustainable (which we assume in this thesis), it has to be produced through electrolysis, using electricity and water as main energy sources. Just as with electricity as a fuel source, we therefore do not include limitations in the total capacity of hydrogen. However, as hydrogen is not yet a mature technology for either the infrastructure as the thermal systems in dwellings, the limitation for this source is set on time. Several studies have estimated when the technology could become available for the built environment. Stedin (van Groot Battavé et al., 2020) predicts the technology to be available by 2030 and a study by DNV-GL (van den Noort et al., 2017) suggests the availability of 250 PJ hydrogen every year by 2030 in the Netherlands.

### *Ending the cycle*

When after a transition decision cycle by a municipality the neighborhood has started its transition, the municipality reevalutates the same three conditions as discussed before. When the conditions are satisfied, the municipality starts another cycle of its decision until it has exhausted the conditions. If this occurs and the cycle has ended, the next municipality starts the same sequence, until all municipalities in the model have finished their cycle. A year in the model ends with all municipalities having finished their cycles.

# F | BPMN


Municipal Transition Decision Cycle
Updating States Procedures
Other municipalities
Municipality
Neighborhoods
Energy sources
Zwembad
Provide information on transition activity
End of year
Transition one-of neighborhoods* within resources
Perceived pressure over treshold?
Resources available?
Transition finished?
Yes
No
Start transition to best evaluated thermal system**
Determine which thermal systems are available
Adjust availability of energy
Provide information on availability of energy
Calculate peak thermal energy demand
Update insulation level
Update transition state
Update transition state
Start of new year
Setup of all model entities is done prior to the sequence as described in this BPMN
*Neighborhood is selected according to chosen transition strategy
**Evaluation method depends on chosen transition strategy
LEGEND
Sequence start
Task
Gateway
Sequence end
Sequence flow
Message flow

# G MODEL NARRATIVE

The model narrative is the final step in the modelling process to describe the processes of model elements. It is a written narrative of the steps of the processes in the model and the agents.

### G.0.1 Setup of the model

The model can be setup in the NetLogo simulation environment by pressing the 'setup' button once. The setup initiates loading in the external datasets into the environment and the creation of the environment in NetLogo.

- Clear the model environment of all previously loaded data and variables.
- Load all external dataframes into the model:
  - Load all GIS-enabled dataframes in the model:
    - Load the dataset containing the municipalities, their geodata and variables.
    - Load the dataset containing the neighborhoods, their geodata and variables.
    - Load the dataset containing the heatsources, their geodata and variables.
    - Set the projection system of NetLogo equal to the projection system of the municipalities projection system (WGS84, EPSG:32632).
  - Load the dataset containing the Relative Advantage values for the neighborhood types.
  - Load the dataset containing the municipalities' network and their information volumes.
  - Load the dataset containing the mapping of municipalities with Gasunie Metering and Regulation stations.
- Create invisible MR-stations for every MR-station in the Metering and Regulations stations dataset at a random location.
- Create 388 municipality agents, as read from the municipalities dataset, each on the center of its designated polygon while storing its variables into the agents variable:
  - Ask all municipalities to look-up their top *n* (*n* to be set with *mp-top-n* slider in interface) other municipalities in their network by information volume in the municipalities' network and information volumes variable. Then create links with each of these top *n*

municipalities and set the weight of this link to the information volume.
  - Ask all municipalities to set their municipal transition goal equal to their household share in the national number of households multiplied by the national transition goal.
  - Ask all municipalities to set their model variables and states to the default values.

- Create 12603 neighborhood agents, as read from the neighborhoods dataset, each on the center of its designated polygon while storing its variables into the agents variable:
  - Ask all neighborhoods to set their neighborhood type from 0 to 11, based on their level of urban density and insulation level.
  - Ask all neighborhoods to set their *nh-filter* variable from 0 to 8 based on its share of housing corporation possession, share of district heating networks per household, share of newly built homes and property value.

- Create 604 heatsource agents, as read from the heatsources dataset, each on the center of its designated coordinates, while storing its capacity value into the agent variable.

- Create 1 green gas source on the top left corner of the model environment and set its green gas stock equal to the *national-gg-potential-PJ* slider value.

### G.0.2 Running the model

The model can be run with the NetLogo simulation environment by pressing the 'go' button once. This initiates the decision-making by the municipalities from tick 0 to tick 31. The model run stops if tick 31 is reached. The procedures described below are run sequentially from top to bottom every tick.

- Updating states procedures:
  - Ask neighborhoods that are currently in transition to countdown the duration left of their transition by 1:
    * If the duration is equal to 0, set the color of the agent from white to equal the corresponding thermal system the neighborhood has transitioned to (All-Electric = Yellow, High/Medium Temperature DHC = Red, Low Temperature DHC = Orange, Green Gas Hybrid Heat Pump = Green, Hydrogen Hybrid Heat Pump = Blue)
  - Ask municipalities to update their transition state.
  - Ask neighborhoods to update their current insulation level if it is below the maximum of 8.5 (corresponding to label A++):
    * Increase the neighborhoods current insulation level with the amount selected by the slider *nh-ins-strategy1*.

      * Check if the neighborhoods are eligible for a transition by determining if their current insulation level is above 3.5 (corresponding to label D at least).
  - Ask neighborhoods to calculate their total peak thermal energy demand by calculating the thermal demand per dwelling type and current insulation level in their neighborhood.
  - Ask neighborhoods to calculate their total peak thermal energy demand per energy source based on their currently used thermal system and calculated thermal peak energy demand.

- Municipal Transition Decision Cycle:
  - Ask municipalities that still have to transition any of their neighborhoods to:
    * Update its currently available resources.
    * Update its currently perceived pressure.
  - ** Ask municipalities that still have to transition any of their neighborhoods, perceive pressure and have resources available to (one of the following strategies that is selected):
    * Strategy 0: Ask a random neighborhood that still requires a transition and is within available resources to transition to a random thermal system that is available to this neighborhood.
    * Strategy 1: Ask a random neighborhood that still requires a transition and is within available resources to transition to a thermal system that has the highest relative advantage still available.
    * Strategy 2: Ask one of the neighborhoods with their highest relative advantage thermal system still available that still requires a transition and is within available resources to transition to a thermal system that has the highest relative advantage still available.
    * Strategy 3: Ask one of the neighborhoods with the highest neighborhood likelihood that still requires a transition and is within available resources to transition to a thermal system that has the highest relative advantage still available.
    * Strategy 4: Ask one of the neighborhoods with the highest neighborhood likelihood that still requires a transition and is within available resources to transition to a thermal system that combines the highest relative advantage score with with the highest score of transition activity in the municipalities network.
    * Update the resources available and perceived pressure.
    * Return to ** if the municipality still has enough resources available and perceived pressure.

### G.0.3 Resetting the model

In order to increase performance between sequential model runs, a reset procedure is implemented that clears the model output and resets the model variables to default. This procedure prevents from deleting the loaded datasets, thus decreasing the computationally heavy procedures in the setup procedure. The reset procedure can be called by pressing 'reset' in the NetLogo environment.

- Ask municipalities to set all model variables to default.
- Ask neighborhoods to set all model variables to default.
- Ask neighborhoods to reset their *nh-filter* variable.
- Ask the green gas source to reset its capacity to its to value.
- Ask the heatsources to reset their capacity to their to values.

# H PARAMETRIZATION

This appendix aims to give an overview of the used parameters in the agent-based model.

## H.1 MODEL AGENTS PARAMETERS

| Parameter Name | Default Value | Source |
|---|---|---|
| *mp-name* | GM_NAAM | Retrieved from CBS dataset |
| *mp-hhs* | AANTAL_HH | Retrieved from CBS dataset |
| *mp-xcor* | GEOMETRY | Retrieved from CBS dataset |
| *mp-ycor* | GEOMETRY | Retrieved from CBS dataset |

Table H.1: *Parametrization of the municipality agents. Dataset variable names of respective datasets are given.*

**Description of municipality agents parameters**

**mp-name**: The name of the municipality that is used for identification purposes.

**mp-hhs**: The number of households of a municipality.

### H.1.1 Neighborhood agents

| Parameter Name | Default Value | Source |
|---|---|---|
| *nh-name* | BU_NAAM | CBS dataset |
| *nh-mp-name* | GM_NAAM | CBS dataset |
| *nh-hhs* | AANTAL_HH | CBS dataset |
| *nh-sted* | STED | CBS dataset |
| *nh-ins-to* | VOORL_BEREKEND | RVO dataset |
| *nh-corp* | P_HUURCORP | CBS dataset |
| *nh-dhc* | P_STADVERW | CBS dataset |
| *nh-nieuw* | P_WONV2000 | CBS dataset |
| *nh-woz* | WOZ | CBS dataset |
| *nh-flatapp* | WONING_TYPE | RVO dataset |
| *nh-vrij* | WONING_TYPE | RVO dataset |
| *nh-rijhoek* | WONING_TYPE | RVO dataset |
| *nh-rijtussen* | WONING_TYPE | RVO dataset |
| *nh-21kap* | WONING_TYPE | RVO dataset |
| *nh-xcor* | GEOMETRY | CBS dataset |
| *nh-ycor* | GEOMETRY | CBS dataset |

Table H.2: *Parametrization of the neighborhood agents. Dataset variable names of respective datasets are given.*

#### Description of neighborhood agents parameters

**nh-name**: The name of the neighborhood that is used for identification purposes.

**nh-mp-name**: The name of the neighborhoods' municipality.

**nh-hhs**: The number of households of a neighborhood.

**nh-sted**: The level of urban density of a neighborhood.

**nh-ins-to**: The level of insulation of a neighborhood.

**nh-corp**: The share of households that are owned by a corporation in a neighborhood.

**nh-dhc**: The share of households that have a district heating network connection in a neighborhood.

**nh-nieuw**: The share of households in a neighborhood that are built after 2000.

**nh-woz**: The average property value of households in a neighborhood.

**nh-flatapp**: The share of households in a neighborhood that are flat apartments.

**nh-vrij**: The share of households in a neighborhood that are villas.

**nh-rijhoek**: The share of households in a neighborhood that are corner dwellings.

**nh-rijtussen**: The share of households in a neighborhood that are row dwellings.

**nh-21kap**: The share of households in a neighborhood that are 2 under one cap dwellings.

### H.1.2 Heatsource agents

| Parameter Name | Default Value |
|---|---|
| *hs-name* | bron_naam: Retrieved from PBL dataset |
| *hs-mw-capacity-to* | MWcapaciteit: Retrieved from PBL dataset |
| *hs-xcor* | X: Retrieved from PBL dataset |
| *hs-ycor* | Y: Retrieved from PBL dataset |

Table H.3: *Parametrization of the heatsource agents. Dataset variable names of respective datasets are given.*

| Parameter Name | Default Value | Source |
|---|---|---|
| *hs-name* | bron_naam | PBL dataset |
| *hs-mw-capacity-to* | MWcapaciteit | PBL dataset |
| *hs-xcor* | X | PBL dataset |
| *hs-ycor* | Y | PBL dataset |

Table H.4: *Parametrization of heatsource agents. Dataset variable names of respective datasets are given.*

#### Description of heatsource agents parameters

**hs-name**: The name of the heatsource that is used for identification purposes.
**hs-mw-capacity-to**: The capacity in MW for this heatsource.

## H.2 REFERENCE PARAMETERS

| Parameter Name | Default Value | Source |
|---|---|---|
| mp-transition-strategy | 2 | Authors interpretation |
| national-transition-goal | 250000 | Climate Agreement (Klimaatberaad, 2019) |
| nh-transition-duration | 2 | Estimation based on pilot projects |
| mp-top-n | 10 | Authors interpretation |
| mp-resource-percentage | 10 | Authors interpretation; validated by municipalities |
| nh-low-ins-transition? | TRUE | Authors interpretation, inspired by VESTA-MAIS (Schepers et al., 2019) |
| nh-ins-strategy1 | 20 | Authors interpretation |
| national-gg-potential-PJ | 60 | Various sources A.2.3 |
| max-distance-heatsource | 15 | Authors interpretation |
| hs-limited | TRUE | Authors interpretation |
| national-h2-availability | TRUE | Authors interpretation |
| national-h2-availability-ticks | 15 | Various sources A.2.4 |
| nh-cost-par | 50 | Authors interpretation |

Table H.5: *Parametrization of the model.*

#### Description of parameters

**mp-transition-strategy**: The type of decision strategy that is performed by municipalities to select the neighborhoods and their thermal system.
**national-transition-goal**: The number of households that have to be transitioned on a yearly basis as determined by national policy.
**nh-transition-duration**: The number of years (ticks) it takes for a neighborhood to finish its transition when started.
**mp-top-n**: The number of municipalities that are considered by a municipality for the transition activity in its network.
**mp-resource-percentage**: The percentage of the total housing stock in a municipality that can be in transition at the same time.
**nh-low-ins-transition?**: The assumption whether low insulated neighborhoods can be transitioned.
**nh-ins-strategy1**: The speed of the national insulation development for neighborhoods.
**national-gg-potential-PJ**: The yearly available greengas stock for the built environment in the Netherlands.
**max-distance-heatsource**: The maximum distance a HT/MT heatsource can be away from a neighborhood.
**hs-limited**: Toggle which determines whether hydrogen heat pumps are an available technology in the experiment.
**national-h2-availability**: The assumption whether hydrogen is an thermal system alternative for the built environment.
**national-h2-availability-ticks**: The assumption from what year hydrogen technology will be implementable in the built environment.
**nh-cost-par**: The weight given to how much the the RA is considered in comparison to the networks activity (Applicable to strategy 4).

## H.3 THERMAL SYSTEMS AND PEAK THERMAL DEMAND

## H.4 CONCEPTUALIZING THE THERMAL SYSTEMS

This paragraph discusses the formalization and parametrization of the different thermal systems and implications thereof. The type of thermal system a neighborhood is using, is the key driver to the mix of energy demand generated per source and one of the two drivers of its volume (the other driver being the insulation level). Many different variations in thermal systems exist, for simplicity purposes the technical specifications are assumed to be equal among the six different thermal systems conceptualized. The choice for these thermal systems is based on analysis by PBL Planbureau voor de Leefomgeving (2020) and discussions with the stakeholder.

**NATURAL GAS-FIRED BOILER** The starting thermal system for all neighborhoods is the natural gas-fired boiler system (NG). While not all households in the Netherlands are currently using such a system, the vast majority is

(Netbeheer Nederland, 2019). This thermal system is solely driven by natural gas.

**ALL-ELECTRIC HEAT PUMP** The all-electric (AE) heat pump thermal systems are, surprisingly, fully driven by electricity delivered through the electricity grid. AE systems are individual thermal systems consisting of heat pumps extracting heat from the air. Such thermal systems typically only are an interesting alternative in conjunction with low temperature heat exchangers and high insulation levels to press cost and capacity expansion of the electricity grid. However, electricity grid expansion is considered out of scope when applying AE thermal systems.

**HIGH/MEDIUM TEMPERATURE DISTRICT HEATING NETWORK** The high or medium temperature (HT/MT) district heating networks are driven by heat from an external heatsource. How the heat is generated, is considered out of scope in the calculations for energy demand as there are many variations of this system. These thermal systems are interesting for denser areas and do not require high insulation levels to be applicable.

**LOW TEMPERATURE DISTRICT HEATING NETWORK** Low temperature (LT) district heating networks are comparable to HT/MT systems. The same as with HT/MT systems, how the heat is generated is considered out of scope. LT heat systems can also be driven by a variety of heat sources, including local geothermal sources, which can be found almost everywhere in the Netherlands (Schoof et al., 2018). The main difference with HT/MT systems is that LT systems require higher levels of insulation as they can provide less heat.

**GREEN GAS HYBRID HEAT PUMP** Green gas hybrid heat pumps (GG) are systems driven by both green gas as electricity. However, as the system is modelled to output peak energy demand on extreme conditions, the majority of the energy output share is green gas. Hybrid heat pumps systems are designed with relatively small electrical heat pumps to deliver the regular base load. The gas-fired boilers are used in peak conditions.

**HYDROGEN HYBRID HEAT PUMP** The hydrogen hybrid heat pump system (H2) is conceptualized as being a comparable system to the green gas system. While technology for thermal hydrogen systems is still maturing, research suggests that hybrid heat pumps are likely systems to be implemented (Dodds et al., 2015; van Groot Battavé et al., 2020). The specifications of these systems are assumed to be equal to the GG systems.

## H.5 INSULATION OF NEIGHBORHOODS

After having updated the transition states of the municipalities and its neighborhoods, the insulation level of the neighborhoods is updated. Several studies have specifically focused on the adoption of energy efficiency measures for households (Hesselink and Chappin, 2019). As this research is mainly focusing on the adoption of the thermal systems by neighborhoods and the adoption mechanics of previous (ABM) studies can not be implemented one-on-one due to the aggregation of households, the insulation of neighborhoods is formalised as a linear process depending on scenario's. The base insulation level of a neighborhood is derived from a dataset of Rijksdienst voor Ondernemend Nederland (2017) containing estimated energy labels of all households in the built environment. These labels correspond to insulation level 0 for label G and 8 for label A++, with a linear increase inbetween.

## H.6 FROM THERMAL SYSTEM TO PEAK THERMAL DEMAND PER ENERGY SOURCE

As described in figure H.2, the peak thermal energy demand has to be calculated first in order to derive the peak energy demands per energy source. To our current knowledge, no data is available for peak thermal energy demand of aggregated neighborhoods. Therefore, it is derived from a bottom-up calculation of peak thermal energy demands of all households in a neighborhood.

Peak thermal energy demand differs per type of dwelling, insulation level and thermal system. To account for the heterogeneity of peak thermal demand of neighborhoods, peak heat demand profiles calculated by Menkveld et al. (2015) are used to determine the unique energy demand outputs per neighborhood. These profiles are based on year 1987, which was an extremely cold year in the Netherlands. The dataset Rijksdienst voor Ondernemend Nederland (2017), which is also used for deriving the energy labels, provides the types of dwellings for the complete built environment. Through the same way as with the energy labels, the distribution of dwellingtypes can be derived for every neighborhood in the Netherlands.

The peak thermal energy demand of a neighborhood is thus derived by combining the peak thermal energy demand per share of dwelling types in a neighborhood and the 'gelijktijdigheidsfactor'. The peak demand per dwelling type is dependent on the type of dwelling (with the types being flat or apartment, detached dwelling, terraced dwelling, corner dwelling and semi-detached dwelling) and its insulation level. It is assumed for this calculation that the insulation level of a share of dwelling types is equal to the neighborhoods insulation level. The 'gelijktijdigheidsfactor' or 'simultaneity factor' is an important component of this equation when aggregating the peak thermal energy demand of households to a higher level (Schepers et al., 2015). Households do not generate their peak demand at exactly the same time, but with a slight offset compared to each other. Thus when combining individual peak demands this has to be accounted for with a factor equal to 0.53 for low and medium insulated neighborhoods and 1 for highly insulated neighboorhoods (low to medium insulation: i from 0 to 5.5; high insulation from 5.5 (Gasunie calculations (Menkveld et al., 2015)). The following formulas for calculating peak thermal energy demand in a given neighborhood with some insulation level j, with abbreviations in table H.6:

| Abbreviation | Explanation |
|---|---|
| *i* | Dwellingtype: flat/apartment, detached, terraced, corner, semi-detached |
| *j* | Neighborhood with given insulation level |
| *PTED(j_* | Peak Thermal Energy Demand [kW] for neighborhood j with given insulation level |
| *hhs_{j}* | Number of households for neighborhood |
| *% hhs_{i, j}* | Percentage of households of dwellingtype i in neighborhood j |
| *HHPTED(i, j)* | Peak Thermal Energy Demand [kW] for household with given dwellingtype and insulation level j |
| *alpha_{i, j}* | Parameter for given dwellingtype i and insulation level j (see H.7) |
| *ins_{j}* | Neighborhood insulation level: [0, 8] |
| *beta_{i,j}* | Constant for given dwellingtype i and insulation level j (see H.7) |
| *GT(j)* | Gelijktijdigheidsfactor (simultaneity factor) for given insulation level |

**Table H.6:** *Abbreviations of terms in formulas for calculation of peak energy demand.*

$$PTED(j) = \sum_{i=dwellingtype}^{5} hhs_j * \%hhs_{i,j} * HHPTED(i,j) * GT(j) \tag{H.1}$$

$$HHPTED(i,j) = \alpha_{i,j} * ins_j + \beta_{i,j} \tag{H.2}$$

for j between 0 and 5.5:

$$GT(j) = 0.53 \tag{H.3}$$

for j bigger than 5.5 (interpolation between 0.53 and 1):

$$GT(j) = 0.23 * ins_j - 0.76 \tag{H.4}$$

| | | Flat/apartment | Detached | Terraced | Corner | Semi-detached |
|---|---|---|---|---|---|---|
| *ins(j) <= 2* | *alpha* | 0 | 0 | 0 | 0 | 0 |
| | *beta* | 13 | 26 | 15 | 18 | 18 |
| *2 < ins(j) <= 5* | *alpha* | -0.29 | -0.58 | -0.33 | -0.40 | -0.40 |
| | *beta* | 13.57 | 27.15 | 15.67 | 18.80 | 18.80 |
| *5 < ins(j) <= 7* | *alpha* | -4.77 | -9.53 | -5.50 | -6.60 | -6.60 |
| | *beta* | 35.97 | 71.93 | 41.50 | 49.80 | 49.80 |
| *7< ins(j)* | *alpha* | 0 | 0 | 0 | 0 | 0 |
| | *beta* | 2 + (3/5) | 5 + (1/5) | 3 | 3 + (3/5) | 3 + (3/5) |

**Table H.7:** *Parameter values for alpha and beta to calculate the peak thermal energy demand per dwelling type with a given insulation level. These values are interpolated based on heat demand profiles given by Menkveld et al. (2015) in figure 10 and 11.*

Depending on the thermal system of use in the neighborhood and its peak thermal energy demand, we can calculate the energy output KPI's, as described in figure H.2. The conversion from universal peak thermal energy demand to energy source specific demand is performed by using the thermal systems efficiency and distribution of energy source use for the system. Both are considered as constant during the simulation of the model. In the following table, the energy efficiency of the different thermal systems is described:

| Thermal system | Efficiency under peak load | Distribution | Source |
|---|---|---|---|
| *Natural Gas* | 90% for low insulation<br>95% from medium insulation | 100% natural gas | Menkveld et al. (2015) |
| *All-electric HP* | 150% | 100% electricity | Menkveld et al. (2015) |
| *HT/MT heat pump* | 100% | 100% heat | Menkveld et al. (2015) |
| *Green Gas HP* | 150% for the electric heat pump<br>95% for the gas fired boiler | 5.3% electricity<br>94.7% green gas | Menkveld et al. (2015) |
| *Hydrogen HP* | 150% for electric heat pump<br>90% for hydrogen fired boiler | 5.3% electricity<br>94.7% hydrogen | Committee on Climate Change (2018) |

**Table H.8:** *Parameters for conversion of thermal demand to energy demand per thermal system.*

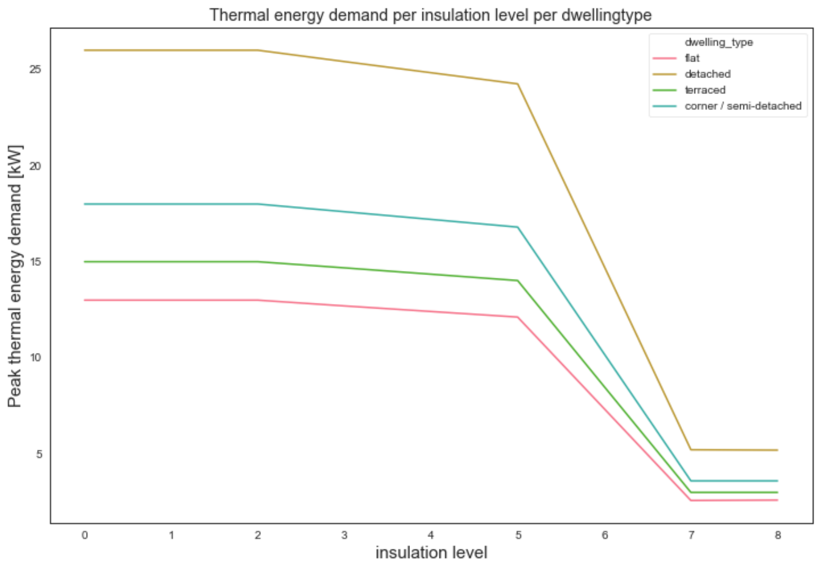



**Figure H.1:** *Thermal energy demand per insulation level per dwellingtype.*

A few things are to be considered when reading this table. It can be noted that the share of gas use for the hybrid heat pumps is almost 20x higher than its electricity use. The reason for this is the significantly higher gas consumption of such systems under extreme peak loads. Same applies for the efficiencies of the heat pumps. The efficiency of heat pumps is dependent on the temperature difference between the heat source and the space, the wider the difference, the lower its efficiency and vise versa. Modern heat pumps can easily achieve efficiencies of over 500%. However, in extremely cold circumstances, the temperature difference the heat pump has to bridge is significantly larger, thus contributing to the relatively low efficiencies of 150%. Furthermore, the energy source distribution for the DHC systems is not further specified than 'heat'. This means that energy source use higher up in energy chain is left out of scope as mentioned before.

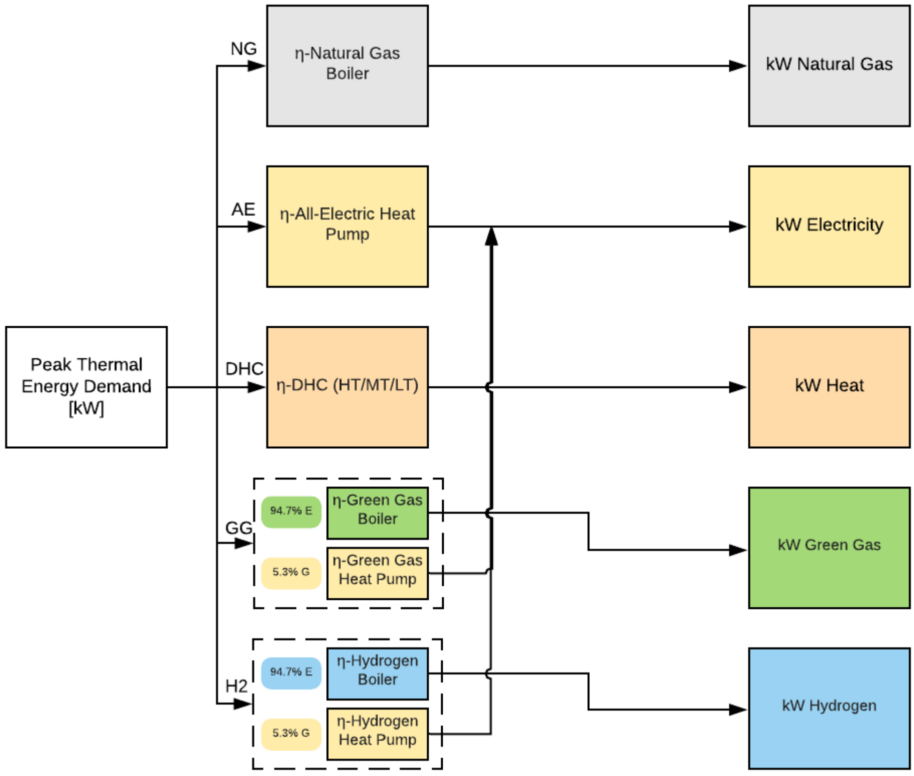



**Figure H.2:** *Model formalisation of peak thermal energy demand for neighborhoods per energy source.*

# I ASSUMPTIONS

- Households are aggregated into their respective neighborhoods. The neighborhoods own the collective characteristics of these households.
- Throughput of all energy transportation infrastructures is unlimited and assumed to grow with demand. Energy sources are limited.
- Municipalities are the final decision-makers in the transition of their neighborhoods.
- The decisions of municipalities only depends on their strategy, observed characteristics, the environment and its own characteristics. Politics and financial incentives are not included.
- The increase of insulation is linear for neighborhoods.
- Peak thermal demand resulting in required capacity at the MR-stations is assumed to be aggregated by municipalities in their respective MR-stations based on appendix C.
- No differences in strategies exist between municipalities. They all operate under the same decision rules. Their characteristics do differ.
- All cost factors are included in Relative Advantage and allocation of cost is not considered.
- Peak thermal energy demand of neighborhoods is solely dependent on the composition of a neighborhood and its insulation level.
- Characteristics of the built environment are considered constant to the input data, the built environment does not grow or shrink over time (except for insulation level and thermal system configuration).
- Amount of resources of municipalities is dependent on the amount of households in a municipality.
- Change in energy consumption behavior is not considered in the energy output.
- The amount of available thermal systems is limited to natural gas-driven, all-electric heat pumps, high/medium temperature DHC's, low temperature DHC's, green gas driven hybrid heat pumps and hydrogen driven hybrid heat pumps. All of these have homogeneous efficiency and energy use characteristics.
- Only the residential built environment is included in this study.
- Spatial availability is not included when considering thermal systems.

- Neighborhoods only transition once.
- Per capita thermal consumption is constant.
- Simulation time for the model is 30 years, which is formalized as 30 model ticks.

# J VERIFICATION

### J.0.1 Static verification

Under static verification, we understand that the correctness of the model code itself. First, the model code is checked for bugs and errors. This has mostly been done iteratively during the programming cycle and after completion. Various errors and bugs have been resolved during the process resulting in a final version that is eliminated of any errors. Secondly, it has been verified that all parts of the code are used and no unused or double parts are present. Thirdly, the order of the procedures has been checked thoroughly to match the design of the conceptual model.

### J.0.2 Behavior verification on individual agent level

The second part of the verification procedure is to determine whether the individual agents (municipalities, neighborhoods and energy sources) follow the implemented procedures correctly that emerge in the desired behavior. This has been checked by inspecting a set of individual agents and checking their development of variables, interactions and states over one time step and through a complete simulation run by considering their input variables, how this is processed and their outcomes. Does the behavior of municipalities set in motion a diversion from natural gas driven systems to sustainable thermal systems according to their chosen strategies, the characteristics of neighborhoods and the environmental settings? Here it is verified that municipalities' strategies are followed correctly and that the correct decisions are made by neighborhoods and energy sources based on the respective variables and states.

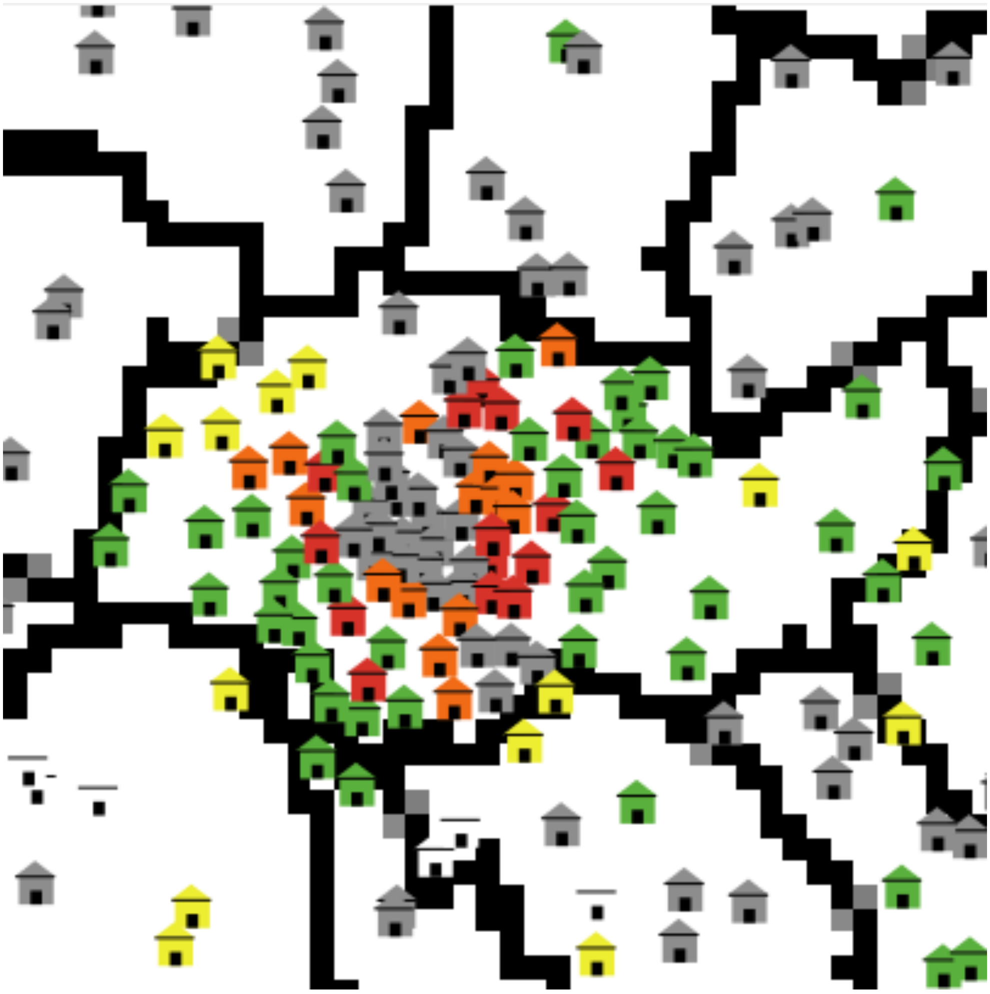


**Figure J.1:** *Snapshot of the municipality Groningen in 2035 with the reference scenario. A clear distinction can be made between the different thermal systems of the neighborhoods.*

### J.0.3 Behavior verification on macro model level

The behavior of the model on a macro level, which is the national aggregation level, has been verified by investigating energy output KPI's and aggregated model behavior KPI's. The model behavior KPI's that are closely checked in this step are the states that the municipalities and neighborhoods go through during a simulation run. Do the municipalities instigate change for the thermal systems of their neighborhoods and does this change the states of the neighborhoods? Furthermore, do the neighborhoods update their insulation levels according to the chosen insulation settings?

The second set of KPI's that is considered and of great importance for answering the main research question are the energy output KPI's. Does the change in thermal systems of the neighborhoods result in the conceptualized change of peak thermal energy demand output per energy source? Aggregating the peak thermal energy demand of neighborhoods to a national level for the built environment results in a peak demand of approximately 65GW hourly average, which corresponds closely to estimations from Klip (2017) and (van der Linden, 2018). According to (Menkveld et al., 2015) and

Gasunie calculations, peak gas demand for the Netherlands totals to 6.3 million m3 per hour, which is within close margin to this models calculation at 7.1 million m3 per hour.

### J.0.4 Extreme value testing on micro and macro level

The next set of verification tests are aimed towards testing how the model and agents behave under extreme settings of the input parameters. All slider parameters have been varied between 0 and 100% of their adjustable settings to review any erroneous or unintended behavior. Errors such as absent reset procedures or 0 as invalid entry were found and solved. The model currently does not produce unexpected behavior under its extreme conditions.

### J.0.5 Variability testing

Just as with many other agent-based models, the model as formalized in this thesis implicates chaotic behavior due to its stochastic nature in agent iteration. While the decision rules for the agents in the model are based on observations and given strategies of these agents, the order in which agents are called by the observer to perform any action is random. As the order in which municipalities are called and the order in which they prefer to transition their neighborhoods is not completely fixed (but rather categorized), chaotic behavior due to random agent iteration is expected (van Dam et al., 2012).

To account for this expected chaotic behavior and determine the required replications in the experiments, the variability of the model is investigated by assessing the KPI's for different timesteps and municipal decision-strategies over many replications. The metric and methodology used for assessing the variability is derived from Lee et al. (2015). Their suggested approach for determining the appropriate sample size is analyzing the variance stability of model outcomes by using the coefficient of variation, which is the standard deviation (of an outcome on a particular timestep and model setting over all previous replications (windowed std. dev.)) divided by the mean (of an outcome on a particular timestep and model setting over all previous replications (windowed mean)). Where the coefficient stabilizes, one can subjectively assume the required amount of replications for the model.

The variance stability is analyzed per aggregation level (municipal level, MR-level and national level) for all energy output KPI's in kW's and per municipal decision strategy. Figure J.2 presented here below is an example for one strategy (strategy 2) and output type (m3 gas). Note that the coefficient of variation metric is dimensionless and can only be used to track stabilization of the metric over the replications. Comparisons between outcomes on like-for-like basis are not sensible.

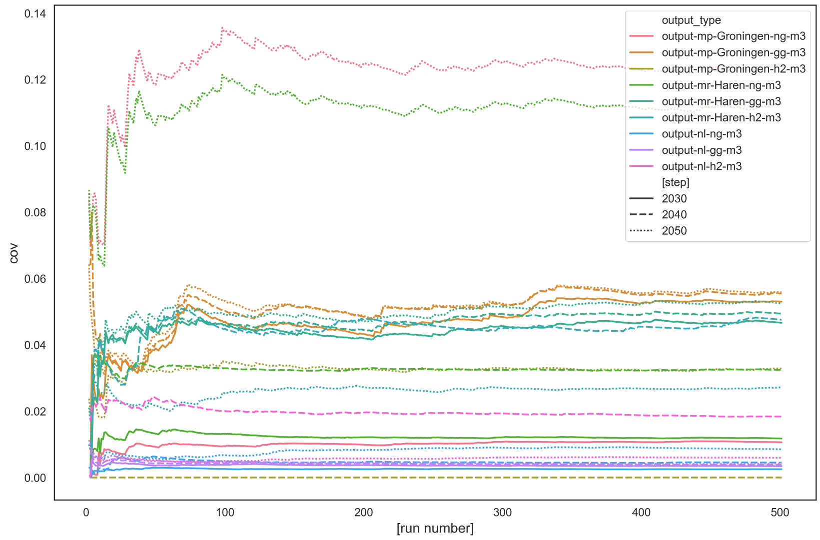



**Figure J.2:** *Variability testing example with coefficient of variation metric for strategy 2; plotted for three aggregation levels (municipal, MR-level and national) for the years 2030, 2040 and 2050.*

A few conclusions can be drawn by testing the variability. Inspecting the figure, one can clearly see that the coefficient of variation tends to stabilize for all plotted output types and time steps between 100 and 200 replications. Some outputs tend to be more variable at specific timesteps than others as a result of different moments in the model simulation run that agents tend to have tipping points for rare or frequently occuring transitions of neighborhoods. For example, when a specific neighborhood has only a very rare chance with the same parameterization at simulation time 2040 to be the first neighborhood in a municipality to transition towards hydrogen, this will highly effect the coefficient of variation. These outlier effects can be attributed to chaotic model behavior. Therefore for stable model results, one should at least run 100 replications.

### J.0.6 Concluding verification remarks

After having performed the above discussed verification procedure iteratively during the modelling process and after final completion of the model, the author is confident that the model is implemented correctly.

# K VALIDATION

This appendix contains the supplementary results validation for the Amsterdam and Drechtsteden municipality.

### *Amsterdam municipality*

Model dynamics on the local level for Amsterdam are compared to the Transition Vision Heat as presented by the municipality of Amsterdam (Over Morgen and Gemeente Amsterdam, 2020). The Transition Vision Heat presents the municipal vision for when and to what thermal alternatives all of its neighborhoods are transitioned towards 2050. Figure K.1 describes the vision of the Amsterdam municipality. The colors in this figure indicate which thermal systems are implemented in which neighborhoods, with the options of electric heat pumps (blue), district heating networks (orange, brown, pink) and renewable gas driven (yellow). The different shades of each color indicate the year for when the transition is planned. Figure K.2 illustrates three reference scenario model simulation stills for this study for the Amsterdam municipal region for 2035 (left) and 2050 (middle and right). The middle and right model simulation stills differ in the availability of hydrogen technology, as the transition vision heat for Amsterdam does not include hydrogen as a viable thermal system option.

Comparing the Transition Vision Heat with the simulation results for the reference scenario yields a very similar distribution of thermal systems for Amsterdam's neighborhoods. The most dominant sustainable thermal systems in the model's simulation are the low and high temperature district heating networks, which geographically correspond to the Transition Vision Heat of Amsterdam, which distinguish local sources (most likely low temperature heating networks) and externally sourced heat networks (most likely medium or high temperature heating networks). Noteworthy is the grey city center of Amsterdam in the simulation results for 2050. This is the result of the assumption that very poor insulated neighborhoods can not make the transition until they are sufficiently insulated. This does not correspond completely with the Transition Vision Heat, where these city center neighborhoods are projected to be heated by renewable gasses around 2040 (which is the latest trajectory), which slightly validates the simulations results anyway. The city center neighborhoods are projected to be heated by non-renewable gas heat pumps, which are not included as thermal system options in the simulation model. The Transition Vision Heat's outliers in the form of all-electric and renewable gas-driven neighborhoods correspond with the simulation models results.

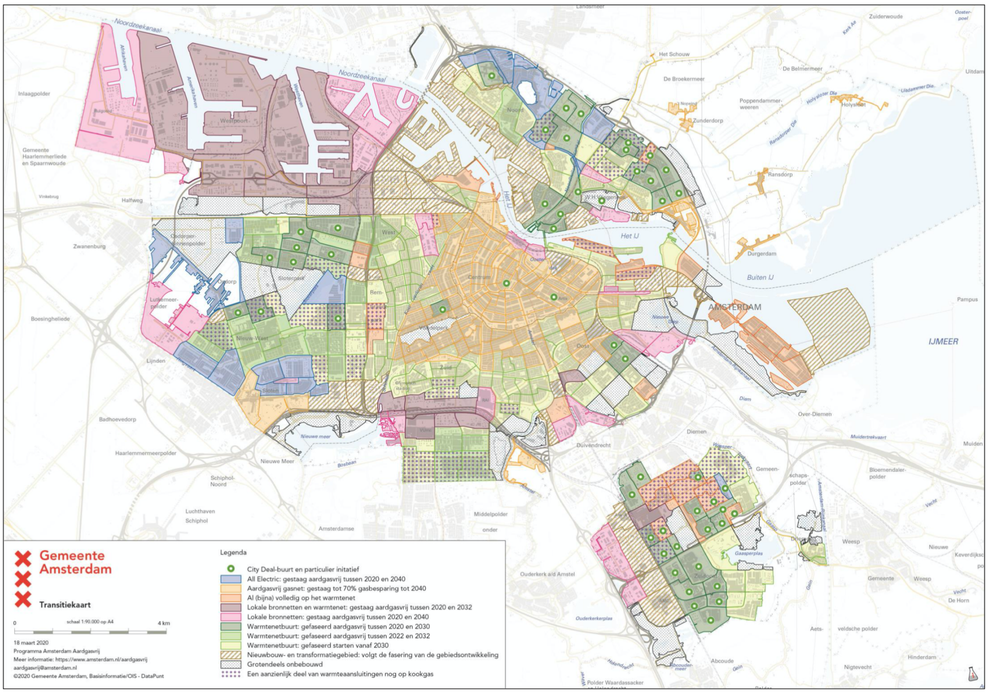



**Figure K.1:** *Meta-analysis of thermal system distribution in Amstelveen municipal region for four different models. Copied from Transitie Visie Warmte report, page 25 (Over Morgen and Gemeente Amsterdam, 2020)*

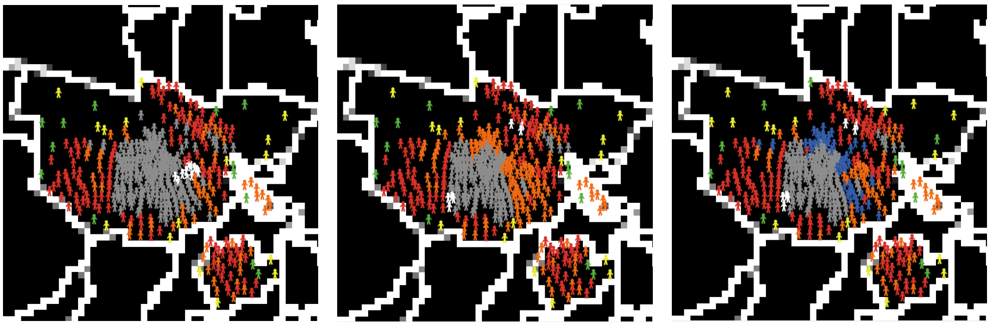


**Figure K.2:** *Three model simulation screen captures of the Amsterdam municipal region. Left is a simulation still of 2035, in the middle for 2050 without hydrogen availability and on the right for 2050 with hydrogen availability from the year 2035. Grey are natural gas driven neighborhoods, green are green gas heat pump, yellow are all-electric driven neighborhoods, orange are low-temperature DHC driven neighborhoods, red are high/medium temperature driven neighborhoods and blue are hydrogen heat pump driven neighborhoods*

### *Drechtsteden region*

Model dynamics on the local level for the Drechtsteden region are compared to results of the VESTA-MAIS model by PBL Schepers et al. (2019). Figure K.3 describes the model results for the Drechtsteden region from the PBL VESTA-MAIS model. The colors in this figure indicate which thermal systems are implemented in which neighborhoods, with the options of electrical heat pumps (blue), high-temperature DHC's, low-temperature DHC's and grey are other not disclosed alternatives. Figure K.4 illustrates three reference scenario model simulation stills for this study for the Drechtsteden region for 2035 (left) and 2050 (middle and right). The middle and right model simulation stills differ in the availability of hydrogen technology, as the PBL model does not include hydrogen as a thermal system option.

Validating the model for the local Drechtsteden region level yields comparable results for certain model parameterizations. Comparing the PBL results with the simulation results of the model designed in this thesis yields that for specific parametrizations, model results are comparable. The PBL results closely correspond to the 2050 model still without hydrogen availability (the middle still in figure K.4). Scanning both images concludes a similar behavior in where electricity, high-temperature DHC's and low-temperature DHC's are implemented. While it is difficult to compare on a neighborhood basis, the comparable layout of both images indicates validity in the model results if parametrization is set accordingly.

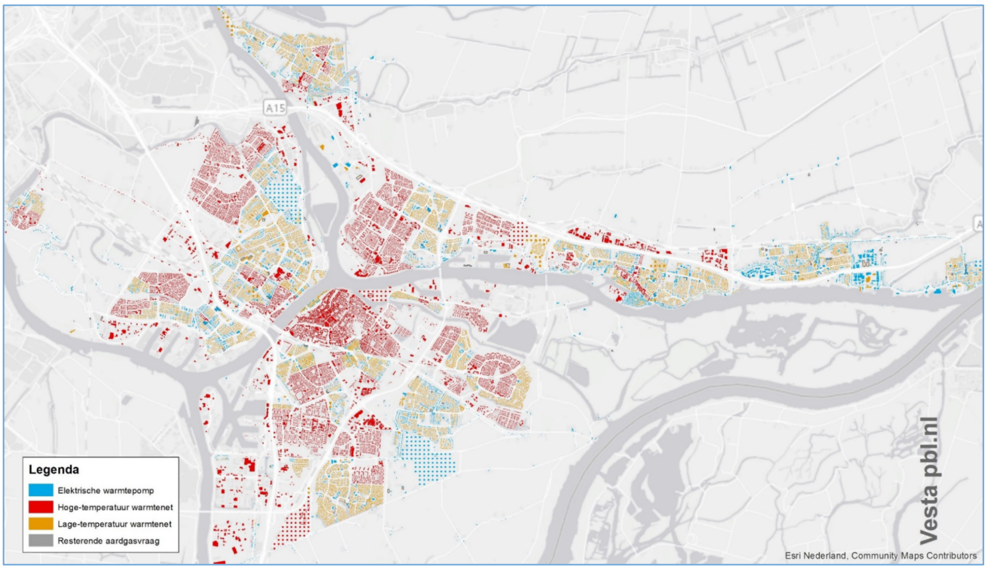



**Figure K.3:** *Thermal system distribution in Drechtsteden region for most cost effective technical end-state. Copied from PBL report, page 9 (PBL, 2018).*

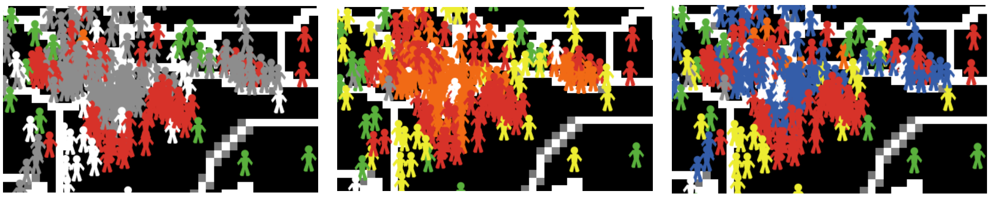


**Figure K.4:** *Three model simulation screen captures of the Drechtsteden region. Left is a simulation still of 2035, in the middle for 2050 without hydrogen availability and on the right for 2050 with hydrogen availability from the year 2035. Grey are natural gas driven neighborhoods, green are green gas heat pump, yellow are all-electric driven neighborhoods, orange are low-temperature DHC driven neighborhoods, red are high/medium temperature driven neighborhoods and blue are hydrogen heat pump driven neighborhoods*

# L EXPERIMENTS

This appendix presents the supplementary findings of several experiments performed with the model. The goal of the experiments is to extract the models general behavior and sensitivity to parameters and assumptions and extracting insights that may support conclusions for the research question.

## L.1 GENERAL MODEL BEHAVIOR AND ASSUMPTIONS

### *National transition goal*

The first model variable that is tested is the national transition goal. This model variable indicates the national speed in households per year that is striven for. This parameter affects the transition goal that municipalities are aiming for. The municipalities' goal is a combination of the national goal and the municipalities number of households. A higher national transition goal implicates municipalities *wanting* to transition more neighborhoods.

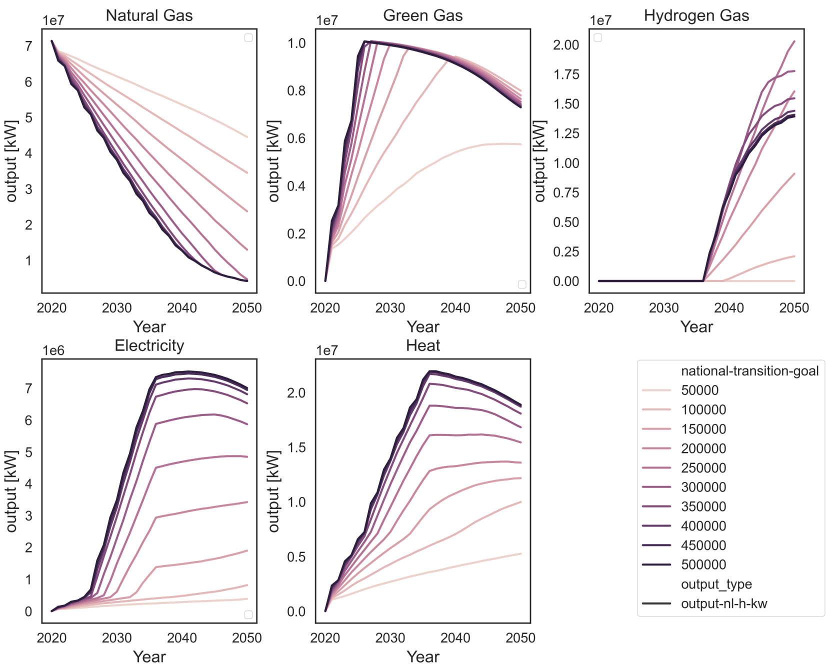



**Figure L.1:** *Peak energy demand output behavior for the varying the national transition speed goal.*

Figure L.1 describes the effect of increasing the national transition goal from 50,000 to 500,000 households per year. The overall trend that can be observed is an steeper downward slope in natural gas development as the transition increases its speed. The resulting effect for the renewable sources is opposite to the natural gas trend, implicating an increasingly steepening trend as the national transition goal increases. Three noteworthy observations in this figure can be done. First, that an increase over 350,000 households per year seems to be the limit for the reference scenario in terms of output returns. The second observation is the decreasing energy output for hydrogen when the speed is increased over 400,000 households per year. The final observation of interest is that even in the scenario of 100,000 household transitions per year in the Netherlands, green gas supply seems to reach its limit before 2040.

Conclusion: the national transition goal seems to have significant effect on all energy outputs. All trends are affected by varying the national transition speed. Investigating output at municipal and MR station level also indicates that in certain circumstances, increasing the speed over certain higher levels, also changes the direction of change for the output. This effect is also observed on a national level with hydrogen.

### *Municipal resource percentage*

The municipal resource percentage parameter influences the amount of neighborhoods a municipality can transition at the same time relative to the municipalities size. The higher the parameter, the more neighborhoods a municipality *is able to* transition.

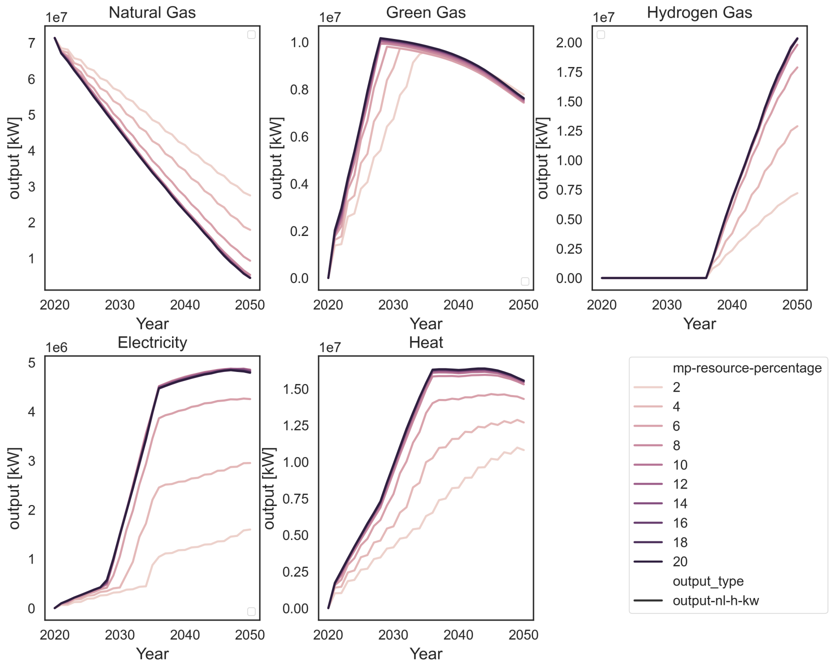



**Figure L.2:** *Peak energy demand output behavior for the varying the municipal resource percentage.*

Figure L.2 describes the effect of increasing the resources for transitioning neighborhoods with municipalities. The overall trend that can be observed is that increasing the amount of resources also increases the speed at which natural gas use is decreased, and the renewable sources are increased. However, an increase over 8 percent does not seem to increase these slopes any further.

Conclusion: the amount of resources that are available for municipalities to transition their neighborhoods seems to have a bounded effect on energy output. All energy development trends are impacted, but to a limited extent. Observing the effect of increasing municipal resources on the municipal and MR-region level indicates a similar conclusion, but the boundary of the resource percentage varies per region.

#### *Neighborhoods transition duration*

The neighborhood transition duration variable indicates how long a neighborhood takes from starting their transition to finishing it. An increasing duration means that municipalities have less room for starting new transitions, as currently transitioning neighborhoods stay in transition for longer.

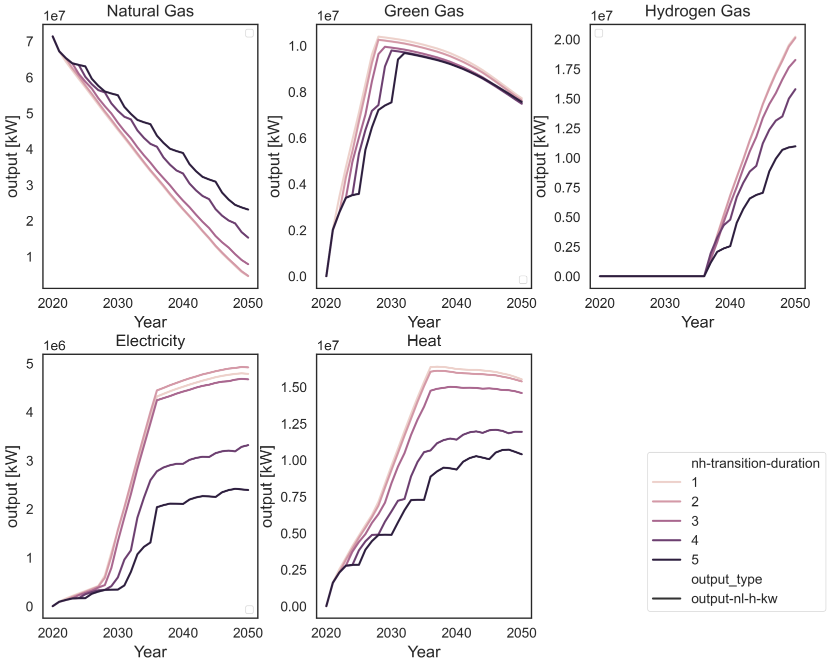



**Figure L.3:** *Peak energy demand output behavior for the varying neighborhood transition duration.*

Figure L.3 shows the effect of increasing the duration of a transition from 1 to 5 years. The overall trend observed is that an increasing duration has a negative effect on the reduction of natural gas development. While renewable gasses seem to be increasingly less steep when the duration is increased. The effect of this parameter seems to be the least on green gas, as the output converges to the same output, but a little less fast. While the effect on electricity seems the most. An interesting observation is that the transition duration of 1, 2 and 3 seem to be grouping together and vary less than a duration of 4 or 5 years.

Conclusion: the effect of the transition duration for neighborhoods is quite significant on energy output. An increasing duration tends to slow down the transitions goal towards sustainability, with most notable effects of increasing the duration over 3 years. Observing the effects on municipal and MR region level yields more interesting insights, as some regions show an inversing effect after an increasing duration.

### *Low insulated neighborhoods cannot transition*

The next model variable that is tested is whether low insulated neighborhoods are eligible for a transition by their municipalities. When this variable is TRUE, neighborhoods with an insulation level below 3.5 can not be asked by their municipality to transition to any of the sustainable thermal systems.

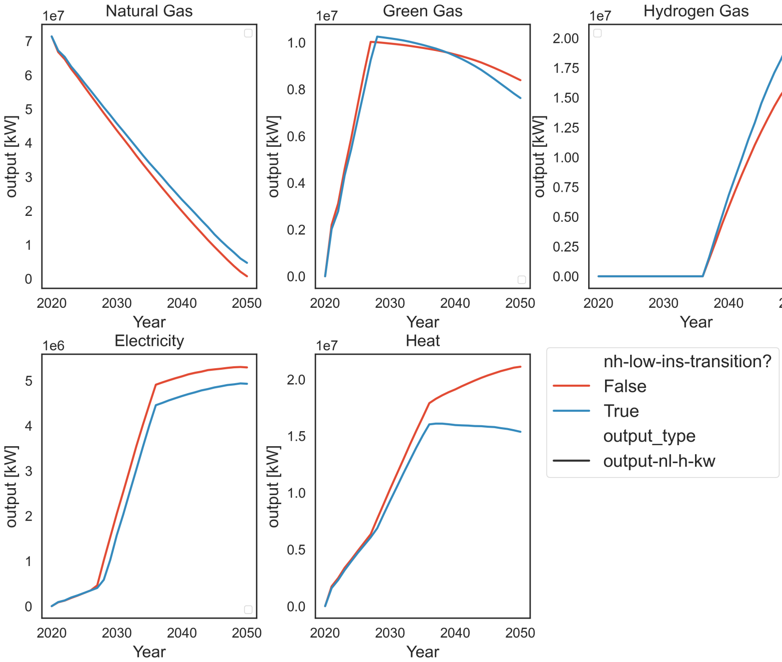



**Figure L.4:** *Peak energy demand output behavior for the assumption whether low insulated neighborhoods can transition or not.*

Figure L.4 describes the difference in model behavior when the assumption described above is either true or false. It shows that the speed at which the natural gas peak demand declines is slightly less than when all neighborhoods can transition regardless of their insulation level. This results in neighborhoods being limited to make a transition when their insulation level is not sufficient. The green gas demand development shows that the output ceiling for green gas is reached a little earlier when all neighborhood transition levels are eligable for a transition, but peaks higher from around 2040. The hydrogen output shows diverging behavior from the moment it becomes available around 2035 by a sharper increase of output when all neighborhood insulation levels can transition. Electricity and heat show similar behavior in their output with a higher increase in output from the start for the assumption when poorly insulated neighborhoods cannot transition. Conclusion: the assumption does not seem to have a drastic effects on national output levels. Investigating MR regions and municipalities for their output indicates that the same conclusion can be drawn on their levels of aggregation.

### *Insulation strategy for neighborhoods*

The insulation strategy of neighborhoods determines the speed at which neighborhoods increase their insulation level. An insulation strategy of 0 indicates that no increases in insulation level occur, while an insulation strategy of 80 indicates the highest possible insulation development of neighborhoods.

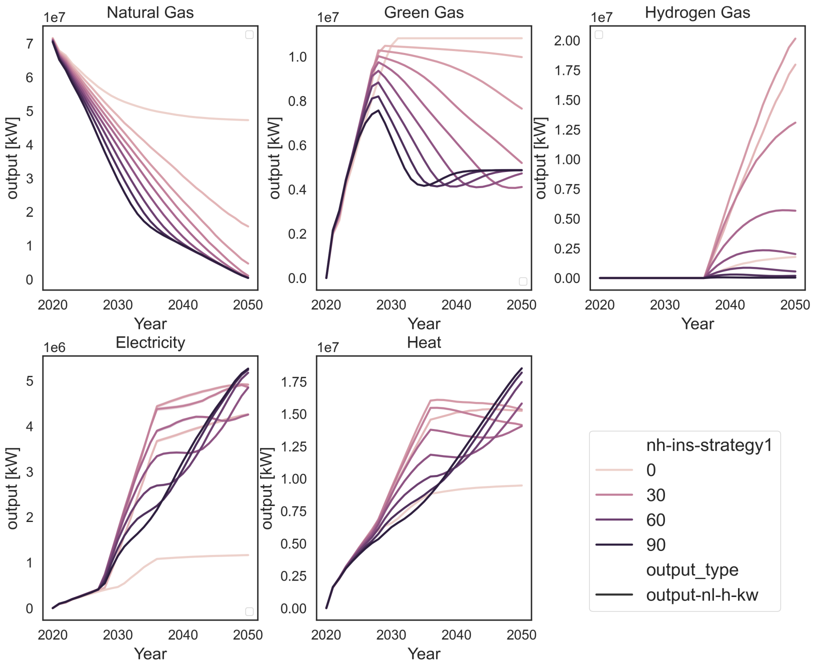



**Figure L.5:** *Peak energy demand output behavior for varying the insulation strategy of neighborhoods.*

Figure L.5 describes the model behavior for increasing levels of the insulation strategy. For the natural gas demand output it shows an increasing downwards slope for more aggressive insulation strategies. Note that for strategies under 30 the natural gas peak demand does not completely converge to zero. This is the result of not all neighborhoods reaching the sufficient insulation level for making a transition as discussed in the previous subsection. The green gas demand output behavior indicates lower green gas demand output for higher levels of insulation strategy. Another observation of the green gas development is the upflicking and converging tails for higher insulation levels starting from 2030. Hydrogen output shows a clear trend of being more implemented for lower levels of insulation strategy (except for when no improvement in insulation is simulated). While electricity and heat show similar trends of lower insulation levels initially inclining faster, but from 2045 being exceeded by higher insulation strategies

Conclusion: the level of insulation strategies of neighborhoods has a significant effect on the energy demand output of the model. This results from the 1) insulation level having a direct effect on thermal energy demand of neighborhoods and 2) preventing or enabling neighborhoods from being eligable of making the transition to any susatinable thermal system at all. Further analysis of municipalities and MR regions on this assumption yields similar behavioral patterns as on the national level.

### *Importance of governance diffusion*

The importance of governance diffusion is the parameter that sets the weights for municipal decision strategy 4 between the Relative Advantage score and the Transition Activity score. A higher number for this variable implicates a higher weight for the Relative Advantage score in comparison to the Transition Activity score.

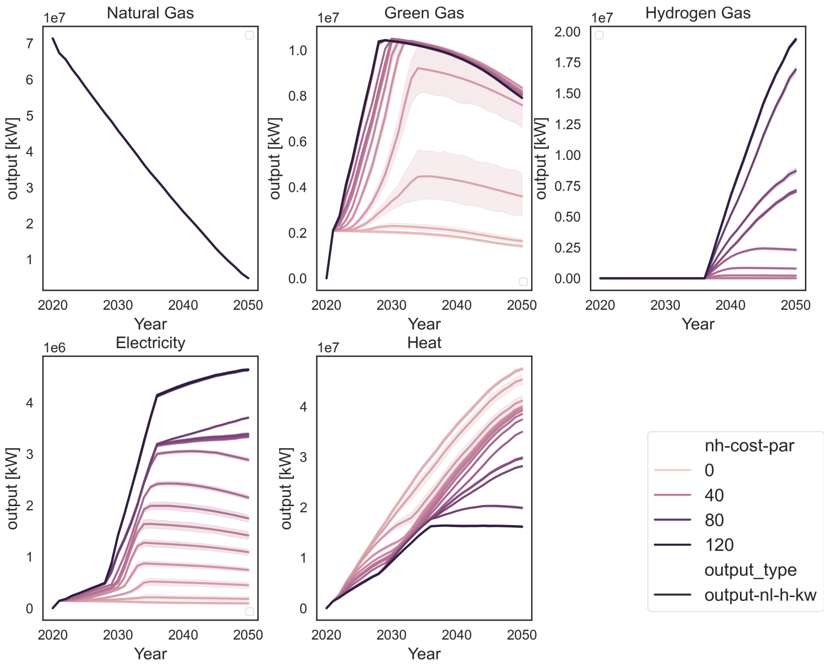



**Figure L.6:** *Peak demand output behavior for varying the weight between Relative Advantage score and Transition Activity score for municipalities.*

Figure L.6 describes the effect of varying the balance of the weight for the Relative Advantage score and the Transition Activity score for municipal decision strategy 4. The effect on the natural gas output is non-existent. Whereas its effects on green gas output are varying widely. The higher the weight towards the Relative Advantage score, thus taking activity by others less in consideration, the higher the green gas output. The same applies to hydrogen and electricity output. The inverse is true for heat demand output, which is increasing if transition activity by others is playing a more serious role in the decision making.

Conclusion: governance diffusion is impacting the distribution of to what thermal systems neighborhoods transition, highly favoring district heating systems over green gas, hydrogen and electricity systems. This trend is also observed on lower aggregation levels. Interestingly, urban industrial areas also show an increasing trend towards green gas, which is not in line with the national trend.

### *Limitation to HT/MT heatsources*

The limitation to HT/MT heatsources is a model assumption that if a neighborhood wants to transition to a HT/MT thermal system, it has to be connected to an existing heatsource. A RVO dataset (refer to appendix D) that contains such identified potential heatsources has been used for this purpose. When this assumption is turned off, it is assumed that a neighborhood can always transition to a HT/MT thermal system. This variable has no influence on the LT thermal system transition possibility.

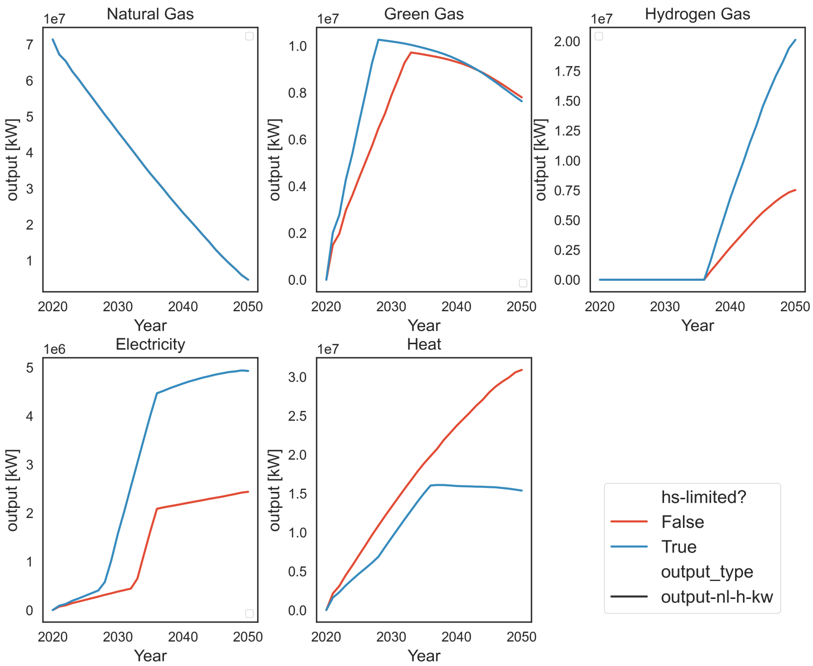



**Figure L.7:** *Peak energy demand output behavior for the assumption whether neighborhoods wanting to transition to a HT/MT system require a corresponding heatsource.*

Figure L.7 describes the effect of the assumption that neigbhorhoods wanting to transition to a HT/MT thermal system must connect to a physical heatsource nearby. The natural gas output suggests that this assumption has no influence on the speed at which natural gas use is reduced. It does however influence the sustainable alternatives. The green gas output shows that more neighborhoods are switching to green gas driven thermal systems if neighborhoods need to connect to an existing heatsource. The same behavior applies for hydrogen and electricity powered thermal sytems. Logically following from these observations, more heat is demanded from neighborhoods when their is no limitation in having a physical heatsource nearby.

Conclusion: the assumption that neighborhoods must have a nearby existing heatsource results in a restriction of heat demand in the model that is being dispersed over the other energy sources. Very similar behavior is oberved at lower aggregation levels.

### *Maximum distance to heatsource*

The maximum distance to HT/MT heatsources is a model variable that determines in what radius a neighborhood can connect to a potential HT/MT source. The higher the variable, the larger the radius. The location of heatsources is retrieved from a RVO dataset (refer to appendix D) that contains geographic locations of identified heatsources in the Netherlands.

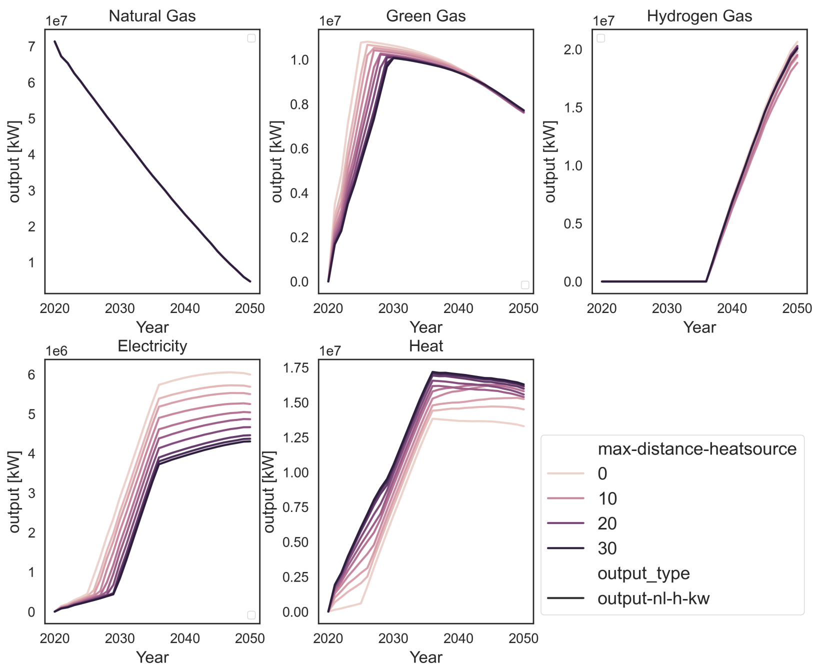



**Figure L.8:** *Peak energy demand output behavior for varying the distance in which neighborhoods can connect to an existing heatsource when wanting to transition to a HT/MT thermal system*

Figure L.8 shows the effect of the radius in which a neighborhood can connect to an existing heatsource when transitioning to a HT/MT thermal system. Natural gas output demand is not impacted by this model variable. However, all other energy demand outputs are impacted in a similar fashion. When the radius in which a neighborhood can connect to a heatsource increases, green gas, hydrogen and electricity output declines. Heat demand output shows the opposite effect as it increases with the maximum radius.

Conclusion: the distance to the heatsource is strongly influencing the distribution of sustainable thermal systems. The bigger the distance, the more potential heatsources can be connected to resulting in more output of heat demand. Also on the municipal and MR region level a similar trend is observed. Rural areas seem to be affected more by higher possible distances.

### *National green gas potential*

The national green gas potential is a model variable that determines the total stock of green gas that can be used for green gas thermal systems. The higher the variable, the more neighborhoods are able to transition towards green gas thermal systems. The variable is measured in PJ.

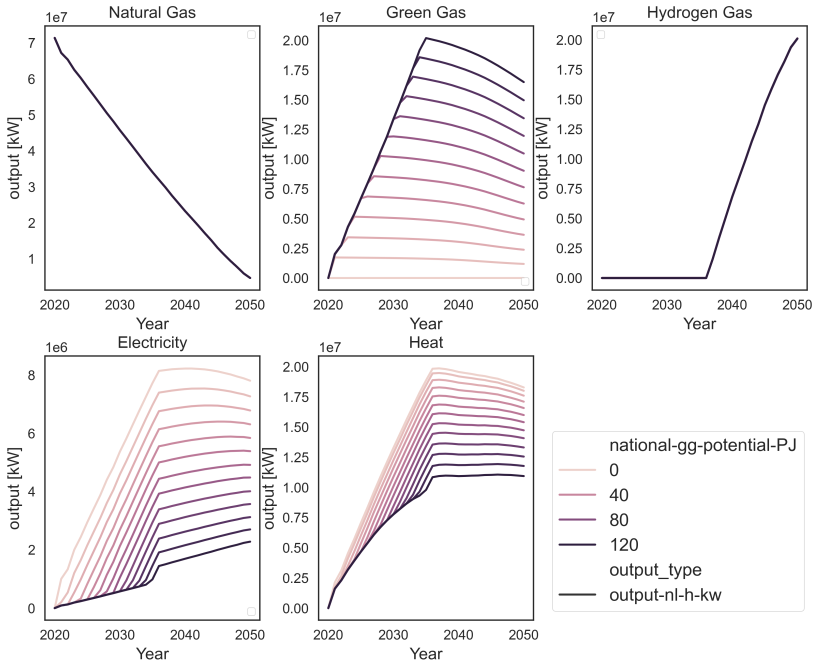



**Figure L.9:** *Peak energy demand output behavior for varying how much green gas potentially is available for neighborhood in the built environnment at a national level.*

Figure L.9 describes the effects of various levels of national green gas availability in the Netherlands. It indicates that the availability of green gas in the Netherlands will not have any effect on the speed at which the use of natural gas declines. For the green gas energy output it shows that an increase in national green gas availability evenly increases its resulting output. The use of hydrogen is not impacted as it only becomes available after the stock of green gas has been depleted. Electricity and heat demand output show similar output as green gas, but reversed.

Conclusion: the national green gas potential is strongly influencing the green gas demand output as expected. More green gas energy demand results in an evenly lower distributed energy output of electricity and heat, but does not seem to impact hydrogen energy demand output as this technology's availability is set after the depletion of the green gas stock. Lower aggregation levels show similar output behavior.

### *Hydrogen availability year*

The hydrogen availability per year indicates from what year the hydrogen hybrid heat pump technology comes available for neighborhoods. The variable indicates the year, meaning that a higher variable corresponds to later access to the technology.

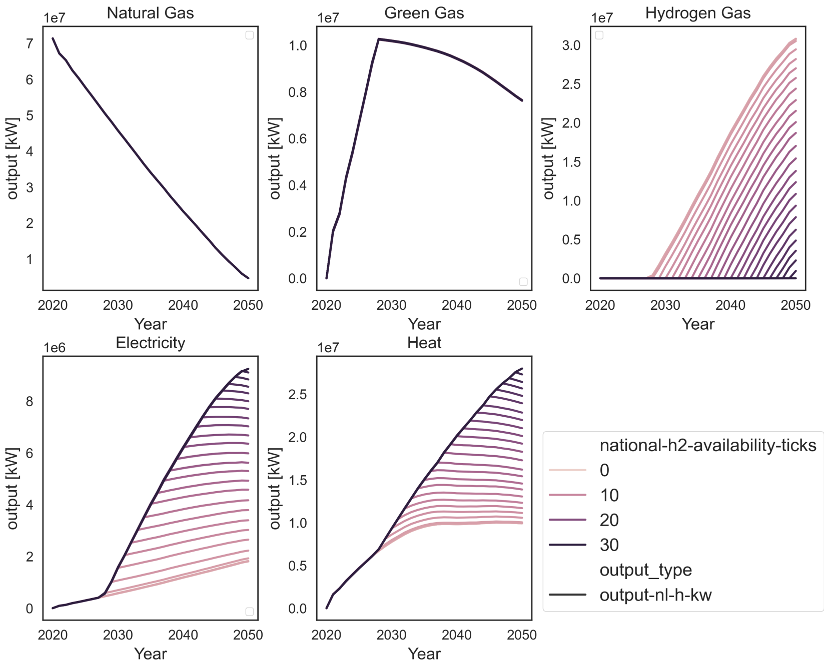



**Figure L.10:** *Peak energy demand output behavior for varying year at which hydrogen technology for thermal use in the built environment becomes available.*

Figure L.10 shows the effect of increasing the availability of hydrogen technology from year 2020 to 2050. The year at which hydrogen becomes available has no influence on the development of natural gas and green gas output. It does influence the output of hydrogen output as hydrogen output increases when the technology becomes available earlier. An increase of the hydrogen output comes at the expense of electricity and heat output.

Conclusion: the availability of hydrogen highly impacts electricity and heat output as they are inversely related to each other. It does not impact the output of green gas or speed at which natural gas is declining. Similar trends are observed on lower aggregation levels

## L.2 INFLUENCE OF MUNICIPAL DECISION-MAKING STRATEGIES

The second set of experiments for this model are aimed towards finding how the model outcomes react to the different implemented municipal decision-making strategies. Similar plots as in the previous section will be used to visualize trends as a result of changing input variables. The experiments are performed by keeping the other model parameters constant at the reference parameterization from section H.5. The runs of the model are replicated 100 times. The design of the experiment is described below in table L.1:

| **Experiment** | **Variable** | **Values** |
|---|---|---|
| *Municipality decision strategy* | mp-transition-strategy | [0 1 2 3 4] |

Table L.1: *Design of experiment for understanding the impact of the municipal decision-making strategies on the model output.*

The municipal transition decision strategy determines how a municipality instigates the transitions for their neighborhoods. This can be varied in which neighborhood is transitioned first, and second, how a thermal system is eventually decided upon.

In this section of the behavior analysis, more emphasis will be put on the behavior at the municipal level, as the impact of varying the strategies will emerge from the lowest level upward.

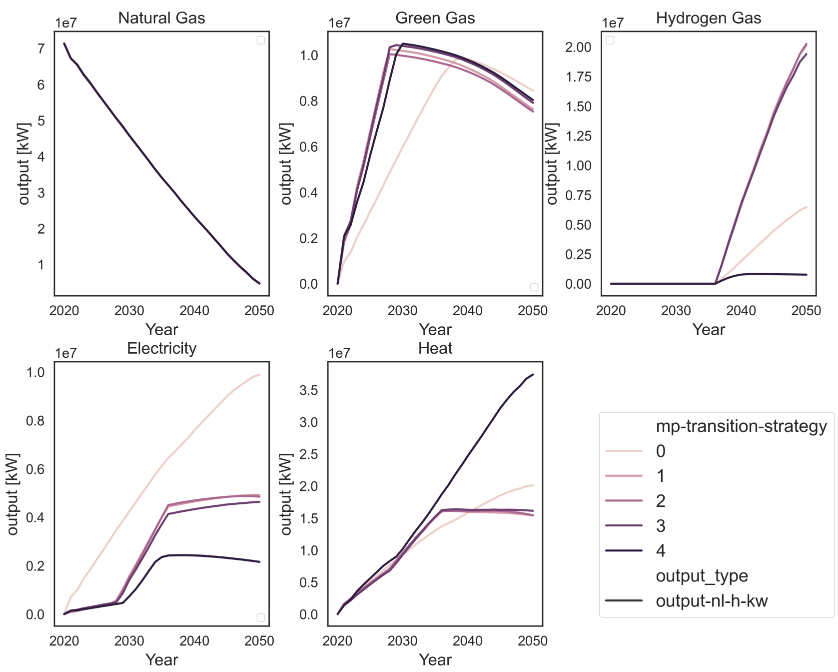



Figure L.11: *Peak energy demand output behavior for the 5 different municipal decision strategies tested.*

***Comparing strategic trends on the national level***

Figure L.11 described the model behavior on the national aggregation level when varying the implemented decision strategy for the reference scenario. The natural gas trend indicates that there is little variation in the speed at which the national natural gas usage declines. The other energy sources do show variation in their output. The green gas trend indicates a very similar development pattern for strategies 1 till 4. Strategy 0 shows a less steep upward incline untill around 2035, after which all strategies tend to converge within a 10% margin as a result of capped green gas stock. Hydrogen energy demand development shows very similar behavior for strategies 1, 2 and 3, but very deviating behavior for strategies 0 and 4. Strategy 4 is very dependent on previous actions by other municipalities, which could not have chosen for hydrogen alternatives, thus resulting in poor favorability for this thermal system. The random strategy significantly underestimates the more directed strategies 1, 2 and 3. Electricity peak demand trends are similar to hydrogen in a sense that the same strategies tend to group in behavioral output. Strategy 0 and strategy 4 again are either over or underestimating in comparison to strategy 1, 2 and 3. And finally, heat development tends to somewhat converge to the same output levels for strategies 0, 1, 2 and three, excluding 4. While the random strategy 0 does overestimate by around 15 %, its trend is somewhat comparable. Strategy 4 is highly overestimating electricity use compared to the other strategies.

From these trends it can be concluded that on the national level, strategies 1, 2 and 3 perform very similarly, only deviating from each other by a minor margin. Strategies 0 and 4 tend to show different behavior, except for natural gas and green gas development.

### L.2.1 Comparing the coefficient of variation between MR-stations

The following two figures describe the coefficients of variation for all MR-stations for methane and all gas. The sensitivity to varying the strategies can be observed per MR-station.

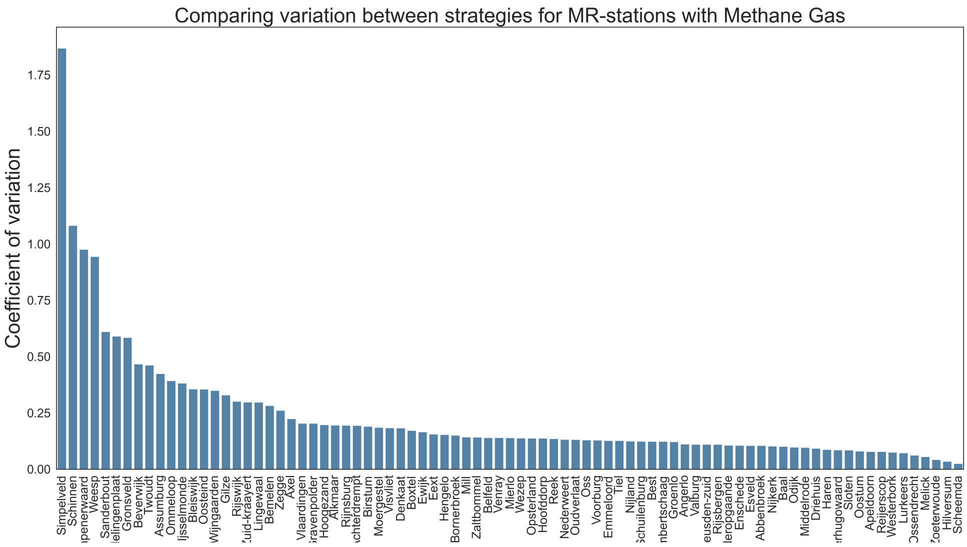



**Figure L.12:** *Comparing the coefficients of variation between all MR-stations for strategies 0, 1, 2, 3 and 4 on Methane Gas peak demand in 2050.*

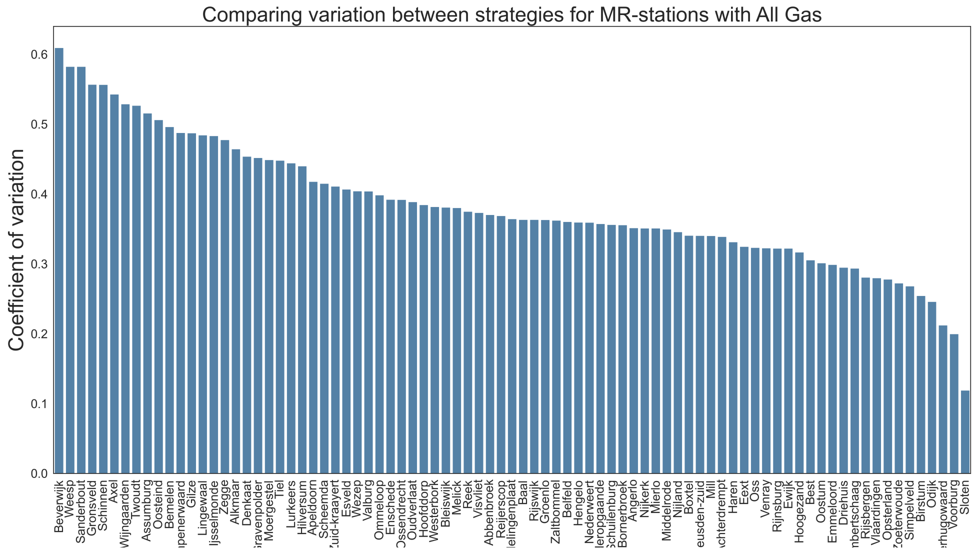



**Figure L.13:** *Comparing the coefficients of variation between all MR-stations for strategies 0, 1, 2, 3 and 4 on All Gas peak demand in 2050.*

### L.2.2 Reflecting on initial experiments

**INFLUENCE OF NEIGHBORHOOD AND THERMAL SYSTEM SELECTION STRATEGIES ON THE NATIONAL LEVEL** For the experiments presented in table **??** and L.11, the model output is analysed for isolated change in the municipal transition strategies and tested for the reference scenario. For the national level, we can observe whether strategy difference in neighborhood selection and thermal system selection influences model output. It learns us a few things. The first observation from these results is the grouping of strategies 1, 2 and 3 whereas strategies 0 and 4 tend to deviate from the group for hydrogen, electricity and partially heat output.

From this observation it can be concluded that how thermal system selection takes place by municipalities significantly influences the development of the thermal transition. Strategies 1, 2 and 3 are similar in how they select the thermal systems for neighborhoods, but are different in how they select the neighborhoods that they want to transition. Strategy 0 selects the neighborhoods thermal system randomly, whereas strategy 4 incorporates decisions of other municipalities in the network. Inspecting the model output for strategies 0 and 4 indicates that difference in thermal system selection significantly influences the development of this transition.

Where thermal system selection strategy seems to significantly alter the development of the transition, the grouping of strategies 1, 2 and 3 seems to indicate that neighborhood selection strategy does not seem to matter significantly. Strategies 1, 2 and 3 are similar in how they select a thermal system for a neighborhood, but different in how the order of transitions for neighborhoods is determined. On a national level for the reference scenario, the development of energy demand for all energy sources is very similar for these strategies, indicating no significant difference.

### L.2.3 Reflecting on inverted strategies

The two previous paragraphs discussed the behavioral effects of the different implemented municipal-decision strategies. An analysis of these five strategies suggested that the strategy determining the thermal system selection for neighborhoods does have a significant effect on the models behavior, but that the neighborhoods order strategy does not. The conclusion that neighborhood selection is not a significant contributing factor to the development of the thermal transition of the built environment is based on three different strategies: 1) random neighborhood selection, 2) based on least regret and 3) based on neighborhood characteristics.

To further test the hypothesis that neighborhood selection is not all that important, a new set of experiments is performed. These experiments include strategies 2 and 3 with their inverted variants. By inverting the selection process for both neighborhood selection and thermal system selection, a well argumented conclusion can be drawn whether neighborhood selection and thermal system selection are indeed important or not. If the inverted strategies perform similar or comparable to the regular strategies, the selection strategy is significantly influencing the models behavior. Table L.2 describes the design of experiments for these additional strategies.

| | **Neighborhood selection** | **Thermal system selection** |
|---|---|---|
| *Strategy 2* | Highest Relative Advantage | Highest Relative Advantage |
| *Strategy 2, neighborhood inverted* | Lowest Relative Advantage | Highest Relative Advantage |
| *Strategy 2, thermal system inverted* | Highest Relative Advantage | Lowest Relative Advantage |
| *Strategy 2, neighborhood and thermal system inverted* | Lowest Relative Advantage | Lowest Relative Advantage |
| *Strategy 3* | Highest Neighborhood Likelihood | Highest Relative Advantage |
| *Strategy 3, neighborhood inverted* | Lowest Neighborhood Likelihood | Highest Relative Advantage |

**Table L.2:** *Experiment for inverted strategies with the reference scenario.*

#### INFLUENCE OF REGULAR AND INVERTED STRATEGIES ON NATIONAL LEVEL

The hypothesis that neighborhood selection is not important, but thermal system selection is, can be confirmed for the national level based on these experiments with regular and inverted strategies. Figure L.14 describes the model behavior for thermal energy demand and how it reacts to the different regular and inverted strategies. When different strategies show similar output development, this indicates that the different strategies do not result in different energy demand behavior for this aggregation level.

Two clear groups can be distinguished: 1) the group which has inverted the thermal system selection and 2) the group that has not inverted its thermal system selection. Based on the output behavior of these two groups two conclusions can be drawn that further strengthen the conclusions from the observations of the initial experiments. The first conclusion is that when municipalities choose exactly the opposite thermal systems than what is considered a 'good practice' for the respective neighborhood types, significantly different energy demand output is generated. The assumptions for the Relative Advantage table that drive the decision-making of municipalities is therefore of crucial importance for the behavior of this model. The second conclusion is that the neighborhood selection strategy is not significantly influencing the thermal energy demand of the thermal system in the built environment on the national level. Even when the transition order of neighborhoods is inverted for selected strategies, only minor changes in output behavior are observed.

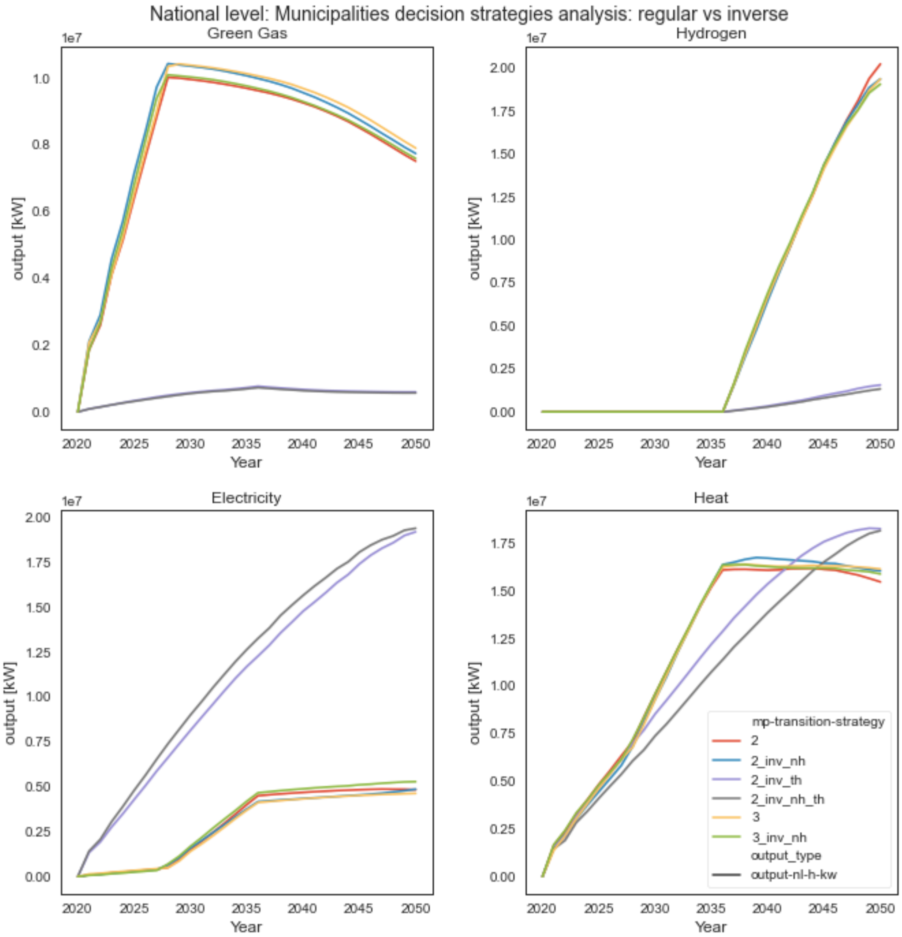



Figure L.14: *Influence of regular and inverted variants of municipal decision strategies on thermal energy demand on the national level.*

**INFLUENCE OF REGULAR AND INVERTED STRATEGIES ON THE MR-REGION LEVEL** Analysing the influence of the regular versus inverted strategies on the MR-region level yields mostly similar conclusions as the national level, but a lot more nuance is necessary for this aggregation level.

The variability between the neighborhood selection strategies on MR-regions seems to derive from three factors. The first factor is a consequence of small fractions being more susceptible to varying probabilities. By observing the behavior of energy demand development per MR-region as a result of the different strategies, it is found that energy demand of a particular source for a given MR-region is especially susceptible for different neighborhood selection strategies when the fraction of this particular source in the total energy demand is low. This correlation is illustrated in figure L.15. For example, when a MR-region only has a minor share of neighborhoods that prefer to transition to green gas, the order of neighborhood transitions matters has a larger effect as the green gas stock may have been depleted earlier. Also, a different decision for one neighborhood when the fraction for a particular energy demand is small contributes to a larger change.

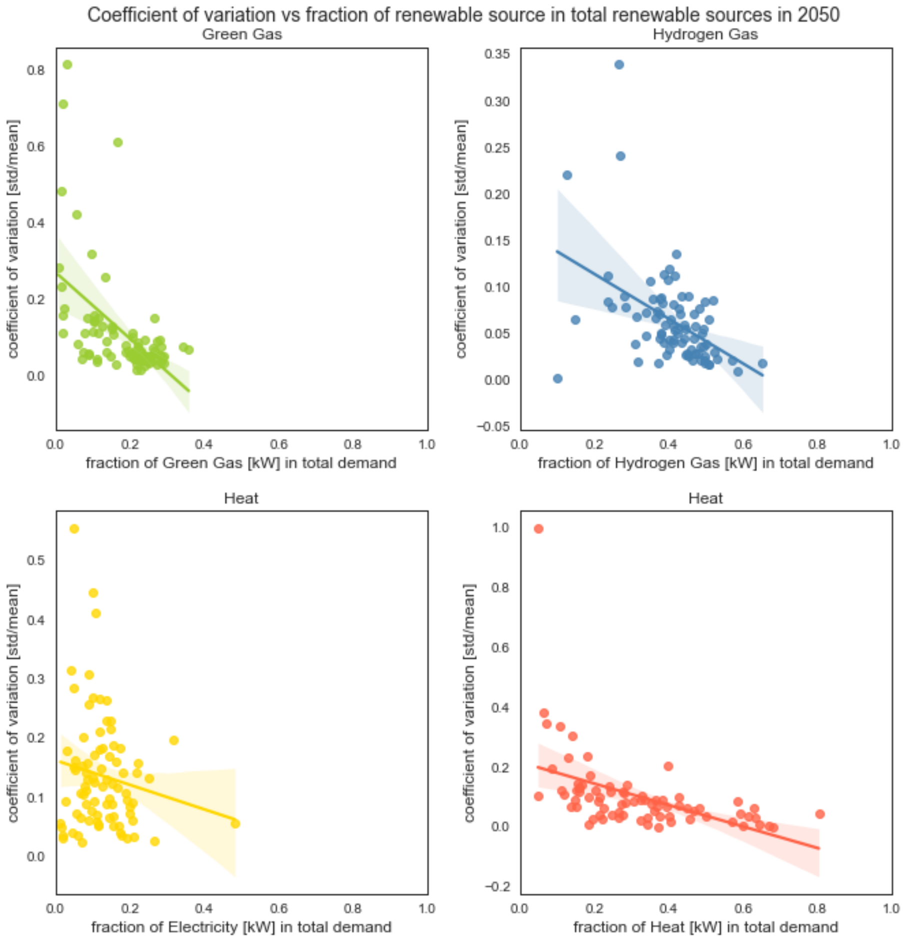



**Figure L.15:** *Correlation between the fraction of energy demand in the total energy demand and its coefficient of variation. The coefficient of variation is calculated as the standard deviation divided by the mean.*

The second factor contributing to the order of neighborhoods being not of particular influence on energy demand is that there is not enough differentiation between neighborhoods with the used datapoints. Strategies 2 and 3 differentiate based on no-regret and neighborhood likelihood. However, due to the use of limited datapoints and thermal systems the difference in preferability between neighborhoods is not significant in many cases. As such, when neighborhoods are relatively comparable within one municipality for a given set of resources for this municipality and the national transition goal, the selection order for neighborhoods is not really different than being random.

The third factor contributing to the order of neighborhoods being not of importance in most MR-regions is that instead of order between neighborhoods is being created over the years, it is being generated within one year (or tick) as a result of the conceptual design. The conceptual design of the model implicates that municipalities will maximize their resources at all times in a given year when possible. Only when all their resources are used, they stop performing actions in a year. When the preferred option of a particular strategy is no longer available, it switches to transitioning second-best neighborhoods. As such, resource maximization of municipalities is bypassing the order given to neighborhoods by transitioning nd-best neighborhoods when first preferred neighborhoods are out of bounds for resources at a given moment.

**CONCLUSION ANALYSIS MUNICIPAL DECISION-MAKING STRATEGIES** Analysing the different implemented and supplementary municipal decision-making strategies on both the national level and lower aggregated levels learns us that municipal decision-making strategies are important for moving the transition forward and are shaping the energy demand configuration to a limited extent. First, it is found in section [refer section 9.1] that the national transition goal, the municipalities resources and the transition time of neighborhoods shape the speed of this transition and may alter its transition paths. Second, by varying the strategies how municipalities determine the transition order of their neighborhoods, it is found that neighborhood selection strategies are not significantly influencing development of thermal energy demand on a national level and only to a limited extent for some MR-regions. But this seems to be caused by conceptual design implications and model artifacts. Confirming whether the order of neighborhoods transitioning is of importance is therefore not possible. And finally, the strategy for the final selection process which thermal system is to be implemented in a neighborhood is found to be an important driver for the development of thermal energy demand per energy source. Strategies that do not solely rely on the predefined Relative Advantage factor show significantly other results in energy demand development. Suggesting that the understanding that municipalities have which thermal system is best fitting to what particular neighborhood is of great importance. Therefore it can be concluded that the amount of households transitioned per year and the strategy determining to which thermal system they transition influence the systems behavior, but that the order in which the neighborhoods are transitioned has a limited effect.

## L.3 GASUNIE SCENARIOS

This section provides additional plots resulting from simulating the stakeholder-driven scenario's as discussed in section 5.2.3.

### L.3.1 Results per scenario

**SCENARIO G1** Figure L.17 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G1. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.

This scenario is characterized by early hydrogen availability, reference green gas availability and a modest insulation speed for neighborhoods. Looking at figure L.16, national green gas output peaks before 2030 and remaining fairly stable after this peak. Hydrogen becomes available in 2035, which shows in the hydrogen share being the only energy output rapidly increasing. Electricity and heat increase their share in the thermal energy mix up till 2035, after which they remain stable.

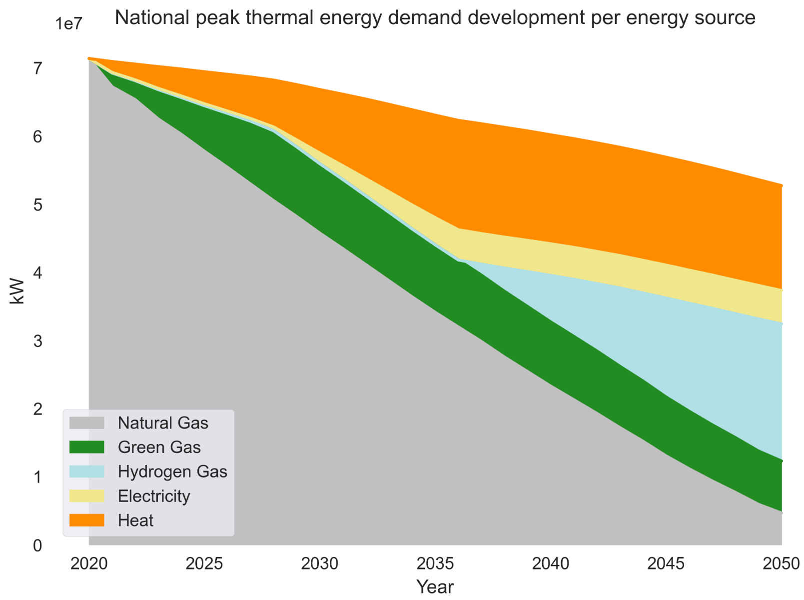



**Figure L.16:** *Peak energy demand output for scenario G1 per energy source.*

Figure L.17 represents the local development of the renewable gasses for 2030, 2040 and 2050. In terms of absolute gas output development, hydrogen is most used in urban areas, whereas green gas seems to be developing more in rural areas. In terms of relative change, a clear trend difference between the western Randstad and eastern provincial areas can be observed. Urban areas tend to use less methane gas towards 2050 than rural areas. Whereas hydrogen seems to dampen the effect of declining gas use over all regions.

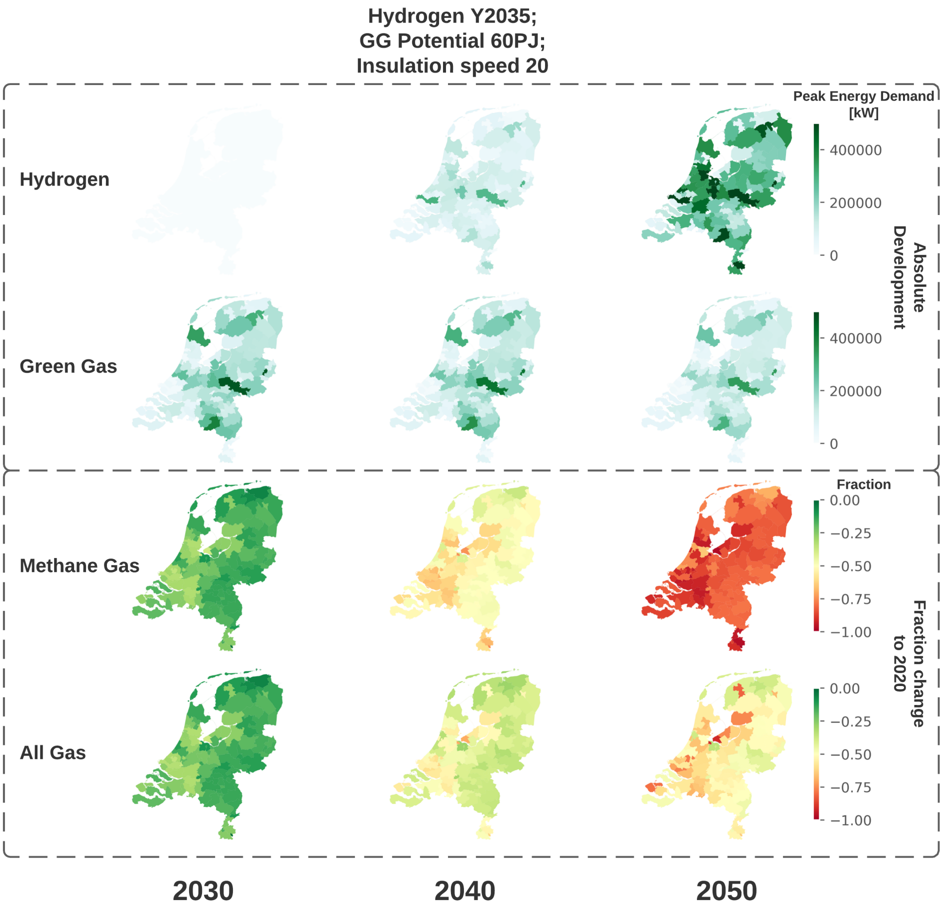



**Figure L.17:** *Peak gas demand output for scenario G1 for 2030, 2040 and 2050.*

**SCENARIO G2** Figure L.19 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G2. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.

This scenario is characterized by early hydrogen development, reference green gas availability and a high insulation speed for neighborhoods. The difference with scenario G1 is thus the doubling of the insulation speed for neighborhoods. Looking at figure L.18, the first observation is that the total energy output is halved as a a result of the doubling of the insulation speed. The second observation is that the share of hydrogen is much smaller in the total output than in scenario G1. The green gas output is only marginally smaller than in scenario G1, indicating that the same level of green gas stock is used for thermal heating in the built environment. Heat and electricity have a larger share than renewable gas in the total output than in scenario G1.

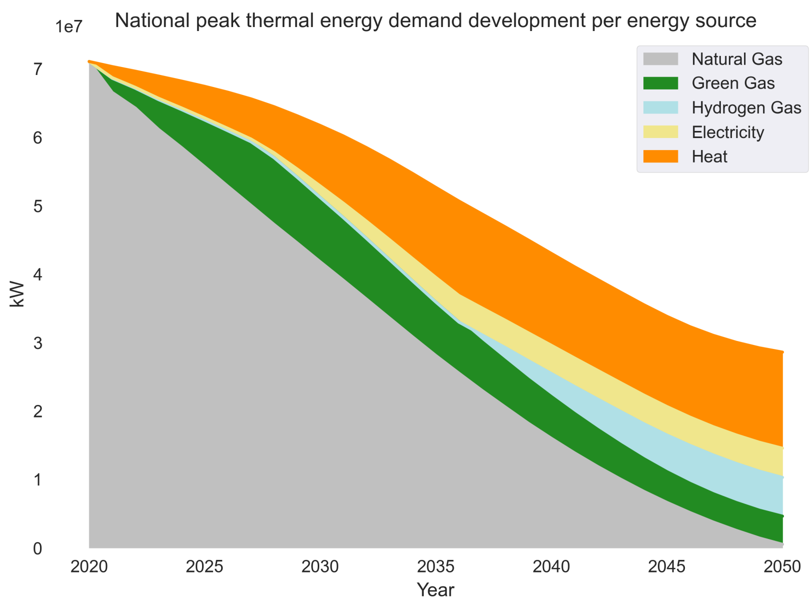



**Figure L.18:** *Peak energy demand output for scenario G2 per energy source.*

Figure L.19 shows a similar scenario to G1, except for a higher speed of insulation for neighborhoods. The result is less use of hydrogen and green gas than in scenario G1 throughout all of the Netherlands, except for the Rotterdam, The Hague, Utrecht and Amsterdam area. When looking at the combined gasses and their fraction development, the same trends can be observed as in scenario G1, but then with a stronger decline of overall gas use. This means that around 2040 all throughout the Netherlands, overall gas use will be reduced by 50% and in 2050 by 75 to 100 %.

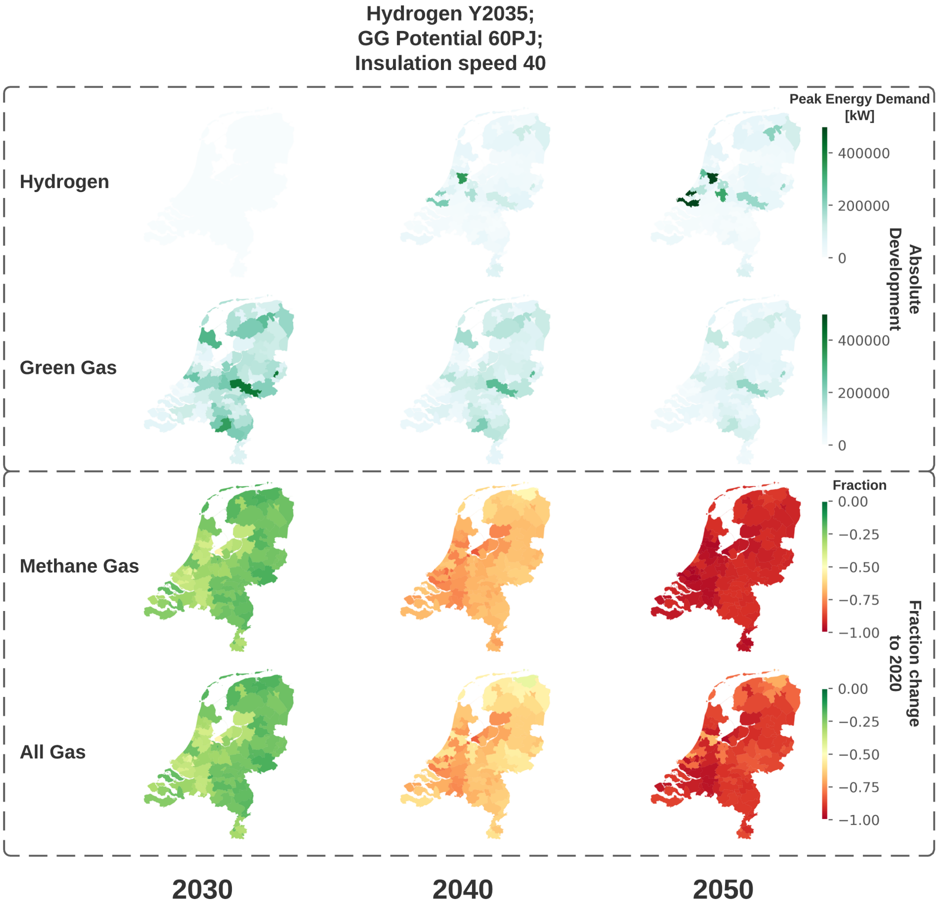



**Figure L.19:** *Peak gas demand output for scenario G2 for 2030, 2040 and 2050.*

**SCENARIO G3** Figure L.21 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G3. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.
This scenario is characterized by early hydrogen development, double the green gas availability and a modest insulation speed of neighborhoods. The difference with scenario G1 is the doubling of green gas availability. Looking at figure L.20, the most notable observation is the significant share of green gas and hydrogen use. Electricity is only contributing a little to the total share. Heat is only increasing towards 2035, after which is remains stable. This scenario is highly gas driven.

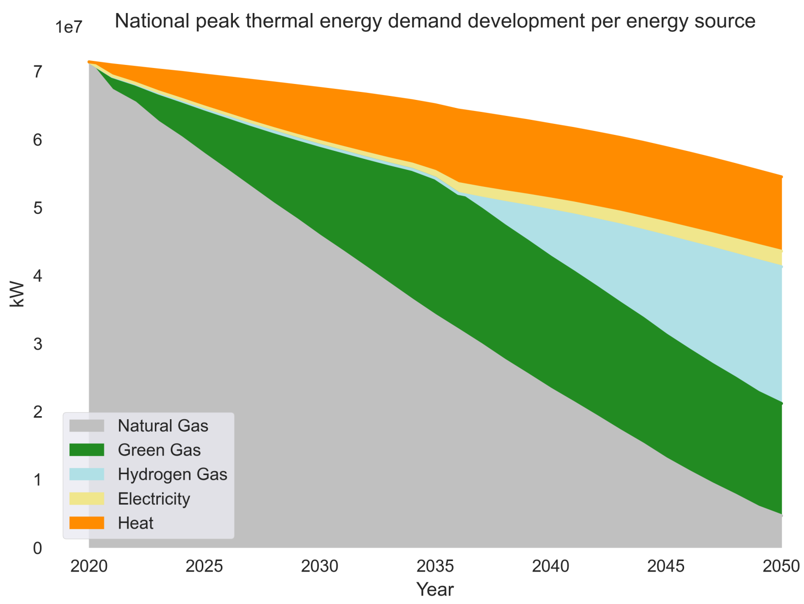



**Figure L.20:** *Peak energy demand output for scenario G3 per energy source.*

Figure L.21 shows a significantly different gas demand development per region than the previous scenarios. Hydrogen seems to develop in a similar fashion to scenario G1, but green gas is playing a more prominent role throughout all MR-regions. Except for some outliers, gas demand as a result of the thermal transition in the built environment will be reduced by less than 50 % in most regions, where rural areas will remain rather gas based. High urban areas will decrease their gas usage more significantly.

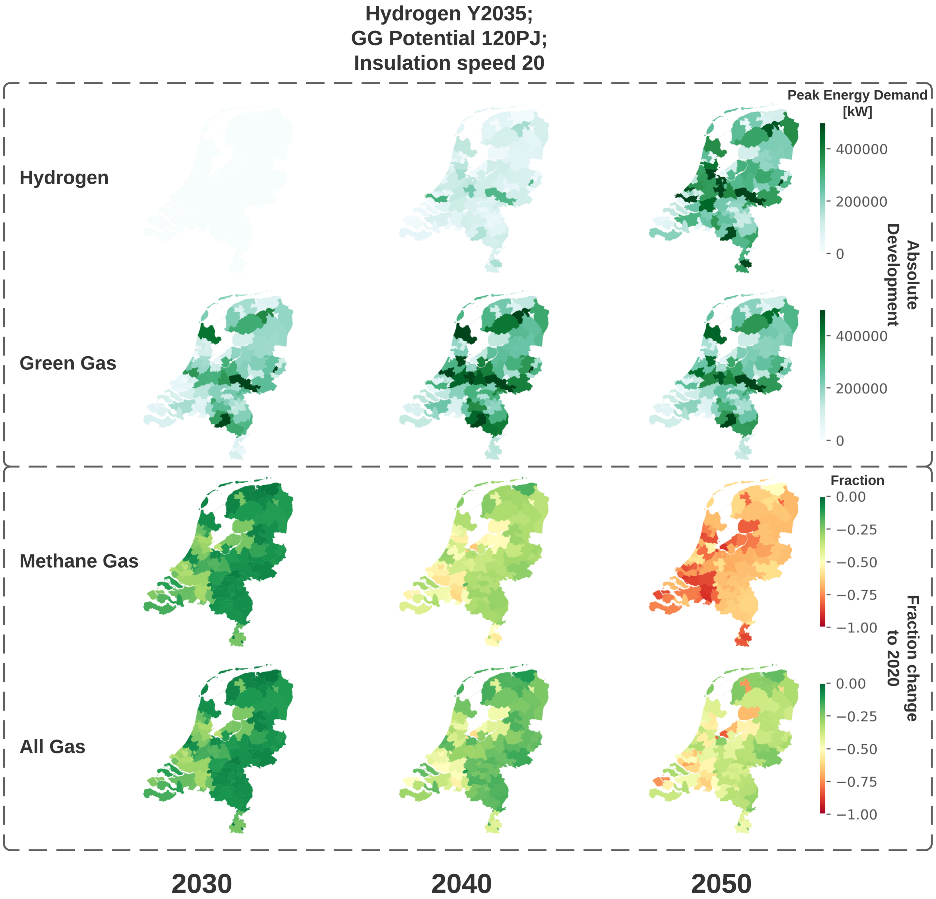



Figure L.21: *Peak gas demand output for scenario G3 for 2030, 2040 and 2050.*

**SCENARIO G4** Figure L.23 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G4. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.

This scenario is characterized by early hydrogen availability, double the green gas availability and a high insulation speed for neighborhoods. Green gas and hydrogen make up a little over half of the national thermal energy demand. Compared to scenario G2, which also incorporates high neighborhood insulation, a lot of heat demand is replaced by green gas use.

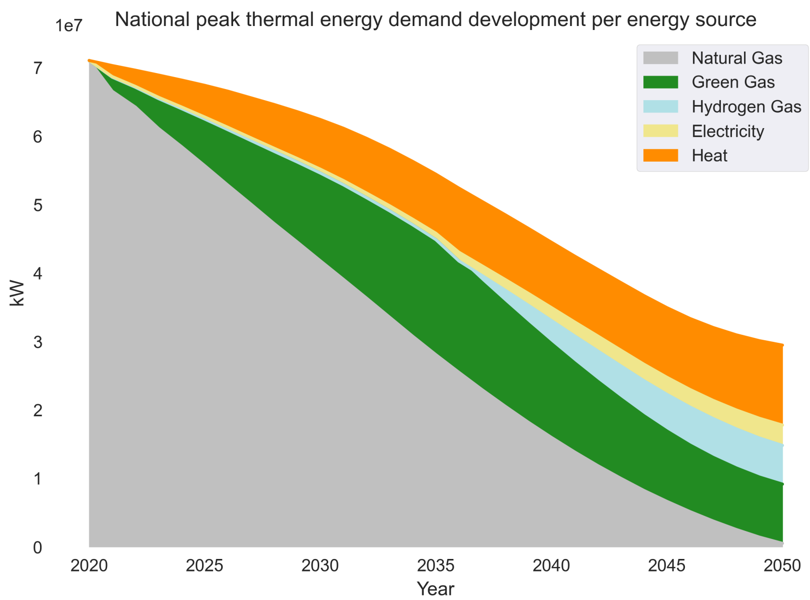



**Figure L.22:** *Peak energy demand output for scenario G4 per energy source.*

Figure L.23 shows hydrogen is only widely used in highly urban areas such as Rotterdam, Amsterdam, Den Haag and Utrecht. While green gas does not seem to be used to its fullest capacity if this scenario is compared to scenario G3. Overall, both methane gas and all gas use drop significantly, only second to scenario G2.

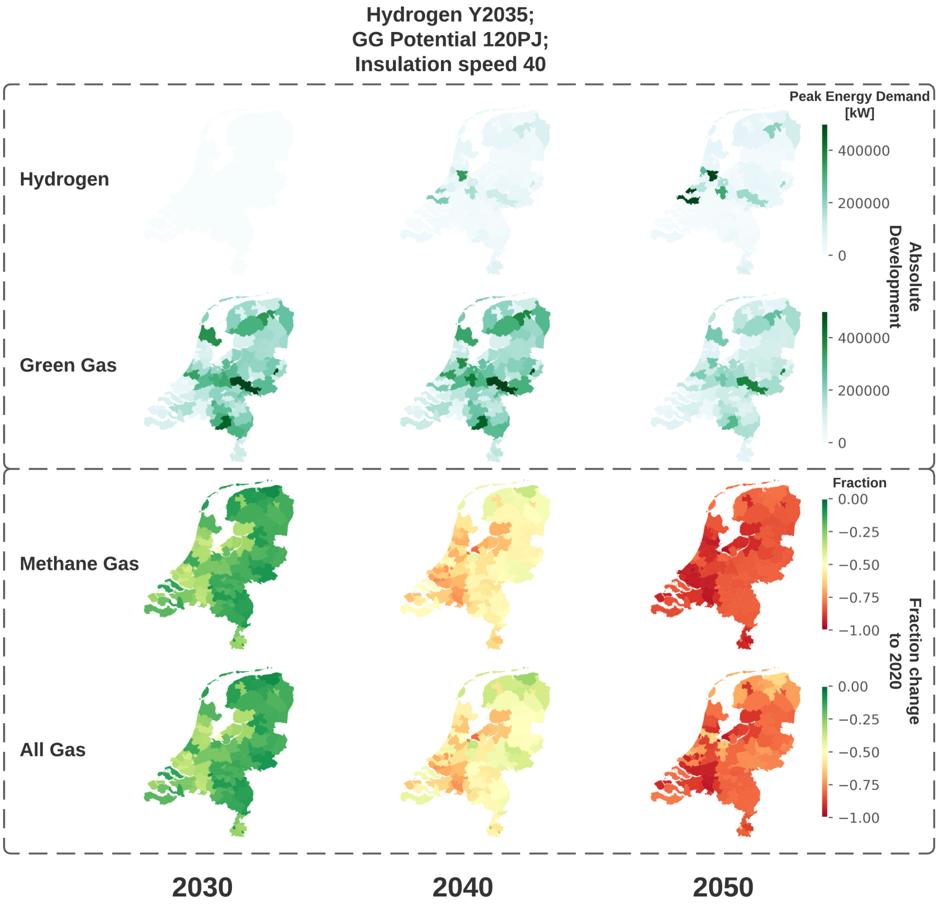



**Figure L.23:** *Peak gas demand output for scenario G4 for 2030, 2040 and 2050.*

**SCENARIO G5** Figure L.25 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G5. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.

This scenario is characterized by hydrogen availability in 2050, reference green gas availability and modest insulation speed for neighborhoods. Compared to scenario G1, this scenario differs in effectively no hydrogen coming available. Ther result is an increased share of electricity and especially heat to make up for the lack of hydrogen. In this scenario more electricity and heat than in any of the previous discussed scenario's is used. All gas is significantly reduced.

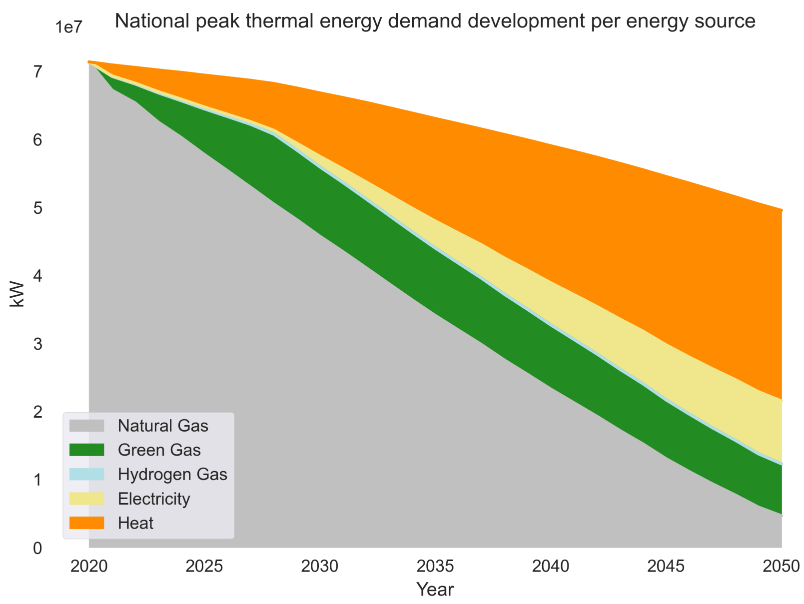



**Figure L.24:** *Peak energy demand output for scenario G5 per energy source.*

Figure L.25 shows hydrogen is not demanded as it is not available for any region. Green gas, seems to be used quite evenly dispersed over the Netherlands. When the fraction of change for 2030, 2040 and 2050 is observed, the same regional development as the other scenario's is observed. Urban areas seem to be moving away faster from gas than the rural parts of the Netherlands. An overall gas demand reduction of at least 75% for all regions is observed.

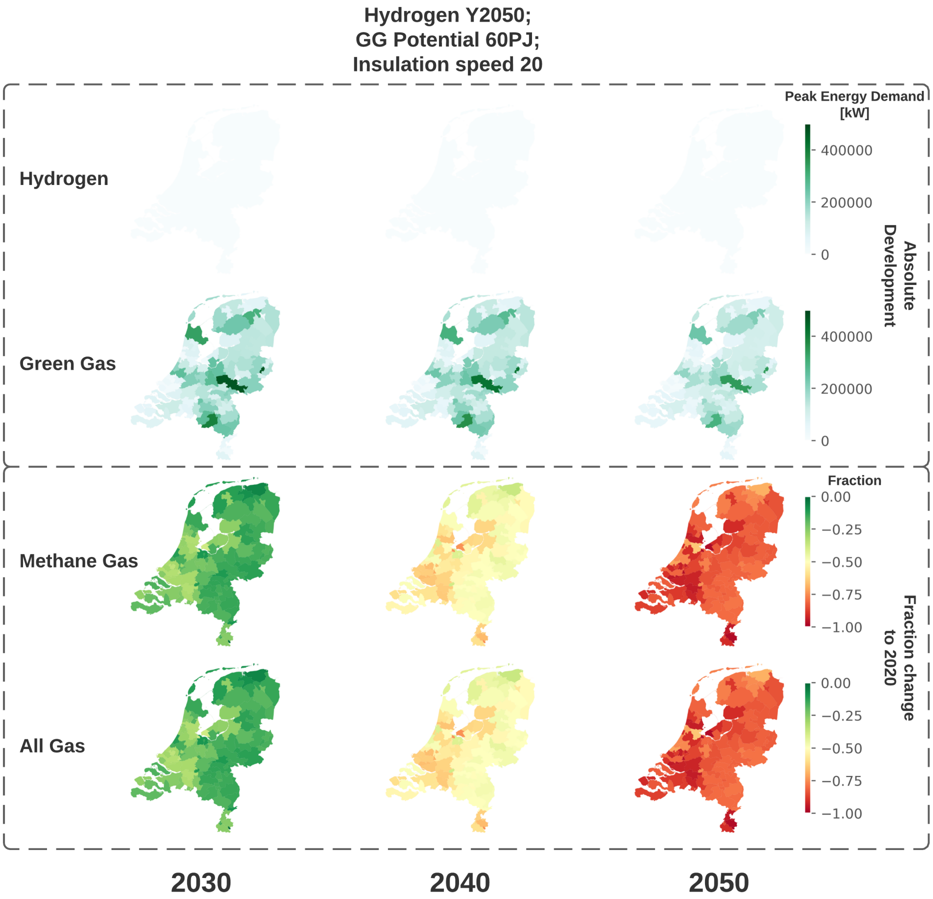



**Figure L.25:** *Peak gas demand output for scenario G5 for 2030, 2040 and 2050.*

**SCENARIO G6** Figure L.27 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G6. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.
This scenario is characterized by no hydrogen availability, reference green gas availability and high insulation speed of neighborhoods. This results in most of the thermal energy demand being driven by electricity and heat use. Only a small fraction of final thermal demand constitutes of green gas.

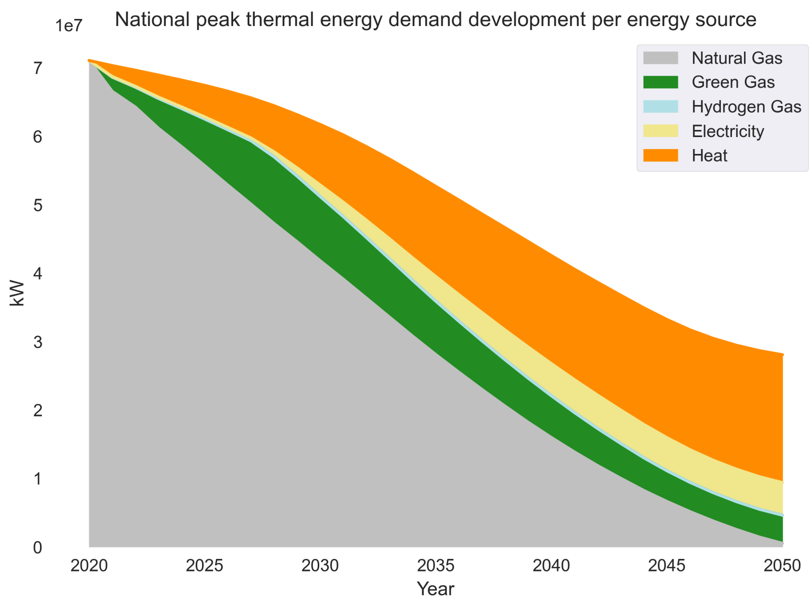



**Figure L.26:** *Peak energy demand output for scenario G6 per energy source.*

Figure L.27 shows a regionally steady decline of gas use. The result is a stronger homogeneous decrease of gas use in the Netherlands. Gas use seems to decrease faster in the Randstad area in comparison to the rural eastern part of the Netherlands. High insulation speed and the unavailability seems to provide a preferable scenario for heat and electricity development.

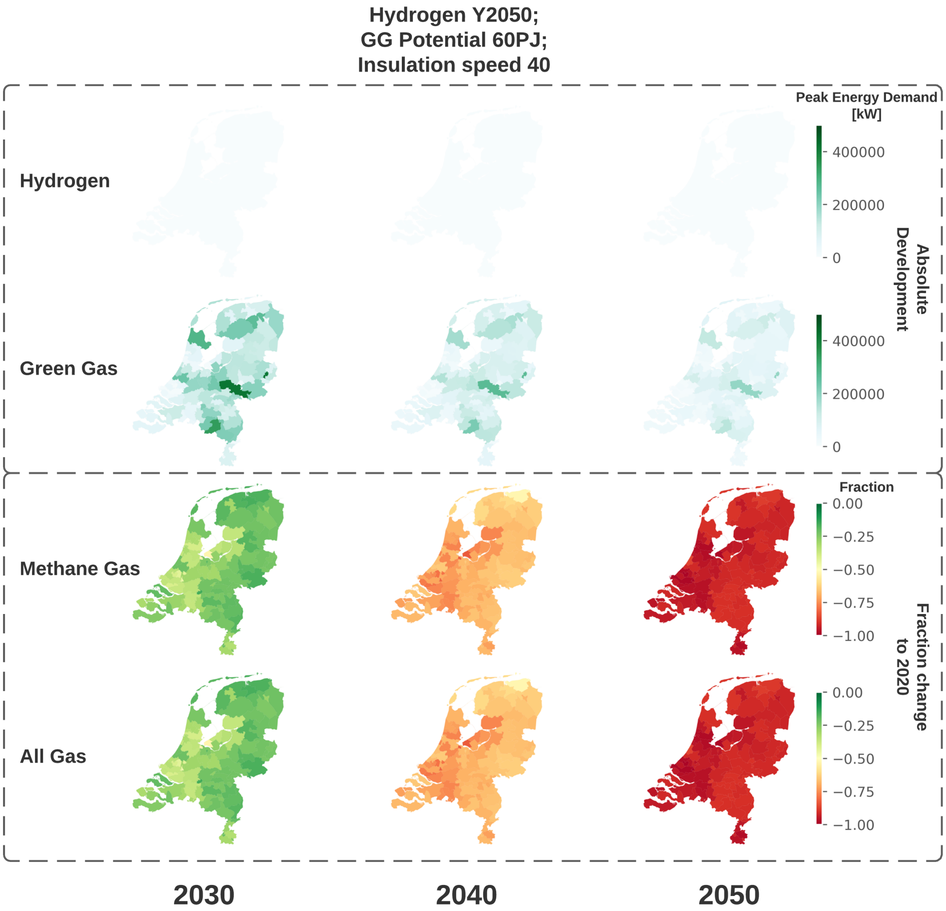



**Figure L.27:** *Peak gas demand output for scenario G6 for 2030, 2040 and 2050.*

**SCENARIO G7** Figure L.29 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G7. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.

This scenario is characterized by no hydrogen availability, double green gas availability and a modest insulation speed. Green gas first becomes the renewable source with the highest share, but as green gas demand peaks, heat becomes more important. Towards 2050, heat is the primary driver of renewable thermal energy demand.

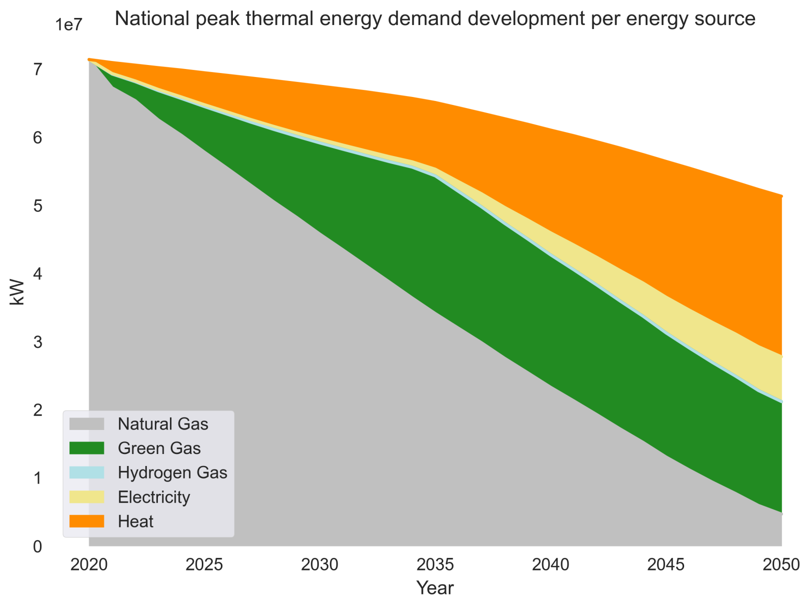



**Figure L.28:** *Peak energy demand output for scenario G7 per energy source.*

Figure L.29 describes the MR level regional heat development. Similar developments as in the previous scenario's are observed here.

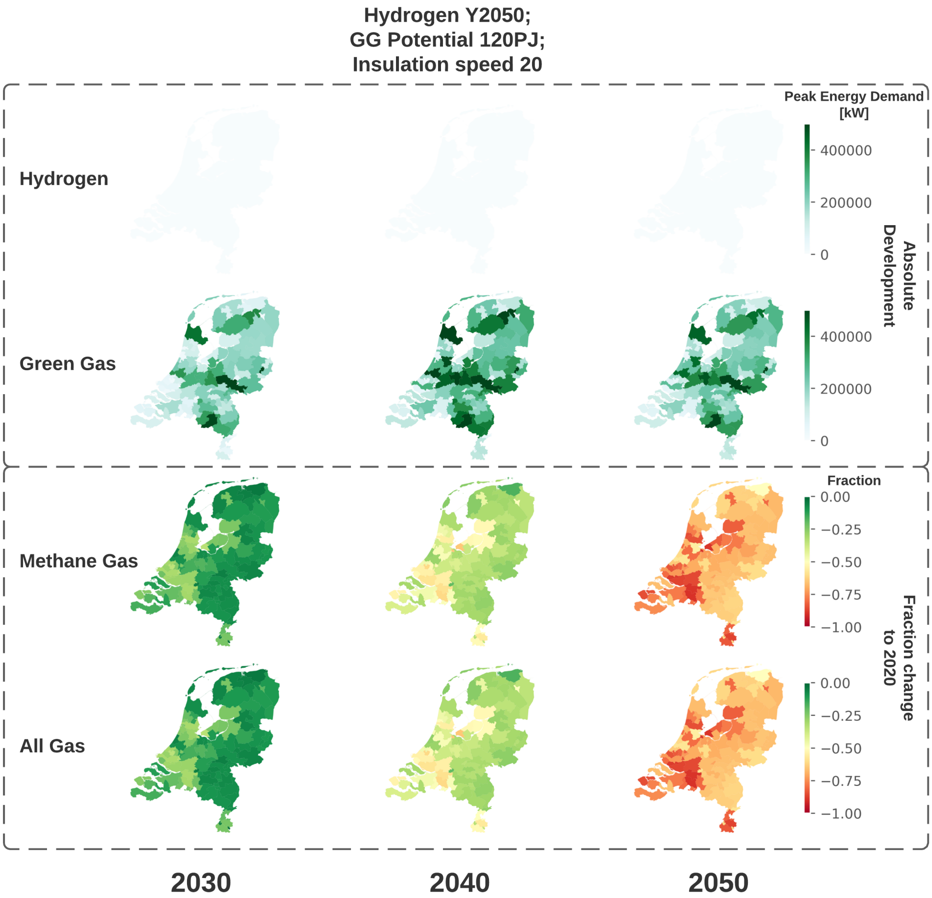



**Figure L.29:** *Peak gas demand output for scenario G7 for 2030, 2040 and 2050.*

**SCENARIO G8** Figure L.31 describes the development of hydrogen, green gas and combinations thereof from 2030 to 2050 for scenario G8. The top two rows describe the absolute developments of hydrogen and green gas peak demand. The methane gas and all gas combinations described in the bottom two rows of the figure are relative developments in comparison to 2020 levels.
This scenario is characterized by no hydrogen availability, double green gas availability and high insulation speed for neighborhoods. Similar to previous scenarios without hydrogen availability, heat develops as the most prominent thermal heat source after the green gas use declines.

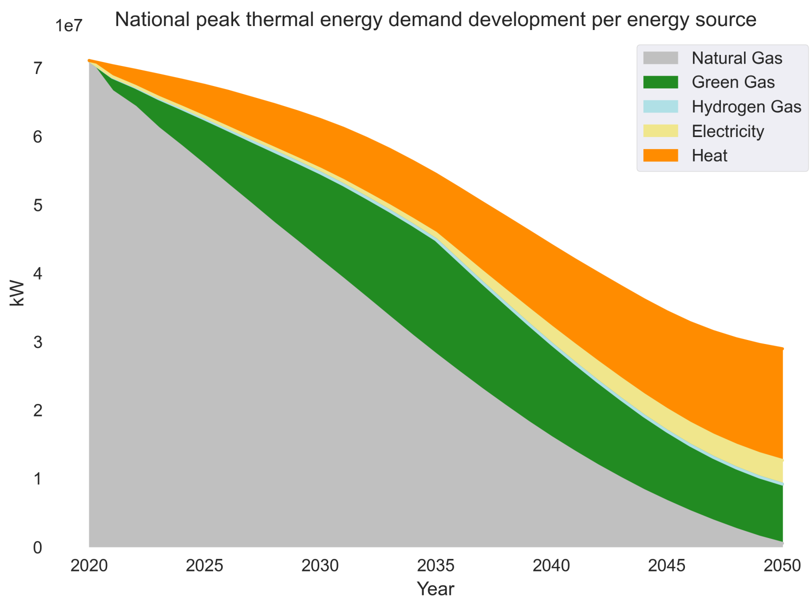



**Figure L.30:** *Peak energy demand output for scenario G8 per energy source.*

Figure L.31 describes the MR level regional heat development. Similar developments as in the previous scenario's are observed here.

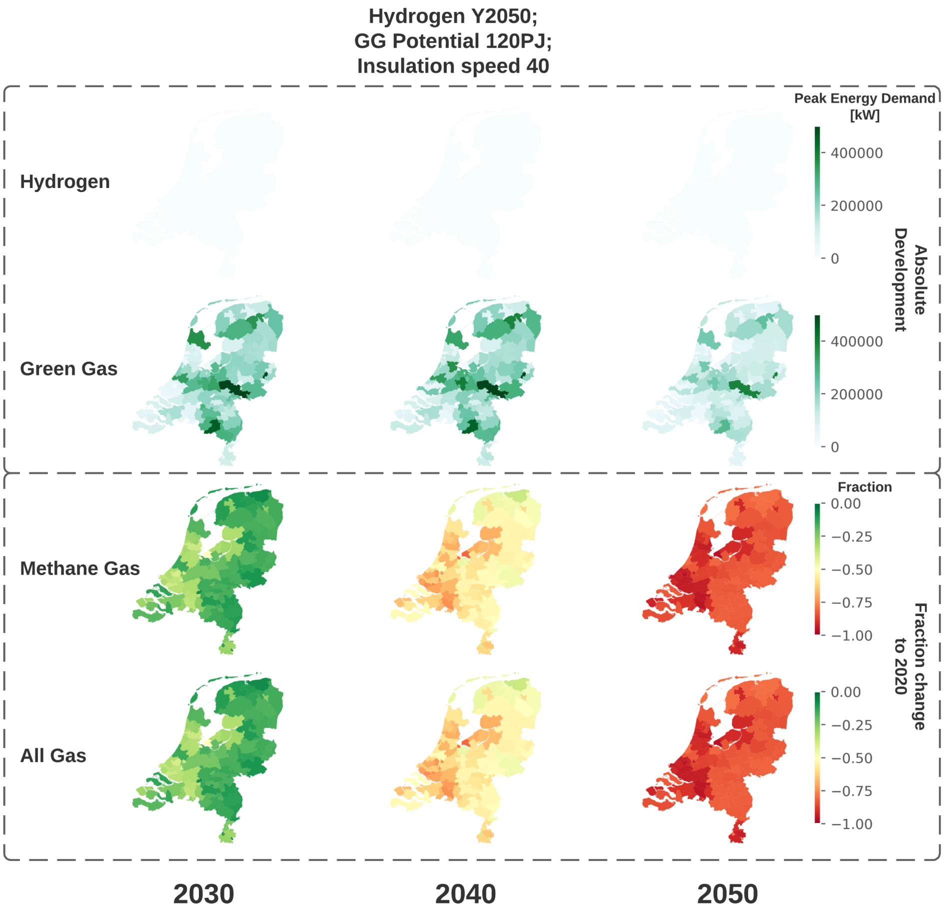



Figure L.31: *Peak gas demand output for scenario G8 for 2030, 2040 and 2050.*

### L.3.2 Results per energy source

NATURAL GAS Figure L.32 describes the difference in impact of the scenario's on national thermal natural gas demand. Only two lines can be observed, which means that the 8 different scenario's result in only two different transition pathways for Natural Gas development on a national scale. The driving model variable for this difference is the insulation speed. A higher insulation speed implicates a steeper downward slope of natural gas development. Scenario's 1, 3, 5 and 7 are equal to the top scenario, while the bottom line represents scenario's 2, 4, 6 and 8.

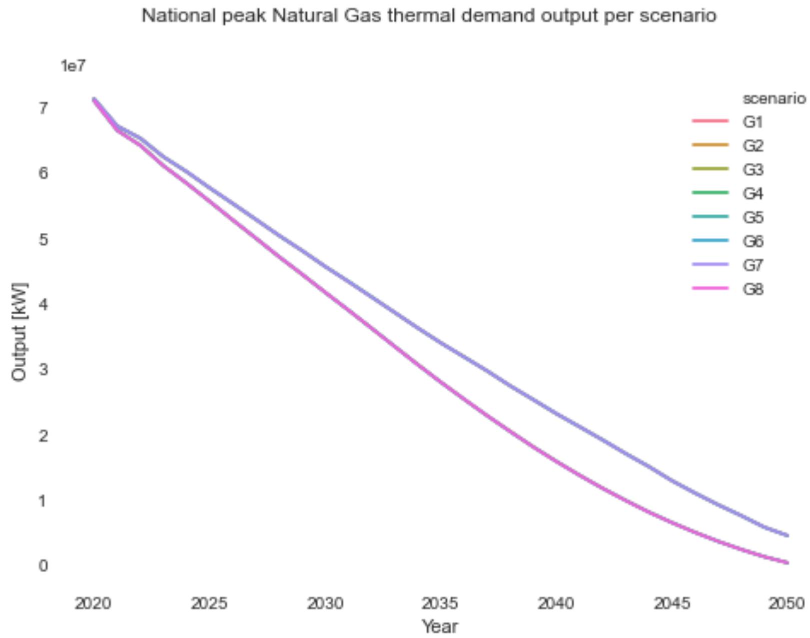



**Figure L.32:** *Natural Gas development per Gasunie scenario.*

**GREEN GAS** Figure L.33 describes the difference in impact of the scenario's on the national thermal green gas demand. Four different trajectories can be observed, which means that 8 different scenario's result in 4 different transition pathways for national Green Gas development. The driving model variables for this difference are green gas availability and insulation speed. The top purple line, representing scenario 3 and 7, both have a modest insulation speed and high green gas availability. The second pink line, representing scenario 4 and 8, both have high insulation speed and high green gas availability. The third green line, representing scenario 1 and 5, both have modest insulation speed and reference green gas availability. The fourth blue line, representing scenario 2 and 6, both have high insulation speed and reference green gas availability.

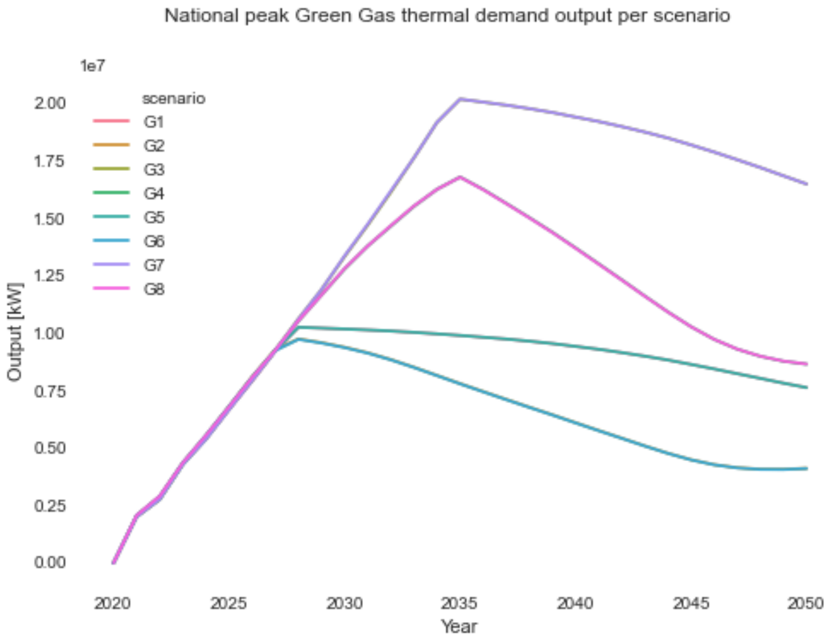



**Figure L.33:** *Green Gas development per Gasunie scenario.*

**HYDROGEN GAS** Figure L.34 describes the difference in impact of the scenario's on national thermal hydrogen availability demand. Three different trajectories can be observed, which means that 8 different scenario's result in 3 different transition pathways for national hydrogen gas development. The driving model variables are the insulation speed and hydrogen availability. The top brown line, representing scenario 1 and 3, both have a modest insulation speed and early hydrogen availability. The second green line, representing scenario 2 and 4, both have high insulation speed and early hydrogen availability. The third flat pink line, representing scenario's 5, 6, 7 and 8 all have 2050 hydrogen availability.

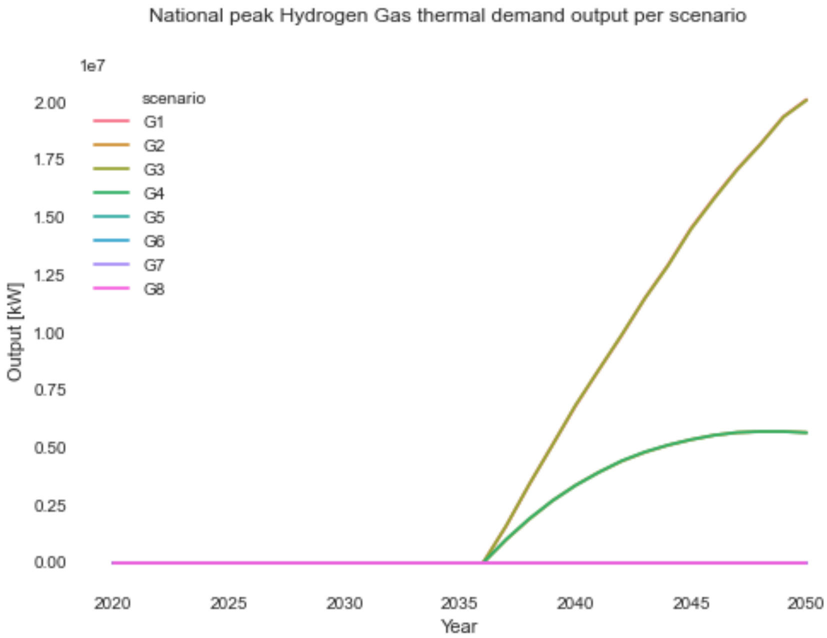



**Figure L.34:** *Hydrogen Gas development per Gasunie scenario.*

**ELECTRICITY** Figure L.35 describes the difference in impact of the scenario's on national thermal electricity demand. Eight different trajectories can be observed, which means that all varied model parameters have influence on the trajectories.

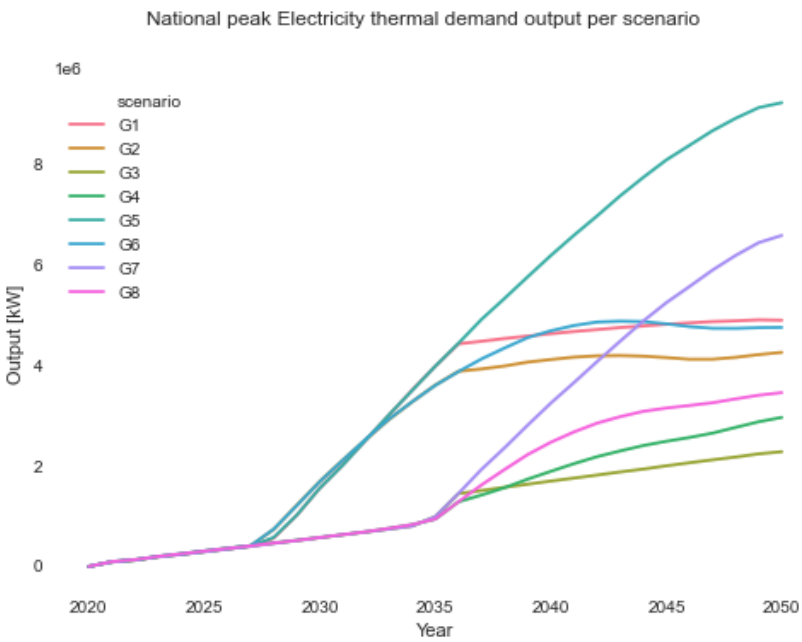



**Figure L.35:** *Electricity development per Gasunie scenario.*

**HEAT** Figure L.36 describes the difference in impact of the scenario's on national heat demand. Eight different trajectories can be observed, which means that all varied model parameters have influence on the trajectories.

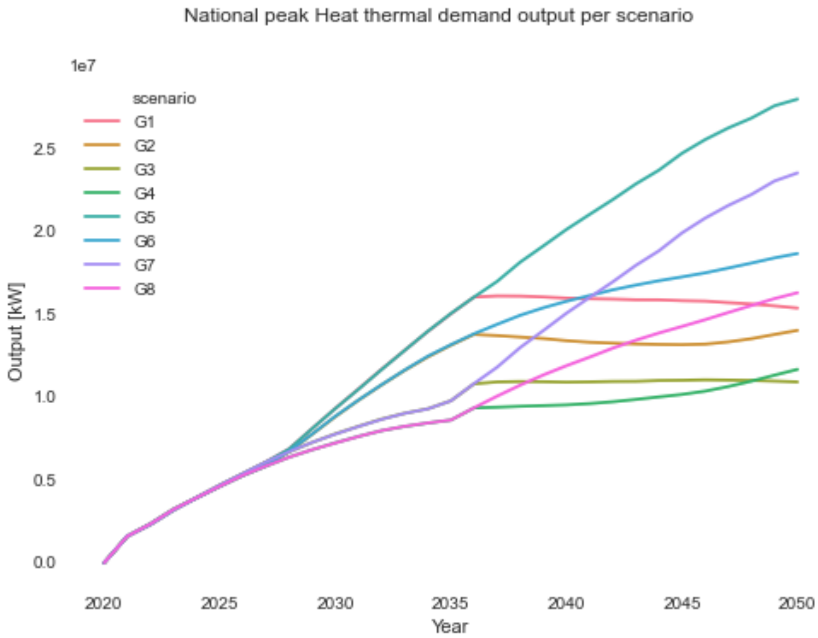



**Figure L.36:** *Heat development per Gasunie scenario.*