The Energy Transition in the Built Environment

Modelling and Visualising Sustainable Urban Development

D.P.J. Wolffenbuttel

TU Delft

Witteveen + Bos

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by

D.P.J. Wolffenbuttel

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Thesis committee:	Dr. ir. I. Nikolic,	TU Delft, Chair
	Dr. ir. W. L. Auping,	TU Delft, First supervisor
	Prof. ir. P. G. Luscuere,	TU Delft, Second supervisor
	Ir. M. Berghuis,	Witteveen+Bos
	Ir. J. van den Houten,	Witteveen+Bos

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TU Delft

Preface

These theses mark the end of my period of a little over seven years at the Delft University of Technology. I remember that when deciding to become an engineer, I was in doubt whether Delft would be the right city for me to study. I am happy that I now know that I could never have been more wrong. That five years were not going to be enough is something I realised quite fast. Delft turned out to be a playground in which I could try new things, fail to listen to useful advice and then learn that next time I should maybe not be that stubborn.

Next to this, this graduation project has further triggered my interest in engineering and showed me that I want to dedicate my career to contributing to a successful energy transition. Since I could not have done this on my own, I would like to use this preface to thank the people that supported me during my studies and graduation project.

First of all, I would like to thank Willem, for always having his door open for me, even on 'papa-day'. We nearly weekly discussed my work, and your constructive criticism has helped me take my work to the next level. Our discussions on the model development were always insightful, even if your kids kept you awake the entire night. I want to thank you for taking the time to review my work during the entire process, and I hope that my work can contribute to your work and the field.

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I also owe thanks to Peter, since he was able to pull me away from the methodologists and help me not to forget to focus on what was relevant for the case. Your comments helped me to take a step back and rethink why I was doing what I was in the first place.

My gratitude goes to Jorrit and Michel for sharing their expertise on the subject and taking the time to talk about my project when I was stuck. Even though some crisis made it more difficult to just walk in any time, you both kept making time for me to shed your light on my work. It is for you that I was able to deliver a dual thesis that is both scientifically relevant as well as practically relevant.

Also, I would like to thank my brother, Timo, for helping out with the computational problems I ran into, without him I would never have been able to deal with the data overload I created for myself. I would like to thank my parents, for the ongoing support, even though my studies took a bit longer than initially expected.

And last, but not least, I would like to thank Manon, for having the patience with me continuously postponing my deadline because the aforementioned gentlemen told me I could do better. I know I have not made it easy for you sometimes, your support has helped me to get through the most difficult challenges, for which I am grateful. When the dust has settled, we'll go on a well deserved holiday.

D.P.J. Wolffenbuttel
Rotterdam, September 2020

Management Summary

Given the Paris Agreement (FCCC, 2015) and the European Union's goals to realise net-zero CO_2 emissions in 2050 (European Commission, 2018b), The Netherlands has developed a climate agreement (Klimaatakkoord, 2019) in which is decided that the country should significantly reduce its contribution to these global emissions. For the Built Environment it means that with a share of 14 per cent, reductions in this sector are expected to have a large impact on the country's CO_2 performance.

Important in realising this goal, is that households should find different systems for the heating of their house. Since currently over 90 per cent of the Dutch households make use of natural gas for heating and cooking an energy transition is required to realise significant CO_2 reduction. However, various systems can be implemented to transit away from the use of natural gas, for which the choice for one or the other is not trivial. Technical, economical, and social feasibility are factors that are often competitive, which makes that deciding what system to implement is a difficult choice.

An important role in guiding this transition is reserved for municipalities. The Klimaatakkoord (2019) depicts that they will have to work together with housing corporations and homeowners to decide what alternative system needs to be developed. However, municipalities are not ready to do so (RTL, 2019; Schuttenhelm, 2020; Straver, 2019). Currently, municipalities lack the resources and expertise to decide what is best, let alone that they can deal with the uncertainties that still exist around the implementation of new systems without proper assistance.

To deal with this, the Dutch government has provided a guideline that should help municipalities develop their transition strategy. The Vesta MAIS model, by (Planbureau voor de Leefomgeving, 2019c) is offered as a tool to investigate the possible systems to be implemented and determine the system that will lead to the lowest national costs. Although brilliant from a utilitarian perspective, the techno-economic approach makes that it can show what is 'best' to do, but not provide any guidance on how and when to realise this. Two critical factors appear to be missing in their approach: time dynamics and the population. Municipalities will never be able to implement their solution as long as their solution is not properly aligned with the wishes and demands of the people that have to deal with the new systems and/or even finance them.

Next to this, this challenge is tackled from different levels of government. This makes that it is difficult for municipalities to develop their strategy, due to the uncertainty of national policy. Insights are needed at both the national level, as well as municipal level, to develop national policies that can stimulate and facilitate the transition at the municipal level.

A solution to this may be a modelling and simulation approach that does incorporate these aspects, by providing time-dependent multi-perspective insights into how neighbourhoods and municipalities may develop over time and what kind of policies will be able to motivate homeowners and housing corporations. In this way, strategies can be developed that are most likely to succeed, rather than strategies that are theoretically 'best'.

Multi-modelling using Agent-Based Modelling (Epstein & Axtell, 1996) and System Dynamics (Forrester, 1961) may be able to provide these dynamic, multi-perspective insights that currently used models are still lacking. As Sustainable Urban Development is a complex concept, different parts of the system are well modelled using either one of the two modelling methods, making that the system as a whole is difficult to model using only one formalism. By combining them, the strengths of these methods can mitigate the weaknesses of the other method and vice versa.

The aim of this research is twofold. On the one hand, its goal is to develop a multi-model to delineate on the opportunities and challenges that the use of this method may bring. On the other hand, the model is directly applied to the relevant case of Sustainable Urban Development to provide policymakers at different levels of government with the insights they need to develop fruitful policies to stimulate the energy transition. These goals are reached by answering the following research question:

How can multi-perspective insights in Sustainable Urban Development be provided using a System Dynamics and Agent-Based multi-model?

As the aim of this study is twofold, so is the answer to its main research question. The first part is the development of the multi-model and consequences of using this new method has on the model development cycle. The biggest advantages of the approach are that the combination of two modelling formalisms will enable multi-perspective interpretation of the system and that it will enable for better model concepts to be developed. Appropriate selection of model formalisms for each of the system's components drives these characteristics. However, this brings quite a few challenges, since multi-modelling a relatively novel method.

As the model development cycle of single models can already be seen as a difficult process, this becomes much more complex when developing a multi-model. It is found that this extra complexity, does not necessarily have to be a drawback for using the method. The fact that conceptualisation becomes more difficult, and different concepts have to be evaluated, makes that in the end, better model concepts can be formulated.

However, the multi-perspective approach makes that the modeller has to deal with enormous data overload. The geographical segregation of model outcomes in the Sustainable Urban Development case makes that the outcomes can be presented to the relevant policymakers based on geographical boundaries, allowing the information to be split into understandable chunks. Nevertheless, this does not directly mean that this can be applied to different cases as well.

Apart from the challenges during the modelling process, the second part of this research, which investigates the results that the multi-model provides, shows that the multi-model is well able to provide the sought for multi-perspective insights. The multi-model successfully enables the inspection of the consequences of policies and uncertainties on the national level, as well as on the municipal level. At the national level, it is found that a CO_2 tax will be indispensable in stimulation homeowners and housing corporations to sufficiently insulate their houses to allow for alternative heating systems. The intermunicipal perspective shows that large differences can be observed in the ability of municipalities to become independent of natural gas between urban and rural areas. As residual heat appears to be a suitable solution for highly dense populated areas, allowing for minimal investments to be made in housing insulation, rural areas depend on the use of individual systems for which that insulation is required. This makes that inequality exists between homeowners and housing corporations in urban areas, of which little investment is expected due to the availability of residual heat and those in rural areas, of which significant insulation and investment in heat pumps are required to become independent of natural gas.

A solution to solving this inequality is to treat heat the same way as that electricity and natural gas are currently governed. By having energy companies provide heat-as-a-service, and having grid operators provide the infrastructure for delivering that heat, regardless of the energy carrier used for delivery, the cost of the energy transition can be distributed fairly. In this way, households will only pay for the heat they require, and not the system that their specific neighbourhood will need to provide that heat, which will be provided collectively. In this way, the risks and needed investments are borne collectively, but households still pay for the energy they require. Allowing for insulation investments to be made where desired, but not enforcing them where unwanted.

As long as such a system is not implemented, municipalities can get started with implementing heating grids where residual heat is a feasible solution because these systems can be implemented relatively quickly due to limited insulation requirements. For municipalities in which heating grids are not feasible, the best starting point is to start with the neighbourhoods that have the largest economic incentive to invest in high levels of insulation. For all other neighbourhoods, hybrid heat pumps may offer a solution for bridging the gap between now and a future in which either new technologies emerge that will allow cheap insulation or alternative high-temperature heating, or where major investments are no longer escapable.

It can be concluded that, although multi-modelling still has challenges that need to be resolved and its computational demand being the most important, the method is well able to live up to the claim that it will allow for the development of better model concepts and provide for multi-perspective interpretation or its results. By resolving these challenges in further research, multi-modelling may very well become a suitable method for evaluating complex systems in common practice.

For Sustainable Urban Development, so far several policies have been evaluated that will stimulate the transition to sustainable heating. However, the currently available policies appear not to be sufficient in realising the goals of the climate agreement. A start can be made by having municipalities use the model to explore the development of neighbourhoods and identify promising neighbourhoods to include in the initial transition strategies. However, as long as no other motivation than economical incentives is developed for encouraging the energy transition, the realisation of our national goal to reduce CO_2 emissions to zero tons in 2050, appears to be improbable.

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I

The Energy Transition in the Built Environment: A Multi-Modelling Approach

1

Introduction

At the moment of writing, many policymakers in the Netherlands struggle with the changes that are imposed by the demands for an Urban Energy Transition (Bassett & Shandas, 2010; den Exter et al., 2015; Keskitalo et al., 2016; Straver, 2019). The dynamic and contested concept of 'sustainability' makes that no 'one size fits all' policy can be used for defining strategies to realise the energy transition (Kemp et al., 2007). With the European Union's (EU) goals of reducing CO_2 emissions to zero tons in 2050, all layers of society should contribute to this goal (European Commission, 2018b). From the big corporations to the individual consumer, and everything in between, new strategies need to be developed to reduce the carbon footprint.

A large contribution to this goal should come from the built environment, which currently contributes to about 14 per cent of the national CO_2 emissions (Schoots & Hammingh, 2019), of which households are responsible for 70 per cent of this contribution. New technologies that have emerged will be important drivers in Sustainable Urban Development. They will allow for the construction of and reconstruction into, climate-neutral houses to reduce the CO_2 output of the built environment (Milieu Centraal, 2020b). Next to this, because of the national goals to no longer be dependent on the use of the country's natural gas reserves (Klimaatakkoord, 2019), new systems need to be developed that will provide the heat that natural gas is currently providing its energy for. An Urban Energy Transition will be necessary to realise national sustainability goals. With nearly 8 million households in the Netherlands (CBS, 2020h), this is a major challenge that goes much further than a technical one alone. A thorough understanding of Sustainable Urban Development and how to develop strategies that will positively contribute to this development are needed more than ever. So, where to start?

1.1. Urban Energy Transition: A Municipal Challenge

An important role in the challenge of the Urban Energy Transition will be played by municipalities. The Dutch government has decided that municipalities will have a directing role in governing the Energy Transition in the Built Environment (Klimaatakkoord, 2019). This means that they especially have to develop the strategies that make urban areas more sustainable, in which energy neutrality or even energy positivity (Luscuere et al., 2016) will play a big part. However, municipalities are not yet ready to do so (Straver, 2019). This is a difficult task, not only because of the large range of options available for Sustainable Urban Development, such as solar panels, heating grids, bio-fuels, and heat pumps, but also because of the uncertainty that the use of these (often new) solutions will bring.

Next to this, decades of path dependency and optimisation have led to how our energy system is currently functioning (Fouquet, 2016). Changing that system is not going to be an overnight job. It will require extensive evaluation of alternatives and careful consideration of the choices to make. It is key to find a solution that works for the stakeholders involved, given all these uncertainties and path dependencies. Systems that are possible replacements for the current national gas network include heating grids (TKI Urban Energy, 2020), heat pumps (Chua et al., 2010), and the use of green gas (CE Delft, 2019b). However, the choice for one or the other solution is not trivial. The trade-off that needs to be made between the technological best, or economically most advantageous, or just something that people find comfortable, is a difficult one to make. The fact that this system is inherently complex and uncertain (Rotmans & Kemp, 2003; Scipioni et al., 2009; Verbong & Geels, 2007) makes that this decision is extra difficult.

This difficulty does not only come forth from the complexities and uncertainties that affect the choice of the to implement solution, but also the complexities and uncertainties in the process of implementation itself. The decision-making process does not end with selecting what to do, but it may even become more complex when implementing it. Indispensable in the process of implementing measures for the Energy Transition in the Built Environment is the selection of the Project Delivery Model and how contractors react to such tenders. For long the selection of the 'correct' procurement method has determined the success of projects (Bannet & Grice, 1990), failing to do so on the other hand, is seen as one of the major reasons for project failure (Lundström, 2013; Masterman, 1992). It is agreed upon, that selection of this method is critical for project success (Al Nahyan et al., 2018; Chen et al., 2011; Mafakheri et al., 2007). It is, therefore, important not only to understand the complexities of the Energy Transition itself but also to understand the complexities of the procurement system that is needed for implementation of solutions in the Energy Transition. Hence the need to create more insights on the complexities of the system, the impact of uncertainties, possible outcomes of solutions and how to implement these solutions. This, to better be able to find truly sustainable solutions.

1.2. Modelling and Simulation in Sustainable Urban Development

Modelling and simulation may be able to provide the insights in complexities, uncertainties and policies that municipalities are still lacking. In the last few years, many models have been developed that provide knowledge and insights on specific parts of the Energy Transition (Netbeheer Nederland, 2019). Although very useful when determining the actual solution to implement or optimising a set of solutions on a neighbourhood scale, many of these models cannot provide an initial direction. Vesta MAIS by Planbureau voor de Leefomgeving (2019c) comes closest by providing a detailed evaluation of the most relevant solutions for all municipalities. From a utilitarian perspective, their view of minimising national costs is absolutely brilliant. However, their model still has its drawbacks. The techno-economic approach evaluating the 'best' solution under various scenarios misses one critical aspect: how and when will you get there?

Two aspects appear to be missing in current (mostly technocratic) approaches of modelling Sustainable Urban Development: time dynamics and population dynamics. Hence, it will be valuable to provide municipalities with time-dependent insights on how the system could evolve, given the people and technologies that play a part. System Dynamics (Forrester, 1961; Sterman, 2002) and Agent-Based modelling (Epstein & Axtell, 1996) are methods frequently used for gaining insights in how systems function. System Dynamics typically has a systematic top-down approach, whereas Agent-Based Modelling is considered an individual behaviour based bottom-up approach. The combination of both employing multi-modelling (Nikolic, Warnier, et al., 2019; Quesnel et al., 2009; Vangheluwe, 2000) may provide for a time-dependent multi-perspective analysis of the system and its components. When looking from both a systems perspective as well as an agent perspective, one can gain a combined insight into the behaviour of the system as a whole, as well as into the individual behaviour within the system.

The insights that one will be looking for in particular are the insights that help understand the effects of policies and uncertainties on system outcome. The Exploratory Modelling and Analysis framework (Bankes, 1993) is a perfect fit for evaluating the possible states of the system to develop robust policies. For Sustainable Urban Development, this is especially helpful due to the different levels of government that have policy authority. The frequently changing national policies that should support and encourage sustainable change (De Boer & Oudshoorn, 2018; Hakkenes, 2020; Vakblad Warmtepompen, 2019), for instance, make that these 'policies' can be seen by policymakers at the municipal level as *uncertainties*. Insight in how to approach the Urban Energy Transition at a municipal level *despite* national policy, as well as insights in the heterogeneous effects of national policy, may provide the handles needed for developing successful strategies in Sustainable Urban Development. A multi-perspective approach will enable policymakers to understand the implications of their policies on different levels of governance, to develop strategies that are fit for purpose.

1.3. Research objective

When looking at the existing literature, it is arguable that one of the major challenges in the field is to help policymakers understand how their policies can contribute to sustainability and the energy transition and how they should be implemented. With many municipalities struggling to develop their Sustainable Urban Development policies under the uncertainty of national policies (RTL, 2019; Schuttenhelm, 2020; Straver, 2019), a large step can be taken in Sustainable Urban Development. By enabling policymakers to understand the (heterogeneous) consequences of certain policies and understand the interaction between various sustainability indicators such as greenhouse gas emissions and economic feasibility, a multi-perspective approach will enable policymakers to better develop fitting strategies for developing sustainable urban areas. The research objective of the proposed research will, therefore, be:

To develop a novel modelling method that will provide multi-perspective insights in Sustainable Urban Development.

One way to gain the insights needed for developing and implementing strategies for Sustainable Urban Development is utilizing modelling and simulation. The works of Feng et al. (2013), T. Lee et al. (2014), Xu and Coors (2012) show that modelling the system is feasible using either System Dynamics or Agent-Based modelling, but that both methods still have their limitations. Hence, this research will try to reach the next step, by combining these methods and presenting the results in a to policymakers understandable manner. This will be done by answering the following research question:

How can multi-perspective insights into Sustainable Urban Development be provided using a System Dynamics and Agent-Based multi-model, and what do these insights imply for the effectivity of national and municipal policies towards the realisation of CO_2 emission reduction in the Built Environment?

To answer this research question, various insights are needed such as what information policymakers need to develop their strategy, what information has to be used to generate the required information, and how this information can be formalised into a multi-model and be presented efficiently and effectively. Therefore the following sub-questions have been formulated:

1. How can Sustainable Urban Development be formalised using a multi-model ecology including System Dynamics and Agent-Based Models?

2. What challenges in multi-model development can be expected and how can these be mitigated?

3. What is the relative performance of multi-models as compared to traditional modelling methods?

4. What stakeholders and concepts are relevant in Sustainable Urban Development and how are these related?

5. What policies at the national level can contribute to obtaining the CO_2 goals of the climate agreement?

6. What are the effects of national policy uncertainty on system developments at the municipal level?

7. How can municipalities coordinate and accelerate the energy transition and what are suitable starting points to do this?

The research objective and research questions in this dual thesis are twofold. On the one hand, they aspire to gain insight into the challenge of Sustainable Urban Development as a part of my studies in Construction Management and Engineering, while on the other hand, they aim for a methodological contribution in the field of multi-modelling, which is a valuable addition to my studies in Engineering and Policy Analysis. This combination in a double degree lends itself for an innovative approach for solving a complex and relevant challenge while supplying a diverse subject to test various case studies for a new methodology. In this way, knowledge and tools from one field reinforce the development of knowledge and tools from the other, and vice versa.

1.4. Dual Thesis Structure

In this dual thesis, I will, on the one hand, investigate the possibilities and performance of multi-modelling as a novel method, as well as that I will directly apply the model to a relevant use case. Hence, this dual thesis is split up in four parts. Following this introduction, the second part will discuss the methodological contribution of this study, whereas in the third part the model will be used to investigate the implications of policy interventions and uncertainty in Sustainable Urban Development. In the last part, I will present a synthesis on multi-modelling for Sustainable Urban Development, and discuss the perks and disadvantages of directly applying a novel method to a use case.

1.4.1. Part II: Multi-Modelling for Complex Challenges

In the first part following this introduction, I will discuss the two modelling methods that will be combined into a multi-model in detail. The characteristics of each of the formalisms will be discussed, as well as the opportunities and challenges that the use of these models will bring.

From there, the methodology chapter will set forth the requirements that the multi-model has to meet to be suitable as a method as compared to single-modelling, as well as the requirements it needs to meet to be of use for Sustainable Urban Development. Then, I will discuss how the multi-model will be designed by elaborating on how the opportunities for multi-modelling will be exploited and how the consequences of the challenges should be mitigated.

Following this, the model chapter will elaborate on the challenges that have been dealt with, to what extent these affected the modelling process and how this process is different from single-modelling. In the results chapter, the final performance of the multi-model will be presented as well as a small presentation on the outcomes of the model. Based on the model development cycle I will evaluate to what extend the model can live up to the opportunities that are presented, and how can be dealt with the challenges it brings.

In the final chapter of the first part, I will conclude on the development of the multi-model by answering the first three sub-questions in this study.

1.4.2. Part III: Energy Transition in the Built Environment

In this part, I will analyse the state-of-the-art literature in Sustainable Urban Development and investigate the current status of the literature on tools that help policymakers in the Netherlands develop and implement their strategies for the Urban Energy Transition. The literature review will look into the current developments in Sustainable Urban Development, the definition of Sustainability, what solutions exist in Sustainable Urban Development, how strategies to implement these solutions are set up, and how this development can better be understood using modelling and simulation.

From this, the methodology will be set forth, in which the advantages and disadvantages of System Dynamics and Agent-Based Modelling are discussed, to conclude on why multi-modelling may be able to strengthen these advantages and mitigate the effects of the disadvantages.

In the model chapter, I will thoroughly discuss the conceptual and pragmatic choices that were necessary to make, to develop a model that is fit for answering the practical research questions of this study. The model focuses on two elements, one the one hand, the Agent-Based model will focus on investment behaviour and investigate how, given various circumstances, neighbourhoods will develop regarding insulation and energy systems. On the other hand, the System Dynamics model will provide for those various circumstances, by developing a wide range of scenarios for the development of the housing market and energy markets, which are expected to be key determinants in neighbourhood investment behaviour.

In the results chapter, I will discuss the outcomes of the various experiments that have been performed. The experiments have been designed so that the different capabilities and incapabilities are brought to light so that policymakers will be able to use the model for finding strategies to deal with their specific policy problem. The chapter will start with an investigation of national outcomes, and find policies and uncertainties that will be key in reaching the national goals and ambitions. Following this, differences between municipalities will be investigated, to follow up with a deep dive into three of the most interesting municipalities. In this examination, intramunicipal differences can be observed, to evaluate the effect of national policies, which are uncertainties to members of the municipal government, to see how these uncertainties can be dealt with.

In the last chapter of this part, I will conclude on the insights that the model has provided for Sustainable Urban Development by answering the last four sub-questions of this study.

1.4.3. Part IV: Synthesis

In the last part of this dual thesis, I will answer the main research question of this study. As this study has the goal to develop a novel method and directly apply it to a relevant use case, practical implications had a huge impact on method development. Nevertheless, these implications will show not only to result in a model that is a better fit for purpose, but also allow for the methodology to be challenged and thus developed even further.

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II

Multi-Modelling for Complex Challenges

Abstract

With the acknowledgement of international grand challenges, the demand for better and ever more complex models is likely to increase a manifold. Where single models may no longer be able to grasp the complexities of a system, multi-modelling (Nikolic, Warnier, et al., 2019; Vangheluwe, 2000) enables the combination of the strengths of different models whilst enabling the development of multi-perspective insights.

In this research, I developed a multi-model to provide policymakers in The Netherlands with insights on how to steer the Urban Energy Transition at both national and municipal level. This is done by combining a System Dynamics (Forrester, 1961) model for evaluating market behaviour at the national scale, and an Agent-Based Model (Epstein & Axtell, 1996) for investigating investment behaviour at the neighbourhood level.

The results from experiments with this model show that multi-perspective insights can be very helpful in designing policies and strategies for dealing with Sustainable Urban Development. It is found that challenges concerning the conceptualisation phase of the Model Development Cycle, could turn out to be opportunities for model development. As formalism selection and possible overlapping scales between models requires extra effort and attention, this attention results in model concepts that will be better evaluated, resulting in better concepts to be developed altogether.

The main challenge that is currently unresolved, is that of the computational performance of multi-models. Although worsened by the choice for Agent-Based Modelling as one of the formalisms used in the multi-model, the computational requirements for the simulation seriously hamper the opportunities for experimentation and analysis. Although solutions can be found to minimise the computational demand or the effects of it, improvements are required in either computational demand or processing supply, for multi-models to become a suitable method for common modelling and simulation practice.

2

Introduction

With the invention of computers, our ability to understand the world has increased a manifold. Modelling and simulation can provide insights into the most complex challenges that our society is facing. Wicked problems (Rittel & Webber, 1973) such as climate change, humanitarian response and resilience, cybersecurity, and mobility (Buchanan, 1992), although inherently complex and uncertain, are better understood with every new modelling and simulation study. Advances in computer technology, computational algorithms and data-driven modelling make that models get better and better in providing the right insights for solving the hardest challenges (Oden et al., 2006).

Modelling and simulation are especially helpful for challenges in which trial and error is no longer a feasible option. Developing a model-based upon our idea of how the world works can provide valuable insights in finding ways to influence that world to our advantage. Two paradigms can be distinguished in modelling and simulation, homogeneous approaches as well as heterogeneous approaches. The most commonly practised method of the first category is System Dynamics (Forrester, 1961). In this paradigm, the leading train of thought is that the system can best be described as a whole, in which feedback, accumulation, and delays are key concepts (Sterman, 2002). On the other end of the spectrum, Agent-Based Models (Epstein & Axtell, 1996) are built around the concept of emergence, as the sum of the whole is greater than the sum of its parts (Bonabeau, 2002).

Academia are unlikely to ever agree on which world view is ’correct’ or ’best’ (Borshchev & Filippov, 2004; M’hamdi & Nemiche, 2018; Scholl, 2001). Both paradigms have their strengths and weaknesses and the type of problem will determine what method has the most potential. However, some complex issues require a combination of the strengths of these formalisms, for which multi-modelling may be able to provide a solution.

2.1. Multi-modelling for complex challenges

In response to the critiques on using one or the other modelling formalism, multi-modelling has emerged: the solution to varying world views. By combining different models, better model concepts can be developed (Duboz et al., 2003; Quesnel et al., 2009; Vangheluwe, 2000) and the performance of models can be improved (Giustolisi et al., 2007; Luoto et al., 2010; Verbraeck, 2004). By developing multiple models, whether from the same formalism or not, a modeller will be able to include multiple world view, creating a set of models that together are better in explaining how the world works. I will not suggest that multi-modelling is the holy grail for solving complex and uncertain challenges. The extensive list of challenges that need to be solved before a suitable model can be developed is a serious drawback (Nikolic, Warnier, et al., 2019). Nevertheless, the opportunities make that it should at least be investigated how these opportunities and challenges relate and to what extend the opportunities make up for the difficulties the method brings. Hence, I will propose a case, that seems a perfect fit for evaluating the performance of multi-modelling complex challenges.

2.2. Case: Sustainable Urban Development

A challenge that is perfect for evaluating the opportunities and challenges of multi-modelling is Sustainable Urban Development. The concept is so broad, that it is incredibly difficult to sufficiently describe the system using only one perspective. To comply with the EU goals of reducing CO_2 emissions (European Commission, 2018b), the Netherlands has developed the Klimaatakkoord (2019) (climate agreement) in which municipalities are responsible for developing the strategies for Sustainable Urban Development. This is a difficult task since they are dependent on the developments in other municipalities as well as developments at national level. A multi-perspective approach is desired in which the system can be analysed from national, as well as intermunicipal and intramunicipal perspectives. The characteristics of the system make that no single formalism will be able to capture its entirety, making that multi-modelling may be a very suitable solution.

2.3. Research questions

Since multi-modelling is a method that has not yet been applied widely, I will develop a multi-model for gaining insights from different perspectives for Sustainable Urban Development to evaluate whether multi-modelling is better able to provide these insights than traditional modelling. The questions that I will be answering to determine the performance of multi-modelling as a method for gaining insights into complex challenges are threefold:

1. How can Sustainable Urban Development be formalised using a multi-model ecology including System Dynamics and Agent-Based Models?
2. What challenges in multi-model development can be expected an how can these be mitigated?
3. What is the relative performance of multi-models as compared to traditional modelling methods?

Answering the first question will focus on the *how* of developing a multi-model. As the development of such methods is relatively novel, I will show its capabilities using a relevant case, namely: the case of Sustainable Urban Development. Next, I will delineate on the challenges that pass by during the development of multi-models and how these have been mitigated in the case of Sustainable Urban Development, to conclude on whether multi-modelling will actually perform better than traditional modelling methods. Spoiler: it depends.

2.4. Thesis structure

In the next chapter, I will discuss the relevant literature in modelling and simulation for multi-modelling, focusing on the strengths and weaknesses of System Dynamics and Agent-Based Modelling, and how they can be combined into a multi-model. Following the methodology chapter, I will elaborate on the challenges that were encountered in developing the multi-model and how these have been dealt with. Following this, the results chapter will discuss the outcomes of the model and how the model performs as compared to traditional modelling methods, to end with a discussion and conclusion on the usability of multi-modelling for understanding complex systems.

3

Methodology

Before developing a multi-model for Sustainable Urban Development, using System Dynamics and Agent-Based Modelling, it is extremely relevant to first delineate the relevant characteristics of these different model formalisms and how to combine these. Using this, I will discuss why these characteristics make that these formalisms are useful for understanding Sustainable Urban Development and why a multi-model is expected to perform better than a single paradigm model.

The review of current models that provide understanding in Sustainable Urban Development (part III, chapter 9) shows that both System Dynamics and Agent-Based Modelling have proven to be very well suitable for modelling systems such as the Energy Transition. It is expected that both the dynamics of the system as a whole and the interaction between stakeholders at the lowest level are of importance in understanding the system. Hence a hybrid form of System Dynamics and Agent-Based Modelling, by means of multi-modelling (Nikolic, Warnier, et al., 2019), may be able to better grasp the complexity of the system. Hence, the strengths of these modelling formalisms will be combined in the multi-model ecology.

The next sections discuss the two model formalisms, why these formalisms are suitable for modelling Sustainable Urban Development and what challenges might arise whilst using these formalisms. Next to this, I will discuss how these opportunities and challenges may affect the model structure and to what extend one formalism can mitigate the weaknesses of the other and vice versa, whilst complementing each other's strengths. With this knowledge, the opportunities and complications of multi-modelling can be delineated as a base for developing the conceptual and corresponding computational models.

3.1. System Dynamics

System Dynamics is a method developed by Forrester (1961) for understanding the dynamic behaviour of systems. It was initially used for understanding industrial systems, widely applied to chemical processes. System Dynamics, however, appeared to apply to a much wider range of subjects, such as economics, public policy, and environmental studies (Richardson, 2020; Sterman, 2002). One of the main reasons for using System Dynamics is that the human mind is simply not able to envision the effects of change of one factor in a system composed of numerous interaction and feedback mechanisms that cause complex non-linear behaviour. System Dynamics, therefore, can help people to better understand these changes and their consequences in two ways.

3.1.1. Characteristics of System Dynamics

The first reason for using System Dynamics is that one can improve its mental models and gain a better understanding of the system and its dependencies by developing System Dynamics models (Keough & Doman, 1992). By writing them out, one is stimulated to evaluate the dependencies in a system further than just direct influences. Conceptualisation tools such as Causal Loop Diagrams (CLD) (Tip, 2011) and Stock-flow Diagrams (SFD) (Lane, 2000) help visualise the system in order to increase the modellers understanding of system behaviour.

Secondly, experiments performed with computer models will give insights into the behaviour of the system and the sensitivity of the system to external factors. The mathematical structure of computational System Dynamics models is a system of coupled, nonlinear, first-order differential (or integral equations), given by:

$$\frac{d}{dt}X(t) = f(x, p) \tag{3.1}$$

where x is a vector of levels, p is a set of parameters, and f is a nonlinear vector-valued function (Richardson, 2020). One can dive deep into the mathematics behind these models and numerical integration thereof, however, this research is a methodological contribution to the possibilities for functional multi-modelling, leaving mathematical understanding and optimisation for further research.

Typically it is argued that this paradigm can best be seen as a top-down approach, in which one translates the modellers understanding of the world, its components, and how these interact, into a model (M'hamdi & Nemiche, 2018; Phelan, 2004). This is mainly a result of the stocks and flows structure, which are aggregates of the individual interactions in the system, creating a more or less homogeneous system.

3.1.2. Strengths of System Dynamics

When looking at the more conceptual side of System Dynamics modelling, once should notice that the stocks and flow structure of System Dynamics models, and the feedback that occurs in these models, makes that System Dynamics is very appropriate for evaluating accumulation, delays and time-dependent states of nonlinear systems. Arguably, this makes it exceptionally useful for estimating aggregate behaviour, in which change over time is the most relevant aspect. This behaviour may include market mechanisms, such as growth and stagnation, ageing mechanisms, such as in population dynamics or radioactive decay, and dynamics in common pool problems, such as the extraction of natural resources (Richardson, 2020).

For Sustainable Urban Development, one of the underlying incentives behind investigating this issue in the first place, may very well be the biggest common pool problem humanity will ever face: the planet as its main resource. Subsystems within the problem include dynamics of the housing market, energy market, and technology market, making the method incredibly suitable for modelling these systems. A summary of System Dynamics capabilities in this case is given in table 3.1.

3.1.3. Weaknesses of System Dynamics

A serious downside to the aggregate level of System Dynamics for understanding Sustainable Urban Development is that one loses sight of individual behaviour. This makes that investment behaviour in the energy transition is difficult to grasp. A big assumption is that it is expected that the modeller can deduct system behaviour from what is known. In general, System Dynamics relates observables, instead of individual behaviour, which contributes strongly to the idea that the method is mere top-down (Parunak et al., 1998). For clearly observable systems, this is less of a problem, since one can easily validate model behaviour on empirically established system behaviour. The uncertain nature of Sustainable Urban Development, however, makes that our expectations of how the system will or should behave may be very wrong. Next to this, the Dutch government decided (Klimaatakkoord, 2019) that municipalities are responsible for guiding the urban energy transition. This implies that policy is implemented from a bottom-up perspective, why then should one use a method for analysis that is merely top-down? A general overview of the strengths and weaknesses of System Dynamics is given in table 3.2.

Table 3.1: Strengths and Weaknesses of System Dynamics modelling for Sustainable Urban Development

Strengths	Weaknesses
Common pool problems	Investment behaviour
Market behaviour	Detailed Geographical differentiation
Technology dynamics	Unknown system relations
Population dynamics	

Although the idea that System Dynamics is a top-down method has been prevalent in the last decades (Richardson, 1991), a lot has changed in computational abilities and software implementations. A data-driven approach, in which behaviours are disaggregated to lower levels, for instance with spatial desegregation (Wallentin, 2018), however, may suggest a more intermediate naming. In this way, the model can be disaggregated to municipal level, which makes more sense given the policy problem. In the end, System Dynamics will always be aggregated to some extend, extensive differentiation will not work well, however, its prejudice of being entirely top-down may be short-sighted. This makes that System Dynamics may, under the right circumstances, be appropriate as well for problems that need another approach than entirely top-down.

Table 3.2: General Strengths and Weaknesses of System Dynamics

Modelling phase	Strengths	Weaknesses
Conceptualisation	Mental Modelling Homogeneous behaviour Delays and feedback	Heterogeneous behaviour Stochasticity
Formalisation	Fast computation Limited path dependency	Equations only
Evaluation Experimentation & analysis	Structural verification Time dependent evaluation Sensitivity Analysis	
Presentation	Representation causal relations	Communicating abstraction of stocks and flows

3.2. Agent-Based Modelling

Typically, on the other side of the conventional top-down, bottom-up spectrum, one finds Agent-Based Modelling (ABM) (Epstein & Axtell, 1996). Agent-Based simulation has widely been used for understanding systems from an interactions perspective for understanding complex systems such as ecologies (Grimm et al., 2005), social phenomena (Bonabeau, 2002), and geographical systems (Heppenstall et al., 2011). The idea is that one does not make a model from a point of view on how the system as a whole functions, but from the perspective of the smallest parts in the system and how these behave. The behaviour of the entire system emerges from a simple set of rules and interactions and regularly becomes complex at a fast rate. This complex emergent behaviour is often counter-intuitive and therefore Agent-Based Modelling may offer various insights in a system that otherwise is difficult to understand (Bonabeau, 2002).

3.2.1. Characteristics of Agent-Based Modelling

Agent-Based Models consist of agents with their own properties and behaviours. Commonly they are set up using a software tool specially developed for this purpose, making that Agent-Based Modelling started making scientific progress somewhere in the late nineties (Bonabeau, 2002). In Agent-Based Modelling, an environment is defined with certain characteristics, in which agents exist that behave according to basic rules, make decisions and adjust their own characteristics based on the characteristics of other agents, the characteristics of the environment, and their own characteristics (Van Dam et al., 2012). In rounds, simultaneousness of behaviour is simulated by asking agents, in a random order, to perform their task and follow the rules. In this way, the simultaneousness of actions in the real world can be mimicked with greater confidence. A major advantage of this 'real' representation is that people can easily understand the 'story' of an agent. An agent wakes up, gets a cup of coffee, reviews the current traffic, and decides whether to go to work by car or public transport. An understandable narrative. A downside to this individualism is that a representation of the system as a whole is much more difficult.

This is mainly because in Agent-Based Modelling it is assumed that system behaviour emerges from individual behaviour, in which the system is greater than the sum of its parts, due to phenomena that cannot be explained based on causal relations on its own. This makes that Agent-Based Modelling is extremely suitable for modelling systems that strongly dependent on individual behaviour, relations between individuals, and heterogeneous environmental characteristics. A downside to all these interactions is that, as the number of agents increases, interaction increases exponentially, making this method computationally expensive. A general overview of the strengths and weaknesses of the method for investigating Sustainable Urban Development is given in 3.3.

3.2.2. Strengths of Agent-Based Modelling

In the case of Sustainable Urban Development, exploring this emergent behaviour is extremely relevant, simply because the energy transition, with a wide range of possible solutions as compared to the transition to gas in the ’60s and ’70s (Canon volkshuisvesting nederland, 2020), is a challenge that has never been tackled before. The behaviour that is expected from participants in the transition, however, is something that can be derived from behavioural economics. Homeowners and housing corporations, for instance, will base their investment decision on its own economical prospects, general interests and the decisions of others (Ameli & Brandt, 2015; Bouwfonds ontwikkeling, 2010). Whether to invest in collective heating solutions or individual solutions will strongly depend on the behaviour of the stakeholders in the nearby area. Making Agent-Based Modelling a suitable method for creating a further understanding of Sustainable Urban Development.

If this behaviour comes from behavioural economics, why then not just use general economic models to gather insights about the energy transition? So far, one can only speculate about the possible developments in the system. Sure, economic models can be applied to how technologies generally develop through time, based on previous experiences with technology development and empirical data. It should not be forgotten, however, that most technologies develop based on economic incentives, whereas the energy transition is something different. Given the limited time-scale of the problem, a change is needed that is not pushed fast enough by economic incentives only. Hence, a method to explore how the system may behave, given current observations of the behaviour of individuals in the system, could offer the insights that are needed for developing suitable strategies for steering the challenge into the right direction, making Agent-Based Modelling very appropriate for exploratory analysis.

3.2.3. Weaknesses of Agent-Based Modelling

Challenges that arise when using Agent-Based Modelling for understanding Sustainable Urban Development often consider one aspect: a major draw-back is that Agent-Based Modelling will become very computationally intensive when approaching real-world scale. It works very well when mimicking a small part of the world (Macal, 2016). But in the case of Sustainable Urban Development in the Netherlands, one should somehow deal with nearly 8 million households (CBS, 2020h). This makes modelling every single agent at least somewhat challenging. Even though computing power has grown exponentially (Nordhaus, 2007), one can still wonder whether modelling at this scale, at this level of detail, is desirable. There are at least two solutions in reducing computational needs: either reduce scale or reduce detail. When reducing scale, one could argue that modelling a few detailed sections of the system is not enough for deriving the behaviour of the total system. On the other hand, reducing detail will reduce the ability to mimic real-life interaction, which is the main reason for using Agent-Based Modelling in the first place. An overview of the general characteristics of Agent-Based Modelling is given in table 3.4.

Table 3.3: Strengths and Weaknesses of Agent-Based Modelling for Sustainable Urban Development

Strengths	Weaknesses
Investment behaviour	Number of components
Geographical differentiation	System Representation
Network effects	
Population Dynamics	
Market behaviour	

Even though everything *can* be modelled using Agent-Based Models, since many programming languages such as NetLogo (Wilenski, 1999) are Turing complete (Turing, 2009), this does not mean that you *want* to do so. The elegance of using differential equations as an alternative can make calculations a lot faster, and a lot easier to explain. This is a major advantage of equation-based methods such as System Dynamics over Agent-Based Modelling, which should not be ignored. Hence, combining both of these formalisms by means of multi-modelling may offer results that are less computationally expensive and easier to understand, due to the speediness and elegance of System Dynamics, whilst retaining the required level of heterogeneity and individual behaviour by using an Agent-Based Model.

Table 3.4: General Strengths and Weaknesses of Agent-Based Modelling

Modelling phase	Strengths	Weaknesses
Conceptualisation	Emergence Heterogeneous behaviour Choice behaviour	Understanding of System as a whole Simultaneity of behaviour
Formalisation	Detailed modelling Turing complete	Computational expensive Path dependent modelling
Evaluation	Behavioural Analysis for verification	
Experimentation & analysis	Time dependent evaluation	Compensation Stochasticity
Presentation	Behavioural stories	System Representation

3.3. Exploratory Modelling and Analysis

For using computational models for understanding interaction and feedback mechanisms in dynamic systems, two paradigms can be distinguished (Auping, 2018). On the one hand, consolidative modelling is used to explain *why* the system is behaving as it is. By using known facts and validating the outcomes of the model with empirical data, a consolidative model can be a powerful method for predicting system behaviour. This is especially helpful in, for instance, engineering systems and understanding natural processes (Hodges, 1991). With this method, understanding of the system will get better by reproducing the system to the best of our ability by mimicking reality and approaching the ’real’ system relations.

In many systems, however, one does simply not know the ’real’ relations that cause the system behaviour. For System Dynamics, this means that approximating system behaviour in a complex system using ’best guess’ relations, will per definition lead to an answer that is wrong. This, however, does not mean that making such a model is useless. The idea that ”Essentially, all models are wrong, but some are useful” (Box, Draper, et al., 1987, p. 424), is strongly applied in the second modelling paradigm, Exploratory Modelling and Analysis (EMA) (Bankes, 1993; Bankes et al., 2013). EMA does not assume the ability to create a single model that ’reliably’ predicts system behaviour. It rather creates a set of plausible models that, given a set of uncertainties, explores possible outcomes of the system. Each of these models is, given certain combinations of these uncertainties, ’correct’. This makes this method especially useful for exploring possible futures and investigate how to deal with these. In this mindset, it is not relevant what the ’exact’ outcome of, for instance, policy intervention is. That is impossible to find out anyway. It is rather the range of outcomes that intervention may have, that is aimed for. Investigation of the sensitivity of the system to certain policy levers in combination with identified uncertainties will give the modeller the ability to evaluate the success of policies, no matter the ’actual’ outcome of these uncertainties.

The same comparison as with System Dynamics can be made for Agent-Based Modelling. Agent-Based Modelling can be performed for at least two purposes. Namely to try to replicate real-world systems in finding the ’real’ driving mechanisms behind these systems, an application of the consolidative modelling paradigm: by thoroughly calibrating and validating models one can prove *why* the system behaves as it does (See & Ngo, 2012). A view from the Exploratory Modelling and Analysis perspective focuses on the understanding of the impact of unknowns on the potential outcomes of the system, making it a fundamentally different approach, with different goals.

Evaluating these two modelling formalisms, it is clear that given the uncertain nature of Sustainable Urban Development, the Exploratory Modelling and Analysis paradigm will provide the most relevant insights. Despite the incredible relevance of what drives Sustainable Urban Development, there is simply no way to validate model outcomes until it is too late. Hence, only exploratory analysis will provide insights that could support decision-makers in developing the right strategies for solving the Sustainable Urban Development challenge.

3.4. Multi-modelling

Multi-modelling, as the name may give away, is a method for combining two or more models into one. The main reason to do so is to combine the abilities of these models. These can, but not necessarily need to be, models from the same paradigm. This could be multiple Agent-Based Models combined, or System Dynamics models, or a combination of different paradigms (Nikolic, Warnier, et al., 2019). One could ask why not to make one bigger model if one's combining multiple models from the same modelling formalism. There are multiple arguments for doing so: if a model has proven to be functional, it can be acceptable to work with a black-box model, saving time and effort in model building. Commercial incentives may require black-box model use (Gomes et al., 2017) and distributed model development could also be a reason for multi-modelling (Verbraeck, 2004). For the problem posed in this research, clearly different reasoning applies: it is argued that two model formalisms may very well approach different parts of system behaviour (Quesnel et al., 2009; Vangheluwe, 2000). A combination of both may hence lead to better results. A challenge, however: one does not simply merge two model formalisms (Nikolic, Warnier, et al., 2019; Vangheluwe et al., 2002).

3.4.1. Characteristics of multi-models

When evaluating the state-of-art on multi-models, several perspectives on *why* to use multi-models can be found. These perspectives are driven by developing better concepts (Duboz et al., 2003; Quesnel et al., 2009; Vangheluwe, 2000) and increasing the performance of models (Giustolisi et al., 2007; Luoto et al., 2010; Verbraeck, 2004). Multi-models can be, but not need to be, a combination of multiple formalisms. This aspect is what makes that a multi-model may conceptually perform better in representing the real world. Some system elements can simply not be modelled well using one or the other formalism. Next to this, multi-models can comprise of multiple models, modelling the *same thing*. This is done to determine whether different system representations result in different outcomes. In this way, the robustness of policies can be increased by accounting for the uncertainty in these outcomes. Another reason to model multiple perspectives of the same system in one multi-model can be to reduce the uncertainty of models themselves. If different models produce the same outcome, one's confidence in these models will increase. In table 3.5 an overview of the possible purposes of multi-modelling is given.

Table 3.5: Possible purposes of multi-modelling

Goal	Method	Reference
Concept improvement	Differentiating abstraction	Vangheluwe (2000)
	Heterogenisation of models	Quesnel et al. (2009)
	Multiple scale representation	Duboz et al. (2003)
Performance improvement	Distributed modelling	Verbraeck (2004)
	Reducing uncertainty	Luoto et al. (2010)
	Increasing robustness	Giustolisi et al. (2007)

Practically, the reason why to use a multi-model does not matter that much. More relevant is whether to combine multiple formalisms or not. When combining multiple formalisms, several possible implementations of multi-models exist, of which Vangheluwe et al. (2002) proposed three:

1. Transformation into one formalism
2. The use of a super-formalism
3. Co-simulation

The choice on how to tackle this will mainly drill down to a software engineering perspective. The larger the models to be transformed, the more difficult transformation will become. The same problem lies with the use of a super-formalism, bigger models will be difficult to submerge into the super-formalism, making co-simulation the more attractive alternative.

3.4.2. Opportunities in using multi-models

As far as the current understanding of Sustainable Urban Development goes, the most important reason for a multi-modelling approach is to improve model concepts by heterogenising the model and allowing for representations at different scales. In Sustainable Urban Development, several elements of the system can appropriately be modelled using System Dynamics, whilst others may better be simulated using Agent-Based interactions. One could argue why either one or the other formalisms is more suitable and find ways to mitigate the downsides that the making of this choice brings. I think, though, that that kind of reasoning negates the opportunities for novel techniques brought by such a complex system. Hence, I will apply both modelling formalisms to the problem, in order to, on the one hand, gain a better understanding of the abilities and disabilities of multi-modelling as a hybrid modelling formalism, and on the other hand, explore possible outcomes of the energy transition in Sustainable Urban Development to find policies that can positively contribute to solving the challenge.

3.4.3. Challenges in using multi-models

Challenges that arise with this approach are not the least. Nikolic, Warnier, et al. (2019) have identified the main principles, challenges and guidelines in this approach. The challenges they identify cover all aspects of the modelling cycle. Both System Dynamics and Agent-Based Modelling are complex methods per se. Combining them will cascade into a model that is to the nth more complex. This makes that deciding what part of the system to conceptually model using which formalism, whilst retaining and communicating the meaning of that choice, is inherently difficult. Conflicting rationalities and abstractions could force the modeller to make normative decisions that will likely affect model results significantly. The same is true for model formalisation. Combining modelling formalisms will fairly likely result in incompatibility issues, difficulties in conserving meaning in the interaction between models and debugging.

When evaluating the developed model, especially validation becomes arduous. With exploratory models, this is assumed impossible per definition, since *all models are wrong*. Only measures of fitness for purpose will do. Defining and testing this fitness will become even more difficult when evaluating multiple formalisms in one model. One test may be valid for one, but not for the other.

Next to this, designing experiments will become much more difficult for the same reasons as mentioned before, but especially retaining meaning and intention is an important pillar in performing them. If one is not able to retain that meaning, the experiment will become useless. A clear conceptualisation will be key in the ability to set up useful and meaningful experiments.

Last but not least: a major challenge in multi-modelling is communication. Designing a simple model is difficult, however, sometimes only a complex model will do. This will make that communication of the model's capabilities and outcomes will become difficult per se. The model meaning will always be hard to grasp. When reviewing the goal of this research *'[...] to provide multi-perspective insights [...]'*, the model will only be valid (read: fit for purpose) if it *actually* provides these insights. This means that others than the modeller must be able to comprehend its outcome and meaning and that the insights themselves need to be correct and valid. So, how to make something that is inherently complex, simple?

3.4.4. Tackling challenges in multi-modelling

I will start with defining the concepts and functionalities of the model. Only an understandable conceptualisation will provide the base for tackling the aforementioned challenges. In a multi-model, some parts of the system can well be modelled using one or the other paradigm, how will one make the distinction in where to model what?

Table 3.6: Opportunities and Challenges of multi-modelling

Modelling phase	Opportunities	Challenges
Conceptualisation	Hybrid selection of formalisms Ability to mimic 'real' behaviour Scale differentiation	Choice of formalism Conflicting abstractions Overlapping scales Conflicting rationalities Retaining meaning and intention
Formalisation	Computational optimisation	Multi-formalism alignment Debugging
Evaluation		Multi-formalism verification Validation nearly impossible
Experimentation & analysis	Time dependent evaluation	Preservation of meaning Result interpretation
Presentation	Choice of view	Model complexity Communication of meaning

During the conceptualisation phase of the model development cycle, several options for conceptualisation and making the distinction between one and the other formalism will be developed, in order to make a well-informed decision on how to finally conceptualise the system. Practicalities will arise when it comes to the formalisation of the model. Both sub-models need to communicate one way or the other, so the points that are connected need to be defined and specified very well. If necessary, this may result in deviations from the original conceptualisation for practical reasons. In the end, capabilities of the software and computer will play a big part in what is possible and what is not.

Although multi-modelling may offer a closer representation of reality, its understandability will decline significantly as complexity increases. Hence, maintaining the model fit for purpose requires a significant amount of attention. Because of this, and the novelty of this method, a lot of attention will be spent on the implementation of the model, hence, in the next chapter, the model will be discussed in detail, by means of the model development cycle.

3.5. Model Requirements

A qualitative method will be used for evaluating the performance of multi-modelling in the case of Sustainable Urban Development as compared to the expected performance of single-formalism modelling. Based on the characteristics of the case and reasons for developing a multi-model, several requirements have been set up. These are are given in table 3.7.

Method	Case
Multi-perspective	National to Neighbourhood level
Heterogenisation of models	Understandable presentation
Workable modelling challenges	Directly usable
Fit for purpose	Data-driven
	Suitable for EMA

Table 3.7: Requirements for to be developed method

The performance requirements have been split up in two elements, the method itself, and the case. The methodological requirements are derived from the aspects of, and reasons for multi-modelling instead of Single-Modelling. The case requirements are a direct result of the insights that the model should generate for Sustainable Urban Development (part III).

3.5.1. Method requirements

The first two requirements come from the opportunity for multi-models to develop better concepts. For multi-modelling to be a better method, it should at least live up to these opportunities. For multi-perspective presentation of results, this means that the model needs to be able to provide insights for policymakers at different geographical scales with their corresponding different questions. Based on the case results, it will be evaluated to what extent this requirement is met. As for the opportunity to heterogenise the model, its success depends on the conceptualisation of the model. As long as the appropriate formalism can be used for formalising different parts of the system, this requirement will be considered to be met.

A rather vague requirement is that multi-modelling should have 'workable modelling challenges'. This requirement comes from the long list of challenges that have been identified for multi-modelling as a novel method. That a new method has such challenges is inevitable, however, what matters is the way such challenges can be dealt with. It will require extra time and effort to deal with these challenges, but as long as this effort is acceptable and does not hinder model development to the extent that its performance is affected, the modelling challenges can be considered workable.

The last method requirement is actually a disguised case requirement. The fact that this research is a combined study into both the methodological development of multi-models as well as gaining insights in Sustainable Urban Development. Hence, although the development of the method is an important aspect, the case for which it is development should not be lost from sight. Thus, part of the performance of the method will be derived from its ability to meet its case requirements, being: fit for purpose.

3.5.2. Case requirements

The case requirements understandably partially overlap with the requirements for the method, as the method is not chosen at random. This means that with the case requirements too, the multi-perspectivity is an important factor in the model its performance, as the ability to provide insights too multiple types of policymakers is the main goal of the study. Practically this means that the model has to be able to provide insights from the neighbourhood level up and till the national level, as this will allow overall evaluation of policies as well as the heterogeneous effects they might cause.

The second requirement is that the results should be presented in an understandable matter, as the experience with modelling and simulation with policymakers is generally limited. Hence, the way the results are presented is key in the way that policymakers will be able to make use of it. This also applies to the fact the model results should be directly usable as a critique on other currently available models is that they do not offer that quality sufficiently.

The last two requirements apply the fit for purposeness of the model. Exploratory Modelling and Analysis has been chosen as the most suitable paradigm for the analysis of an uncertain and complex issue such as Sustainable Urban Development. The data-driven requirement comes from creating the 'certain' base from which to start the analysis, in order to safeguard that fitness for purpose.

3.6. Model Design

In the previous sections, various strengths and weaknesses have been identified for the two formalisms to be combined, as well as multi-modelling itself. A major reason for multi-modelling is that by combining different formalisms, the strengths of these formalisms can be combined, whilst its weaknesses can be averted. How this will be realised, is discussed in the next subsections.

3.6.1. Exploiting Opportunities

Two main opportunities have been identified that makes multi-formalism multi-modelling surpass single-formalism modelling. These are the ability to use the most appropriate formalism where necessary, resulting in better concept development, and the ability to provide multi-perspective insights.

As for concept development, I will not argue that using different formalisms for different parts of a system will always lead to better model concepts, some are just better approximated using only one, apart from the fact that multi-modelling brings additional challenges. However, given the complex and geographically segregated nature of Sustainable Urban Development (part III chapter 9), a multi-model concept is expected to outperform a single-formalism concept. This opportunity is manifested by the fact that multi-model concept development requires evaluation of what part of the model is to be modelled using what formalism. This forces the modeller to more carefully evaluate the representation of the system in the model. Different options for conceptualisation need to be evaluated because the choice for one or the other conceptualisation is not trivial. The development of these options makes that choice of formalism is considered more carefully than with single-formalism modelling, in which the choice depends on the suitability of the formalism for 'most' of the system. The fact that it needs to be accepted that some parts of the system can not well be modelled using that formalism is no longer an issue in multi-modelling, resulting in better models.

Multi-perspective interpretation of the model is something that can be more or less achieved using different formalisms, depending on the subject. System Dynamics enables this through vectorisation of stocks (subscripting) changing its characteristics to no longer only allow a top-down approach, but also allow for more intermediate approaches. Agent-Based Models can in theory always be aggregated to higher levels, resulting in a more systems representation. Performance-wise, this will however never supersede System Dynamics, since it just not built for it. Multi-modelling will allow for using the right formalism for the right perspective. Practically, in the model for the Sustainable Urban Development case, this can be exploited by providing the national, aggregated perspective utilizing the System Dynamics model. The lowest level, the intramunicipal level, can be provided with the details from the Agent-Based Model. The intermediate level, the perspective that will allow the inspection of intermunicipal differences can be obtained from the cutting edge between the two formalisms.

3.6.2. Mitigating Challenges

The challenges for multi-modelling can be classified over the five elements of the development cycle. The first challenges encountered in model development are the challenges that relate to conceptualisation. This is interesting because the ability to create better concepts is offered as one of the main reasons for multi-modelling in the first place. This brings the opportunity to use that ability to directly also mitigate the risks that it brings. Difficulty in the conceptualisation will lie with formalism selection and the interfacing between these formalisms. Next to this, ensuring that the meaning and intention of the models is ensured can be difficult in designing mutually dependent models (Nikolic, Warnier, et al., 2019). A solution to this is the same solution that is expected to contribute to better concept development: the development of various alternatives before choosing a final model concept. By doing so, the advantages and disadvantages of modelling choices can be weighed and evaluated before implementation, making that these challenges will eventually contribute to better results.

The second set of challenges comes from formalisation. Aligning the two formalisms for sensible interaction is considered a difficult task (Vangheluwe et al., 2002). Co-simulation employing an intermediate formalism, a so-called message-bus (Mosshammer et al., 2013), will enable intermodel communication. By predetermining the factors that will be transferred between the models, the syntactic (right format), semantic (correct information) and pragmatic (desired information) data quality (Price & Shanks, 2016) can be ensured, allowing for the right communication between models.

The third and major challenge is the evaluation of the model. This challenge already exists with single-formalism models and worsens with multi-formalism models (Nikolic, Warnier, et al., 2019). The same steps as with conventional verification and validation will be taken, but are expected to take much more time and effort. By starting with evaluating the separate models before connecting them, major debugging issues could be prevented. However, problems with this are bound to happen, although unpredictable. A flexible approach in evaluating the model will be performed to allow for incremental improvements to the model.

As extra tools and communication methods need to be implemented for the multi-model, it is going to be more computationally expensive than single-modelling. This is an inescapable fact caused by extra and sequential actions. This combined with the fact that an Agent-Based Model will be part of the model, and these models have high computational requirements (Epstein & Axtell, 1996), the multi-model can be expected to be slow. If no measures are taken to mitigate this, it is a real risk that computational performance will significantly hinder its usability. Hence, computational requirements will be limited by minimising the communication needed between the models and using efficient data structures for merging, converting and communication of information and data.

Computational performance is likely also going to affect the experimental setup of the study. High computational demand makes that a more select number of experiments needs to be chosen for evaluation. Key in this are two things: selecting the most interesting variables to vary and minimising the number of replications needed. The latter is a consequence of the use of Agent-Based Modelling as a modelling formalism. Its stochasticity makes that replications are necessary to be able to conclude on the results (Epstein & Axtell, 1996). Although one of the key reasons for using Agent-Based Models: the interaction between agents should be minimised until the point the model represents real-life behaviour just enough. Limiting interaction will decrease the stochasticity and thus the replication demand of the model. The coefficient of variation in these replications will be used as a determinant for the minimum number of required (Lee et al., 2015).

Lastly, the presentation of model results will be more difficult with multi-modelling than with singular modelling. This has to do with the fact that the visualisation and presentation tools offered by the modelling software (SD: Ventana Systems (2010), ABM: Wilenski (1999)) can no longer be used. However, this challenge can be solved using the EMA-workbench (Kwakkel, 2018), which has built-in tools for analysis and presentation, which is already used for performing the Exploratory Modeling Analyses. The multi-perspective approach makes that the outcomes that are presented should be clearly identifiable as from one or the other perspective. By presenting data using choropleth maps (Slocum & Egbert, 1993), it will always be clear from what perspective the results are presented.

4

Multi-model

This chapter will discuss the multi-model development cycle for the multi-model that has been developed for the Sustainable Urban Development case (Part III of this thesis). Whereas case-specific choices and arguments will be presented in the model chapter of the case study, this chapter will focus on the methodological challenges and opportunities of multi-modelling and how they have been dealt with. Hence, I will present the main challenges for each step of the multi-model development cycle and discuss the implications of multi-modelling as a method.

4.1. Conceptualisation

In the conceptualisation phase of the model development for the Sustainable Urban Development case (section 11.1), five main model concepts have been identified, these are:

1. Housing Market
2. Technologies
3. Energy Market
4. Individual Investment Behaviour
5. Collective Investment Behaviour

With the model being a multi-formalism multi-model, a significant methodological challenge comes forth from the fact that the model clearly needs to be conceptually divided into two sides, with on the one hand behaviour on the system scale (the System Dynamics model), and on the other hand behaviour on the individual scale (the Agent-Based Model). Concepts that fit within the system scale may include the housing market, energy market and technology market and can typically be modelled well using System Dynamics concepts (Dangelico et al., 2010; Kwoun et al., 2013; Naill, 1992; Teufel et al., 2013). On the other side, investment behaviour can be scaled under individual behaviour which is typically modelled using Agent-Based models (Farmer & Foley, 2009; Wei et al., 2003).

Some elements, however, may fit in both formalisms. Population dynamics can be modelled both using aggregates or individual behaviour. The housing market may be evaluated with changes in the market as a whole, or the creation, destruction, and change of individual elements, namely: houses. Because choosing one or the other option is not necessarily right or wrong, one first needs a further understanding of the possibilities and their characteristics.

Given the main properties of System Dynamics and Agent-Based modelling, their ability to better deal with either homogeneous systems or heterogeneous systems, at least two conceptual paradigms can be distinguished. In Sustainable Urban Development, System behaviour can be divided in *geographical differentiation* and *behavioural differentiation*. Decisions and events will happen at different geographical levels, such as households, neighbourhoods, municipalities and the nation, and are based on different types of behaviour, either collective or individual.

Figure 4.1 shows the combinations of behaviour and geographical scale that work well with one or the other formalism. As discussed in the methodology section, System Dynamics deals well with

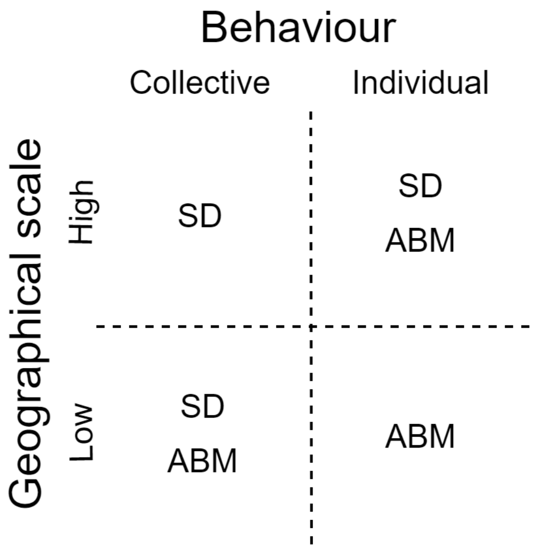


Figure 4.1: Preferred formalisms for levels of aggregation

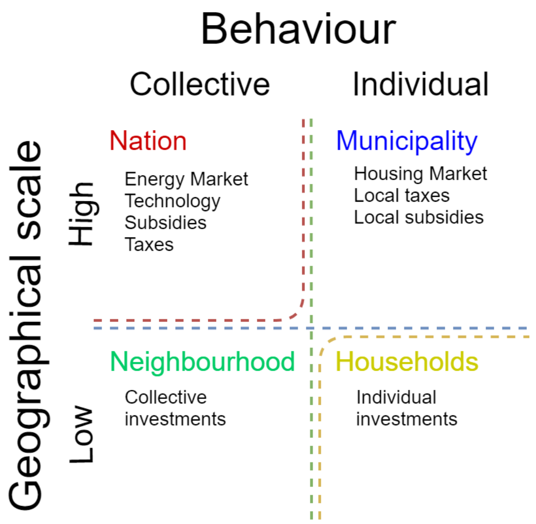


Figure 4.2: Possible segregation of concepts

systems as long as they can be evaluated as homogeneous populations to some extend. Agent-Based models perform well with heterogeneous populations. With different types of behaviour and different types of geographical scale combined in one model, this will result in an overlap between the two formalisms.

For choosing the right formalism for different model aspects of Sustainable Urban Development, at least four concepts can be developed, as shown in diagram 4.2. Each quadrant can be represented by different aggregations of stakeholders: the nation, municipalities, neighbourhoods and households. A division can be made in segregating the model purely on the type of behaviour (green line) or the geographical scale (blue line). Alternative conceptualisations can be made drawing the line at the point where one formalism performs best, by only modelling collective behaviour at a high geographical scale using System Dynamics (red line), or by only modelling individual behaviour at a low geographical scale utilizing Agent-Based Modelling (yellow line).

The four identified options of segregation bring forth a very interesting discussion. How does this choice matter? Does it matter at all? The conceptual discussion on this issue appears not to have been conducted often. Reasons for multi-modelling, and how to do so, mainly include reducing uncertainty and making more robust models by evaluating multiple perspectives (Giustolisi et al., 2007; Luoto et al., 2010). Next to this, allowing for the creation of more heterogeneity within models is opted as a reason for multi-modelling (Quesnel et al., 2009). Vangheluwe et al. (2002) discusses how to build a model from multiple formalisms: transforming to one formalism, co-simulation or using one super-formalism. All to allow for different levels of abstraction (Vangheluwe, 2000).

But why choose one or the other abstraction? And where to create more heterogeneity, and where not? Purely for formalisation purposes? As the aforementioned researchers found, for the formalisation of the model, the choice of one or the other conceptualisation matters for sure. When modelling Sustainable Urban Development, high geographical segregation will definitely affect the number of agents needed in the Agent-Based model, increasing computational needs accordingly. The same holds for behavioural segregation on its own. If one is to model *all* different behaviour, that will be very computationally demanding.

From the System Dynamics perspective, working with a low-level aggregation will require an immensely high level of detail within the System Dynamics model. This will result in multi-dimensional evaluation by vectorising most of its functions, quickly reducing computational benefits of System Dynamics.

Evaluating these two options, choosing a high, or low level to segregate the model formally, will increase computational power needed, making that finding a way in between, will likely optimise computational performance.

4.1.1. Two model concepts

With the analysis so far, no definite reasoning for choosing one or the other multi-model concept is found, except for the fact that computational power will be an important factor. Hence, in this subsection, I will develop two model concepts. One from a behavioural segregated perspective, and one from a geographical segregated perspective.

Both perspectives have to contain the elements that have been identified as important in the Sustainable Urban Development case. These elements are summarised in the subsystem diagram presented in 4.3. In this diagram, a first partition has been made for the elements that will be modelled using one or the other formalism. These are the elements that are commonly formalised using these formalisms. Market mechanisms are done well in System Dynamics, whereas individual behaviour can only be modelled using Agent-Based Modelling. The next subsections will dive deep into the implementation possibilities for the elements that can be modelled using both formalisms.

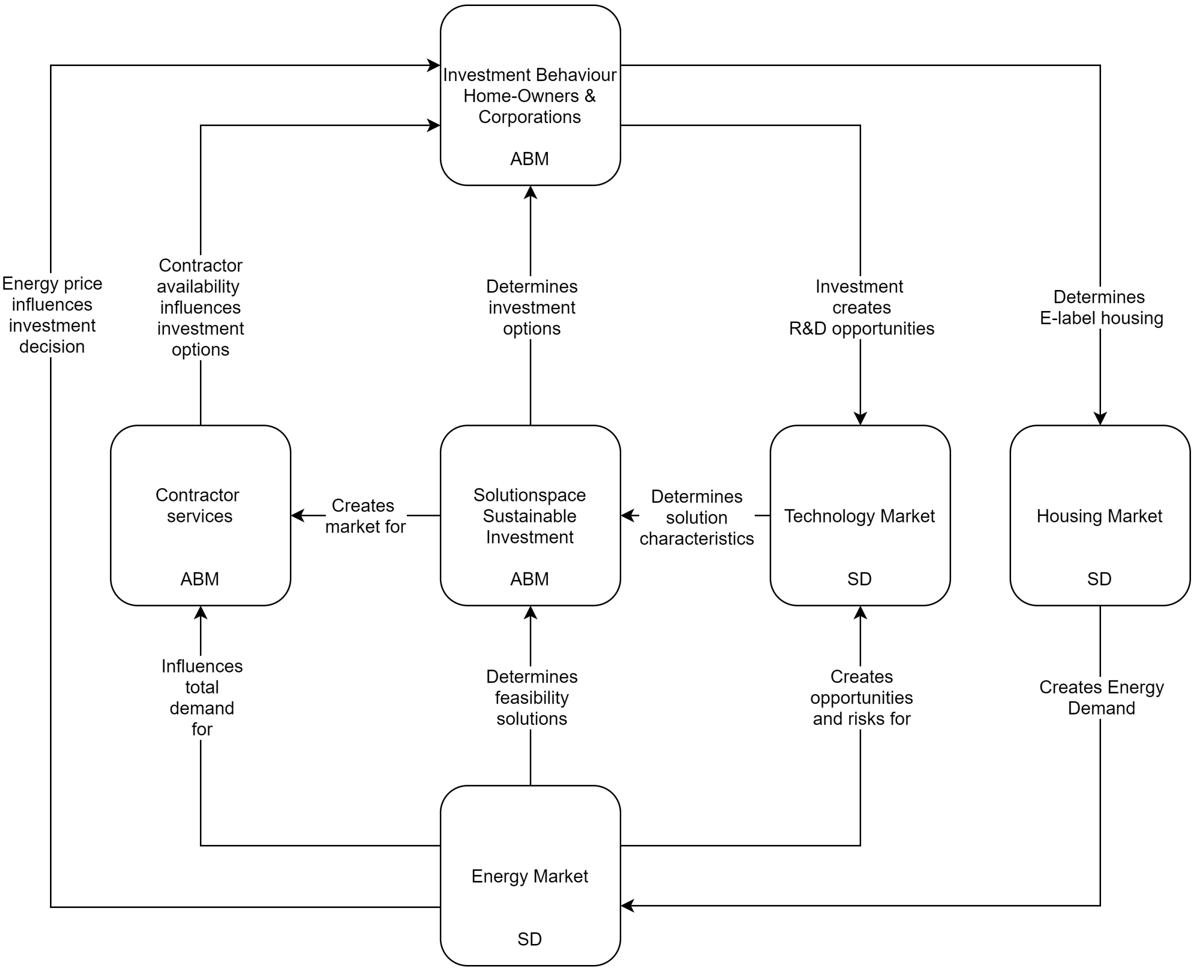


Figure 4.3: Subsystem Diagram for multi-model ecology

4.1.2. Behavioural segregated model concept

The behavioural segregated model concept, as the name suggests, lays its conceptual border between the System Dynamics model and the Agent-Based model at the scale of behaviour. All behaviour that can be seen as ’making decisions’, that is, individual behaviour, is part of the Agent-Based model, whereas all ’environmental behaviour’, that is, collective behaviour is part of the System Dynamics model. Entities that can be seen as individuals in its purest form would only include one-person households. This excludes a large proportion of investment behaviour, which is not desirable. To be more practical, it is arguable that organisations that act on behalf of a group can also be seen as individuals. This makes that municipalities, housing corporations and energy suppliers can also be added to this group of individuals. All behaviour that is at a higher aggregation level, market behaviour, population dynamics, and technological developments should then be modelled using System Dynamics. This conceptualisation is given in figure 4.4.

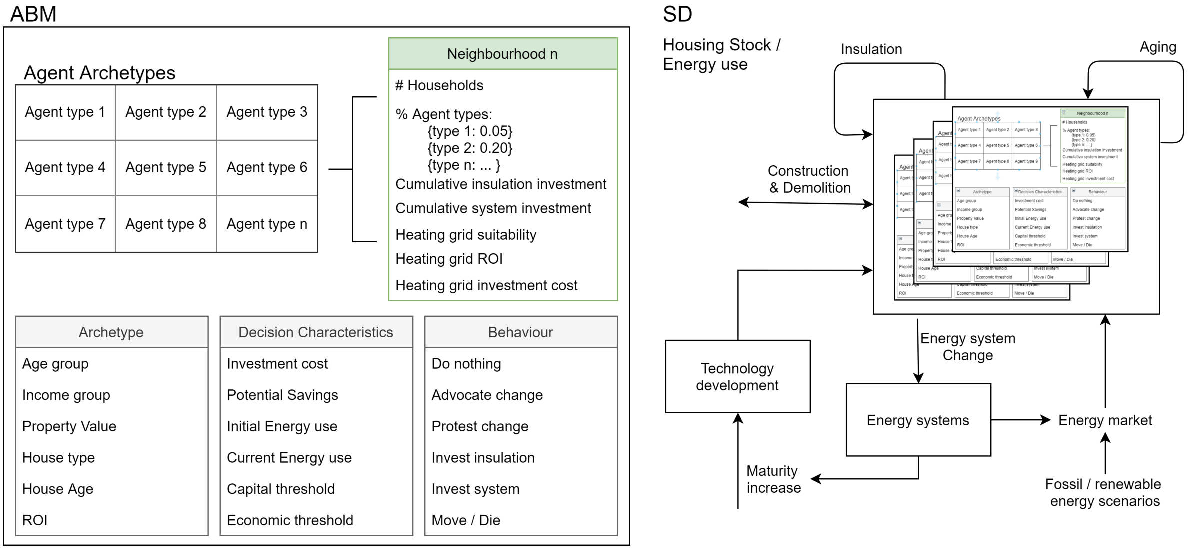


Figure 4.4: Behaviourally segregated model concept

This option directly brings some challenges, concerning the proposed scale in this research. If one is to model individual investment behaviour of homeowners, that would mean that nearly 4.5 million agents are needed (CBS, 2020o). That will for sure result in a computational disaster, next to the fact that the behaviour of homeowners may not be that different from each other anyway, making the differentiation not necessarily useful.

A solution to this is to work with archetypes. By identifying the characteristics that determine different behaviour, one can aggregate individual behaviour to neighbourhood level by weighing the decisions of individuals the number of these individuals in each neighbourhood. In this way, the neighbourhood will behave on behalf of the underlying archetypes, each archetype has to be evaluated only once, reducing computing requirements significantly. A drawback to this is that interaction between these archetypes is no longer possible given this structure, which negates one of the major strengths of Agent-Based Modelling.

4.1.3. Geographical segregated model concept

The multi-model ecology for the geographically segregated model concept is illustrated in figure 4.5. As the figure shows, the Agent-Based model and System Dynamics model will be separated between the individual behaviour of stakeholders, such as homeowners, housing corporations, contractors, and municipalities, and the behaviour of markets. To make the best use of the abilities of both model formalisms, the geographical scope for the Agent-Based Model lies at the neighbourhood level, of which multiple neighbourhoods together compose a municipality. Using statistical distributions, the different aspects of stakeholders and heterogeneity of the neighbourhood can be preserved, so that each neighbourhood can behave according to its heterogeneous characteristics. This makes that the model does not need to incorporate every single individual, reducing computing time significantly.

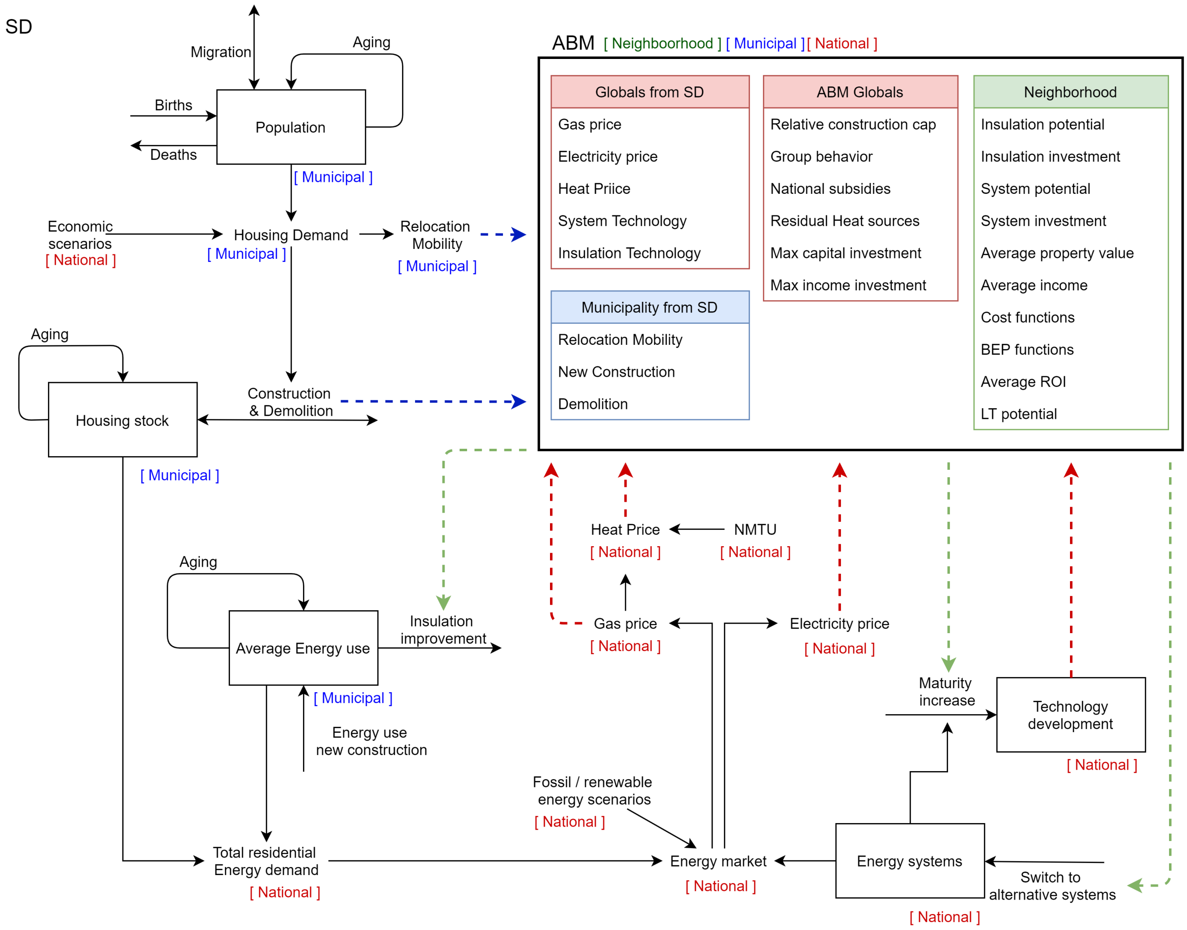


Figure 4.5: Geographically segregated model concept

The System Dynamics model, on the other hand, will be modelled at both municipal level as well as at nation-wide level using vectorised functions, utilizing subscripts. In this way, processes that take place on both levels can be combined. The Agent-Based Model will feed the System Dynamics model with the developments regarding investment in the housing stock and effects on R&D. The information from the markets in the System Dynamics model will then again be fed to the Agent-Based model as input for investment decisions. In this way, aggregate municipal developments can again be used as individual input at the municipal level.

4.1.4. Model concept selection

Now that two completely different model conceptualisations have been presented, next is to think about which concept to further develop. For robustness and uncertainty reduction one could argue to develop both, as opted by Giustolisi et al. (2007) and Luoto et al. (2010). Time is limited, unfortunately, so although both options are viable and will likely produce varying results, it has been chosen to further develop one model.

For behavioural economists and Agent-Based modellers, this probably won't be a difficult decision. The abilities of the Agent-Based model will most likely be reflected best in the behavioural segregated model. A reason not to do so, however, is because of the scale of this research. Behavioural analysis of one neighbourhood, or maybe one municipality will certainly be of great value. The fact that this research aims to provide insights for *all* municipalities, however, makes that this becomes a difficult challenge. The archetypes proposed in the model concept do offer a solution to this. Unfortunately, this will reduce the possible interaction between there archetypes significantly if computational power is to be obtained by reducing the number of agents. This makes that most relevant argument for this segregation is negated for the sake of computational power. Next to this, on the other side, the System Dynamics model has to be built with a very high level of detail, that likely all gains from thinning the Agent-Based model will be lost because of multi-dimensional implementation of stocks and flows. This combination of losses on both sides is undesirable to the extent that this conceptualisation becomes inferior to the geographical segregation. Although this conceptualisation is very interesting ranging from individual scale to neighbourhood or municipal level, it isn't likely to be feasible ranging from neighbourhood scale to national level, at least not with the computational resources available to the author of this thesis.

Geographical segregation is not the perfect conceptualisation either, unfortunately. Due to the scale of the problem, this makes that each neighbourhood is represented by one agent only. This means that the heterogeneous population of a neighbourhood needs to be aggregated into one homogeneous agent. Because of this, the same perk of Agent-Based Modeling is negated as with the behavioural segregated concept. It appears that this is an inescapable drawback of the proposed scale of the model. The solution offered for this problem, however, is deemed acceptable. By mimicking heterogeneity through statistical distributions, this aspect is not entirely lost.

So to answer the question from subsection 4.1, whether the choice of conceptualisation matters: conceptually it is only a matter of perspective. How does the modeller think the world looks like? What behaviours are predominant in the system? In this view, both perspectives are equally interesting or useful. In the end, the difference lays in formalisation. Depending on the scale of the model, detailed modelling of interactions may simply not be feasible.

One aspect, however, does make the geographical segregation its concept performs better: it is probably easier to grasp. With the research goal to provide municipalities with the relevant insights to develop Sustainable Urban Strategies, one can probably better understand what is going on when talking geographical segregation, rather than behavioural segregation, especially if one has to deal with archetypes. This is not necessarily a problem that comes with this type of conceptualisation, it is the combination with multi-modelling that makes the model more abstract, and therefore more difficult to understand. All-in-all, geographical segregation is expected to better perform in reaching the goals of this research.

4.1.5. Conceptualisation performance

Looking at the challenges imposed with multi-model conceptualisation, formalism choice, conflicting abstractions, overlapping scales and conflicting rationalities, the approach to develop several concepts to pick the 'best' one, can ensure the quality of the overall concept. Although conceptualisation for sure requires more time and effort, the evaluation of the two options in the case of Sustainable Urban Development has led to an extra careful consideration of alternatives before choosing where to draw the conceptual border between the two models. Moreover, it can be argued that this is also beneficial to the conceptualisation as a whole since the modeller is forced to evaluate various options. In this way, a choice could also be made based on practical limitations, leading to a more realistic concept. All in all, accepting the extra time and effort needed for conceptualisation, multi-modelling does provide the right circumstances for better model concepts to be developed.

4.2. Formalisation

The next challenge that multi-modelling brings in the model development cycle is the combination of the two models during formalisation. Focus here will lie on how the models can be coupled, the technical difficulties that this coupling will bring, and how can be guaranteed that the intended meaning of outcomes is preserved during intermodel communication. A second challenge to be discussed is the effects of multi-modelling on the computational performance of models. As it is clear that computational performance will not likely improve, I will discuss the measures that are taken to minimise these effects.

4.2.1. Model coupling

A major challenge comes from the fact that it is not easy to let two different commercial-off-the-shelf software packages communicate. Interfacing problems concerning consistency (Boer & Verbraeck, 2003) will occur. A solution to this is to manage this interaction using a so-called ’message-bus’ (Mosshammer et al., 2013). This message-bus will be used to interpret the output of one model and then translate it to usable input for the next model. This will be done in a Python environment that can control the models in use and manage communication between these models. The Python environment will act as an intermediate formalism, that translates the information from one formalism into useful information to the other formalism. Care should be taken to prevent computational problems by enabling more communication between the models than strictly necessary. Hence, a minimal working amount of data is selected to communicate between models.

Figure 4.6 gives an attribute diagram for the multi-model for the case of Sustainable Urban Development. On the left side, the System Dynamics model and the policies and uncertainties that influence the model are given (red), with the corresponding characteristics. On the right side, the Agent-Based model is given with the concurring policies and uncertainties (green). The middle (yellow) represents the message-bus that will contain the information that is sent from one to the other model. It indicates which information is transferred and how. In the bottom of the diagram, one finds the key performance indicators that will be of interest to the model users.

4.2.2. Computational limitations

A second challenge that is already slightly touched upon in model coupling is the risk that computational requirements increase quickly. Due to the requirement for the model to have a data-driven approach, as a base for the exploratory analysis, it is tempting to overuse the available data. Although modelling every single house individually will lead to more detailed and more accurate results, it is simply not computationally feasible. By treating groups of agents as ’little System Dynamics models’, one can homogenise them by keeping track of heterogeneous characteristics. In the case study, this is done by grouping homeowners and housing-corporations on geographically relevant characteristics: their neighbourhood. By reducing the number of agents from roughly 8 million to a little over 13 thousand, is a huge computational improvement. The heterogeneous characteristics are tracked through (statistical) distributions, that will safeguard the heterogeneous characteristics of the system. Detailed information on setting these characteristics can be found in chapter 11.

4.2.3. Formalisation performance

The challenges that have been found in the formalisation of multi-models are numerous. The extra time and effort that is needed for mitigating the consequences of these challenges is a serious downside to multi-modelling as a method. Nevertheless, the problems that can occur are manageable and do not appear to affect the model’s abilities significantly. Although computational performance is an issue that keeps reoccurring, careful management of this problem will ensure that its consequences will not harm the model’s capability to provide the knowledge to reach the intended goals.

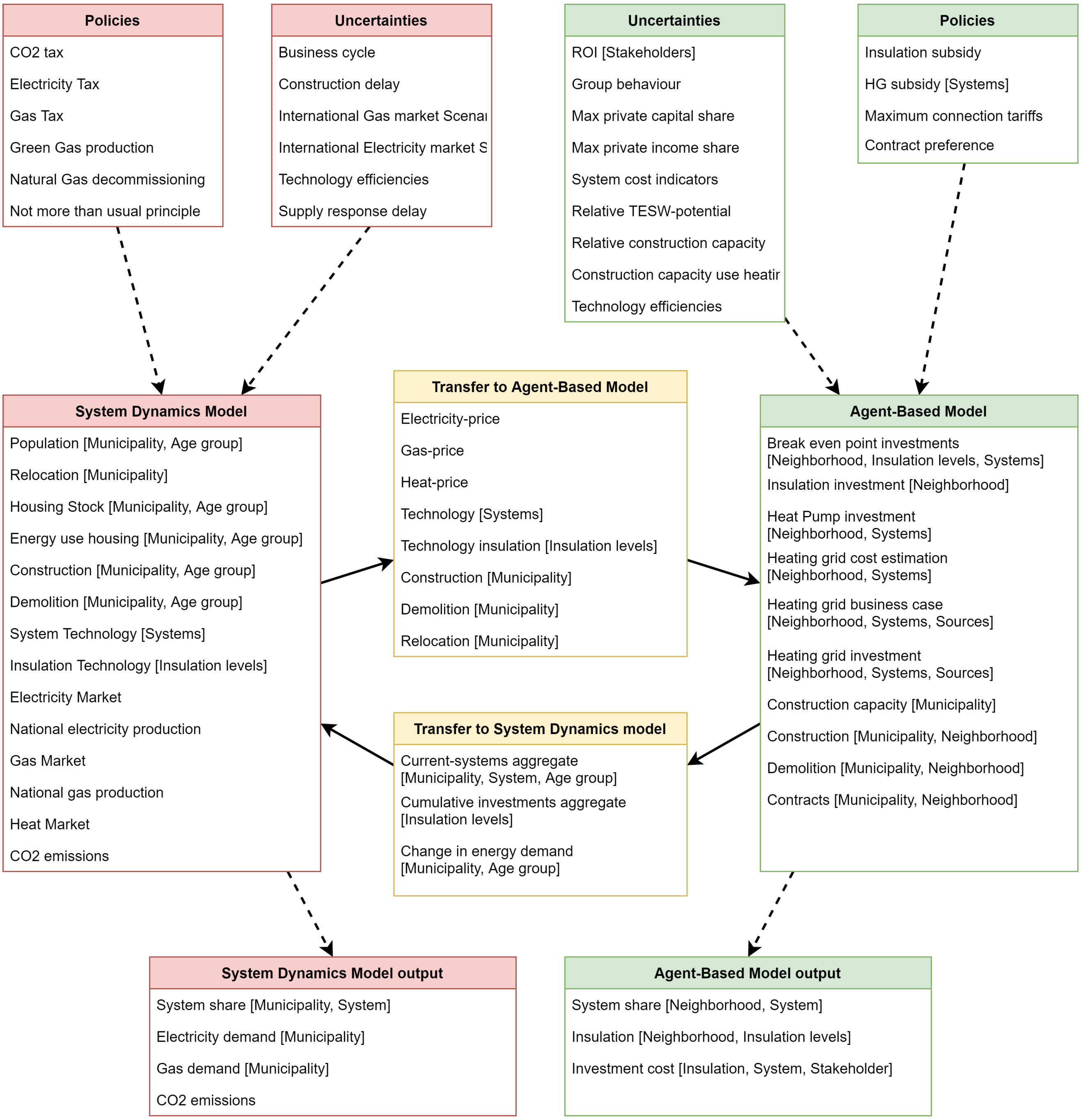


Figure 4.6: Model attribute diagram

4.3. Evaluation

As indicated by Nikolic, Warnier, et al. (2019), verification and validation of multi-models become a challenge. Especially because the entirety of the model can only be evaluated after the models are coupled. This, combined with the fact that the exploratory nature of this study makes that the model per definition is not ’valid’ (Hodges & Dewar, 1992). Since the model cannot be proven ’right’, this makes that the model can only be validated on fit-for-purposeness, which can only be done after the model is coupled, because only then one can evaluate the fit-for-purposeness of the entire model.

Nevertheless, this does not mean that partial verification and validation tests cannot be performed along the way. By carefully testing every submodel after it is built, one prevents major bugs and setbacks later in the process. Although some small issues are nearly inescapable, this leads to a minimum of bugs and trouble when testing the model as a whole. This is incredibly important, as the computational requirements for one run increase quickly with the complexity of the model. Hence, the next subsections will discuss how this is realised using partial validation tests and how the multi-model is validated as a whole.

4.3.1. System Dynamics Submodel evaluation

Evaluation of System Dynamics models can be performed from two perspectives, evaluating model structure, and evaluating model behaviour (Barlas, 1996; Senge & Forrester, 1980). This is no different in multi-modelling. However, in the partial evaluation of the multi-model, the most relevant of these is evaluating the structure, since model behaviour will depend strongly on the other submodel. Senge and Forrester (1980) propose several tests for doing so. A test that is intuitively performed by all modellers, is the structure verification test. During the modelling process, structures are continuously evaluated in finding the *right* way to do so. In the Sustainable Urban Development case, it is ensured that the model matches observable structures in the real system, by discussing these structures with experts at Witteveen+Bos and Delft University of Technology repeatedly.

Confidence in these structures can be increased by performing extreme condition tests. If the model still performs to expectation under extreme conditions, it is likely to well represent the system under normal conditions, as well as that it will be able to describe behaviours outside of the current regions of behaviour (Senge & Forrester, 1980). Especially this last argument is valuable in modelling the energy transition since the change of the system is one of its goals.

The model developed appears to perform well under extreme conditions. For instance, crashing the housing market by reducing new construction to zero, leads to high market pressure following population growth. The average energy use of housing no longer changes with no insulation improvement and quickly drops to nearly zero with infinite insulation investment. In the unlikely extreme scenario in which all houses become fully energy conservative, natural gas prices drop significantly caused by a drop in demand. The model its performance in extreme conditions increases confidence in the model by showing logical behaviour in these conditions.

Following the extreme conditions, dimensional-consistency testing utilizing unit analysis can also reveal faulty model structure. The software package Vensim (Ventana Systems, 2010) in which the model is built, enables to perform this unit check during the modelling process (Peterson & Eberlein, 1994), allowing for mistakes to be found and resolved easily. In this way, no mayor mistakes were found when evaluating the submodel as a whole.

Given these structure tests, for the purpose of modelling the energy transition, the System Dynamics submodel can be considered fit-for-purpose. Although not perfect, no mayor mistakes are found and the structure allows for realistic behaviour to be produced. A next step is to evaluate the Agent-Based Model so that following that the multi-model as a whole can be evaluated.

4.3.2. Agent-Based Submodel evaluation

For Agent-Based Models, a similar validation process can be used as in System Dynamics. Heppenstall et al. (2011) propose four steps in structural validation, face validation, sensitivity analysis, calibration and output validation. The first three of these validation steps are performed continuously in the modelling process. For every submodel, it needs to follow the right logic, respond to external impulses correctly, using the right parameters. As with the validation of the System Dynamics model, output validation is dependent on the interaction of the two models and will be performed when evaluating the multi-model as a whole.

In the Sustainable Urban Development case, the most relevant aspect in the Agent-Based Model is investment behaviour. The data-driven aspect of the model makes that calibration is not much required, whereas the model behaviour does tell a lot about whether the right logic is applied. Although investment behaviour in the model is based upon the (not necessarily valid) homo economicus assumption, the right implementation of this assumption is key for the model to be able to produce usable results.

Extreme condition tests help to perform face validation and sensitivity analysis that can investigate this implementation. With extremely high demanded return on investment, one can expect very limited investments, whereas extremely low demanded return should result in many investments. This can be confirmed in the model, to the point that an error occurs with an ROI of 0 (division by 0). This is no problem, however, since such a situation in the real world will never exist.

Because of the choice to aggregate to neighbourhoods in the model, many characteristics are implemented as a share of items. For instance, the level of insulation, given by the energy labels, is stored as a list with the shares of each energy label. This means, that after investment, a shift has to take place between items in this list, as well as that the sum of these items should always be 1. The latter is not entirely true, unfortunately. Cases have been found in which the sum of shares of energy labels add up to a tenth of a per cent more or less than one. Nevertheless, this is not a serious problem, because it can be explained due to rounding errors. Next to this, the size of the deviation is very limited, barely impairing the model results.

4.3.3. Multi-model evaluation

The fact that the model is built with the purpose of Exploratory Modelling and Analysis, makes that the model lends itself very well for validation tests such as boundary adequacy and behaviour-sensitivity tests. The wide range of experiments performed makes that the boundaries of the model can be evaluated very well. With initial testing, a small error was discovered in which the initial states were not reset adequately between experiments. After resolving this issue, in the full model experiments, no behavioural anomalies were discovered.

One issue did occur: two out of fifteen hundred experiments failed completely. The initial thought was that a division by 0 had occurred, either by some stochastic anomaly or by the specific input parameters of these experiments. However, the input parameters did not suggest extreme behaviour, since none of the inputs was the minimum or maximum of that input for all experiments. Hence, the experiments were repeated exactly, to determine whether the problem would occur again, which it did not. This makes that the experiment failure cannot be assigned to model implementation (alone). The problem could have occurred due to a software or hardware problem at the server on which the experiments were performed, which is difficult to trace. This is not much of a problem, since it only affects the model outcomes to the extent that two experiments are useless, which is an acceptable 0.13 per cent. Although desirable to solve, this issue is no reason to disregard any of the other results, because it does not affect model validity for its intended purpose of Exploratory Modelling and Analysis.

In the end, model validity is only obtained by gaining trust and confidence of the model user. Hence, further behavioural evaluation is performed in the case part of this thesis (III). There, section 11.4 indicates that although slightly overestimating energy use and thus CO_2 emissions, the model behaviours can be explained well based on existing theories and practice, allowing for the conclusion that the model is fit-for-purpose.

4.4. Experimental setup

Because of the high computational requirements of the multi-model, combined with the computational requirements of Exploratory Modelling and Analysis, this aspect has to be taken into account during the development of the experimental setup. On the one hand, the resolution of the model makes that it is impossible to investigate every aspect of it. On the other hand, the computational requirements make that the amount of experiments that can be performed is limited. Hence a dynamic experimental setup is used, to limit the number of experiments that need to be performed. Next to this, the number of replications to compensate for stochasticity is limited to the minimum required for the purpose of this model. The next sections will discuss how this is done.

4.4.1. Dynamic experimental setup

To be able to investigate the right parts of the solution space, a dynamic approach is used to develop the experimental setup. This setup is divided into three rounds. In the first round, the minimum number of replications is determined, which will be further discussed in the next section. In the second round, open exploration (Kwakkel, 2018; Pruyt et al., 2013) will be performed varying a wide range of uncertainties and policies with the predetermined number of replications, to evaluate the outcome at the municipal and intermunicipal level. With these outcomes, scenario discovery (Bryant & Lempert, 2010) can be used to identify the relevant uncertainties and policies for the national outcomes. From there directed search methods can be used for enabling robust decision-making at the national level. At inter-municipal level, however, regional differences can be observed, in order to determine the municipalities to be investigated using open exploration in further experiments. In the third round, based on findings from the second round, three municipalities will be chosen to further investigate in detail as a proof of concept. With outcomes at the neighbourhood level and scenarios from the national level, it can be investigated how these municipalities may change over time, given these scenarios, to determine robust policy options. When the findings prove to be fruitful for these three municipalities, future research will be able to enable an analysis of the 352 other municipalities in the Netherlands.

4.4.2. Replications

Another aspect that needs to be taken in mind is the number of replications that are performed. Considering a fixed amount of time to perform experiments, every extra replication will require a significant reduction of the experiments to perform. Due to the stochastic nature of Agent-Based Models, to be able to compare outcomes between experiments, a pool of samples is needed to compensate for that stochasticity. Since the runtime of the multi-model for the Sustainable Urban Development case is about 12 minutes using a 2.6GHz processor, limiting the number of replications is key in producing a relevant number of experiments to investigate. Luckily, the way that the Agent-Based Model is developed, makes that the model is only minimally stochastic at the national level. This is shown in figure 4.7.

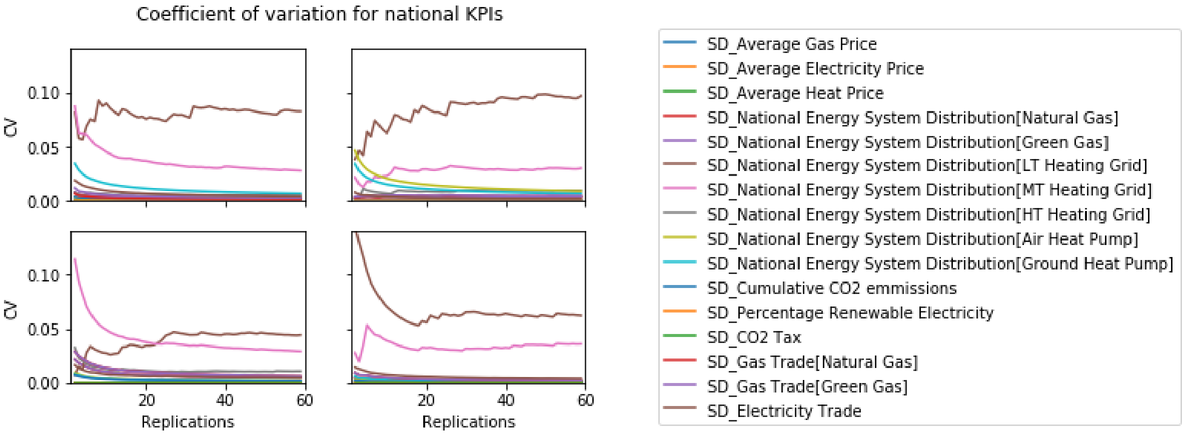


Figure 4.7: Coefficient of Variation for outcomes at national level

As indicated by Lee et al. (2015), the coefficient of variation is a valuable indicator for determining the minimum number of replications. The point where the coefficient of variation stabilises with an increasing number of replications is considered the minimum number of replications. As for the key performance indicators indicated in figure 4.7, one can observe that most indicators stabilise somewhere around five to ten replications, except for two factors that appear to stabilize at twenty replications. Given the runtime of the model, twenty is still considered too much. Even though statistically not the best choice, in this study it will be necessary to stick with an absolute minimum of four replications for its broadest analyses. This is deemed acceptable, since the coefficient of variation is considered pretty low for all evaluated variables, even for those reaching the point of stability the latest. In the second round of experiments, diving into municipal indicators, a shorter runtime will allow for a higher number of replications. For further research, it is encouraged to work with a higher number of replications for the national analysis, but for now, given the exploratory modelling and analysis approach and a proof of concept as a goal, a large number of experiments for exploration is preferred over statistical significance in the analysis.

5

Results

In this chapter, I will discuss two types of results. On the one hand, I will present some of the case results, to demonstrate the presentation abilities of the multi-model, as well as how the behaviours of the model can be explained using the underlying multi-model structures. On the other hand, I will evaluate the performance of the multi-model, as compared to single-paradigm modelling, so that future studies will be able to incorporate the considerations found in this research to decide whether a multi-model will be fit for their purpose.

5.1. Presentation

Presentation of results may very well be the most important job for modellers. When model outcomes are not presented right, it is unlikely that policymakers will be able to use the results to their advantage, let alone the risk that they will be steered in the wrong direction. As indicated in chapter 3, multi-modelling makes that preservation and presentation of meaning becomes a more difficult task. Nevertheless, it also brought the opportunity to present the results from various perspectives, which is considered one of the main perks of multi-modelling. Hence, the next sections will discuss the three perspectives from which the outcomes can be evaluated, to show how this opportunity unfolded in the Sustainable Urban Development case study.

5.1.1. National Perspective

The first perspective to discuss is the highest level of aggregation: the national perspective. Because the lower governments work together to in the end realise national goals, makes that investigation of the main key performance indicator should be done at this level. With CO_2 emissions being that KPI, the model can evaluate the development of these emissions over time for each experiment. This results in a tangle of lines, with the best scenario leading to about half of the emissions as the worst scenario. Employing time series clustering (Steinmann et al., 2020), the upper and lower half of these outcomes can be selected into a 'better' (orange) and 'worse' (blue) group. Using a pairsplot (figure 5.1), one can evaluate how the use of different energy systems relate to each other, grouped on whether they lead to the desired outcome or not. From there one can find that at a national level, the use of renewable electricity will be key in realising the lower half of CO_2 outcomes. As could be expected, the use of alternative heating solutions such as heating grids and heat pumps compete with gas connections, and more common use of these alternatives lead to fewer CO_2 emissions. From figure 5.1 one can learn that the use of heating grids and heat pumps appear not to be competing. This makes that stimulating and subsidising these options will not be at the expense of the other, making stimulation of these options complementary policies at the national level. If this is also the case at lower levels, can be investigated at lower levels of aggregation. Further case analysis of national results can be found in chapter 12.

These outcomes show that the model results at national perspective can be presented very well by grouping the outcomes on desirable and undesirable outcomes. By colour coding, these groups, the 'spaghetti' of outcomes can better be understood and the roles of various performance indicators can be presented clearly. Figures such as 5.1 give policymakers in Sustainable Urban Development clear insight in the importance of various solutions and policies in realising the national CO_2 goals, to

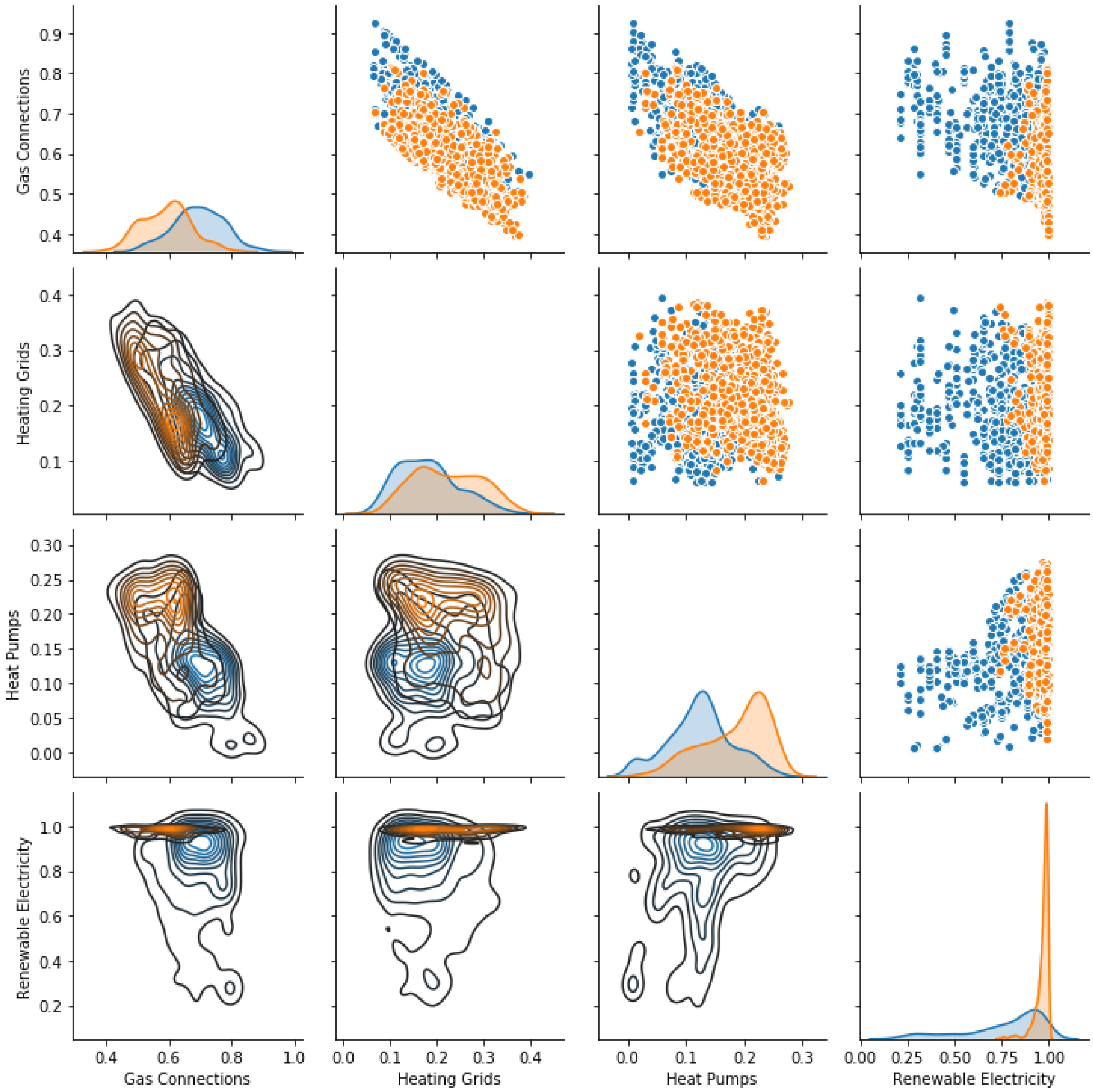


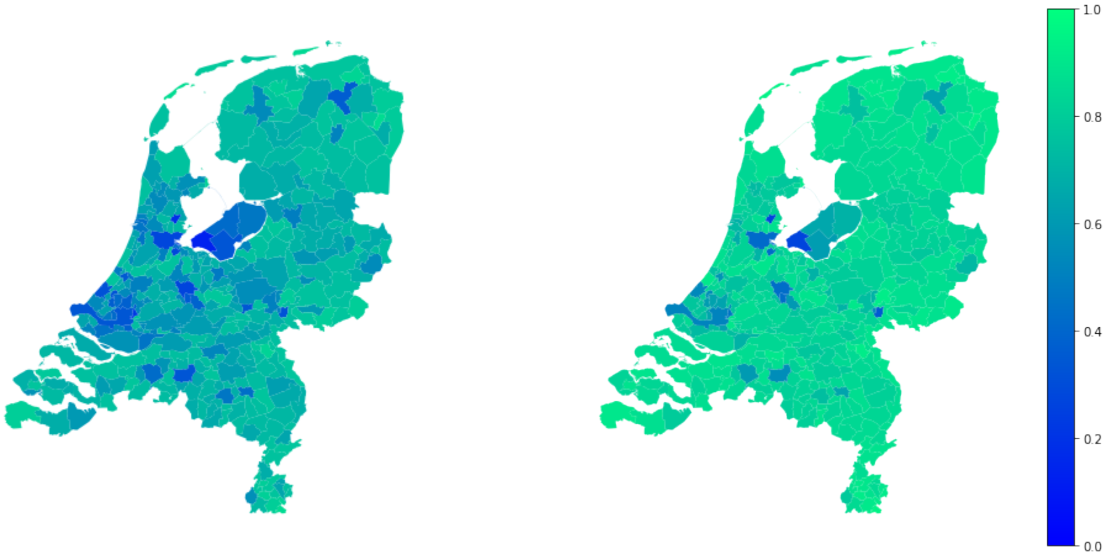
Figure 5.1: System contributions for low CO_2 emission cluster

develop policies that will enable the realisation of Klimaatakkoord (2019) aspirations.

5.1.2. Intermunicipal Perspective

One level lower into the multi-model, one find the intermunicipal perspective. Here, the heterogeneous effects of policies and uncertainties can be evaluated. With 355 municipalities and 1500 experiments, presenting such data using graphs and tables is rather difficult. By using the CO_2 clusters from the previous analysis, the number of experiments can be reduced to 2. However, the high number of municipalities still makes the data difficult to represent. A solution to this is the use of choropleth maps (Slocum & Egbert, 1993) to present municipal differences. Figure 5.2 shows the intermunicipal differences for the use of gas systems in 2050, separated on the two CO_2 clusters. From these maps can be identified that despite the CO_2 scenario, urban areas appear to perform better in realising natural gas free neighbourhoods than rural areas. Similar maps can be made for any statistic desirable by policymakers, enabling determination of differences between municipalities and the investigation of factors that cause these differences.

The visual presentation through choropleth maps shows that the multi-model is very well able to present model outcomes at intermunicipal level. As choropleth maps have been commonly used for



(a) Low CO_2 emission cluster

(b) High CO_2 emission cluster

Figure 5.2: Mean final (green) gas use for CO_2 clusters

geographical applications in the last decades (Slocum & Egbert, 1993), the ease of use of such figures makes that meaning of the outcomes presented on these maps can be safeguarded very well.

5.1.3. Intramunicipal Perspective

The same kind of maps as used in the intermunicipal perspective can be used to present the results at intramunicipal scale. Figure 5.3 shows plausible building years for scenario independent heating grids. By evaluating the average development of heating grids and the coefficient of variation for this development, neighbourhoods can be found that will develop heating grids with most certainty.

Figure 5.3: Plausible building years for scenario independent heating grids

Presentation of results at this scale enables policymakers to investigate more concrete steps for policy development. Whereat national and intermunicipal scale the model allows investigation of policies that stimulate the use of different energy systems in general, the intramunicipal perspective provides insights into the concrete development of systems given these policies. This helps policymakers to focus on the specific neighbourhoods that require extra attention. In the case of heating grids, a 'batting order' can be identified for municipalities for detailed studies in the feasibility of heating grids for the most promising neighbourhoods. The development of other neighbourhoods can then be postponed until the unfolding of the future and its uncertainties allow for better analysis.

5.2. Method Performance

The case in this study has provided an opening for in-depth investigation and development of the use of multi formalism multi models and their usability for such cases. In chapter 3 the methodological requirements for this multi-model have been specified. These are:

1. Multi-perspective
2. Heterogenisation of models
3. Workable modelling challenges
4. Fit for purpose

In the next subsections, each of these requirements will be evaluated and discussed. The third requirement about the challenges of multi-modelling will be discussed on the base of the model development cycle.

5.2.1. Multi-perspective interpretation

The main practical reason for multi-modelling in this specific case was that it would provide insights from different perspectives. Sustainable Urban Development is managed at different levels of government, making that policy at one level, is uncertainty at other levels. The results from the case study show that the multi-perspective approach works very well. The model can provide insights into the main key performance indicators at the national level, evaluate the policies and uncertainties that influence system outcome and develop advice for policies that in general perform well. In the next level, at the intermunicipal perspective, the model can show the heterogeneous effects of the policies and uncertainties that were only evaluated homogeneously in the national perspective. This enables policymakers at the national level to develop policies that focus on for instance urbanised areas or rural areas specifically. In the case, it was found that urbanised areas are less scenario and policy sensitive, which provided the insight that the focus in realising the goals should lie on the more rural areas. This is an insight that single-perspective modelling could not have provided.

The most detailed perspective, at the municipal level, has shown that even within municipalities there still is huge heterogeneity. Insights in this heterogeneity help policymakers to prioritise on neighbourhoods that require immediate attention or neighbourhoods that can wait for a while. This insight provides policymakers with a sense of direction, which was identified as one of the challenges that municipalities are currently struggling with.

5.2.2. Heterogenisation of models

As found in section 4.1.1, multi-formalism modelling allows the development of more diverse model concepts, which can be evaluated on their conceptual value as well as the practical feasibility. This enabled to model different parts of the system using the formalism that fit the individual parts best. In this study, this allowed for very detailed modelling of investment behaviour of homeowners, housing corporations and heating companies, while market mechanisms could be approached with a more holistic approach. The System Dynamics model provided for dynamic scenario development that provided the environmental circumstances for the investment behaviour in the Agent-Based Model. The main perk from this choice is that systems in which there is no clearly identifiable 'agent' that makes decisions, can better be explained from a System Dynamics perspective. In this way, model users can better be informed about how the model works, to create greater confidence in the model.

5.2.3. Reflection of challenges in multi-modelling

As multi-modelling is a relatively novel method, various challenges were to be expected in the modelling process. This section will one-by-one discuss these challenges, how they have been dealt with and what the consequence was to model development.

1. Conceptualisation

As thoroughly discussed in the conceptualisation section, formalism selection turned out to be a challenge as well as an opportunity. The ability to view concepts from different perspectives makes that evaluation of the 'best' perspective is incredibly difficult. Next to this, modellers are in general educated into specialists for one or the other formalism. Wearing two hats makes that one is constantly split between two fundamentally different trains of thought. Designing the 'right' concept in that split is very difficult. On the other side, however, it does enable the development of concepts from different perspectives. In the case, this enabled the development of two fundamentally different concepts of which the most practical concept was chosen to further develop. Although conceptually the other concept was fine, practical limitations made that one concept was better. Such challenges are more difficult to overcome when working with only one formalism. In that case, that one formalism needs to be used for something that it is not made to do, either increasing model complexity significantly or creating such abstraction that its meaning is no longer preserved. Although conceptualisation becomes a more difficult challenge in multi-modelling, in the end, it does allow for better concepts to be developed, making multi-modelling perform better than traditional methods.

2. Formalisation

The formalisation of multi-models mainly is plagued by extra time and effort spent on making the model work as it should. Although manageable, unless new methods and tools are developed for making the formalisation easier, the extra effort to develop multi-models should always be taken into consideration when deciding to develop a multi-model.

3. Evaluation

Partial verification and validation turn out to be a viable approach in evaluating multi-models. However, the risk that issues pop up after coupling of the models cannot be fully mitigated. The approach in which models are built around dummy input does allow for inspection of the consequences of the ’right’ input from the other model. Nevertheless, the complexity of such models makes that estimating that input is not trivial. This means, that although multi-models *can* be evaluated to the same extent as other singular modelling options, it does not mean that it is *easy*. In the end, since coupling can only be done at a later stage of model development and that multi-models are sensitive to developing high computational requirements, makes that evaluating multi-models will be a time-consuming endeavour.

4. Experimental setup

The element of the model development cycle that suffers most under the consequences of high computational demand of multi-models is the experimental setup. Frankly, the higher computational demand of a single experiment will always result in allowing for fewer experiments. Although one can make smart decisions in what experiments to run and optimising model performance and intermodel communication, computational performance is always going to be worse than that of a single model. This means that as long as computational power is not plentiful, the ability to perform fewer experiments should be taken into account when deciding to develop a multi-model.

5. Presentation

The preservation of meaning in model development and intermodel communication was safeguarded by ’double-modelling’ communication variables. The difference in the abstraction of the model formalisms makes that variables cannot directly be communicated with meaning to the other model. Hence, especially from the Agent-Based Model to the System Dynamics model, variables were aggregated from Agent-Based abstraction to System Dynamics abstraction, before they were communicated to the System Dynamics model. Computationally this may not be the most efficient or effective method, but it does ensure that the meaning of the transferred information is preserved correctly. Although Vangheluwe et al. (2002) argues that one can better transform the formalisms into one common formalism, rather than perform co-simulation as was done in this study, I found that this method works very well, especially due the size of both models. Transformation of the Agent-Based Model into a System Dynamics would never have been able to grasp the sought for model behaviour sufficiently. Even though single-formalism modelling in many cases is a lot easier, in developing a model with this size and complexity, co-simulation provides the right handles to retain that complexity.

A challenge that is insurmountable when working with different formalisms, is that model presentation is no longer evident. However, the use of Python and the EMA-workbench (Kwakkel, 2018) enabled the development of a custom interface which could be used to investigate model outcomes. The geographical characteristic of this study made that presentation using choropleth maps (Slocum & Egbert, 1993) turned out to be very useful. The generalisation of algorithms enables fast extraction of information from whatever geographical entity desired. Although the exact model behind the interface is a black box to non-modellers, its presentation makes that it is very well understandable to its users.

5.2.4. Fit for purpose

As discussed in section 4.3, the most important measure for the validity of the model and thus usability is that it is fit for purpose. Generally, this is a subject as part of the evaluation of the model, when deciding whether or not the model is valid. As this study has a separate approach in developing the model and then applying it to a case study, the extent to which the case requirements are met actually determine the validity of the model. Hence, the next section will discuss the performance of the model with regards to these requirements.

5.3. Case performance

In this section, the case-specific performance of the multi-model will be discussed. To do so, five requirements were identified, which the model has to fulfil in order to be suitable for the Sustainable Urban development problem. These are:

1. Multi-perspective
2. Understandable presentation
3. Directly usable results
4. Data-driven input
5. Suitable for Exploratory Modelling and Analysis

5.3.1. Model strengths

The strengths of the multi-model for Sustainable Urban Development mainly lie in how the results can be presented to its users. With the goal to provide insights to policymakers at various levels of government, the model is designed so that it can display results at three different levels: the national, intermunicipal and intramunicipal level. Presentation of the lower aggregate levels can very well be done using choropleth maps (Slocum & Egbert, 1993), enabling policymakers to on the one hand compare differences between municipalities or neighbourhoods, as well as differences over time.

Next to this, the model input is mainly based on direct data from Kadaster (2020) and CBS (2020i). This makes that it will be easier to discuss the results with stakeholders based on the direct characteristics of their municipality or neighbourhood, instead of discussing relative abstract model outcomes.

5.3.2. Model weaknesses

A challenge that unfortunately is not directly overcome due to the time scale of this study, is the ability to provide results that are directly usable for every municipality. Although the model is ready to perform the experiments necessary to produce these insights, this will still require quite some modellers expertise to perform. An easy to use user interface with a database of model results in the back-end would allow the usability of the model to be improved significantly.

The model opportunities towards the ability to perform Exploratory Modelling and Analysis is currently not yet fully exploited. Although the multi-perspective ability of the model works very well with Exploratory Modelling and Analysis principles, its computational requirements, on the other hand, hinder the performance of the desired analyses to their maximum ability.

5.4. Computational performance

The aforementioned challenges show that computational performance is a huge challenge to multi-modelling. To provide some insight into this, further investigation of the model and statistical description of its results require quite some extra experiments. Currently, 1500 experiments have been performed with 4 replications. Ideally, one would evaluate at least 10000 experiments with about 20 replications. This means that the total amount of runs should be increased from 6000 to 200000. On a reasonable computer (Win10, quad-core 2.6GHz processor, 8GB RAM) one simulation takes about 12 minutes. The high memory demand (about 2.4GB per simulation) allows for 2 parallel runs, without reducing single simulation time. Evaluating 200000 experiments would then take a little under three years. A high-performance cluster (6000 runs were performed in 2 days) may reduce the computational time needed to about 2 months, which is still very long. About half of that computational demand comes from model interaction, which makes that concerning computational performance, the included single formalism models outperform the multi-model by a factor 2. This is a significant drawback of the method.

Next to computational power needed to perform the experiments, the multi-perspective capability of the model makes that it generates enormous amounts of data. In this case, it was chosen to select only three municipalities (>600 neighbourhoods) out of 355 municipalities (>13000 neighbourhoods) for evaluation. This resulted in 34GB of data. Evaluating all municipalities would then lead to 750GB of data, and performing the extra desired experiments would result in 25TB of data. Presenting such data is simply impossible. However, time-series cluster analysis (Steinmann et al., 2020) proved to be a valuable tool to reduce the amount of data to be presented by grouping similar scenarios into one combined experiment. For this study this resulted in a reduction to 1 GB of data, so for the entire set of experiments, after combining replications and setting up stereotype scenarios, the total dataset can be reduced to about 150GB. Although this is still an enormous amount of data, decentralisation of policymaking makes that every policymaker can select its relevant part of the data, reducing the data to reasonable and understandable chunks. Making that extending the model to provide the relevant insights for all municipalities, is only a few steps away.

6

Discussion

Methodologically, this research has shown how multi-formalism multi-modelling can be applied to a large and complex problem, to provide for multi-perspective interpretation of the system. This is valuable because it creates insights in the dependencies and possible competing interests which may be overlooked when only evaluating one perspective (Seck & Honig, 2012; Zeigler et al., 2018). It appears that multi-modelling can very well fill in the gap that single-formalism modelling leaves behind in cases such as Sustainable Urban Development. Nevertheless, a lot of room for improvement in multi-modelling still exists. Computational requirements and added complexity and effort in the modelling process makes that especially under time pressure, the extra added value as compared to single-formalism modelling is not yet fully exploited at this stage. As Nikolic, Warnier, et al. (2019) indicated, it is a time-consuming challenge to develop the handles for keeping and preserving meaning in the interaction between the multi-models.

6.1. Multi-model development cycle

Several challenges still exist in the process of multi-modelling. A multi-formalism approach makes regular modelling techniques and approaches do not always apply. This means that for multi-modelling, the development cycle (Auping, 2018) needs to be revisited. The first in this cycle being conceptualisation.

Although better concepts can be developed using multi-modelling, the conceptualisation phase in multi-modelling requires a more extensive completion. It is desirable to develop multiple concepts which can be evaluated on their conceptual 'correctness' as well as practical feasibility. As modellers are typically educated to be specialists in one or the other formalism, although often insightful, it is very difficult to have to wear two hats and think from different perspectives. Next to this, a big risk that multi-formalism modelling brings is the temptation to model the entire world. The fact that multi-formalism modelling *allows* one to model many and more diverse concepts, does not mean that one *needs* to do so. Being able to develop simple models is still a virtue (Chwif et al., 2000), although not necessarily achieved in this study.

Transforming the model concept into a computational model is then the second challenge. The main question that is constantly in mind: how can it be done? Building an extensive multi-perspective multi-formalism multi-model is simply a lot of work. Developing one proper and complete model is time-consuming, let alone two or more. A major challenge that comes up in building the models is that one constantly has to take into account that a huge submodel (namely: the other formalism model), is still absent, but should be incorporated at a later stage. In single formalism modelling, either this part would be modelled using solutions and constructs endogenously, or it would be considered exogenous using scenarios. Applying that strategy, however, is not evident in multi-modelling, since one would want to build the model around the input of the other model which, however, for both is nonexistent. The complexity of both separate models makes it very difficult to properly align sensible interaction. To deal with this, it was chosen to use one formalism as a shell around the other model. This resulted in the System Dynamics model providing a set of scenarios for the Agent-Based model, where highly dependent interaction and feedback was sought for, resulting in a lower level of complexity of the model as a whole.

The same problem makes that verifying and validating a multi-model is difficult. A problem that arose in developing a multi-model from scratch, is that the model gets large and complex very fast before the model is coupled and tested as a whole. The rapidly increasing computational demands make that verifying and validating the model is a time-consuming task. Although formalism independent tests such as unit checks and structural validation (Nikolic, Lukszo, et al., 2019) can be performed without too much tumult, examining model behaviour is an arduous challenge. With simulation runs taking nearly a quarter of an hour, performing boundary adequacy and extreme value tests may take as long as performing the experiments themselves. Although these tests can also partially be performed during the model formalisation process, 'dummy' input that is used for the other model whilst not yet coupled may hide underlying issues that only surface after the entire model is finished, or even only during experimentation. Performing dummy experiments is an inescapable effort to be able to vouch for the validity of the model as a whole.

When performing experiments, the major drawback appeared to be computational power. This may partly be attributed to the extent of the Agent-Based Model, of which computational demand is a common drawback (Bonabeau, 2002), but model interaction is a time-consuming task on its own as well. The combination of two models that both have its relevant uncertainties makes that one quickly requires an enormous set of experiments. Time constraints made that fewer uncertainties could be taken into account than was desirable. Now that the model has proven to be functional, extra experiments will be able to expand the quality and content of the model's outcomes, but this is going to remain a time-consuming endeavour.

6.2. Exploratory multi-modelling

Exploiting the possibilities of Exploratory Modelling and Analysis (Bankes, 1993) using multi-modelling appears to have a somewhat paradoxical. On the one hand, multi-modelling provides opportunities for exploring a system to its fullest. Multi-perspective interpretation allows for an even wider exploration of systems than EMA alone. A drawback to this is that the tools that are currently available for EMA, such as Scenario Discovery (Bryant & Lempert, 2010), are dependent on high numbers of experiments. Now let this just be one of the major shortcomings of the multi-model developed in this study: its computational requirements make that obtaining a large number of experiments is extremely time-consuming. Especially directed search algorithms such as many-objective robust decision making (Kasprzyk et al., 2013) benefit from high numbers of experiments, making that applying these tools to the model is not trivial. Nevertheless, initial exploration using limited experiments still provided the initial direction that was intended to find in this study. It should be taken in mind however, that with different purposes for developing a multi-model, the combination of multi-modelling and exploratory modelling may not be that fruitful due to computational limitations.

6.3. Multi-modelling: a modular approach

A solution to the challenges identified in the model development cycle of multi-modelling as well as exploratory multi-modelling may be to treat the process as if it were single models. By implementing a modular approach, in which the separate models are completely developed using separate model development cycles, many of the challenges currently experienced may be evaded. Initial evaluation of and experimentation with the separate models will allow gaining confidence in the performance of the models in earlier stages and will allow for a preliminary exploration of the model's sensitivities and relevant factors. In this way, on the one hand, the model development process may become easier due to the reduced complexity, and on the other hand, final experimentation may require fewer experiments because a better initial selection can be made of the variables that are important for exploratory analysis.

This solution also offers an opportunity for a more collaborative approach in which multiple modellers develop separate models in their field of expertise, which can then be coupled later. A strict organisation in the development of these models will be key in the compatibility of the separate models. Although it is advised to develop models that are fully independently usable, a challenge that will remain is to combine the modules into one. A conceptualisation process in which states and variables are identified that will be used in both models should provide the handles needed for coupling the models at a later stage. As both models will have methods to evaluate these states and variables, a discussion that then will remain: what part of the models will be used endogenously, and what part of the model will be provided exogenously by the other model?

In the end, it is expected that the downsides of the modular approach will supersede the challenges of multi-modelling that it may avert. Nevertheless, since multi-models tend to become big and complex very fast, even with a modular approach, development periods and computational requirements are expected to remain large as long as no groundbreaking changes are made in the ability to develop multi-models.

7

Conclusion

Multi-modelling as a novel method for gaining multi-perspective insights in Sustainable Urban Development has proven both horrendous as well as brilliant. Its capability to investigate homeowner behaviour, as well as the consequences of system-level behaviour, makes it a very useful method. Despite the large room for improvement, it offers a great perspective on the common practice of multi-modelling as a multi-perspective approach. Conclusions on model development will be presented by answering the research questions of this study.

How can Sustainable Urban Development be formalised using a multi-model ecology including System Dynamics and Agent-Based Models?

In developing a multi-model for Sustainable Urban Development, it was found that a convenient characteristic of the case is that it can be geographically segregated. After all, that characteristic is also what makes that a multi-perspective approach is desired, for which multi-modelling can be applied. The geographical segregation made that the national perspective could be modelled using System Dynamics and that the other perspective, at the municipal level, could be modelled using an Agent-Based Model.

By modelling the market behaviour using System Dynamics, it allows for dynamic scenario development in terms of market behaviour where other models make only use of static predetermined scenarios. This enables the replacement of the idea of a few ’plausible’ scenarios that will be the wrong per definition with an ensemble of scenarios that will better be able to approximate real market dynamics. Next to this, the stochasticity of the model could significantly be limited by not only using Agent-Based modelling, reducing the required computational demands a manifold.

The Agent-Based model, on the other hand, turned out to be incredibly useful for the modelling investment behaviour. Where Planbureau voor de Leefomgeving (2019c) assumes insulation investment up to label B for all houses, the Agent-Based model allows evaluation of the evolution of insulation investment, based on the environmental circumstances. In this way, neighbourhoods can be found that may not be able to reach the ’base insulation level’ that the Vesta MAIS model assumes and allows policymakers to investigate realistic heating options for these neighbourhoods. This approach has the advantage that one does not investigate what *should* be done, rather than what *can* be done.

Using a message-bus (Mosshammer et al., 2013) in an intermediate formalism, in which information is saved and prepared for exchange, has turned out to be a viable method for ensuring the preservation of meaning in intermodel communication. Although computationally expensive, using a message-bus does allow for any type of data to be converted and communicated whilst maintaining its meaning.

What challenges in multi-model development can be expected and how can these be mitigated?

Challenges with multi-modelling are manifold (Nikolic, Warnier, et al., 2019). Nevertheless, they are not unsolvable. Actually, some challenges turn out to be an opportunity: formalism selection and overlapping scales for instance. Multi-formalism modelling allows for and even encourages multi-perspective concept development. Dwelling upon the consequences of once's conceptualisation is often underexposed. Thinking about what part of the concept should be modelled using which formalism, forces the evaluation of the consequences of that decision in much greater detail. In this case, purely from a conceptual perspective, the choice for one or the other world view appeared not to be relevant. However, the choice had major practical implications. Such a restriction may not have surfaced in single-paradigm modelling, making that the development at that point could have stalled. This makes that the proposition by Duboz et al. (2003), Quesnel et al. (2009), Vangheluwe (2000), that multi-modelling is a solution to developing better concepts, is perfectly valid.

Challenges in preservation and presentation of meaning can successfully be mitigated by using an intermediate formalism for communication of model outcomes and communication between models. This is a combination of the solutions proposed by Vangheluwe et al. (2002), namely a combination of a super formalism and co-simulation. Although opted by Vangheluwe as the least viable option, it is expected that the use of co-simulation in multi-models at this scale and level of detail will remain insurmountable.

The biggest challenge that remains in multi-modelling, especially for models of this level of detail, is the computational requirement. These kinds of models cannot easily be developed using a regular personal computer. Although the model turned out to provide the insights that were aimed for in the case study, there is still a lot of room for improvement in computational terms. When this challenge can be overcome, it will allow for much more extensive and in-depth analysis of the model outcomes.

What is the relative performance of multi-models as compared to traditional modelling methods?

Overall, the multi-model has shown to perform fairly well with regards to the reasons for which the multi-model was developed in the first place. The model concept provides an extensive view of the system that is to be modelled, and different parts are modelled using the appropriate formalisms. The multi-model has successfully been able to provide insights from different geographical scales, which so far has proven to be difficult (BackHoom, 2019; ECN, 2019b; Energy Transition Group, 2013). Nevertheless, the development of a multi-model is a bigger effort and more time consuming than developing a traditional model. Computational requirements are likely to negatively affect the evaluation and experimentation phase if no measures to deal with this are taken. This makes that the suitability of multi-modelling will always depend on the characteristics of the system to be modelled, the skills of the modeller, and the timeframe in which the model needs to be developed. As long a the problem is complex and detailed, the challenge to be solved demands insights from various perspectives and time is ample: multi-modelling may be able to provide these perspectives.

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III

Energy Transition in the Built Environment

Abstract

With the EU goals (European Commission, 2018b) to reduce CO_2 emissions to zero tons in 2050, The Netherlands has set up a climate agreement (Klimaatakkoord, 2019) in which municipalities get a leading role in reducing the carbon footprint of the Built Environment. To realise these goals, an energy transition is inevitable and strategies need to be developed for remodelling neighbourhoods into sustainable living environments. Before the end of 2021, municipalities have to come up with a plan in which they decide what neighbourhoods will be transformed and when. A problem in this is that currently, municipalities do not have the resources and tools to do so (RTL, 2019; Schuttenhelm, 2020; Straver, 2019).

Currently, existing models, such as the Vesta MAIS model (Planbureau voor de Leefomgeving, 2019c) offered by the national government, are missing two crucial aspects which should help municipalities to set up their strategies: time dynamics and population dynamics. The techno-economic approach does present the 'best' solution but is missing how to get there. Next to this, uncertainty around national policies makes that it is very difficult to decide on a robust policy.

To deal with the aforementioned challenges, I use a multi-modelling approach (Nikolic, Warnier, et al., 2019; Vangheluwe, 2000), using System Dynamics (Forrester, 1961) and Agent-Based modelling (Epstein & Axtell, 1996) in which on the one hand, the time dynamics and population dynamics aspects are incorporated, and on the other hand multi-perspective insights on effects of national policies on national goals as well as insights on the heterogeneous effects at the municipal level are provided.

An important finding is the crucial role of a CO_2 tax on the realisation of national goals. Without this tax, homeowners and housing corporations will not be motivated sufficiently to significantly invest in insulation measures, making that fewer alternative heating systems will be implemented. Next to this, it is found that major differences can be distinguished between rural and urban areas. Heating grids will be a viable starting point for urban municipalities to start their transition due to the availability of residual heat. For rural municipalities, this will be more difficult due to a dependency on low-temperature systems. There, starting with the neighbourhoods that have the most potential to insulate is advised.

8

Introduction

In 2015, a large step has been taken in the acknowledgement of climate change as a pressing issue for the future of our planet. The Paris Agreement (FCCC, 2015) has united 195 countries of the world intending to limit global warming to a rise of 2°C. In a response to this, The Netherlands developed the Klimaatakkoord (2019) to comply with the United Nations' intentions as well as to comply to the goals set up by the European Commission (2018b), as a followup on the Paris Agreement.

To realise the EU goals of reducing CO_2 emissions to zero tons in 2050, a significant contribution should come from the Built Environment which in the Netherlands is responsible for 14 per cent of the national CO_2 emissions (Schoots & Hammingh, 2019). With ongoing urbanisation (Bulkeley, 2006), Sustainable Urban Development will be key in reducing these emissions.

The largest contribution to this development should come from the Dutch households, as 70 per cent of the CO_2 emissions can be contributed to their heating demand. The major cause of these CO_2 emissions is the fact that so far over 90 per cent of the households' heating demand is satisfied by the use natural gas and only 10 per cent of the electricity used, is produced using sustainable sources (Schoots & Hammingh, 2019). Although the total demand for energy for households has been declining in the last decades due to better insulation, a CO_2 free Built Environment is still far away.

To realise a climate-neutral Built Environment, a mayor energy transition is needed by switching from natural gas to sustainable energy solutions. The Klimaatakkoord (2019) states that in 2050, all houses should be heated without natural gas by using sustainable heat sources and electricity. With nearly 8 million households (CBS, 2020h) in The Netherlands, this is not an overnight job.

8.1. Urban Energy Transition: A Municipal Challenge

To complete this task, a central role has been assigned to the Dutch municipalities. Their task is to develop strategies that make urban areas more sustainable, in which Energy Neutrality of even Energy Positivity (Luscuere et al., 2016) will play a big part. Concretely this means that before the end of 2021, they have to decide which neighbourhoods should be transformed and when, to have the first 1.5 million households heated sustainably before the end of 2030 (Klimaatakkoord, 2019). Together with property owners, the municipalities have to decide what sustainable solution is the best to implement.

However, municipalities are not ready yet to make that decision (RTL, 2019; Schuttenhelm, 2020; Straver, 2019). To be fair, it is not an easy task, as many energy systems exist that may replace the current natural gas network, such as heat pumps (Chua et al., 2010), heating grids (TKI Urban Energy, 2020), and 'green' gasses such as biogas and hydrogen (CE Delft, 2019b; TNO, 2020a). The suitability of such systems does not only depend on the availability of the resource, but also on the characteristics of the neighbourhoods, its houses and the people that live in it. The complexity of such a large system with various (new) technologies to be implemented that will be used by a vast amount of stakeholders, makes that manually finding an optimal, cost-effective solution, that is also supported by all the stakeholders involved, is nearly impossible. Combined with the current uncertainty on national policies to stimulate the transition, developing a fitting strategy, is very difficult. How do municipalities know where to start, if the world they have to deal with is both complex *and* inherently uncertain?

8.2. Decision support for Sustainable Urban Development

Conveniently, the Dutch government has provided the municipalities with a guide on how to tackle this problem (Planbureau voor de Leefomgeving, 2019b). In this guide, a model developed by Planbureau voor de Leefomgeving (2019c), Vesta MAIS, is used for determining the best solution for each neighbourhood from a techno-economic perspective. Although incredibly detailed, two crucial aspects are to be missing in such approaches for Sustainable Urban Development: time and people. Hence, investigating the dynamics of the system based on the behaviour of the stakeholders in the system will be of extra value to policymakers currently struggling with how to develop suitable strategies that will gain sufficient support from its stakeholders. A combination of System Dynamics (Forrester, 1961) and Agent-Based Modelling (Epstein & Axtell, 1996) by means of multi-modelling (Nikolic, Warnier, et al., 2019; Vangheluwe, 2000) may be able to provide the insights that current models are still lacking.

The insights that one will be looking for in particular are the insights that help understand the effects of policies and uncertainties on system outcome. The Exploratory Modelling and Analysis framework (Bankes, 1993) is a perfect fit for evaluating the possible states of the system to develop robust policies. For Sustainable Urban Development, this is especially helpful due to the different levels of government that have policy authority. The frequently changing national policies that should support and encourage sustainable change (De Boer & Oudshoorn, 2018; Hakkenes, 2020; Vakblad Warmtepompen, 2019), for instance, make that these ’policies’ can be seen by policymakers at the municipal level as uncertainties. Insight in how to approach the Urban Energy Transition at a municipal level despite the national policy, as well as insights in the heterogeneous effects of national policy, may provide the handles needed for developing successful strategies in Sustainable Urban Development.

8.3. Research Questions

This study will provide solutions to the aforementioned challenges in Sustainable Urban Development by developing a multi-model that will help to answer the following research questions:

1. What stakeholders and concepts are relevant in Sustainable Urban Development and how are these related?
2. What policies at the national level can contribute to obtaining the CO_2 goals of the climate agreement?
3. What are the effects of national policy uncertainty on system developments at municipal level?
4. How can municipalities coordinate and accelerate the energy transition and what are suitable starting points to do this?

8.4. Thesis structure

To gain an elaborate understanding of Sustainable Urban Development, I will start with an extensive literature review on the current state of Sustainable Urban Development, what sustainability means, and what kind of solutions can be implemented in the built environment to realise a natural gas-free future. After this, I will introduce the methodology used in this theses followed by a detailed description of the model that has been developed. The results chapter will discuss the model outcomes based on three different perspectives: the national, intermunicipal and intramunicipal perspective. By doing so, the effects of national policies on national outcomes as well as the heterogeneous effects on municipalities can be investigated. I will conclude with advice for both the national and the municipal government on tackling the Energy Transition in the Built environment, so that hopefully, the national goals of realising net-zero CO_2 emissions in 2050, can be reached.

9

Sustainable Urban Development

In this chapter, I will assess the current literature on Sustainable Urban Development to identify the gap that exists in the tools and knowledge necessary for defining suitable strategies in Sustainable Urban Development.

In the first section, the current developments regarding the urban energy transition will be discussed, followed by a sidestep into what being sustainable actually means. From there Sustainable Urban Development in the Netherlands will be discussed, after which will be looked into how strategies for Sustainable Urban Development are currently set up. Lastly, the review will touch upon the presently available models, their strengths and limitations, and what can be done to further improve one's understanding of the possibilities and impossibilities in Sustainable Urban Development.

9.1. Current developments

With the developments in the last few decades regarding the energy transition, the importance of urban development has grown enormously. With the expected world population growth and ongoing urbanisation, the impact that urban areas make on the environment continues to grow. About three-quarters of global energy consumption takes place in urbanised areas (Dhakal, 2009; Grubler et al., 2012) and given the climate change the world is dealing with, the importance of urban sustainability is not to be underestimated (Vojnovic, 2014). Vojnovic' research investigated the current status on politics, policy and practice, and found that it is not necessarily science that is lacking in enabling urban sustainable change, but that the governments of wealthy and high polluting countries (the USA, Japan and England for instance) lack the interest to commit to emission binding limits. It is argued that a lot can be learned from middle-income countries (Hungary, Chile and Costa Rica for instance), who appear to gain a similar quality of life, at a smaller ecological footprint. It appears that high-income country politics and culture standards need to make a significant change, to allow for the pursuit of urban sustainability.

So what makes that these countries do not choose to pursue sustainability as one of their main targets even though many countries agree that they should reach for sustainability? The Paris Climate Agreement, unfortunately, does not offer a blueprint for reaching its objectives (Clémençon, 2016), making that immediate action by the signing countries is not a matter of course. One could speculate on answers to the question why climate policy is not yet gaining momentum: Westerners may focus too much on the economy and are afraid to lose their competitive edge when switching to sustainable alternatives if others do not follow. Or path dependency makes that the switch to more sustainable solutions is not sustainable on its own (disposing of your still functional combustion engine car and buying a brand new electric one is less sustainable than keeping the old one, depending on the definition of sustainability one is using). Or people just do not want to give up their commodities (Engelman, 2013).

One can wander off in further speculation of reasons not (yet) to be sustainable, but an urgent problem is that very few people know what they are talking about when talking 'sustainable'. Sustainability is a concept that nowadays is used for nearly everything, without careful consideration of its use (Choguill, 2007). Next tho this, sustainability is a very subjective concept, often making it's meaning indefinite. The subjectivity of the matter makes that various perspectives result in competing interests, causing for difficult and complex decision making (Aklin & Urpelainen, 2013; Cheney et al., 2004; Gremmen & Jacobs, 1997). This indistinctness and internal competition make it understandable that policymakers dealing with 'The Energy Transition' and 'Sustainability' struggle in defining strategies to enable Sustainable Urban Development.

9.2. Definition of Sustainability

Many are familiar with the concept 'Sustainable Development' as by the United Nations Brundtland Commission in 1987: "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland et al., 1987), which is a good start. However, sustainable development is a concept that is much more complex (Choguill, 2007). Next to this, *the* definition of being sustainable nowadays seems to cover everything between 'doing a little better than what we did before' and 'tree-hugging'. From the last century on, the definition of 'sustainability' has become somewhat vague. The overuse of the term makes that it loses its value and becomes a useless term that nobody gets or wants to deal with (Engelman, 2013).

So far, several attempts to define 'Sustainability' have been made. The CBS (2019) extends the definition by Brundtland et al. (1987) by mentioning that economic, human and social aspects also constitute sustainability. Stichting Duurzame Samenleving (2014) take this even further by developing the Municipal Sustainability Index (Gemeentelijke DuurzaamheidsIndex [GDI]) in which they try to include these aspects of sustainability, from youth employment to sports, and from CO_2 emissions to the use of renewable energy. This is a decent attempt, especially if a comparison is to be made with other municipalities and if one wants to look at the total performance of a municipality. However, in the case of this research, in which the focus will lie on energy in the urban environment and the way to implement sustainable solutions, this definition is way too broad. A definition is needed that is less generic and fits the specific application of the tasks to be performed. Hence, a further understanding of Sustainability in the Built Environment will be developed in the next section.

9.3. Sustainability in the Dutch Built Environment

When one discusses sustainability in the built environment, one typically refers to the physical consumption of natural resources. These include the use of energy, air, water, materials and topsoil. 'Extraction and conversion processes lead to depletion and harmful emissions, and as such to challenges in terms of ecology, economy and equity' (Luscuere et al., 2016). These challenges in ecology consist of preserving biodiversity, mitigating or preventing negative health effects and climate change, whereas economy refers to the scarcity of resources and costs and benefits.

Next to this, circularity is a term that continues to pop up more and more in the context of sustainability (Geissdoerfer et al., 2017). A strict definition of the word, in which all-natural resources are endlessly renewable in the short term, can be seen as the 'ultimate sustainability' for these natural resources. Although the practice is still far from accomplishing this (Stahel, 2016), one should still have a 'dot on the horizon' to aim for.

Sustainability in the Built Environment can roughly be separated into two categories: sustainability during the building, renovation and demotion of constructions, and sustainability during the lifetime of the building itself. Because of the challenges imposed by the climate agreement (Klimaatakkoord, 2019), this study will focus on natural resource use during the lifetime of the built environment.

Figure 9.1 shows how these natural resources are used in the built environment during the lifetime of housing. All of the identified natural resources may be of importance during the lifetime of buildings. However, energy accounts for over 50 percent of household CO_2 emissions (Munksgaard et al., 2000). Hence, although all of the aforementioned natural resources should be taken into account in Sustainable Urban Development, this study will focus on the use of energy, which is the most relevant aspect in the light of the Dutch Climate Agreement (Klimaatakkoord, 2019) and the Paris Climate Agreement (FCCC, 2015).

9.3.1. Energy in the built Environment

Regarding energy, the most discussed elements of sustainability are likely the effects on climate change and the scarcity of fossil fuels. The burning of fossil fuels for both electricity and heat production causes both challenges to exist due to the limited availability of these fuels and the CO_2 emissions that come with it (Kriegler et al., 2016). Aiming for sustainable energy use and production hence includes both

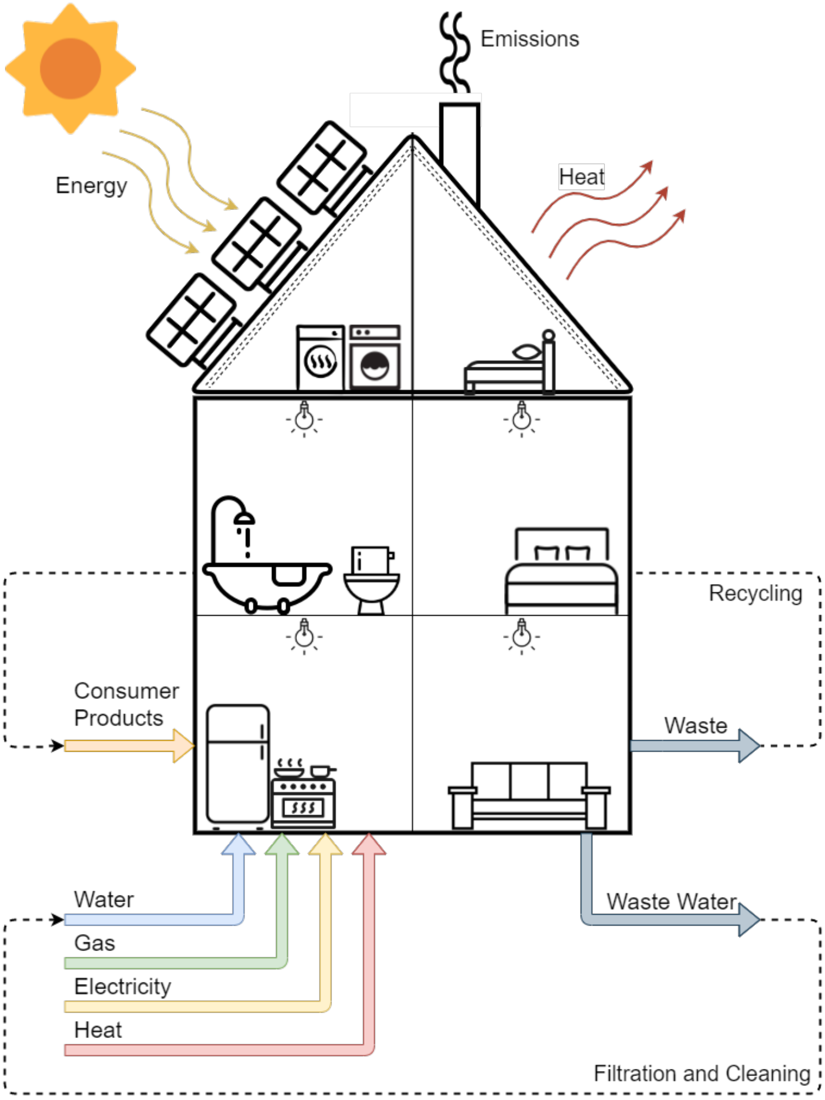

Figure 9.1: Natural resource use during lifetime

the reduction of energy use and the production of energy without harmful emissions. One should take in mind, that the reduction of energy use can only be achieved on a local level, whereas renewable energy production can be reached both centralised and decentralised, strongly influencing the options to realise these goals.

Solutions that contribute to this on a local/individual level include insulation of buildings, photovoltaic power, solar collectors, and the use of biofuels or (green) hydrogen for heating. However, collective options can exist on both a local level and a central level, such as heating grids powered by geothermic or residual heat systems. Options that can be implemented on a high level include, wind-, hydro-, solar- and wave- and tidal power, but also the production of energy using biomass and/or biofuels. However, biomass is, just like nuclear power, disputed as a truly sustainable source of energy (Cho, 2011; Van Dongen & Van Mersbergen, 2019). This is because the burning of biomass or biofuels still emits greenhouse gasses in the process, that uptake by newly planted forests may take too long, and that chopping trees for biomass is a serious hit for biodiversity and soil fertility. Next to this, opposition to biomass is also fueled by the concern of another natural resource in jeopardy: clean air. To protect this resource, state law depicts threshold values for the emissions of NO_x (Rijksoverheid, 2020b). This is a clear example of how a solution to one problem can be a problem itself in another field. This makes that to be able to develop successful strategies, one must be aware of the opposing stakes and competing interests (Aklin & Urpelainen, 2013).

To reach the set goals by the climate agreements, an energy transition in the built environment is inevitable. From the municipal perspective, the tasks that these agreements bring them, mainly focus on the energy transition in the built environment. Moving away from natural gas and fossil fuels, in order mitigate climate change as well as limiting social unrest due to Earthquakes in The Netherlands main gas extraction area, Groningen, (Ekker & Start, 2019), whilst remaining economical independence from natural gas exporting countries such as Russia, is the main priority (Cukier & van der Walle, 2018).

9.4. Definition of Sustainability in this Thesis

Given the challenges that municipalities are facing, and all these different interpretations of 'Sustainable', it is, therefore, extremely important to define what is meant by 'Sustainable Urban Development', and what this means for the energy transition in urban areas. Without a clear understanding of the definition of 'sustainable', no policymaker will ever develop a strategy for reaching it. Unless one considers functional ambiguity, to easier *claim* that one's goals are reached. However, it is assumed that municipalities using the knowledge obtained from this research will actually try to realise their sustainability goals, for which ambiguity is not expected to be misused.

From here on, in order to prevent indistinctness of the definition of 'Sustainability', this research will work with the following definition of 'Sustainable Urban Development':

'Sustainable Urban Development is development in which urban areas try to become CO_2 neutral, by using renewable energy sources and reducing energy consumption, on the condition of economic and social feasibility.'

In the view of this assumption, to ensure clarity of its meaning and use on the energy aspect of 'Sustainable Urban Development', this means that this research will solely focus on energy use and energy production, which in turn means that greenhouse gas emissions do not exceed greenhouse gas absorption in mitigation measures, for housing to be 'sustainable', to meet the general definition by of Brundtland Commission to not compromise the ability of future generations to meet their needs (Brundtland et al., 1987). CO_2-neutrality is chosen as the sustainability metric for energy because it is less ambiguous than energy-neutrality, which is also commonly used (RVO, 2020a). This is because it lies closer to the actual goals of reducing CO_2 output. Next to this, it, on the one hand, allows for a wider range of solutions than energy-neutrality alone and on the other hand, reduces the ambiguity caused by seasonal supply and demand asymmetry. Buildings that require more energy than they produce, will hence have their 'sustainability' depend on the 'renewableness' of the natural resources they need.

The economic and social feasibility condition ensures that solutions that will be offered are practicable by including return on investment and the social support needed for implementing sustainability measures. This means that the willingness to invest should be high enough (both socially and economically) and that people are able to pay for it. The definition of the willingness to invest will be set in the model conceptualisation (subsection 11.1).

9.5. Urban Energy Transition in The Netherlands

In the case of Sustainable Urban Development in the Netherlands, it is the municipalities that have been assigned the task to deal with the urban energy transition (Vereniging van Nederlandse Gemeenten, 2019a). Because this is a new task for the municipalities, it can be expected that they still lack the knowledge, executive force and capacity to develop their strategies (Vereniging van Nederlandse Gemeenten, 2019a). Developing strategies to become sustainable will remain a difficult task, as long as municipalities are not given sufficient tools to develop their strategies.

9.5.1. Current approach

To deal with this, the national government provided municipalities with a guideline (Leidraad voor de Transitievisie warmte) on how to approach the energy transition (Planbureau voor de Leefomgeving, 2019b), so that municipalities can set up their 'Transitievisie Warmte' (EN: Heat transition vision). This 'Transitievisie Warmte' has to be developed before the end of 2021, which is imposed by the Dutch Klimaatakkoord (2019) (EN: Climate Agreement). In this guideline, a model (Vesta MAIS) developed by Planbureau voor de Leefomgeving (2019c), is used for setting up five possible strategies per neighbourhood, for each municipality, providing valuable initial insights in the technical and economical possibilities. Municipalities are enabled to add their own municipal data so that they can develop their local strategies. However, this turns out not to be that easy (Straver, 2019).

9.5.2. Municipal challenges

Challenges that arise with the current approach, are that the model provided by Planbureau voor de Leefomgeving (2019c) used is quite static, and looks from only a technical and economical perspective, in which it assumes full control of the municipality. In reality, municipalities will have to deal with social interaction and individual behaviour, making the issue much more complex than what is currently considered in the model. Next to this, static homogeneous neighbourhoods are assumed, whereas the individual behaviour of the people in a heterogeneous population may be very relevant for the feasibility of collective solutions.

This homogeneity is also reflected in the fact that in the guideline assumes that all houses can and should be isolated to Label B+, although, for many monumental buildings, that is not economically feasible (Vereniging van Nederlandse Gemeenten, 2019b), not to mention the absence of support (and currently: the legislation just not allowing it) for such aesthetically unpopular renovations for monuments, if even technically feasible at all.

This lack of heterogeneity is something that keeps popping up when working with the model. The same holds when looking at costs, even though currently under development by Planbureau voor de Leefomgeving (to be published autumn 2020), the costs for end-users are not incorporated, which will be an important factor in social and economical feasibility of any solution. At this point the costs are aggregated at a high level, making that, although included in the model, individual aspects are missing in the output, local data is expected to be obtained by the municipalities themselves, making that specialised knowledge is needed for getting more relevant and detailed predictions, which many of the municipalities are currently lacking.

Next to this, municipalities are struggling with determining when to start with what neighbourhood (RTL, 2019; Schuttenhelm, 2020). Although the value and completeness of Vesta MAIS should not be underestimated, it is a shame that its techno-economic approach makes that its will easily lead to ”the model says X”. Based on several scenarios it presents the ’best’ solution with the lowest ’national costs’, but it does not tell much about how to get there. Insights in what neighbourhoods will be the ’easiest’ to (motivate to) transform, and when, would be valuable additions to the techno-economic approach.

All in all, Vesta MAIS is a technically strong model to help decide what is best, however, it still does not provide for insights that help understand where to start, which is crucial for the inexperienced municipalities to make a well-considered decision.

9.6. Available solutions for the Urban Energy Transition

Numerous research (Grubler et al., 2012; Planbureau voor de Leefomgeving, 2019c; Vringer et al., 2016) has been conducted into the solutions that are available for climate-neutral energy use in the Built Environment. Since this research will focus on energy, alternative energy systems and methods for reducing energy use will be discussed for the two main uses of energy in the urban environment: heat and electricity.

9.6.1. Heat

The largest amount of energy consumed by residential areas in the Netherlands is heat, which is currently provided using natural gas for about 90 per cent (CBS, 2020e). Intending to become climate neutral, the use of natural gas needs to be eradicated (Klimaatakkoord, 2019). Currently, consensus exists on the three main alternatives for reaching this goal (Planbureau voor de Leefomgeving, 2019c), these are Heating Grids, Heat Pumps, and Green Gas.

Energy Label

Some of these solutions require a higher degree of insulation to be feasible. The degree of insulation in the Netherlands has been categorised through energy labels. Obtaining this energy label has been mandatory for selling or renting out a house since 2015 (Milieu Centraal, 2020a), intending to gain insight into the current state of the Dutch housing stock. The labels have been classified from G to A (and even A+, A++, and A+++), of which label G means nearly no insulation at all, from label C, is decently insulated and everything above A is exceptional and includes various sustainable installations.

Heating Grids

Heating grids are considered a viable option for heating in densely populated areas(CE Delft, 2009; Papa et al., 2019). An important aspect that determines the suitablility of houses to connect to such a heating grid is the delivery temperature and the degree of insulation of these houses. Four delivery temperature levels can be distinguished (ECW, 2020):

1. Very Low Temperature, at 10 - 30 °C (VLT)
2. Low Temperature, at 30 - 50°C (LT)
3. Medium Temperature, at 50 - 70°C (MT)
4. High Temperature, at 70 - 90°C (HT)

The delivery temperature can directly be obtained from the primary source or upgraded at the network or house level to the desired temperature. Primary sources that can be used for heating grids include industrial residual heat (HT/MT), residual heat from utilities (LT/VLT), Geothermal Heat (HT/MT/LT/VLT), Thermal Energy from Surface Water (VLT), and Heat Cold Storage (VLT). Methods to upgrade delivery temperature could be through burning (green) gas or utilizing heat pumps (TKI Urban Energy, 2020).

This delivery temperature is relevant for the types of houses that need to be connected to it: the primary concern, the level of insulation. The better isolated the houses are, the lower the delivery temperature can be, which is desirable because of the higher efficiency of low-temperature heating grids as well as a reduction of the energy demand. Table 9.1 gives an overview of the labels that are considered suitable for the different levels of delivery temperature.

Delivery Temperature	Required Energy label	Required extra systems
High Temperature	All labels are suitable	Directly usable for heating and tap water
Medium Temperature	Label E or better	Directly usable for heating and tap water
Low Temperature	Label C or better	Additional Heat pump for label C, boosters for tap water
Very Low Temperature	Label B or better	Additional Heat pump required

Table 9.1: Heating grid delivery temperature options

The reason that heating grids are likely only feasible for highly dense populated areas, is that the investment costs are relatively high, and thus need a high amount of customers in a small area before the system becomes economically feasible. Next to this, urban areas are more likely to have high/medium temperature primary sources nearby, due to the proximity of industrial clusters, reducing the need for insulation in its potential service area.

Heat Pumps

Heat Pumps may replace the current gas boilers by heating the house using electricity as primary source (Chua et al., 2010). Several options for Heat Pumps exist. They can be fully independent (all-electric) or use (green) gas for peak demand (hybrid) (CE Delft, 2018a). This means that the 'sustainability' of heat pumps depends on the renewability of the electricity and the gas used. All-electric heat pumps require a higher level of insulation than hybrid ones since the delivery temperature of all-electric systems is lower. This means that hybrid heat pumps, in theory, can be applied to houses with all energy labels, but will start to perform reasonably from label E and higher. All-electric heat pumps can be applied to houses with Label B or higher (CE Delft, 2018a; Planbureau voor de Leefomgeving, 2019c).

Upsides to heat pumps as compared to heating grids are that heat pumps don't need the extensive amount of infrastructure and can be managed at the house level. A significant downside of (many) houses switching to all-electric systems is the demand increase of the electricity delivery net which may result in the need for costly net reinforcements.

Green Gas

Green gas is a broad term that is used for all forms of 'renewable' gas. This can be Biogas from fermenter installations using waste products or specially grown energy crops, as well Hydrogen gas from either electrolysis (Green Hydrogen) or natural gas with Carbon Capture and Storage (Blue Hydrogen with CCS).

Although considered sustainable, biogas and blue hydrogen are not CO_2-*free* (TNO, 2020a), whereas green hydrogen from wind and solar energy is. Nevertheless, because green gas is likely easily implementable given the currently available infrastructure and the absence of the need to insulate to a high degree, green gas is considered a viable option for sustainable heating. However, the current prospects for the production of both biogas and hydrogen, and the costs thereof, are still very uncertain (CE Delft, 2019b; Rabobank, 2019; TNO, 2020a), and depending on availability, competition with the industrial and mobility sectors makes that it may not be economically feasible for the built environment to make use of green gasses on a large scale.

9.6.2. Electricity

The second type of energy that is used in the built environment is electricity which has several purposes. All housing makes use of electricity for the use of powering appliances. Although the use of appliances has increased over the years, these appliances have also become more efficient, making that the general trend of electricity use for appliances is slightly downwards (Schoots & Hammingh, 2019).

Opposing this trend is the increase of electrical heating utilizing heat pumps as well as the use of electric vehicles (Schoots & Hammingh, 2019). This makes that the amount of electricity demanded by the built environment, despite improvements in efficiency, is likely to keep stable or increase, depending on developments in the electrical heating and electric mobility sector.

This makes that the sustainability transition needs to come from the source: renewable production thereof. Although key to the sustainability of electric solutions in Sustainable Urban Development, decisions on the use of renewable sources are at higher geographical levels than neighbourhoods. If one considers the use of photovoltaic panels on rooftops as a 'reduction' of electricity use of that particular building, this makes that the development of renewable electricity can be considered exogenous to the built environment.

9.7. Developing Sustainable Urban Development strategies

As a first step for developing Sustainable Urban Development strategies is to make the definition of sustainability clear, followed by finding out what information policymakers require before they can develop sustainable energy strategies. A second step is to identify key performance indicators of Sustainable Urban Development and find methods to evaluate these (proposed) policies. To help improve urban sustainability, Fitzgerald et al. (2012) propose a quantitative method for evaluating the policies aimed at enhancing urban sustainability. Its focus lies on evaluating intended strategies to enable further evidence-based decision making. It is deemed vital to understand the economic, technical, and ecological consequences of new policies to manage them effectively.

Next to investigating these consequences of possible solutions and finding what exact solution is the most effective and efficient, an important step is to think about how this can successfully be realised. An important aspect of this is the choice of the Project Delivery Model/Project Delivery System because this choice is a key factor in project success. Policymakers select the Project Delivery Model to be used, and this selection is generally based on criteria such as technical risks, financial risks, institutional constraints and opportunities such as return on investment (Al Nahyan et al., 2018).

An important decision to be made by clients (in the Netherlands) when selecting a Project Delivery Model, is whether to procure the project using a traditional contract (UAV), using an integrated contract (UAV-gc) or by using an alliance contract. The main difference between these contracts regards the responsibility and liability of the client and contractor on the different elements in the construction process (Cobouw, 2012; Regieraad Bouw, 2009). A traditional contract uses a Project Delivery Model that separates the different phases of a project, the so-called 'Design Bid Build' model. For each phase that is tendered, a separate contract is set up, possibly with different contractors. An advantage to this method is, that full control remains with the client. A downside to this is that procedures typically take longer, and scope change during the project is difficult and expensive because the specifications have already fully been determined and laid down in the contract.

Another criticism of this method is that the interfacing between contracts results in many inefficiencies, with an integrated contract or ’Bouwteam’ (EN: Building team) offered as a solution. A Bouwteam contract is a form of early contractor involvement, which has a goal to be able to implement the practical side of execution into the design, to reduce the aforementioned interfacing problems. In integrated contracts, this is taken a step further, because the contractor is made fully responsible for two or more of the project phases. This could be from the initiation phase to designing, building, maintaining, financing, operating and possibly even demolition, or any number of consecutive elements. Advantages are that the process as a whole can be optimised, leading to lower executing times and lower cost. However, to be able to achieve this, control over the project is handed to the contractor, leaving fewer strings to pull for the client (Regieraad Bouw, 2009). Next to this, the risks in this model are also transferred to the contractor, but it appears that contractors are not willing to take that risk anymore, making the contract less suitable (Koenen, 2019). An Alliance may offer a solution to this, in which the client and contractor are co-responsible for tasks and risks. This is a decent motivation for collaboration and aims to get rid of the typical client-contractor hostility. However, determining what responsibilities lay with which party, or determining that it will be fifty-fifty, is not that easy.

A lot has been written about how policymakers should approach Project Delivery Model selection (Al Nahyan et al., 2018; Bannet & Grice, 1990; Chen et al., 2011; Mafakheri et al., 2007; Masterman, 1992). However, the contractor perspective remains underexposed (Eriksson & Pesämaa, 2007), although, very relevant for the choice of contract. Ng et al. (2002) did look into contractors’ perspectives on integrated Project Delivery Models. They found that public clients need to adapt to more flexible administrative procedures, to increase contractors’ willingness to invest in public-private partnerships (PPP’s), which is difficult considering the general risk-aversion of policymakers (Love et al., 2008). Unfortunately, this is in line with the current developments in which contractors are becoming more risk-averse too (Koenen, 2019), making the use of integrated contracts less attractive.

A shortcoming in the work of Ng et al. (2002) is that they investigated projects in which an agreement on the Project Delivery Model was already made, whereas the reasons to accept such a contract in the first place, apparently maybe even more important when selecting the correct Project Delivery Model. This may especially be true for projects dealing with high levels of complexity and uncertainty, such as implementing solutions for Sustainable Urban Development. Therefore, it will be very interesting to investigate the individual behaviour of contractors and clients (homeowners, grid-operators, housing-corporations, municipalities), to see under what circumstances projects do or do not work out well.

Another method for developing urban sustainability is using pilots and other projects as reference for the implementation of new projects, by making use of best practices. However, even though a vast amount of examples exist, such as ’Programme Natural Gas Free Districts’, ’The Testing Grounds’ of the Ministry of the Interior and Kingdom Relations and ’District of the Future’ in the Netherlands (Het Secretariaat van het Gelders Energieakkoord, 2019; Rijksoverheid, 2018, 2019), much is unclear about how these best practices are used for policymaking (Bulkeley, 2006). Bulkeley argues that best practice should not necessarily focus on lesson drawing and transferring of knowledge to new contexts, but that it should be used for better understanding of the problem itself and allow the policy problem to be challenged and reframed. However, for future uncertain solutions, such best practices simply do not exist yet. Hence, other methods should be developed for deciding what systems to implement in Sustainable Urban Development.

9.8. Modelling Sustainable Urban Development

Modelling and simulation may offer a solution in dealing with uncertainty when looking at the energy transition because it can theoretically explore the solution space. So far, many models have been developed to gain a better understanding of of the energy transition and Sustainable Urban Development (BackHoom, 2019; CE Delft, 2019a; De Twee Snoeken, 2019; ECN, 2019a, 2019b; Energy Transition Group, 2013; Geodan, 2019; Planbureau voor de Leefomgeving, 2019c; Quintel Intelligence, 2019). Unfortunately, not all these models are useful for municipalities to develop their strategies. The model needs the ability to look into a wider range of aggregation, varying from house level to regional level (CE Delft, 2019a; ECN, 2019a, 2019b; Geodan, 2019; Planbureau voor de Leefomgeving, 2019c; Quintel Intelligence, 2019), which is needed in the initial exploratory phase of policymaking. One could argue that this is still a wide range of options, although that may be part of the problem. Especially in the orientation phase, it may be difficult to select the appropriate model from this range, because municipalities have not yet obtained the necessary knowledge to make that decision in that phase.

Netbeheer Nederland (2019) developed a tool for selecting the appropriate model, but still gives so many detailed selection options, such as whether a model needs to include heat pumps or geothermal options, of which policymakers often do not have the knowledge to make an appropriate selection (Planbureau voor de Leefomgeving, 2019a). Starting with models that are open for inspection may then offer the possibility to look around before selecting the appropriate model. Though, this leads to an even more narrow range (Geodan, 2019; Planbureau voor de Leefomgeving, 2019c; Quintel Intelligence, 2019), of which the work of Quintel Intelligence (2019), the Energy Transition Model, comprehends so many aspects that one can no longer see the forest for the trees, Vesta MAIS, by Planbureau voor de Leefomgeving (2019c), as discussed in subsection 9.5.2, needs modelling and programming expertise to be able to make use of its full abilities, and PICO (Geodan, 2019), even though looking promising, also expects very detailed choices, which municipalities may not yet be able to make.

Table 9.2: Existing tools for Sustainable Urban Development

Model	Aggregation level	Model use	Reference
Woonconnect	Low	Service only	De Twee Snoeken (2019)
Warmtevraagprofielen	Low	Service only	ECN (2019b)
Vesta	Flexible	Expert model	Planbureau voor de Leefomgeving (2019c)
Pico	Flexible	Expert model	Geodan (2019)
LEAP	Low	Service only	Energy Transition Group (2013)
Energietransitiemodel	High	Easy to use, difficult to understand	Quintel Intelligence (2019)
CHESS	Flexible	Service only	ECN (2019a)
CEGOIA	Flexible	Service only	CE Delft (2019a)
Backhoom	Low	Data use through API	BackHoom (2019)

Models that are currently available for determining what Project Delivery Model is most suitable for implementation, include the works by Al Nahyan et al. (2018), Mafakheri et al. (2007) and Chen et al. (2011). In their work, the indicators for determining the most suitable Project Delivery Model in these models are mostly similar, such as the basic project objectives such as cost, schedule and quality, and indicators for project difficulty such as complexity, risk and uniqueness of the project. They base these indicators on questionnaires to determine the importance of various indicators on Project Delivery Model selection, to set up a model that can predict the most suitable Project Delivery Model for new projects, based on the valuation of indicators by the client. However, as Chen et al. (2011) indicate, a large database of projects is needed for making such a model accurate, which is currently not the case. Next to this, one could also argue that using *what* Project Delivery Model was selected in various projects, may not result in much predictive value of the model for *project success*. Another criticism of such models is that they have a very one-sided perspective only. Project Delivery Model selection is only looked upon from the client perspective, whereas it is argued that the interaction between client and contractors is actually very important. If this interaction is not considered, choosing a suitable Project Delivery Model will remain very difficult.

How then can a policy-maker decide what model to use, if it is still unclear what needs to be investigated in the first place? And if policymakers do know what they want to implement, how do they ensure this is done properly? Given that many solutions are at a low implementation level, and goals are still at a higher, more general level, clearly a model that integrates these two at a level of aggregation that helps policy-makers understand what the available solutions are and how they affect the most suitable approach in implementing the solution and reaching its goals, is still missing. A better insight in the dynamics of the total system, with on the one hand selection of solutions, and on the other hand selection of methods to implement, is needed to develop suitable strategies. A model is needed that provides insights in the effects of policy intervention and uncertainties on the national level, as well as insights at the municipal level so that municipal policies can be designed that work despite the policies and uncertainties at the national level. Key in this will be that the model can provide these insights on a time-dependent basis, which other models are currently missing.

9.9. Modelling Urban Dynamics

For investigating Urban Dynamics, a System Dynamics (SD) model is a suitable method for analysis (Forrester, 1961; Richardson, Pugh, et al., 1981; Roberts, 1981; Wolstenholme, 1990). System Dynamics is a widely accepted method for modelling complex systems in for instance resource management, energy system modelling and environmental impact analysis, since works started by Forrester (1961), because of its ability to help understand System Dynamics and complexities, which is difficult for the human mind to process on its own. Ever since the development of this method, several models have been developed for different Urban Dynamics applications (Dyson & Chang, 2005; Forrester, 1970; Jifeng et al., 2008), but fewer looked into the sustainability aspect yet.

Xu and Coors (2012) and Feng et al. (2013) made promising starts though. Feng et al. (2013) looked into how energy use, and in addition to that CO_2 emissions, will develop in Beijing in the coming 20 years and to what extend different sectors would play their part in this consumption. They conclude that System Dynamics has the ability to effectively provide a base for urban energy planning and management. Xu and Coors (2012) on the other hand combined a System Dynamics model with Geographical Information System (GIS) (Tomlinson, 2007) analysis and 3D visualisation to help policymakers grasp a better understanding of the problem and the impact of possible policies. It was found that the integration of GIS, 3D visualisation and System Dynamics results in a better ability to explain the interaction and variation in urban sustainability indicators, making it a useful tool for policymakers.

What still is missing in works such as by Feng et al. (2013) and Xu and Coors (2012) is the aspect of individual behaviour. Agent-Based Modelling (Crooks & Heppenstall, 2012; Epstein & Axtell, 1996; Van Dam et al., 2012) may offer a solution to this. Agent-Based models are frequently used to provide a bottom-up perspective on systems such as geographical systems and urban systems (Batty, 2007; Heppenstall et al., 2011; Huang et al., 2014; T. Lee et al., 2014). For the Energy Transition in the Built Environment, this means that individual behaviour of municipalities, contractors, homeowners and housing corporations could be used as input to investigate the effects of their behaviour on the system as a whole. Where System Dynamics aggregates populations and behaviours, Agent-Based Modelling allows for heterogeneous populations and individual behaviour, better grasping the complexity of that individual behaviour. This is extra relevant in multi-stakeholder systems, such as the energy transition.

The interaction between municipalities, homeowners, housing corporations and heat companies will, in the end, determine what solutions can successfully be implemented, and which can not. By combining this individual behaviour with a selection of technically suitable solutions, better insights can be provided on the effectiveness and robustness of certain policies.

Table 9.3: Modelling approaches in (Sustainable) Urban Dynamics

System Dynamics	Agent-Based Modelling
Forrester (1970)	Batty (2007)
Dyson and Chang (2005)	Heppenstall et al. (2011)
Jifeng et al. (2008)	Huang et al. (2014)
Xu and Coors (2012)	T. Lee et al. (2014)
Feng et al. (2013)	

T. Lee et al. (2014) have shown that Agent-Based modelling can provide valuable insights exploring the individual behaviour of homeowners to test policies on improving CO_2 reduction. However, there are two limitations to their work. A first is that they only look into the selection of options and not the implementation, for which the addition of the implementation process is expected to be of great value. A second is that they treat technology as exogenous and constant to the system, ignoring the possible feedback implementation of solutions has on technological developments. For this, one could argue that System Dynamics is the better alternative. Both methods have their perks and disadvantages, a successful combination of both may very well reduce these limitations and offer a solution for addressing the complexity of the Energy Transition in the Built Environment.

Because this issue is not only pressing in the context of the energy transition and with these model formalisms, new methods have been developed for combining the strengths of various modelling disciplines. One of these is multi-modelling (Luoto et al., 2010; Nikolic, Warnier, et al., 2019; Quesnel et al., 2009). Using a multi-model ecology, that is *"an interacting group of models and data sets co-evolving* *with one another within the context of a dynamic socio-technical environment"* (Nikolic, Warnier, et al., 2019, p. 2), System Dynamics and Agent-Based modelling can be combined by using the appropriate formalism in different parts of the system. In this way, the abilities of both methods will together better approach the complexity of the total system.

Next to this, multi-modelling will allow for multi-perspective interpretation of the model outputs (Seck & Honig, 2012; Zeigler et al., 2018). This means that on the one hand national (aggregate) trends and behaviours can be observed through the System Dynamics model, and on the other low-level individual behaviour can be inspected. This characteristic makes that the model will be useful not only to policymakers at the national level but also for policymakers at the provincial and municipal level, a huge benefit for the applicability of the model.

Multi-modelling does bring a couple of risks that need to be monitored and/or mitigated. The first risk is that the method is relatively new, so teething problems are to be expected. Next to this, multi-modelling brings several other challenges, such as multi-formalism alignment, due to the different model disciplines used, scaling of the internal models, because of different time frames used by the models, but most importantly: analysis and interpretation will become more difficult. Analysis and interpretation is a difficulty for modelling in general, especially if the results are not presented to just the modeller, but also a layman in modelling, such as most policymakers. multi-models tend to quickly reach the 'model comprehension barrier' after which people can just not understand its meaning anymore (Nikolic, Warnier, et al., 2019). This makes that extra care should be taken by designing models in such a way, that the correct meaning is preserved and presented as intended.

Even though this novel method has these drawbacks, it is very likely still the most suitable method for grasping the system complexities, whilst allowing for multi-perspective interpretation of its outputs, making it very suitable for modelling the Energy Transition in the Built Environment.

10

Methodology

10.1. System Dynamics

System Dynamics is a method developed by Forrester (1961) for understanding the dynamic behaviour of systems. It was initially used for understanding industrial systems, widely applied to chemical processes. System Dynamics, however, appeared to apply to a much wider range of subjects, such as economics, public policy, and environmental studies (Richardson, 2020; Sterman, 2002). One of the main reasons for using System Dynamics is that the human mind is simply not able to envision the effects of change of one factor in a system composed of numerous interaction and feedback mechanisms that cause complex non-linear behaviour. System Dynamics, therefore, can help people to better understand these changes and their consequences in two ways.

When looking at the more conceptual side of System Dynamics modelling, once should notice that the stocks and flow structure of System Dynamics models, and the feedback that occurs in these models, makes that System Dynamics is very appropriate for evaluating accumulation, delays and time-dependent states of nonlinear systems. Arguably, this makes it exceptionally useful for estimating aggregate behaviour, in which change over time is the most relevant aspect. This behaviour may include market mechanisms, such as growth and stagnation, ageing mechanisms, such as in population dynamics or radioactive decay, and dynamics in common pool problems, such as the extraction of natural resources (Richardson, 2020). This characteristic makes that this method is traditionally seen as top-down.

For Sustainable Urban Development, one of the underlying incentives behind investigating this issue in the first place, may very well be the biggest common pool problem humanity will ever face: the planet as its main resource. Next to this, understanding the dynamics of the housing market, the energy market and technology market will be very helpful in defining strategies for implementing new energy technologies in the built environment. This makes that System Dynamics is incredibly suitable for modelling these systems.

10.2. Agent-Based Modelling

Typically, on the other side of the conventional top-down, bottom-up spectrum, one finds Agent-Based Modelling (ABM) (Epstein & Axtell, 1996). Agent-Based simulation has widely been used for understanding systems from an interactions perspective for understanding complex systems such as ecologies (Grimm et al., 2005), social phenomena (Bonabeau, 2002) and geographical systems (Heppenstall et al., 2011), amongst others. The idea is that one does not make a model from a point of view on how the system as a whole functions, but from the perspective of the smallest parts in the system and how these behave. The behaviour of the entire system emerges from a simple set of rules and interactions and regularly becomes complex at a fast rate. This complex emergent behaviour is often counter-intuitive and therefore Agent-Based Modelling may offer various insights in a system that otherwise is difficult to understand (Bonabeau, 2002).

Agent-Based Models consist of agents with their own properties and behaviours. Commonly they are set up using a software tool specially developed for this purpose, making that Agent-Based Modelling started making scientific progress somewhere in the late nineties (Bonabeau, 2002). In Agent-

Based Modelling, an environment is defined with certain characteristics, in which agents exist that behave according to basic rules, make decisions and adjust their own characteristics based on the characteristics of other agents, the characteristics of the environment, and their own characteristics (Van Dam et al., 2012). In rounds, simultaneousness of behaviour is simulated by asking agents, in a random order, to perform their task and follow the rules. In this way, the simultaneousness of actions in the real world can be mimicked with greater confidence. A major advantage of this 'real' representation is that people can easily understand the 'story' of an agent. An agent wakes up, gets a cup of coffee, reviews the current traffic, and decides whether to go to work by car or public transport. An understandable narrative. A downside to this individualism is that a representation of the system as a whole is much more difficult.

This is mainly because in Agent-Based Modelling it is assumed that system behaviour emerges from individual behaviour, in which the system is greater than the sum of its parts, due to phenomena that cannot be explained based on causal relations on its own. This makes that Agent-Based Modelling is extremely suitable for modelling systems that strongly dependent on individual behaviour, relations between individuals, and heterogeneous environmental characteristics. A downside to all these interactions is that, as the number of agents increases, interaction increases exponentially, making this method computationally expensive.

In the case of Sustainable Urban Development, exploring this emergent behaviour is extremely relevant, simply because the Energy Transition, with a wide range of possible solutions as compared to the transition to gas in the '60s and '70s (Canon volkshuisvesting nederland, 2020), is a challenge that has never been tackled before. The behaviour that is expected from participants in the transition, however, is something that can be derived from behavioural economics. Homeowners and housing corporations, for instance, will base their investment decision on its own economical prospects, general interests and the decisions of others (Ameli & Brandt, 2015; Bouwfonds ontwikkeling, 2010). Whether to invest in collective heating solutions or individual solutions will strongly depend on the behaviour of the stakeholders in the nearby area. Making Agent-Based Modelling a suitable method for creating a further understanding of Sustainable Urban Development.

If this behaviour comes from behavioural economics, why then not just use general economic models to gather insights about the energy transition? So far, one can only speculate about the possible developments in the system. Sure, economic models can be applied to how technologies generally develop through time, based on previous experiences with technology development and empirical data. It should not be forgotten, however, that most technologies develop based on economic incentives, whereas the Energy Transition is something different. Given the limited time-scale of the problem, a change is needed that is not pushed fast enough by economic incentives only. Hence, a method to explore how the system may behave, given current observations of the behaviour of individuals in the system, could offer the insights that are needed for developing suitable strategies for steering the challenge into the right direction, making Agent-Based Modelling very appropriate for exploratory analysis.

10.3. Multi-modelling

Multi-modelling, as the name may give away, is a method for combining two or more models into one. The main reason to do so is to combine the abilities of these models. These can, but not necessarily need to be, models from the same paradigm. Multiple Agent-Based Models combined, or System Dynamics models, or a combination of different paradigms (Nikolic, Warnier, et al., 2019). One could ask why not to make one bigger model if one's combining multiple models from the same modelling formalism. There are multiple arguments for doing so: if a model has proven to be functional, it can be acceptable to work with a black-box model, saving time and effort in model building. Commercial incentives may require black-box model use (Gomes et al., 2017) and distributed model development could also be a reason for multi-modelling (Verbraeck, 2004). For the problem posed in this research, clearly different reasoning applies: it is argued that two model formalisms may very well approach different parts of system behaviour (Quesnel et al., 2009; Vangheluwe, 2000). A combination of both may hence lead to better results. A challenge, however: one does not simply merge two model formalisms (Nikolic, Warnier, et al., 2019; Vangheluwe et al., 2002).

As far as the current understanding of Sustainable Urban Development goes, the most important reason for a multi-modelling approach is to improve model concepts by heterogenising the model and allowing for representations at different scales. In Sustainable Urban Development, several elements of the system can appropriately be modelled using System Dynamics, whilst others may better be simulated using Agent-Based interactions. One could argue why either one or the other formalisms is more suitable and find ways to mitigate the downsides that the making of this choice brings. I think, though, that that kind of reasoning negates the opportunities for novel techniques brought by such a complex system. Hence, I will apply both modelling formalisms to the problem, in order to, on the one hand, gain a better understanding of the abilities and disabilities of multi-modelling as a hybrid modelling formalism, and on the other hand, explore possible outcomes of the Energy Transition in Sustainable Urban Development to find policies that can positively contribute to solving the challenge.

10.4. Exploratory Modelling and Analysis

For using computational models for understanding interaction and feedback mechanisms in dynamic systems, two paradigms can be distinguished (Auping, 2018). On the one hand, consolidative modelling is used to explain *why* the system is behaving as it is. By using known facts and validating the outcomes of the model with empirical data, a consolidative model can be a powerful method for predicting system behaviour. This is especially helpful in, for instance, engineering systems and understanding natural processes (Hodges, 1991). With this method, understanding of the system will get better by reproducing the system to the best of our ability by mimicking reality and approaching the ’real’ system relations.

In many systems, however, one does simply not know the ’real’ relations that cause the system behaviour. For System Dynamics, this means that predicting system behaviour in a complex system using ’best guess’ relations, will per definition lead to an answer that is wrong. This, however, does not mean that making such a model is useless. The idea that ”Essentially, all models are wrong, but some are useful” (Box, Draper, et al., 1987, p. 424), is strongly applied in the second modelling paradigm, Exploratory Modelling and Analysis (EMA) (Bankes, 1993; Bankes et al., 2013). EMA does not assume the ability to create a single model that ’reliably’ predicts system behaviour. It rather creates a set of plausible models that, given a set of uncertainties, explores possible outcomes of the system. Each of these models is, given certain combinations of these uncertainties, ’correct’. This makes this method especially useful for exploring possible futures and investigate how to deal with these. In this mindset, it is not relevant what the ’exact’ outcome of, for instance, policy intervention is. That is impossible to find out anyway. It is rather the range of outcomes that intervention may have, that is aimed for. Investigation of the sensitivity of the system to certain policy levers in combination with identified uncertainties will give the modeller the ability to evaluate the success of policies, no matter the ’actual’ outcome of these uncertainties.

The same comparison as with System Dynamics can be made for Agent-Based Modelling. Agent-Based Modelling can be performed for at least two purposes. Namely to try to replicate real-world systems in finding the ’real’ driving mechanisms behind these systems, an application of the consolidative modelling paradigm: by thoroughly calibrating and validating models one can prove *why* the system behaves as it does (See & Ngo, 2012). A view from the Exploratory Modelling and Analysis perspective focuses on the understanding of the impact of unknowns on the potential outcomes of the system, making it a fundamentally different approach, with different goals.

Evaluating these two modelling formalisms, it is clear that given the uncertain nature of Sustainable Urban Development, the Exploratory Modelling and Analysis paradigm will provide the most relevant insights. Despite the incredible relevance of what drives Sustainable Urban Development, there is simply no way to validate model outcomes until it is too late. Hence, only exploratory analysis will provide insights that could support decision-makers in developing the right strategies for solving the Sustainable Urban Development challenge.

10.5. Model Initialisation: A data-driven approach

Because of the uncertainties that arise in a complex subject as Sustainable Urban Development, validation will be a challenge per definition. Hence, this research needs a clear base from which to start, to incrementally build up from ’known knowns’ to ’known unknowns’.

A solution to this is a data-driven approach that will allow to build up behavioural aspects on real data. *Big data and data-driven* are terms that have been gaining momentum in the last decade, with the evolution of computing and digital storage techniques. It is expected that data science will have a great impact on the traditional sciences, changing from field research to processing information and knowledge that is stored in databases of computers (Hey et al., 2009). Especially for geo-spatial applications, the use of data-driven methodologies will create great value that can transform abstract models into models that can closely mimic reality. With the right data, there is no longer a need to hypothesize about spatial distributions and characteristics (Miller & Goodchild, 2015), one can simply import the data, *voilà*! Unfortunately, it is not that simple.

For developing a data-driven model, a very thorough data gathering and processing need to be performed to create the necessary inputs for the model. Public data resources such as CBS (2020i), CPB (2019), RVO (2020b) and Kadaster (2020), as well as findings from research centers and advisory firms (ABF Research, 2020; CE Delft, 2018b; Ecofys, 2018) will be extracted and combined for model input. In doing so, one has to deal with faulty and missing data and transform it into usable data for the model whilst safeguarding its original meaning. This will be done using Python scripts that will be further elaborated in the formalisation section of the model chapter (section 11.3).

Although using the right data is an important aspect in creating a model that is 'valid', it is by far not the most important. If relevant data is available, one should, of course, use it as much as possible. However, big data has the characteristics that it is messy, populations have less clear boundaries than traditional sampling and one can often only speak about correlations, instead of causality (Miller & Goodchild, 2015). This makes that thorough conceptualisation and formalisation, but also extensive experimentation and analysis, become even more important when using data-driven initialisation. Although big data is often opted as *the* solution in improving science (Hey et al., 2009), it is far from being the holy grail.

10.6. Experimentation and analysis

Given the exploratory nature of this research, it will per definition create a data-overload. Hence, smart selections need to be made for analysis, for the purpose to substantiate this work as a proof of concept. An important aspect to keep in mind whilst doing so is the objective of this research: providing insights for municipalities.

In order to reach that objective, simulation software tools that helps develop this understanding will be used. Tools that help the modeller set up these equations for the System Dynamics model include STELLA (Steed, 1992), Vensim (Ventana Systems, 2010), and Powersim (Powersim Software AS, 2020). As for Agent-Based Modelling, Netlogo (Wilenski, 1999), Anylogic (The AnyLogic Company, 2020), and GAMA (GAMA Platform, 2020) may be used for instance.

As there are numerous reasons to differentiate between these software packages (Abar et al., 2017; Bureš, 2015), for instance, computational performance of ease of implementation. This research will make use of Netlogo and Vensim, simply because these are the only packages that are currently supported in the EMA workbench (Kwakkel, 2018), which is chosen for connection and analysis of the models. Due to rounding errors and implementation choices, the use of other software packages may result in different outcomes. However, as for a proof of concept in multi-modelling, these differences are considered negligible.

10.6.1. Experimental Setup

With the model fully developed, the next step is to determine the experiments to perform with the model. The model will have a wide range of uncertainties and policies that can be tested, as well as a wide range of geographically separated entities to view the outcome of these experiments. Even with an unlimited amount of time, it is extremely hard, if not impossible, to investigate the entire solution space that the model offers.

This means that when developing the experimental setup, two sides of this problem need to be taken along. On the one hand, one cannot simply test everything: with every extra variation, the number of experiments needed increases exponentially. The runtime of the model is expected to be quite extensive, this means that to stay within reasonable computing periods, the number of experiments should be limited. For every factor f that is varied with n options, the amount of experiments increases with n^f. When varying 10 uncertain factors, with only a 'high' and a 'low' option, this already results in 2^{10} = 1024 experiments. When varying with 3 levels, the number of experiments increases to 59.049 and with 4 levels one needs 1.048.576 experiments. With a model with this amount of uncertainty, the number of experiments and thus computing time needed for a reasonable full factorial is going to be immense.

Solutions to this include for instance Latin Hypercube sampling (McKay et al., 2000). Which helps to create a diverse set of samples that will explore as much of the solution space as possible with limited numbers of experiments, by ensuring that without any influence of factor dominance, all components are represented.

In this research, however, only using such techniques is not enough. The model is developed so that in the end, any policymaker at the municipal level can view their jurisdiction and evaluate the effects of scenarios and policies on their municipality. This means that information is generated on such a low scale, that the sum of it all results in enormous amounts of data, which can never all be processed. With this research being a proof of concept, this means that a smart selection can be made of municipalities that will help prove the usefulness and generality of the model as a whole, after which in further research, other municipalities may be explored at their request.

To make a smart selection of experiments, a dynamic approach is used. The selection will be performed in three rounds. First, sensitivity analysis will be used to determine the number of replications that are needed for each experiment. The stochastic nature of Agent-Based Models (Epstein & Axtell, 1996) makes that one needs to create a pool of samples for each experiment to allow for statistical or principal component analysis for example. With a limited amount of scenario's and a high amount of replications, the coefficient of variation can be determined for each amount of replications (Lee et al., 2015). Because of the expected long runtime of the model, it will be key to find the minimum acceptable amount of replications.

In the second round, open exploration (Kwakkel, 2018; Pruyt et al., 2013) will be performed varying a wide range of uncertainties and policies with the predetermined number of replications, to evaluate the outcome at the municipal and intermunicipal level. With these outcomes, scenario discovery can be used to identify the relevant uncertainties and policies for the national outcomes. At inter-municipal level, however, regional differences can be observed, to determine the municipalities to be investigated using open exploration in further experiments.

In the third round, based on findings from the second round, three municipalities will be chosen to further investigate in detail as a proof of concept. With outcomes at the neighbourhood level and scenarios from the national level, it can be investigated how these municipalities may change over time, given these scenarios, to determine robust policy options. When the findings prove to be fruitful for these three municipalities, future research will be able to enable an analysis of the 352 other municipalities in the Netherlands.

10.6.2. Model Analysis

During the process of experimentation, the outcomes will be analysed using the EMA-workbench (Kwakkel, 2018). This workbench is specially developed for performing Exploratory Modelling and Analysis (Bankes, 1993). Two methods that can be used for analysis in the EMA Workbench are open exploration and directed search, of which open exploration will be the most relevant in the first part of this study.

Open exploration provides the tools to investigate the models KPI's sensitivity to the uncertainties and policy levers in the system. This makes that open exploration can be used to identify the relevant uncertainties and policy levers in the system, which can be selected for further investigation. This is especially relevant in this research. Since investigating every part of the solution space will simply not be feasible.

After identifying the most relevant uncertainties and levers, sample scenario's and policies can be set up for further exploration, utilizing Scenario Discovery (Bryant & Lempert, 2010). A useful tool for doing so is the Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1999). Lempert et al. (2006) suggested using PRIM as a tool in scenario discovery because it helps to identify the set of factors that contribute to reaching a set goal for one or more key performance indicators.

With the 'stereotype' scenarios and policies identified, on a municipal level, further exploration will be performed on a relevant section that will be identified by the first exploration. This exploration provides insights into the relative differences between municipalities to determine what municipalities may be interesting to compare in more detail.

11

Model

This chapter will discuss how the model is built up using the model development cycle. First, the model conceptualisation will be discussed, followed by formalisation, evaluation, and experimentation and analysis. The goal of this chapter is to gain understanding and confidence in the model concepts, structure and implementation, so that its results may be interpreted correctly and that they may appropriately be used for policy development.

11.1. Model Conceptualisation

In this section, I will discuss my understanding of and perspective on the system and how these are built up. The conceptualisation is split into two elements, with in the first place, building on the stakeholder analysis, the Agent-Based Model, which focuses on the individual behaviour of the stakeholders involved. In the second place the System Dynamics model, which describes the overall behaviour of the system, mainly focused on the developments of markets in the system. The two submodels will be coupled using a message-bus, that will combine the two model concepts into one co-simulation model. Details to this endeavor are discussed in part II, chapter 4.

11.1.1. Model concept identification

In this subsection, I will identify the relevant concepts and aspects that need to be included in further conceptualisation. So, from what elements is Sustainable Urban Development built up? As identified in chapter 9 this research will focus on *energy*, using the following definition for Sustainable urban development:

'Sustainable Urban Development is development in which urban areas try to become CO_2 neutral, by using renewable energy sources and reducing energy consumption, on the condition of economic and social feasibility.'

Let's decompose this definition. In this definition, the concept of *energy* is applied to *urban areas*. Several definitions for urban areas exist (Baten, 2003; Dijkstra & Poelman, 2014), but they have in common that it is an area which provides utilities and infrastructure, where people live together in a high population density. This area thus consists of *a population*, *a living environment* and *utilities*. This means that the model should facilitate the representation of all of these aspects. Population dynamics can offer insight into the developments of the population over time, where the housing market can represent the developments in the living environment. Utility on its part is a broad concept that can include the working environment, infrastructure, recreation facilities and many more. To develop a proof of concept, the focus will lie on the living environment and leave utility for further research.

In terms of *Energy*, aspects as *consumption* and *production* are relevant, as well as *reduction* and *renewability* thereof. This means that the use of energy, and the aspects that lead to reduction of consumption, as well as renewable production of the energy consumed, must be considered. The main goal for the above: *CO_2 neutrality*.

The energy used in the living environment consists of two elements: energy used for atmospheric purposes, such as heating and lighting, and energy used for powering appliances (Eurostat, 2020). This distinction is also categorised as 'house-bound energy use' and 'user-bound energy use' (RVO, 2020a). The closing remark of *economic and social feasibility* implies the importance of *economic and social incentives for change*. This means that people must have incentives and opportunities for reducing their energy use and enabling renewable energy production. In this, the availability of technology, the cost of consumption, and public opinion will play a big part. Dynamic concepts such as the technology s-curve (Foster, 1988), market mechanisms (Kwoun et al., 2013; Teufel et al., 2013) and artificial societies (Epstein & Axtell, 1996) are very well suited for describing such phenomena.

Enablers in reaching the goals set in the definition, apart from technocratic ones, have so far not been discussed: the stakeholders in the system. At least, homeowners, housing corporations, energy suppliers, municipalities and contractors will play an important part in making decisions that result in change, or no change at all, based on the economic and social incentives mentioned above. This, combined with the fact that investment behaviour will depend strongly on the market and business cycle, shows the inter-relatedness between all of these concepts. The interrelation between these concepts makes that using a simulation model may provide very useful insights.

11.1.2. Main model concepts

The previously identified model concepts can now be summarised into the main elements that will compose the model. From the definition of Sustainable Urban Development, four different concepts have been identified that are considered essential in modelling Sustainable Urban Dynamics which will be further discussed in this section:

1. Housing Market
2. Technologies
3. Energy Market
4. Investment Behaviour

The first is the housing market. How many houses there are in the country and the amount of energy they use will together determine the main part of the energy used in the living environment. Hence it is important to understand what the housing market looks like and how it develops.

Second are the technologies that are ought to contribute to the reduction of the use of energy, and enable the use of sustainable energy for the demand that is inescapable. When looking back at the figure that represents resource use during the lifetime of a dwelling (figure 9.1), energy reduction can be achieved by, on the one hand, reducing the amount of heat that leaves the building, and on the other hand, reduce the electricity and heat used inside the building. The biggest contributor to energy loss in households is heat (Anisimova, 2011). Insulation technologies can significantly reduce this energy loss (TNO, 2020b).

When considering the use of sustainable sources for energy in urban areas, this can be achieved in three ways, with the main performance indicator in this, CO_2 emissions. These emissions can be reduced by renewable electricity productions, such as wind-, solar- and hydropower. This is evident for the use of electricity itself, for heating there are more options. The first is to heat the house using electricity, using heat pumps (CE Delft, 2018a). Another option is to deliver heat to the house directly through a sustainable heated heating grid (TKI Urban Energy, 2020). Lastly, green gas may replace the current natural gas for heating employing a high-efficiency boiler (CE Delft, 2018a).

The suitability of each of these options, will not only depend on the characteristics of the housing stock, but also on the third element that is of major importance in Sustainable Urban development: the energy market. The price of electricity, natural gas, green gas and heat will be key determinants in the success of proposed policies (Ameli & Brandt, 2015; Bouwfonds ontwikkeling, 2010). Economical incentives will always drive investment decisions. As long as 'conventional' techniques are cheaper and more cost-efficient than renewable, it will be difficult to push for a change. A clear understanding of the energy market will then be key to understanding why certain investment decisions can or cannot be made.

The last element that is expected to play a dominant role in the energy transition is the investment behaviour of the involved stakeholders. In the end, the energy transition can be realized in two ways:

reducing the amount of energy used and using sustainable resources. Doing only one or the other is expected not to be enough (TNO, 2020b), which means that investments are needed in both.

Key in this will be the question of how these investments are made. In general, investment behaviour depends on the characteristics of possible investments, such as investment cost, expected return, and risk (Stermole et al., 1974). These will be evaluated on the characteristics of the investor themselves, on its available resources, return expectations and willingness to take a risk but also on the characteristics of the environment. This investment behaviour can be represented as in figure 11.1. Depending on internal and external factors, stakeholders will determine the thresholds that need to be passed for investment. Based on internal characteristics, one can then identify to what extent these thresholds are met so that investments can be made. These investments will then, in turn, affect the characteristics of the investor, which will be used in evaluating further investments.

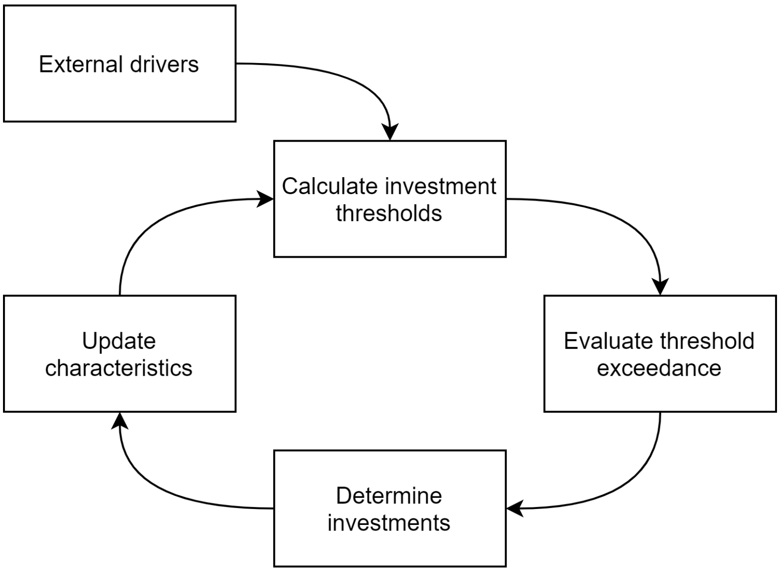

Figure 11.1: Investment behaviour

This investment-cycle can be applied to all sorts of investments, so in this model, the cycle is relevant for insulation investment, investment in individual systems (heat pumps and high-efficiency boilers), and investment in collective systems (heating grids).

The next step in gaining a further understanding of how these investments are made is to investigate the stakeholders that are making these investments. These will be discussed in the next section.

11.1.3. Stakeholder Identification

A first step in developing the model conceptualisation is to assess the involved stakeholders and their abilities and disabilities. Since the model will use individual behaviour as one of the main drivers of the system, it is extremely relevant to gain a thorough understanding of the involved stakeholders, what drives them, and how they behave. For this, a thorough stakeholder analysis has been performed, to get the necessary insights for the conceptualisation of the model. The full analysis can be found in appendix A.

When looking at sustainable urban development as defined in subsection 9.4 several stakeholder types are typically involved. 'Stakeholder types' are discussed here, instead of actual stakeholders, because of the scope of this research in which the behaviour of the stakeholder types is assumed to be similar for different actors within that group. Because the final scope of the model lies at the national level, it is not desirable to work with every single 'real' actor, not only because of the immense computing time to be expected but also because of the unavailability of data and limited added value. Therefore, based on real actors in real projects (appendix A.1), aggregated stakeholder types have been defined, which have their own characteristics and behaviours.

These stakeholder types can be categorised into two dimensions, namely whether they are individuals or collectives, and whether they belong to consumers or producers of energy (services) or the government. The individuality will be a key determinant for their abilities, and the type of stakeholder will be very relevant for the interaction they will have with the other stakeholders. The categorised stakeholders can be shown in table 11.1.

Table 11.1: Categorised stakeholders

	Individual	Collective
Consumer	Homeowners Tenants Companies Housing corporations Local residents	Homeowners association Tenants association Entrepreneurs association
Producer / facilitator	Energy Suppliers Energy service companies Grid operators Contractors	Energy co-operations
Government*		Municipality Province State

*The government has a collective role per definition

Table 11.1 shows that stakeholders have a diverse role and characteristics in this problem and are organised differently as well. This will be very important in developing the core behaviour and characteristics of these stakeholders for the model concept. To gain an understanding of the most relevant stakeholders to model, a stakeholder analysis has been performed using declarations of intent of energy transition projects and energy transition business cases. From this analysis, a Power-Interest-Attitude matrix has been derived, to determine what stakeholders should be included in the model, and what stakeholders should be considered during further development of the strategy, but will be omitted in the model. The Power-Interest-Attitude diagram is shown in figure 11.2.

From the right upper corner of the Power-Interest-Attitude diagram in figure 11.2, can be derived that the most important stakeholders to be included in this research are homeowners, companies (consumers) and their associations, governmental institutions and energy (service) suppliers, energy co-operations, housing corporations, and contractors. In the Agent-Based Model, these stakeholders can be characterised based on their behaviours which will be formalised into an agent-type. From these stakeholders, four types of behaviour can be identified:

1. Investment behaviour energy consumption
2. Individual investment behaviour energy system
3. Collective investment behaviour energy system
4. Policymaking (taxes and subsidies)

Now that the types of behaviour have been identified, the model concept can be further developed. In multi-modelling, the next step is to determine what parts of the model are going to be modelled using what formalism. Detailed discussion on how that is done and what methodological choices are made, can be found in chapter 3. The next section will discuss the result of this endeavour, the final model concept.

11.2. Final Concept

A general overview of the final concept is given in figure 11.3. It gives an overview of the agents that will be included in the Agent-Based Model, how the environment is set up and how it relates to energy, housing and technology markets in the System Dynamics model. For each agent, its characteristics

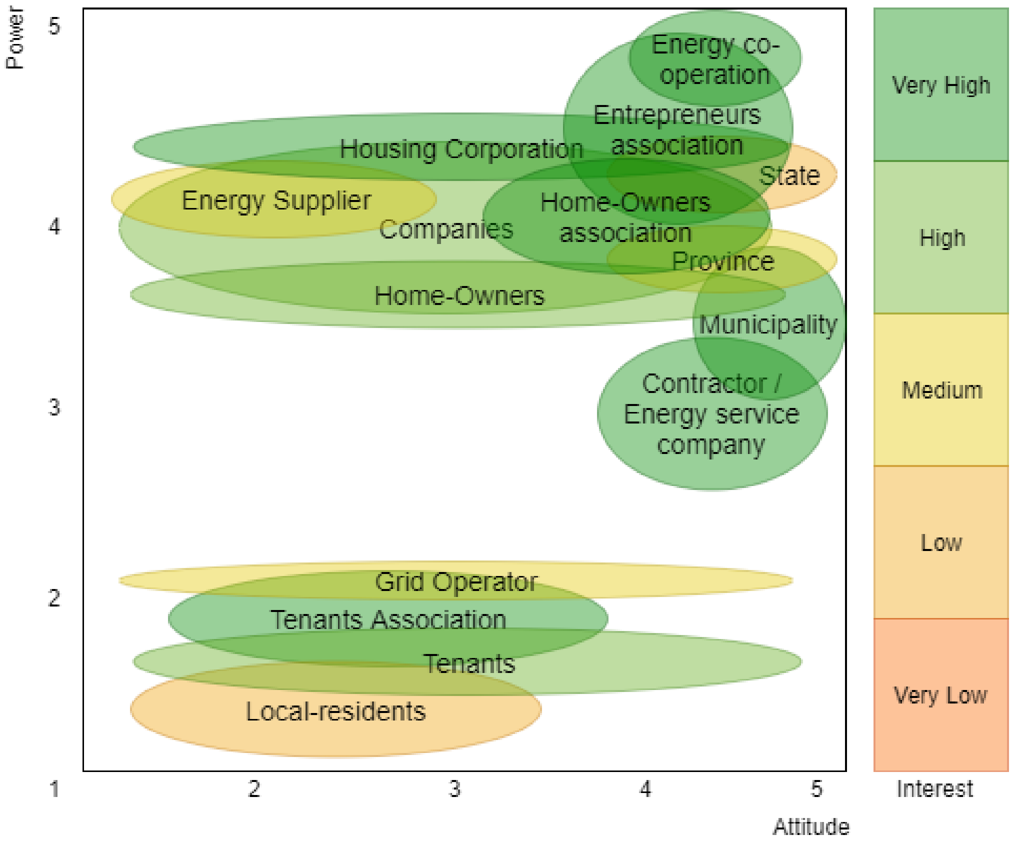

Figure 11.2: Power-Interest-Attitude Diagram

are displayed. The interaction between the two models is given by the arrows that connect the left part of the diagram, the Agent-Based Model, with the right part which depicts the System Dynamics model. The next sections will discuss both the models into more detail.

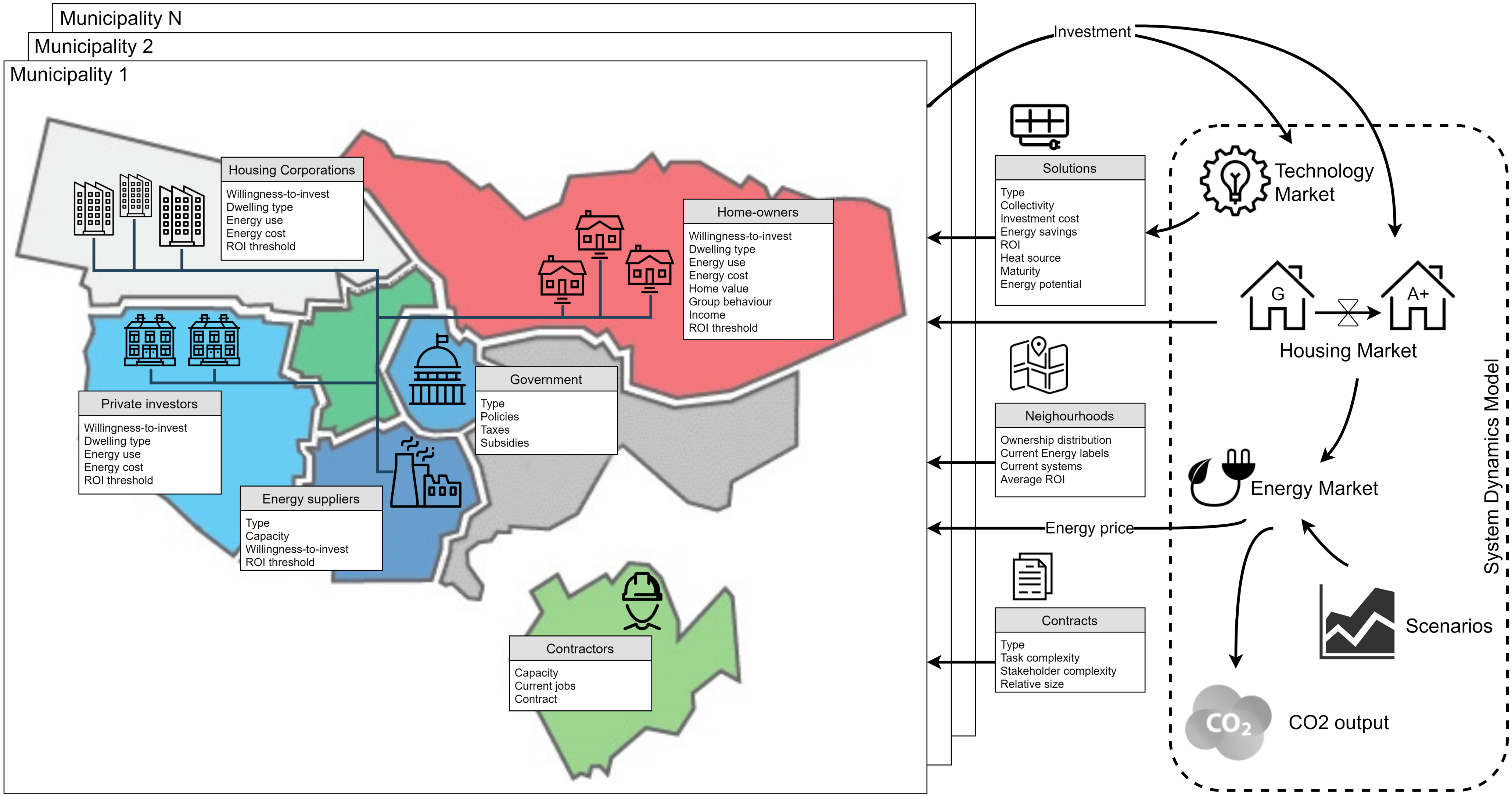

Figure 11.3: Final Model Conceptualisation [a]

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[a] Citymap by Stadswandelkantoor (2019), icons from thenounproject.com

11.2.1. Agent-Based Model

The Agent-Based Model will build upon the identified stakeholders and their behaviours in section 11.1.3. For this, a set of characteristics of these stakeholders is needed, that allows creating the different agents. In this way, a range of possible behaviours of stakeholders can be modelled and investigated, to gain a better understanding of the possible consequences of these behaviours. Based on the five types of behaviour that have been identified in the stakeholder analysis, four different agents can be set up in the model. These are:

1. Homeowners (private and corporation)
2. Energy suppliers
3. Governmental institutions
4. Contractors

The first three of these will be continuously evaluating the investment cycle. Based on their own characteristics and the characteristics of the environment, they will evaluate possible investments and decide whether to invest or not. This cycle is presented in more detail in figure 11.5. The next subsections will discuss the model narrative, for each of these agents.

Homeowners
In this model, the behaviour of homeowners is central to the behaviour of the system. Their behaviour will be crucial to accomplish the goals for the Energy Transition in the Built Environment. This behaviour is modelled as follows. In each timestep, homeowners check what the current status is of the suitability of energy solutions for its household(s) (dwelling type). This will be done on the base of the cost of these solutions, the expected energy savings and how this affects the energy bill. This will determine the return on investment (ROI) for each of the possible solutions. Based on the homeowners available capital and income, an ROI-threshold will be determined that needs to be passed to decide to invest. This is done for both investments in insulation, as well as investment in individual energy-solutions such as heat pumps. If no solutions transcend the ROI-threshold for the individual homeowner, the round will finish. When solutions are passing the ROI-threshold, the availability of construction capacity will determine whether the investment can actually be done. If this capacity is sufficient, investments are made, and the households' characteristics are updated. The biggest difference collectives (corporations) have with the individual homeowners, is that housing corporations don't have the capital or income restraints. It is assumed, that as long as the return on investment is high enough, investors and lenders will be available to fund the investment.

Energy suppliers
A special role lies with the energy suppliers in this model. They evaluate the collective potential for heating grids. Based on the characteristics of groups of houses ([parts of] neighbourhoods or districts), the availability of heat sources (Residual heat, Heat Cold Storage and Thermal Energy Surface Water), a business case can be made for these systems. If the business case is positive, it is assumed that energy suppliers will be allowed by the municipality to set up a heating grid. This investment will, in turn, affect the characteristics of the housing stock of housing corporations and homeowners, which will affect their decision making in the next round.

Governmental institutions
Governmental institutions have several instruments to influence the system. They can tax, subsidise or set boundaries for investments. They will do this based on pre-determined strategies that will be used as input to the model.

Contractors
In each round, for investments that are made, contracts are set up with contractors. Characteristics of these contracts are stored so that for each of these, and combinations of, contracts can be determined what suitable project delivery models may be. Next to this, the capacity of contractors will influence the ability to transform neighbourhoods. A maximum share of houses can be renovated each year, so that a steep transition curve may be limited by construction capacity.

The logic for selecting appropriate project delivery models is derived from the Socrates model (De Koning, n.d.) developed at Witteveen+Bos. In this model, four categories have been identified which are important for selecting a proper project delivery model: the client, project characteristics, project choices and market characteristics. Three of these categories cannot be estimated in advance using a model, these are time and people dependent. However, the model may be able to provide insights into project characteristics that make that one or the other contract may be more suitable. Three project-specific characteristics can be used for estimating contract suitability:

1. Task complexity
2. Size of the contract
3. Stakeholder diversity

Where task complexity refers to the maturity of the technology implemented, the size of the contract is evaluated relative to the largest project and stakeholder diversity is defined as the percentage of homeowners in a neighbourhood. For all of these project characteristics, a traditional model always scores well, hence to stress the differences between these contracts, it is chosen to alter the model so that other options are preferred, if also available. This resulted in the scheme of preference as presented in table 11.2.

Aspect	Most suitable	Neutral	Least suitable
High task complexity	Building team	Integrated	Life-cycle
Low task complexity	Life-cycle	Integrated	Building team
Large contract	Life-cycle		Building team / Integrated
Small contract	Building team / Integrated		Life-cycle
High stakeholder diversity	Building team	Integrated	Life-cycle
Low stakeholder diversity	Life-cycle	Integrated	Building Team

Table 11.2: Project characteristics and contract suitability

This scheme is used to determine for every type of project what the most suitable contract would be at each moment. In this way, insights can be gathered on the development of the 'most suitable' contract, so that policymakers will be able to presort on that choice for implementation of the actual solutions. A visual representation of this scheme is given in figure 11.4.

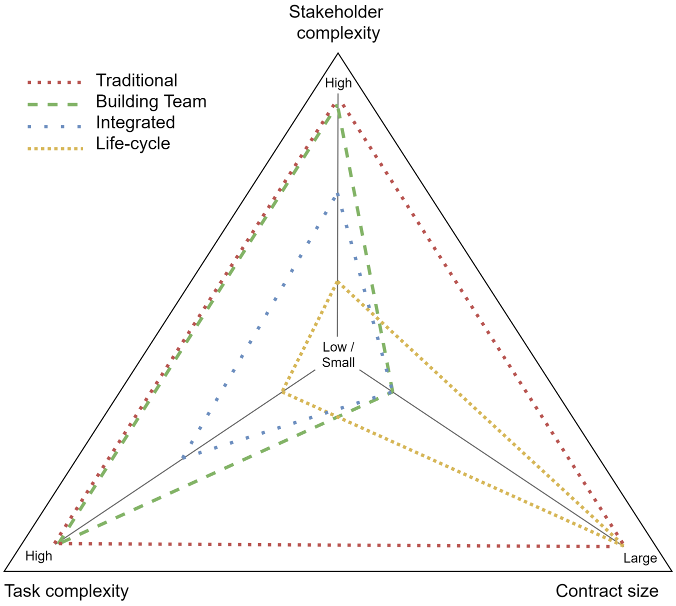


Figure 11.4: Project delivery model suitability for project characteristics

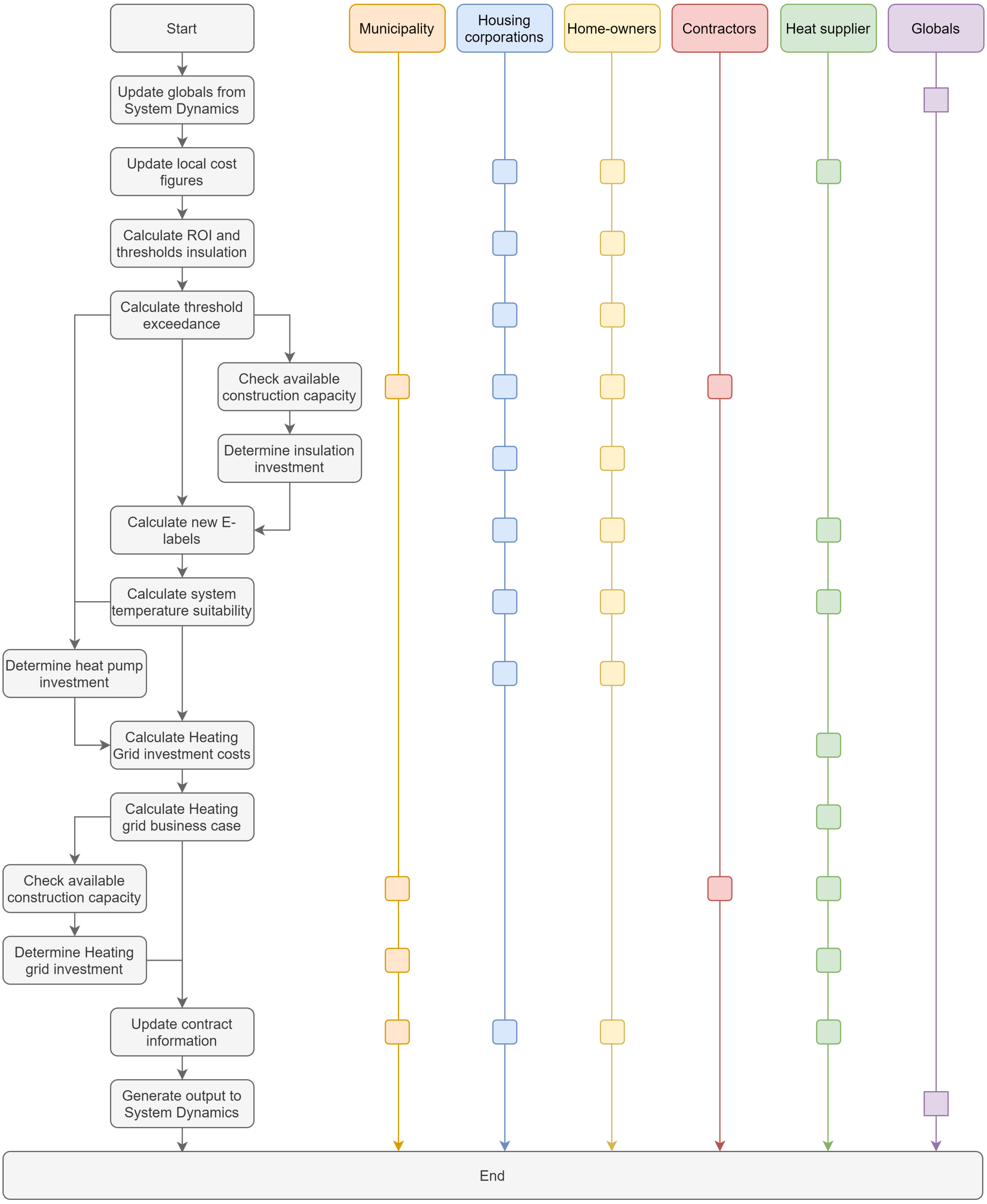


Figure 11.5: Action diagram Agent-Based Model

11.2.2. System Dynamics Model

As discussed in section 4.1 the System Dynamics model will be responsible for evaluating three different markets in the system. These are:

1. Housing market
2. Energy market
3. Technology market

Combined with scenario input, these markets will determine the 'state of the world' of the Agent-Based Model. The loop of the model as a whole starts with the Agent-Based Model, which determines the investments made in each municipality. From there, it will communicate these investments to be input for the housing market and technology market. From there, the housing market and scenarios are used as input for evaluating the energy market, from which the corresponding energy prices will then be fed into the Agent-Based investment model together with the changes in the technology market, completing the loop.

For the System Dynamics model, a whole different approach to the conceptualisation of the model is needed than with Agent-Based Modelling. Whereas the conceptualisation of the Agent-Based Model lies the focus on the involved stakeholders (agents) and how they interact with each other, System Dynamics focuses on causal relations between system elements. A visual way of presenting these relations is through a Causal Loop Diagram (Haraldsson, 2004), which for this model, is given in figure 11.6.

From the Causal Loop Diagram, one can differentiate three main elements which will drive the system. The first element is the price of energy, split up in gas, heat and electricity. These prices influence the second element, the investment in energy solutions. From here, the investment in energy solutions determines the demand and supply of energy, split over the energy carriers. This demand, then again influences the energy prices, completing the loop. Performance of the system is measured using CO_2 emissions, which is composed of gas demand, electricity demand and the renewable share of electricity. External factors that will influence the system employing scenarios are given in red, policy levers that will be used to evaluate different policies are given in blue. It should be taken in mind, that the connections between gas import and gas price, and between electricity import and electricity price, are given with a dashed line, indicating that the effect of Dutch imports on the price of gas and electricity may be minimal.

Given this model concept, it is hypothesised that the system will express three different behaviours. This first is balancing behaviour when looking at investments in energy solutions. This behaviour makes sense because collective and individual solutions are mutually exclusive, a heat pump is no longer a viable solution if a heating grid is already present and vice versa. Secondly, balancing behaviour can also be expected because of the feedback loops via the energy prices. A high energy price will motivate to invest in energy solutions, however, this will decrease demand, leading to lower energy prices, making investments less attractive. Thirdly, enforcing loops will increase the overall attractiveness of investments in energy solutions because of technological development. The more investments take place, the more technology is expected to develop, making the investments even more attractive. It can be expected, that depending on the external factors and policy levers, an equilibrium will be reached dividing the energy demand over the various energy carriers. Policies on the use of fossil fuels, in the end, will be key determinants on the performance of the system when considering CO_2 emissions.

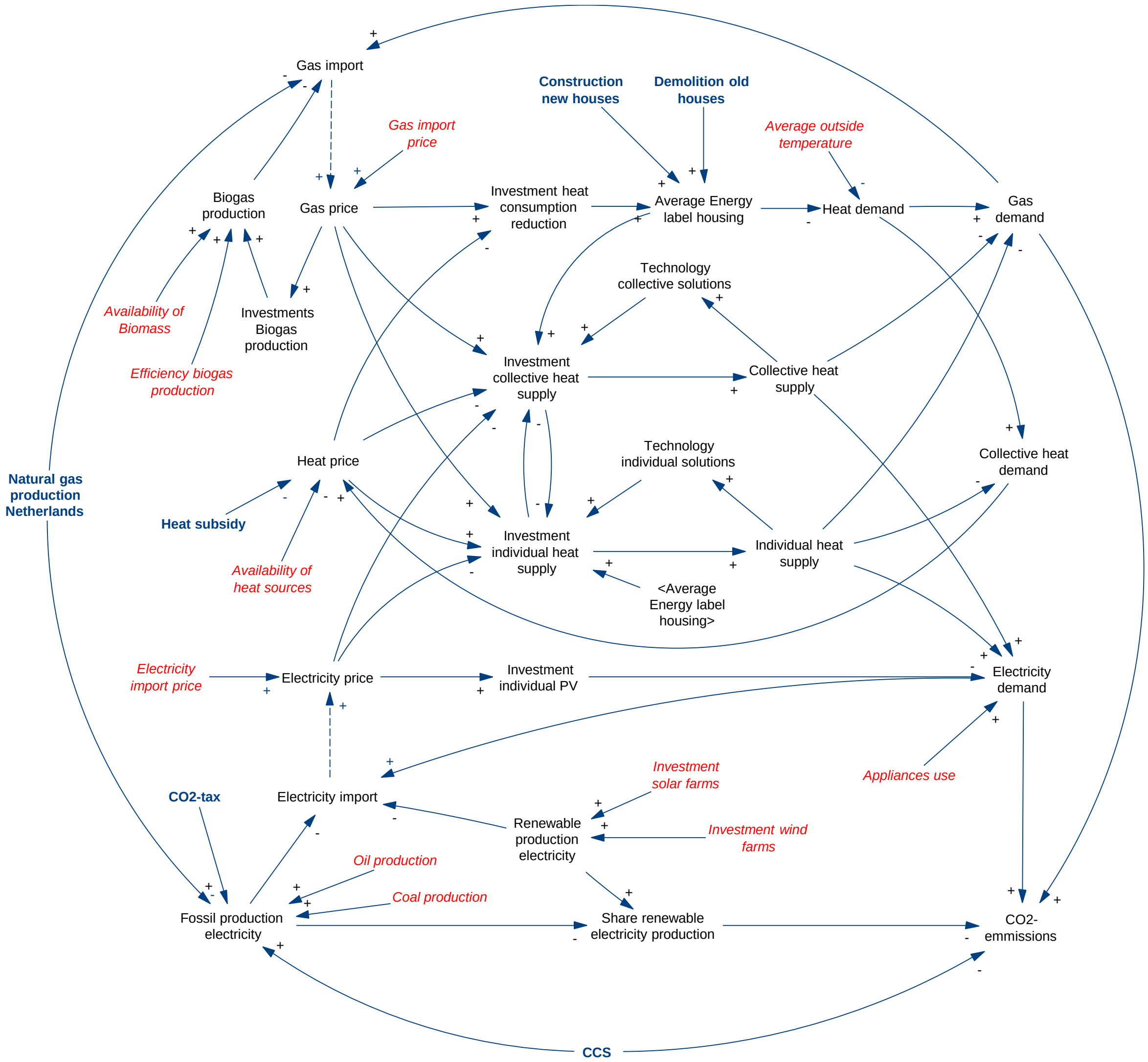


Figure 11.6: Causal Loop Diagram

11.3. Model Formalisation

This section will elaborate on the formalisation of the model, being the computer implementation of the conceptualisation described in section 11.1. Three elements will be discussed, the formalisation of the Agent-Based Model, the System Dynamics Model, and the gathering of the data necessary for initialising the model.

11.3.1. Agent-Based Model

The Agent-Based Model will be described on the base of actions diagram presented in the Agent-Based Model conceptualisation (figure 11.5), which shows the actions of the stakeholders involved in the model. As discussed in section 4.1.4, it will be computationally very expensive to model each and every actor separately. Therefore, it is chosen to aggregate to the neighbourhood level and keep track of the heterogeneous characteristics of these neighbourhoods through (statistical) distributions. This means that a neighbourhood will act on the behalf of homeowners, housing corporations and energy suppliers.

The general behaviour of neighbourhoods will be based on the investment cycle that was defined in the model concept. In the next sections, I will shortly describe the four main processes that will be performed each timestep. After this, I will dive into the detail of the more complex investment procedures.

1. Update of world and agent characteristics

Each timestep, based on the input from the System Dynamics models, the characteristics of the environment and the neighbourhoods will be updated. Global variables such as energy prices (Gas, Electricity, and heat), the maturity of technologies and the construction, demolition and relocation factor per municipality will be updated.

2. Evaluation of threshold values for investment by neighbourhoods

In the second procedure, threshold values for investment will be evaluated. Based on housing characteristics from RVO (2020b) and Kadaster (2020), the threshold for the break-even-points of different insulation levels and individual heating solutions can be defined. These thresholds are based upon the following equation for return on investment (ROI):

$$ROI = \frac{GasPrice * PotentialYearlySavings}{InvestmentCost} \tag{11.1}$$

Since the gas price will be calculated endogenously and thus be variable, gas price is moved to the left side of the equation. When the ROI of an investment in insulation is larger than the minimum ROI demanded by the investor, the investment can be made, given by the following requirement:

$$\frac{ROIminimum}{GasPrice} < \frac{PotentialYearlySavings}{InvestmentCost} \tag{11.2}$$

Because the heterogeneity in investment cost and potential savings of individual solutions in each neighbourhood, these characteristics will be approximated by a cumulative gamma distribution that will allow calculating the percentage of houses for which the threshold is met. This exceedance probability is given by:

$$F(x,k,\theta) = \frac{1}{\Gamma(k)}\gamma\left(k, \frac{x}{\theta}\right) \tag{11.3}$$

In which **x** represents the minimum ROI over gas price, **k** is the estimated shape parameter and θ is the estimated scale parameter. Further detail on setting up the distribution parameters for this function can be found in the data-gathering section 11.3.4.

Similar evaluation is performed for heat pumps. A difference is that the threshold is also dependent on the electricity price and the efficiency of the heating pump. Heating grids are a bit different. The potential of a heating grid does not depend on one house but the entire neighbourhood. So, based on the neighbourhood characteristics (number of potential connections, suitable technologies and the length of distribution pipes needed) and available subsidies, the total investment cost, variable production costs and expected income can be calculated. If the potential income over investment cost is larger than the desired ROI, an investment can be made.

3. Determination of feasible investments by neighbourhoods

After evaluation of the ROI exceedance of investments, the exact investment needs to be determined. For insulation and heat pump investment this means that the new investments are the potential investment minus the current investments.

4. Update of investment effects of investments in neighbourhoods

The last step is to update the effects of the investments made in the timestep. For investment in insulation, this means that the energy labels of houses in the neighbourhood need to be updated. For heat pumps and heating grids the percentage of houses in the neighbourhood that make use of these heating solutions is updated.

As is shown in the conceptualisation in figure 11.5, these rounds will not be performed in parallel for each investment option. Because investment in heat pumps and heating grids are dependent on investment in insulation, insulation will be calculated first. Second to be evaluated, are heat pumps. This choice is made because these investments are individually based. It is expected that people will invest in individual solutions until certainty exists about a collective solution. This is relevant because the potential for heating grids will decline when the number of heat pumps in a neighbourhood increase.

11.3.2. Investment logic: an example of heating grids

The investment in heating grids is dependent on many factors. In the next sections, I will discuss how the business case is set up. Let's start with the factors that influence the heating grid business case, as shown in table 11.3.

Table 11.3: Factors for heating grid business case

Investment cost	Yearly cost	Potential income
Available primary sources	Production cost of source	Maximum connection contribution
Temperature of grid	Maintenance cost of investment	Maximum fixed contribution
Distance to source	Production cost of distribution	Maximum Tariff (gas price equivalent)
Distance to network connection	Network Demand	Network Demand
Length of distribution net		Production subsidy
Capacity of distribution net		Investment subsidy
Number of potential connections		
Connection value of potential connections		
Temperature suitability of potential connections		
Project management cost		

*Equations for determining the actual cost have been derived from the Vesta MAIS model by Planbureau voor de Leefomgeving (2019c).

The logic that evaluates all possible options for heating grids can be described as follows. Each neighbourhood computes the costs for the elements that are needed for all types of heating grids and sources, for each temperature level. These are investment costs for the distribution net, indoor investments and potential individual additions for boosting the delivered temperature if necessary. Then, for high and medium temperature heating grids, neighbourhoods will look for the closest HT/MT-source that has sufficient capacity to supply the neighbourhood with heat. If there is a neighbourhood near, that already has a heating grid, that is connected to other neighbourhoods that lie closer to the potential heat source, the best option is set to connect to the existing grid, and connect that grid to the source. If this is not the case, a direct connection to the source will remain the best option.

For low-temperature heating grids, two options are evaluated: Heat Cold Storage (HCS), and Thermal Energy Surface Water (TESW). Each neighbourhood has a potential for HCS and a potential for TESW, that is based on the availability of surface water in the neighbourhood, and a factor that approximates the relative potential of one hectare of surface water to HCS. If the potential is larger than the required capacity of the neighbourhood, then HCS or TESW are saved as LT options.

For each option, now the business case is calculated, for which the following equations are used:

$$\begin{aligned} TotalInvestmentCost = {} & InvestmentPrimarySource + GridCost + IndoorInvestmentCost - \\ & MaxConnectionContribution * NumberConnections - InvestmentSubsidy \end{aligned} \tag{11.4}$$

$$YearlyCost = MaintenanceCost + ProductionCost * Demand + DistributionCost * Demand \tag{11.5}$$

$$\begin{aligned} YearlyIncome = {} & Demand * MaxTariff + MaxFixedContribution * NumberConnections \\ & + ProductionSubsidy * Demand \end{aligned} \tag{11.6}$$

Based on different production costs of heat sources and different maintenance costs, a return on investment can be calculated for each option. The option with the highest ROI is considered the best option. If this ROI is higher than the minimum ROI required by heat companies, the business case for that heating grid will be positive.

$$ROI = \frac{YearlyIncome - YearlyCost}{TotalInvestmentCost} \tag{11.7}$$

If the construction capacity of the municipality is large enough to build the grid, the investment is made. This is done by connecting the neighbourhood to the applicable source (via another grid or not). Each grid member is asked to update his list with grid members of his grid so that in a next round each neighbourhood is informed about the current state of the grid.

Algorithms based on the same principles are used for the other investment decisions: investment in insulation, and investment in heat pumps. The full model code can be found in appendix B.

11.3.3. System Dynamics Model

The System Dynamics model will provide the boundary conditions and global information for the Agent-Based Model at the municipal and national level using the software Vensim (Ventana Systems, 2010). Information from the Agent-Based Model is aggregated to set up the Housing Market, Energy Market and Technology Market and to calculate the overall effects on CO_2, of which its reduction is one of the major goals for the model's users. The model is divided into multiple submodels, setting up the aggregated markets mentioned before.

Housing Market

The housing market is divided into four submodels, the main being the submodel for the housing stock. In this submodel, ageing, construction and demolition of the housing stock are simulated. The housing stock is subscripted in two dimensions: municipality and age. This means that formally, the housing stock consists of 3905 stocks. This enables detailed modelling and analysis of the characteristics of these houses, on a municipal level.

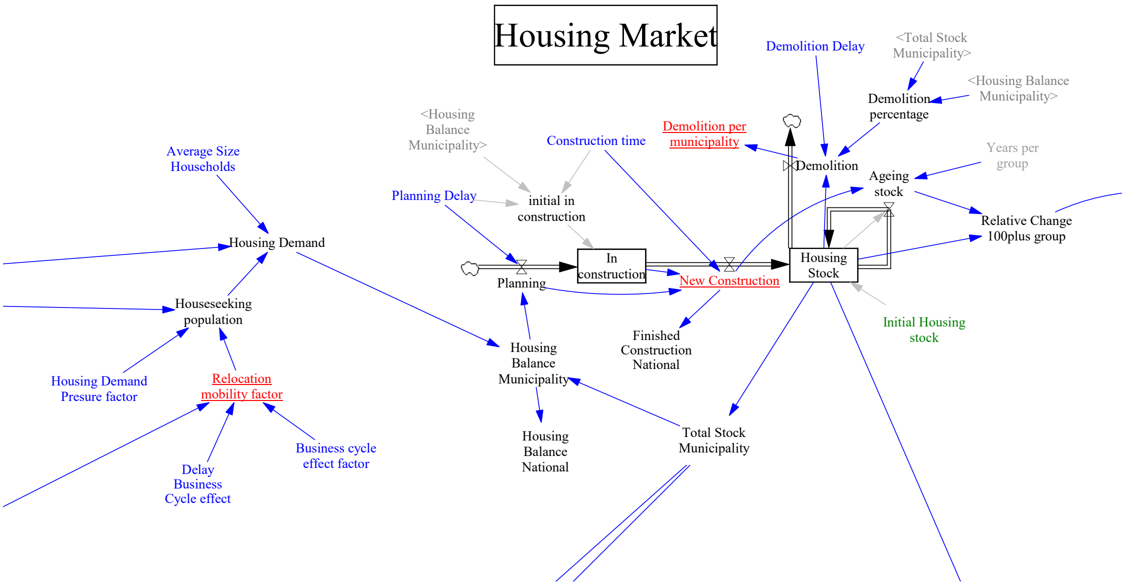


Figure 11.7: Submodel Housing Stock

Demolition and construction are based on the demand for dwellings per municipality. This is determined using the existing stock and the expected development of the population of these municipalities multiplied by a business cycle dependent factor that approximates relocation mobility, which is calculated in the business cycle scenario submodel. These business cycle scenarios can then be used to determine the dependence of the success of policies on economical developments.

Population dynamics are modelled using the Cumulative Gompertz Distribution (Gompertz, 1825), which is commonly used by demographers for estimating population dynamics. The model is fed with the current population by CBS (2020c) and prognoses from the Primos Database by ABF Research (2020) are used for calculating migration. These prognoses include ageing, births and deaths, so they are compensated for these aspects using a compensation factor, to allow for endogenous calculation of cohort developments. This is done because it is expected that the ageing of inhabitants will have a large influence on the willingness to invest in sustainable improvements in housing.

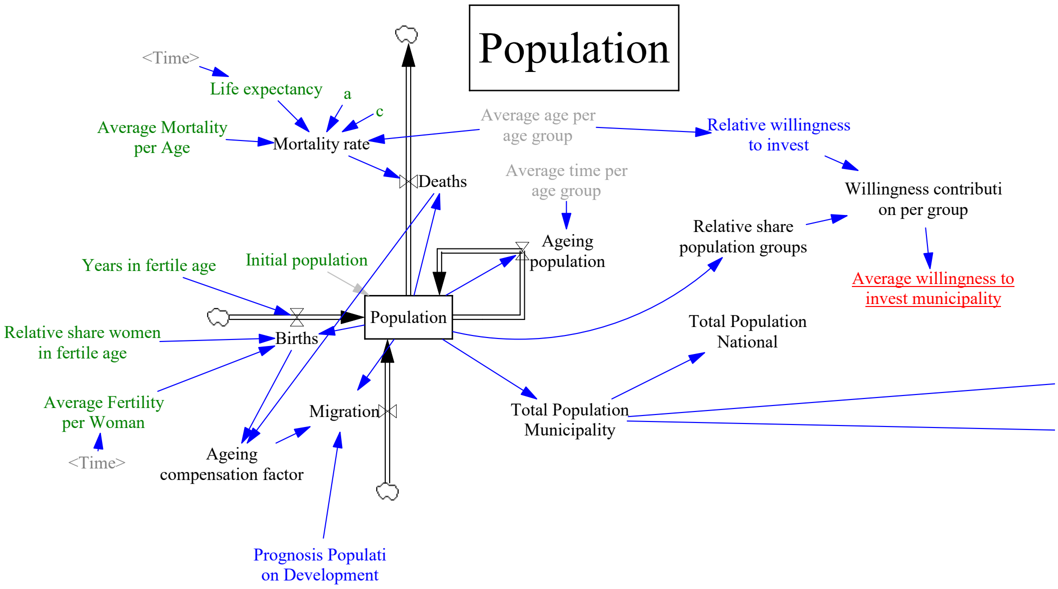


Figure 11.8: Submodel Population

The average energy use of the housing stock is modelled using a co-flow of the housing stock model. This means that the average energy use follows the same ageing structure as the housing stock. In this way, the total energy use per set of houses with common characteristics can simply be calculated by multiplying the number of houses with the average energy use. New houses that are built will have a lower average energy use due to improvement of insulation of new houses, which is approximated by the improvement factor. Compensation is necessary for the last group, the 100plus group because that group cannot age any further. This is done by compensating for the average period houses spend in that group. A decline of energy use fed by investment events in the Agent-Based Model will then decrease the average energy use, which in turn influences investment decisions in the Agent-Based Model. In this way the events in the Agent-Based Model can be aggregated easily, to calculate the new average to be used later.

To determine what part of the energy needed for heating comes from natural gas, and what part comes from electricity, the model keeps track of the systems used for heating. By multiplying the total heat demand per group with the distribution of systems per group, the heat demand per system per group can be calculated. By dividing by the corresponding efficiency factors for these systems the final energy demand in M^3 or kWh / year can be calculated.

The distributions of systems per group are calculated by the energy systems submodel. The Agent-Based Model provides the submodel with the rate at which systems are changing, and the relevant distribution over the types of houses that these rates correspond to. Initialising these systems is a difficult task because no data is openly available of the type of energy system dwellings use for heating. Hence an approximation has been made with the distribution of the types of systems in use, combined with the distribution of these types of systems over the age of houses.

The combination of the population, business cycle, housing stock and average energy use submodels together composes the housing market. Information that is generated with these models will provide the Agent-Based Model with the needed data for defining the boundary conditions in the decision model.

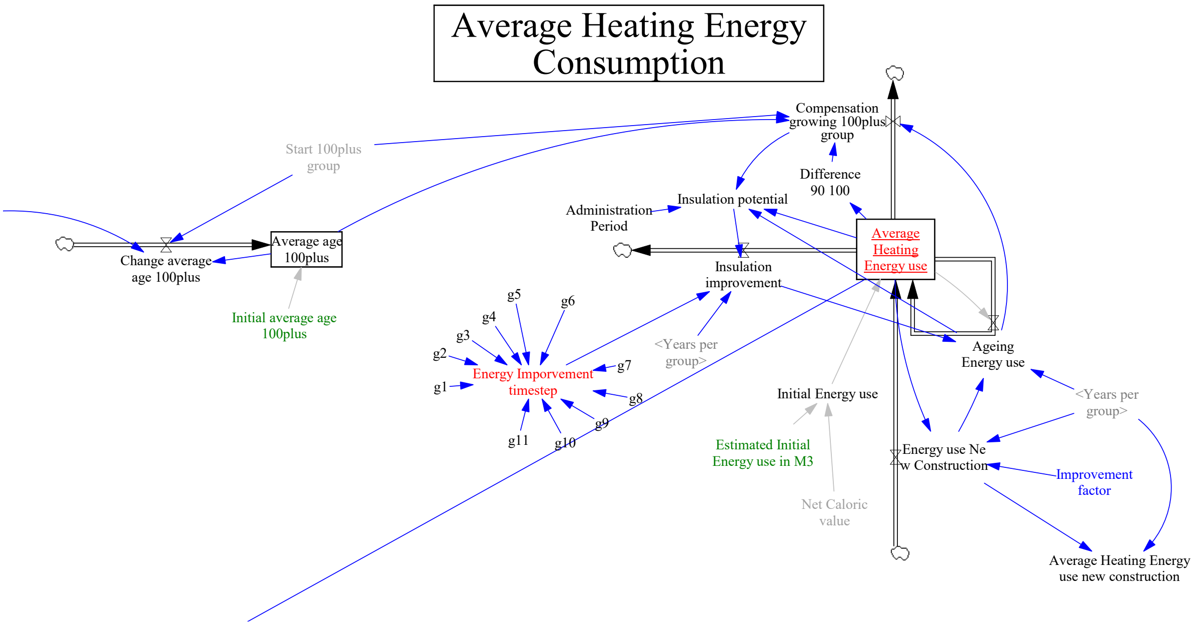


Figure 11.9: Submodel Energy Consumption of Housing Stock

Energy Market

The Energy Market consists of five submodels. Two of these model the supply side of gas and electricity markets, and two others model the demand side from a built environment perspective. The last model calculates CO_2 emissions based on the type and amount of energy consumption.

The supply side of the energy market operates with a relatively simple mechanism. Because exploratory analysis of scenario outcomes will be performed, it is not necessary to implement a hugely detailed market model, since general trends are sufficient for policy testing.

Domestic production of natural gas and green gas is entered as a policy lever since the Dutch government has announced to cap natural gas production (Schoots & Hammingh, 2019). Green gas prognoses by CE Delft (2019b) are used as input for green gas production. Domestic production of electricity, on the other hand, is calculated endogenously. Based on a yearly base increase, multiplied by a factor for the relative cost of renewable electricity, the investment in renewable electricity production is determined. Aiming at net zero imports, limiting dependence on neighbouring countries (Rijksoverheid, 2020c), grey production facilities will be decommissioned following an increase in renewable production.

Foreign supply and demand are calculated based on the scenario variable for the relative share of Dutch demand in the European market. Under the assumption of a demand-driven economy, supply follows that demand with a scenario variable for the response time. A basic equation for calculating the price by multiplying the cost of production by the ratio of demand and supply is used to determine market prices.

Policy levers that influence the supply side of the energy markets include VAT, a CO2-tax, energy tax, a policy lever for CO_2-taxation of imports, and the speed at which natural gas production is decommissioned. The outcome of these submodels, prices for electricity and natural gas, will subsequently be used in the Agent-Based Model to evaluate investment options in insulation and a change of energy

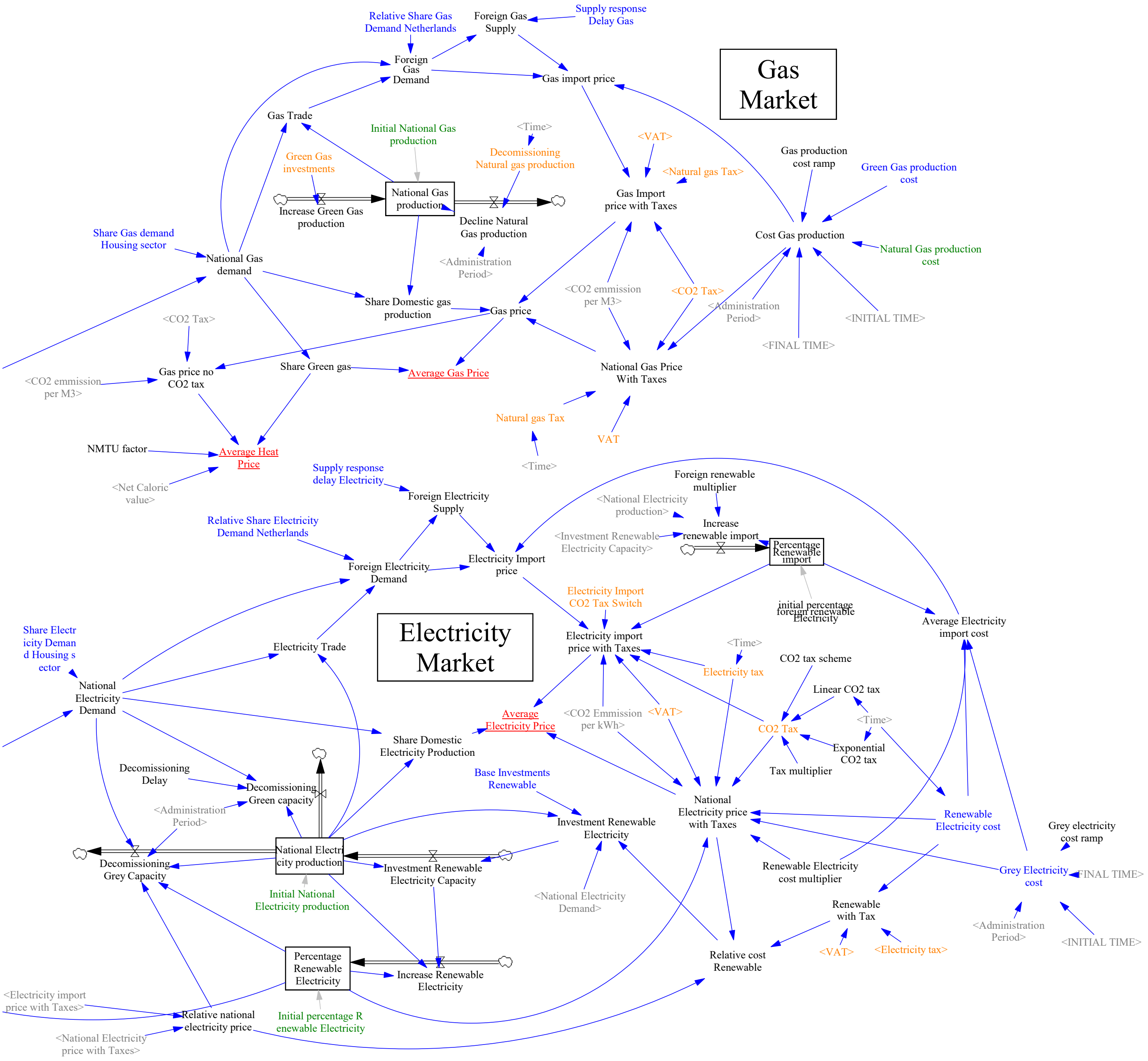


Figure 11.10: Submodel Energy markets

carrier for heating.

Technology Market

As discussed in the Housing Market section, the technology market is directly influenced by the investments in the housing stock. The share each system has influences the maturity of the corresponding technology using the technology S-curve (Foster, 1988). While the maturity of a technology is under 50%, the maturity increases with the product of the 'investment effect' and the share of the energy system multiplied by its current maturity resulting in exponential growth. With a maturity over 50%, the increase is multiplied by its remaining maturity, finishing the S-curve by asymptotically approaching the natural or physical limitations. The same principle is applied to the maturity of energy systems, as well as the maturity of insulation technologies. The insulation investment, and system distributions, are derived from the output of the Agent-Based Model.

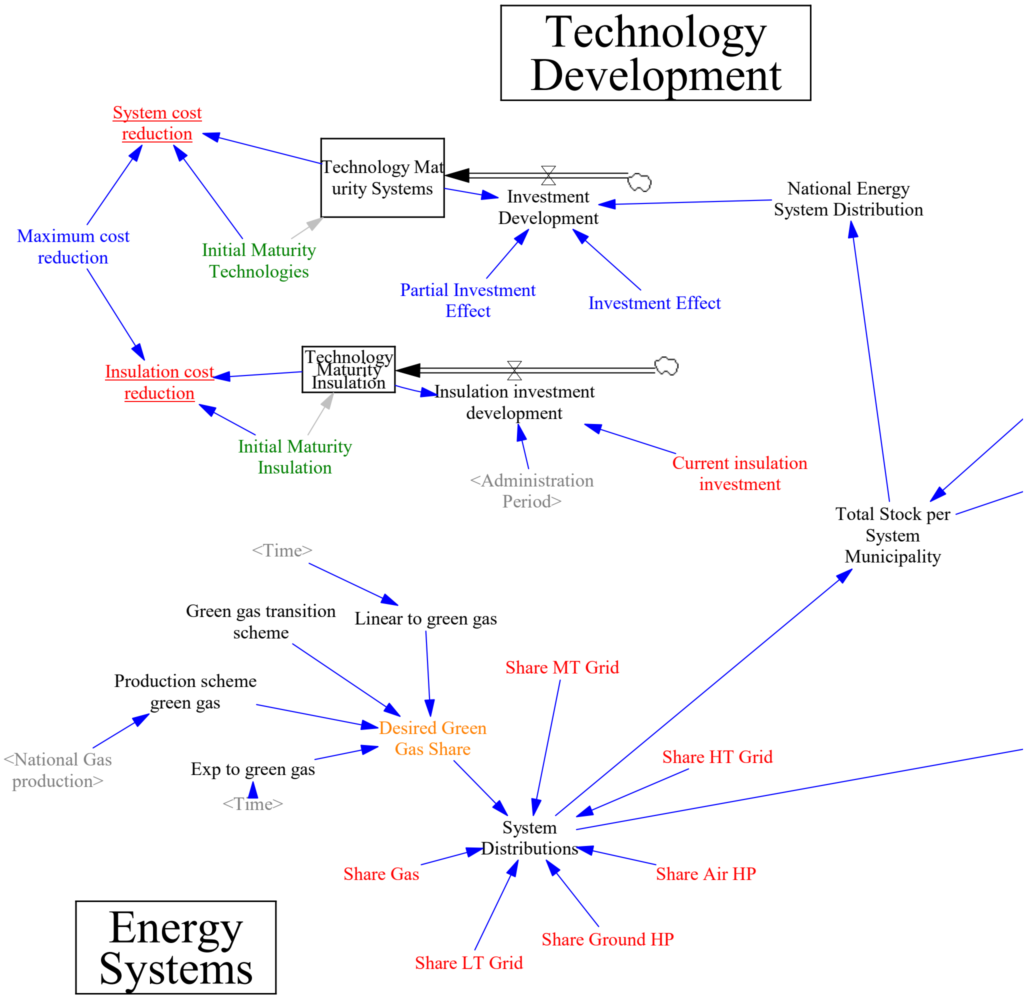


Figure 11.11: Submodel technology market

11.3.4. Model initialisation: Data gathering

To initialise the model, a vast amount of data is needed on the characteristics of neighbourhoods and municipalities. How exactly this data has been collected, cleaned and prepared for model use, can be found in appendix D. Relevant to highlight in this thesis is for what purpose different datasets have been used and combined. Table 11.4 gives an overview of the most important datasets used, and to what part of the multi-model they apply. To gather all necessary information about the housing stock, several datasets have combined into an elaborate dataset containing all relevant data about houses in the Netherlands, the 'Base Data'. From this dataset, in both the System Dynamics model as well as the Agent-Based Model information is used for model initialisation.

Table 11.4: Data sources used for model initialisation

Model	Submodel	Data use	Data description	Reference
Base Data	Housing stock characteristics	General information	Base registry addresses and buildings (BAG)	Kadaster (2020)
		Energy Labels	Energy labels Database	RVO (2020b)
		Energy use estimation	Average energy use per characteristic	CBS (2020e)
		Neighbourhood characteristics	General statistics	CBS (2020n)
		Household size estimation	Household size per postal code	CBS (2020h)
		Total cost estimation	Investment cost per label improvement	CE Delft (2018b)
		Potential savings estimation	Potential savings per label improvement	CE Delft (2018b)
		Investment restriction	Monumental buildings	Dataplatform Nederland (2015)
SD	Housing Market	Housing stock initials	Number of houses	Base Data
			Initial energy use	Base Data
SD	Population	Population prognosis	Growth per municipality	ABF Research (2020)
ABM	Neighbourhoods	Housing stock initials		Base Data
		Heating grids	Current distribution	CE Delft (2009)
ABM	Residual Heat Sources	MT sources	Source characteristics	Planbureau voor de Leefomgeving (2019c)
ABM	System cost	Calculation rules	Validated cost functions	Planbureau voor de Leefomgeving (2019c)

The Base Data dataset has a very high resolution, the BAG and energy labels database are set at the house level. At this level, for each house the natural gas demand and electricity demand are estimated based on house characteristics from Kadaster (2020) and averages for those characteristics from CBS (2020e).

Since the System Dynamics model works at the national and municipal resolution, and the Agent-Based Model uses municipal and neighbourhood resolution, the data in this dataset needs to be aggregated. For the housing market in the System Dynamics model, this is done by aggregating using means per municipality, split over age groups of these houses, since the age group may provide relevant information with regards to energy use. As for the housing stock in the Agent-Based Model, general statistics such as the mean for income and property value are used, as well as distributions for the energy labels and heating systems present.

To determine the break-even-point for investment, and total investment cost for each insulation step, gamma-distributions have been estimated. Although these distributions can probably not be proven statistically equal to the real distribution, visual inspection of various distributions suggests that a gamma-distribution reasonably represents the data, at least for neighbourhoods with larger numbers of households. A random selection of neighbourhoods shown in figure 11.12 shows the estimation of the distribution. Outliers in small neighbourhoods may unfairly force the estimation into extremely long tails, which means it will account for too much weight on the start, implying that the cost is underestimated. Even though it is obvious that for some neighbourhoods this estimation on cost will be completely off, the error that this assumption creates, however, is expected to be acceptable, because it mainly applies to the smaller neighbourhoods. In further research, this shortcoming may be overcome by finding a better approximation, for instance by removing outliers and defining better estimators. However, the problem of small samples will remain. The only solution that may solve this, is by using the actual data, instead of an approximation. Unfortunately, the intended computational advantage to be gained using approximations will then be entirely lost.

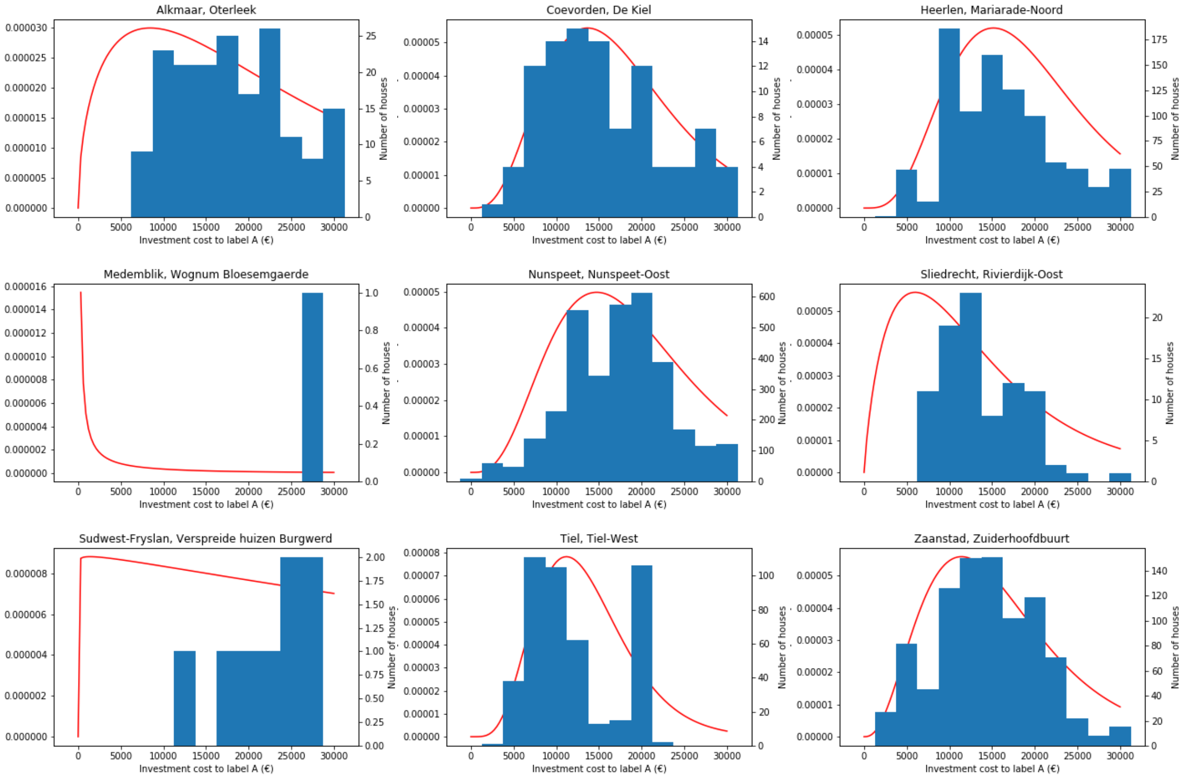


Figure 11.12: Estimated Gamma Distributions for investment cost

Although not perfect, the distributions estimated for each neighbourhood will be key in the development of neighbourhoods. With the current break-even-point based on demanded ROI and energy prices, the cumulative density function of the estimated gamma distribution will estimate the percentage of houses for which the threshold is met. In other words, it determines what percentage of houses will make the investment. In the real world, the threshold and the investment decision will be dependent on many more factors with their own distributions. Assuming independence between these factors, the Central Limit Theorem (Rosenblatt, 1956) suggests that it is reasonable to expect that the combined distribution will approach a normal distribution, except for the fact that it is a cost function, which makes that its values need to be greater than 0 per definition. This makes the Gamma Distribution a reasonable alternative.

These estimations combined with general statistics from the Base data will set up the general characteristics of each neighbourhood, which in turn enable the evaluation of investment decisions over time.

11.4. Evaluation

During and after the modelling process, the model has extensively been verified and validated. This section will discuss several tests that will substantiate the validity of the model. Even though it is per definition impossible to create a 'valid' exploratory model to say something about the future that is per definition uncertain (Hodges & Dewar, 1992), it is of great importance to evaluate the model and gain confidence in it outcomes and to learn about its boundaries and limitations. In the the context of Exploratory Modelling and Analysis, validity is about understanding its *fitness for purpose* (Auping, 2018), rather than *precision* or *truthfulness*.

For the modelling process, this means that during the model conceptualisation phase and the model formalisation phase, common verification and validation checks have continuously been performed, such as extreme value tests, boundary adequacy tests, and unit checks (part II, chapter 4). Next to this, the model structure has frequently been discussed with energy and modelling professionals from Witteveen+Bos and Delft University of Technology during the conceptualisation and formalisation phases of the modelling process to ensure model validity.

11.4.1. Verification

Verification of the model could be considered the 'easy' part of evaluating. Calculations are right or wrong. However, it is not that simple, I will not be able to discuss every single equation to prove that the model was build right. To gain confidence in the model outcomes, I will discuss a single test that will show that the model outcomes make sense, but for those interested, the entirety of the model can be inspected in appendix B.

An aspect of the model that lends itself very well for verification is the fact that the model is loaded with a lot of data at a very high resolution mostly in the Agent-Based Model, combining this information into high-level aggregates in the System Dynamics model. Most of these figures are estimated at the house level and produce national outcomes. This means that these outcomes have to resemble the aggregates from CBS (2020i).

Table 11.5: Model outcomes and reference values for 2017 (input parameters)

Variable	Model Outcome	Reference value	Reference
Total Natural Gas Demand	323 PJ	288 PJ	CBS (2020d)
Total Electricity Demand	86 PJ	81 PJ	CBS (2020d)
Total CO_2 emissions	19.39 Mton	17.3 Mton	CBS (2020q)
Total number of households	7.95 million	7.79 million	CBS (2020h)

As one can observe from table 11.5, the model appears to overestimate energy use and thus CO_2 emissions slightly. The difference of about 10 per cent in final energy demand of households can be explained by the fact the definition of households is not as clear as one might expect. Multiple households may live on one address or one household may have multiple homes. This makes that the total number of homes derived from the BAG is different from the numbers from CBS (2020h). Next to this, due to privacy-related issues, the energy demand had to be estimated based on postal code averages, accounting for the rest of the discrepancy. Access to the real data per household would solve this issue. However, because the focus in this study lies with trends and behaviour rather than exact estimations, this discrepancy is not very relevant.

11.4.2. Validation

To create a model that is 'valid', or fit for purpose, in this study, it is important to mimic 'real' behaviour to the maximum extent possible. Although abstract models can provide valuable insights and provide for the creation of new ideas, this research needs a practical and clear output. As municipalities struggle to develop their heat transition vision, they are expected to benefit from concrete insights that will help them decide how to approach different municipalities. Costs are expected to play an important role, and various models have been developed that provide the insights needed in that aspect. Hence it has been decided not to reinvent the wheel and use the techno-economic cost functions and key figures set up by Planbureau voor de Leefomgeving (2019c), which have thoroughly been validated with key stakeholders from the field (ECW, 2019).

This makes that gaining confidence in the validity of the model concerns four major aspects: is the investment behaviour in the Agent-Based Model, the behaviour that drives system change, realistic? Are the market scenarios that are created in the System Dynamics model credible? Can we gain confidence in the way information is communicated between the models? And lastly: does the model outcome make sense?

1. Investment behaviour

The investment behaviour in the model is based upon two big assumptions. The first is the Homo Economicus assumption, although this idea has been prevalent in classical economical theory, criticisms on the idea have to lead to the transformation of the concept in the last decades (Thaler, 2000). Nevertheless, a rational incentive is one of the few incentives that can be modelled using publicly available data. The problem with getting data on other incentives for investment and participation in the energy transition is that they still need to be empirically determined, meaning, the system has to be observed before the model can be developed. That is like developing a weather forecast for yesterday. The only reason the weather can be forecast (to some reasonable extend, at least), is the fact that the weather has been studied for a while, and patterns are recognized and reasonably understood. As for the energy transition, this is simply not the case. One could make the comparison with how the Netherlands rapidly implemented its gas network at the end of the ’60s, beginning of the ’70s (Canon volkshuisvesting nederland, 2020), however, implementing one system is hard to compare with implementing various systems with numerous uncertainties to deal with. Although starting with a different assumption may theoretically make that the results resemble reality closer, the practical constraint of the availability of data and knowledge makes that the Homo Economicus assumption is still the best option.

The second major assumption has been described thoroughly in the data-gathering section (section 11.3.4). With an enormous amount of data, for computational purposes and to minimise the downsides of the Homo Economicus assumption, it has been chosen to approximate the cost functions for every neighbourhood employing a Gamma Distribution. As discussed earlier, this estimation is likely to perform better for heterogeneous neighbourhoods with a large number of houses. Small homogeneous neighbourhoods will probably not fit the estimated curve very well. Although this is a drawback that needs to be considered when evaluating the data, the Central Limit Theorem makes that it is a suitably educated guess. The S-shaped Cumulative Density function makes that it fits well with the theories on the technology S-curve (Foster, 1988) and the long tail from the curve is also considered adequate since outliers only exist on the high side, not on the low side. All in all, the gamma distributions is considered a good first estimation, but for further research investigation into a better descriptive estimation is encouraged.

2. Market scenario behaviour

The System Dynamics model provides for the scenarios in which agents make their investment decisions. For these decisions to be valid, the scenarios confidence needs to be gained in the development of these scenarios. Although variation in these scenarios is limited due to the computational restraints, the variation that is there has to make sense. In figure 11.13 the variety of energy scenarios is presented.

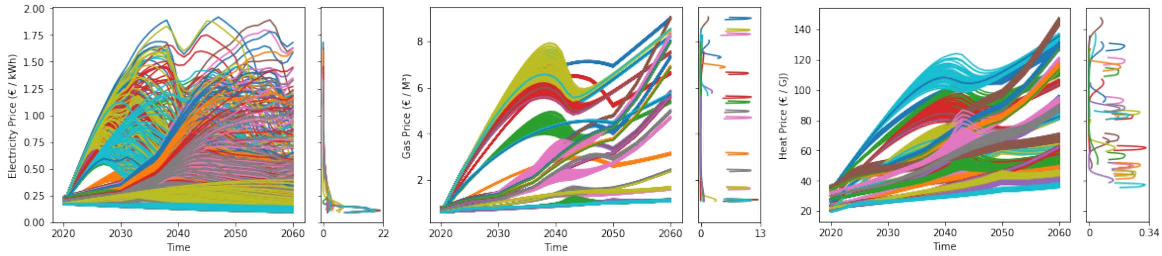


Figure 11.13: Market scenarios: energy prices

As the experiments are grouped on policies in the diagrams, it can be observed that the energy scenarios are highly dependent on the policies. This is to be expected because of the significant effect of CO_2 tax on energy prices. Electricity prices seem to have more scenario variation as compared to Gas prices, which can be explained due to the share of renewable electricity that will influence electricity prices. Although a wider variation in scenarios is desirable for analysis, for the proposed open exploration, this variation is sufficient.

3. Intermodel communication validity

As indicated in the methodology chapter (chapter 10), a big challenge in multi-modelling is to preserve meaning between models. Especially since the level of aggregation and abstraction may be different, it is key to find a way to communicate the *right* data. In this model, this is mostly relevant for communication from the Agent-Based Model to the System Dynamics model. The information from the Agent-Based Model at neighbourhood resolution is aggregated to the municipal level, to feed this into the System Dynamics model using subscripts. Information from the System Dynamics model is mostly at the national level, which are the globals in the Agent-Based Model. The resolution from the subscripted variables (mostly per municipality or system), is present also in the Agent-Based Model, imposing limited challenges there.

4. Model outcome

The most important quality of the model should be that it produces results that are interpretable and make sense. Models that are 'right' but unclear, are useless, models that are clear, but look wrong, for whatever reason, are useless too.

The systems evaluated in the model, make that different systems can be expected in different types of municipalities. Heating grids can be expected in high-density areas, residual heat solutions will be present around industrial clusters and heat pumps will only work with properly insulated houses. Green gas will be the solution for any place that electric or a heating grid are not available options. This means that it is reasonable to expect heating grids in dense urban areas, heat pumps in younger neighbourhoods and green gas in thinly populated older neighbourhoods. Anticipating the results in section 12.3, it appears that the results, although varying in the intensity of use per system, per experiment, the outcomes match the aforementioned description, making it reasonable to accept that the model is capable of producing valid results.

11.5. Experimental setup

As discussed in section 10.6 a dynamic approach is used for the experimental setup. Since it doesn't make sense to present the setup, then results, then the new setup, and so on, this section is going to contain some spoilers. First I will discuss the initial setup that leads to the chosen amount of replications, after which I will discuss the experimental setup for the second round in which open exploration is performed. Afterwards, I will state the experiments that I developed based on the results from the first experiments. The results of both rounds of experiments, I will fully discuss in the results chapter 12.

11.5.1. First experiment: Open Exploration of national KPIs

As the number of replications is determined (part II, chapter 4), the setup for the first explorative experiments can developed. With unlimited time and computing power, the preferred approach would be to sample overall uncertainties and policy levers, to find the most relevant factors, and then sample ample extra over these factors. This is unfortunately not the case, so a selection is made of factors that are expected to be relevant.

As can be seen in table 11.6, there are uncertainties in both the System Dynamics model, as well as in the Agent-Based Model. Three types of uncertainties have been chosen to investigate. On the one hand, market/system uncertainties, such as the investment in renewable electricity and green gas and a change in production cost, as well as the expected cost for heating grids have been chosen because they will be key determinants in price developments. Because agents in the model make decisions based on the price of investments and consumption, this is extremely relevant. The second group of uncertainties includes the uncertainty of the business cycle, and the third group includes human behaviour. One the one hand focused on the investment behaviour of homeowners, but also on the ROI heat companies demand for their investments. It is expected to be very valuable to determine how 'willing' people need to be to invest in their home, to reach national goals. The same holds for the heat company's ROI. At what ROI will enough heating grids be feasible?

Table 11.6: Experimental setup: uncertainties experiment 1

Model	Variable	Unit	Min	Exp. Value	Max	Reference
SD	Base investments Renewable electricity	1/Year	0.025	0.08	0.125	CBS (2020g)
SD	Maximum cost reduction	Dmnl	0.1	0.3	0.5	Assumption
SD	Green Gas Investments	M^3/Year^2	1.0e8	1.7e8	4.0e8	CE Delft (2019b)
SD	Green Gas production cost change	Dmnl	-1e-3	0.0	1e-3	Scenario-assumption
SD	Natural Gas production cost change	Dmnl	-1e-3	0.0	1e-3	Scenario-assumption
SD	Grey Electricity cost change	Dmnl	-1e-3	0.0	1e-3	Scenario-assumption
SD	Renewable Electricity cost multiplier	Dmnl	0.5	1	2	Scenario-assumption
SD	Expected Period Business Cycle	Year	4	8	10	Korotayev and Tsirel (2010)
SD	Expected Amplitude Business Cycle	1/Year	0.01	0.03	0.05	CBS (2020j)
ABM	Group Behaviour	Dmnl	0	N/A	1	Assumed completely uncertain
ABM	Heat company ROI	Dmnl	0.03	0.08	0.15	Assumption
ABM	Max income share	Dmnl	0.01	0.05	0.15	Assumption
ABM	Max capital share	Dmnl	0.01	0.05	0.15	Assumption
ABM	Relative construction capacity	Dmnl	0.01	0.05	0.1	Assumption
ABM	Heating grid cost scenario	Dmnl	Low	N/A	High	Planbureau voor de Leefomgeving (2019c)

Policy levers that have been chosen are mainly based on the current ambitions of the Dutch state to subsidise sustainable Development. These have mostly been derived from RVO (2019), and Planbureau voor de Leefomgeving (2019c) and are given in table 11.7. Next to this, political debate is going on about a CO_2 tax, that is currently only imposed on industries in the climate agreement (Klimaatakkoord, 2019). In my opinion, a CO_2 tax may very well be a valuable asset in stimulating people to invest in their homes, as well as a way to finance those who are not able to afford the investments needed. Hence, three CO_2 tax-schemes have been implemented:

1. A zero-policy: no tax at all
2. A linear CO_2 tax
3. An exponential CO_2 tax

These taxes raise from €0.03 per kg in 2020 to €3 per kg in 2060, extrapolated based on the current expected growth of the CO_2 tax for industries until 2030 (Klimaatakkoord, 2019). A multiplier is implemented to vary the steepness and final value of this tax-scheme.

A similar scheme is implemented for the demanded share of green gas that is used. Based on the assumption that the state will enforce their goal to get rid of natural gas in 2050 (Klimaatakkoord, 2019), this means that either no gas is used at all, or that the gas that is used is 100% renewable, or 'green'. The rate at which this will happen will be key in the CO_2 emissions as well as the gas trade balance, depending on national production (which is an uncertainty as given in table 11.6).

Policy options such as forcing neighbourhoods to switch to natural gas free heating have been chosen to be ignored. This has two reasons. 1: Nearly no tools exist to enable municipalities to do this. 2: Since in the building environment policymakers always have to deal with homeowners, who *own* their house and thus have the right to decide whether or not to invest in their home, developing

Table 11.7: Experimental setup: policies experiment 1

Model	Variable	Unit	Min	Exp. Value	Max	Reference
SD	NMTU factor	Dmnl	1	1	2	Rijksoverheid (2020d)
SD	CO_2 Tax	Dmnl	0	1	2	Categorical, Policy-option
SD	Tax multiplier	Dmnl	0	1	3	Policy-option
SD	Green Gas transition scheme	Dmnl	0	1	2	Categorical, Policy-option
ABM	Insulation subsidy	Dmnl	0	0.2	0.5	RVO (2019)
ABM	LT Production subsidy	Dmnl	0	0.2	0.5	Planbureau voor de Leefomgeving (2019c)
ABM	MT Production subsidy	Dmnl	0	0.2	0.5	Planbureau voor de Leefomgeving (2019c)
ABM	LT Investment subsidy	Dmnl	0	0.2	0.5	Planbureau voor de Leefomgeving (2019c)
ABM	MT Investment subsidy	Dmnl	0	0.2	0.5	Planbureau voor de Leefomgeving (2019c)

a tool that empowers municipalities to enforce their way, will likely result in a *huge* stream of opposition. Hence, investigating how to stimulate change by taxing 'bad' behaviour and subsidising 'good' behaviour, makes much more sense. Next to this, the model is build based on the idea of individual behaviour, if a policy is to 'get rid of individual behaviour', the model is not likely going to produce any valuable outcomes.

11.5.2. Second experiment: Open Exploration for municipal case studies

In the second experiment, the municipalities will be selected for further investigation. Based on the results from the first experiment, Amsterdam, Rotterdam and Arnhem have been chosen to evaluate. This, because from the initial analysis it appears that these municipalities perform better than others, so it will be very interesting to find out why that is the case. Especially Arnhem may be very interesting because initial data suggests that it performs very well on low-temperature heating grids. To align the findings from the results with the outcomes from the first experiments, it is chosen to work with the same set of experiments as in the first round.

12

Results

In this chapter, the results from various perspectives will be presented. First, the national outcomes will be discussed, in which the effects of policies and uncertainties on the main goal to reduce CO_2 emissions will be evaluated. Following this, the role of the different energy systems in obtaining this goal will be discussed on a high level, after which regional differences will be discussed from the inter-municipal perspective. At that point, policies at the national level can be interpreted as uncertainties at the municipal level. Here the heterogeneous effects on the use of the different energy systems will be investigated. From there, three relevant municipalities will be chosen to dive deep into the intra-municipal differences to formulate concrete advice on how to tackle the urban energy transition at the municipal level.

12.1. National outcomes

At the highest level, the main key performance indicator that is to be investigated is CO_2 emissions. This section will discuss the policies that contribute most to realising the goals in the Klimaatakkoord (2019) and will evaluate the possible effects of uncertainties on the realisation of these goals. Important in this will be the economic and socially feasible energy mix that contributes the strongest in achieving the lowest CO_2 emissions.

12.1.1. The role of energy systems in CO_2 emissions

For national policymakers, the most relevant KPI is cumulative CO_2 emissions. In the end, reducing these is one of the main reasons for performing the energy transition (Klimaatakkoord, 2019). As it can be expected that alternative energy systems will contribute strongly to CO_2 emission reduction, I will start with an analysis thereof at the national level.

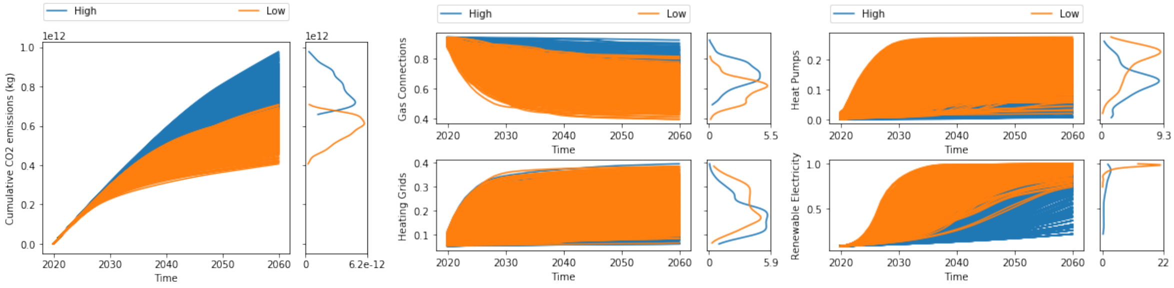


Figure 12.1: KPI's clustered on high and low CO_2 emissions

Figure 12.1 shows the outcomes of the performed experiments. A large amount of experiments gives the user the ability to understand the range of outcomes one can expect. A next step is to determine what experiments have led to desired outcomes, and how they were configured. To do this, two ranges of outcomes for CO_2 emissions have been selected utilizing time-series cluster analysis

(Steinmann et al., 2020): a high outcome and a low outcome. Although possible to create a larger set of clusters, the limited amount of experiments in this study makes that most behavioural variation is explained by these two clusters.

From figure 12.1, one can observe the role of different energy systems in the two distinct outcomes for CO_2 emissions. It appears that the use of renewable electricity is key to keeping emissions low. This is kind of an open door, however, it is interesting to notice that the role of electricity is important enough that its sustainability is key in the overall sustainability of the built environment. It may be no coincidence that the same holds for the use of heat pumps. Most experiments that lead to low emissions output have a relatively high use of heat pumps. For heating grids, on the other hand, the difference is not as clear, but a higher relative share in heating grids is also more likely to lead to desired results. Nevertheless, from this data, it cannot be concluded that one or the other systems work better, because of the possible competition that exists between systems. This is clearly illustrated by the fact that the use of gas connections suggests an opposite trend as to heating grids and heat pumps. Limited use of gas connections results in lower emissions. Important to take in mind is the fact that this study does not look into the availability of green gas solutions. All gas used is assumed to be green in 2050, as depicted by the Klimaatakkoord (2019). This means that if demand is higher than national supply, either green gas needs to be imported, or the demands of the climate agreement will not be met. The role of green gas will hence be further discussed in 12.1.4.

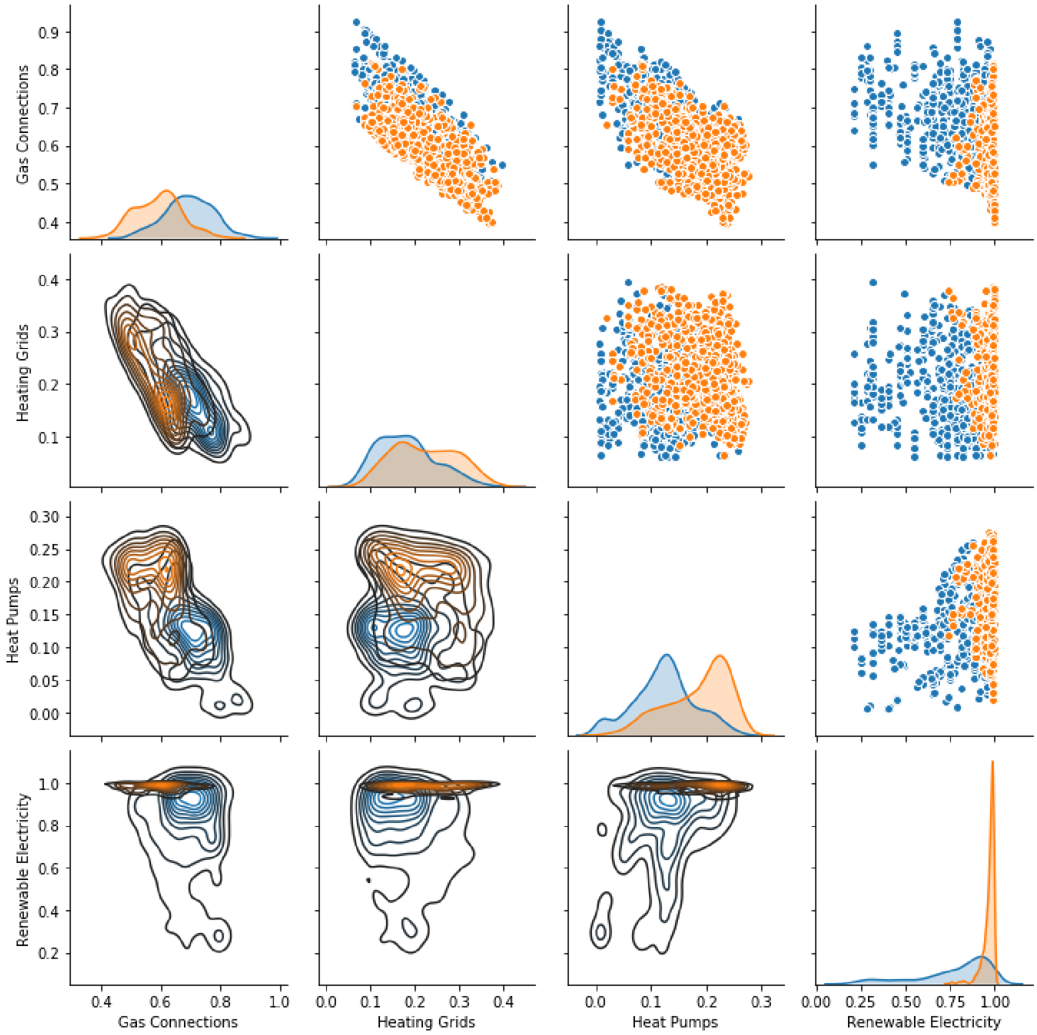
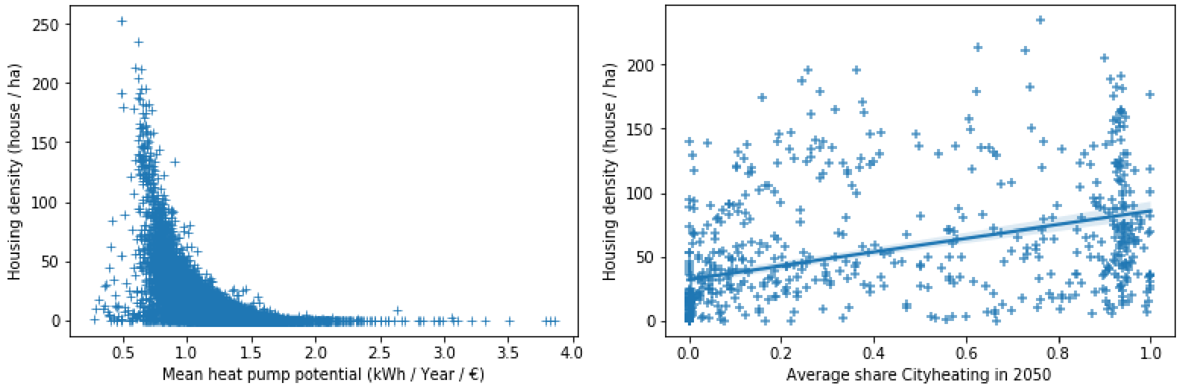


Figure 12.2: System contributions for high (blue) and low (orange) CO_2 emission cluster

Figure 12.2 shows the relation between the different energy systems and their influence on the realisation of CO_2 goals. As expected, a negative relationship can be observed between the use of alternative heating systems and the use of gas systems. This relationship appears strongest for the use of heating grids. Unexpected is the fact that this relation appears not to exist between heat pumps and heating grids, or at least minimally. This is useful since this insight suggests that the use of these systems is complementary, not competitive. For policy development, this means that is sensible to stimulate both systems, rather than to fear that stimulating one system will come at the expense of the other.

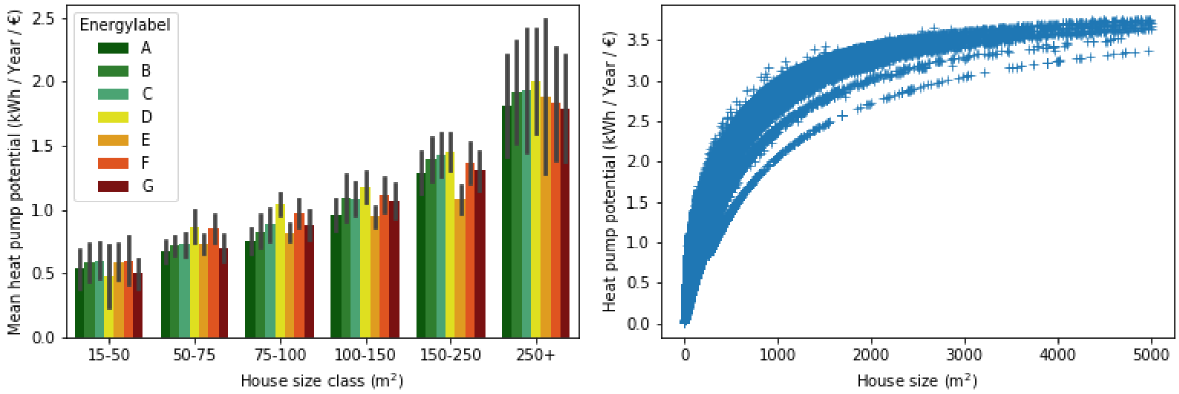


(a) Heat pump potential and housing density

(b) Average heating grid implementation

Figure 12.3: System suitability and housing density

This absence of competition between heat pumps and heating grids can be explained due to the types of houses and neighbourhoods for which these systems are economically attractive. A known fact is that heating grids will likely only be feasible in highly dense populated areas (CE Delft, 2009; Ekker, 2019; Papa et al., 2019). Interesting then is to find out that heat pumps become economically more attractive in thinner populated areas, as shown in figure 12.3. This can be explained because the average housing surface is larger, and thus requires more energy in less densely populated areas so that potential savings outweigh the fixed investment cost of heating pumps sooner. Figure 12.4 shows the relation between house size, energy label and heat pump potential. Since the cost of heat pumps is dependent on a fixed cost, and a variable cost based on required power, larger housing will have a relatively low share of fixed cost in investment, making that the investment needed for each GJ that it needs to produce, drops with increasing size. The current level of insulation appears not to be very important for the relative potential of the heat pump itself since houses need to be insulated to label B or higher anyway. This means that quick wins can be made with large houses, that already meet the insulation requirements.



(a) House size and Energy label

(b) House size up to 5000 m_2

Figure 12.4: Heat pump potential

12.1.2. The impact of policies and uncertainties on CO_2 emissions

After the initial investigation of the role the different systems in obtaining low CO_2 emissions, the next step is to find out how policymakers can steer into the desired outcomes and to what extend uncertainties influence that outcome. Hence, scenario discovery (Bryant & Lempert, 2010) is applied utilizing the Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1999). This analysis enables to investigate what (sub)set of policies and scenario's lead to (un)desired outcomes. In this analysis, the same clusters for outcomes are used as in the initial investigation of CO_2 emissions are used to find what policies and uncertainties influence desired outcomes.

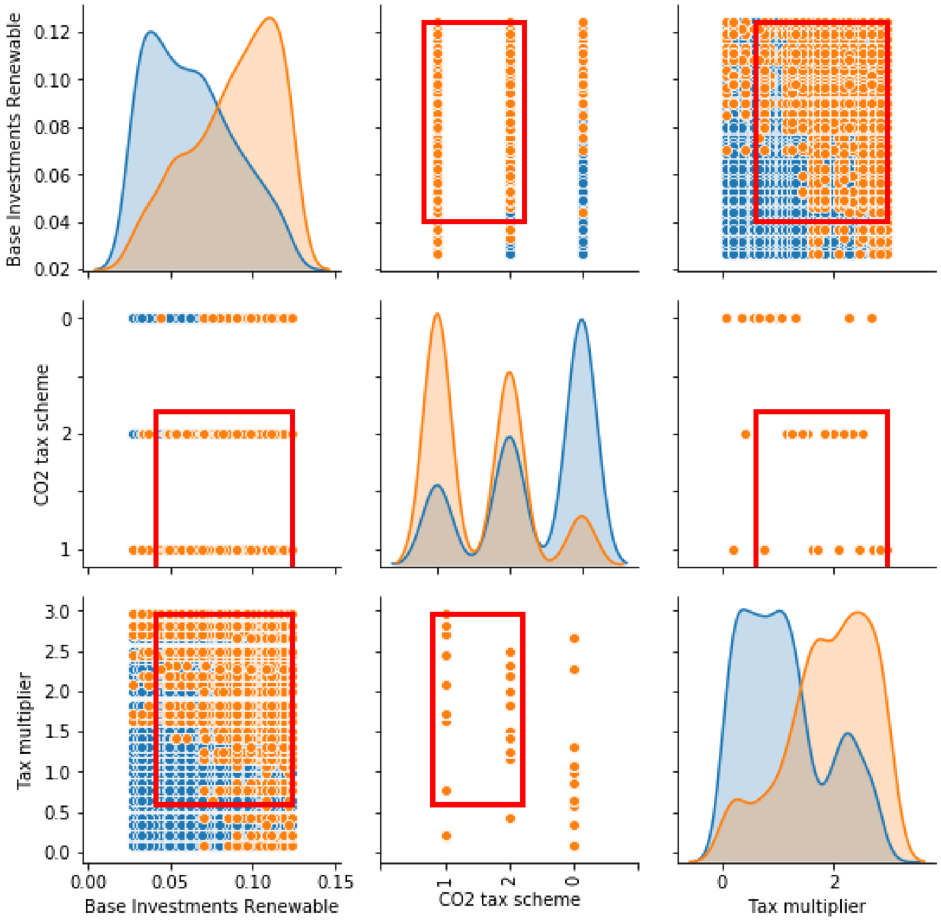


Figure 12.5: PRIM findings for high (blue) and low (orange) CO_2 emission cluster

In figure 12.5, a pairs-plot of the three most important factors that influence CO_2 emissions is displayed. In these plots, one can evaluate the dependencies between these factors and find what inputs result in desired outcomes. The most important factor in this appears to be the CO_2 tax scheme. Very few of the experiments in which tax scheme 0 (no tax) is applied, lead to low CO_2 emissions. Tax scheme 1 (linear increase) and tax scheme 2 (exponential increase) appear to be more successful, in which the linear scheme performs best. As can be expected, the height of that tax is also important, from which it can be deduced that multiplying the base scheme with more than one increases the likelihood of desired outcomes strongly. Lastly, as was already found in the initial analysis, the investments in renewable electricity are very important. Low emissions are more frequently obtained with a base investment that is higher than 8 per cent per year. This is dependent on the taxes since the needed base investment is lower for experiments in which the tax is applied. This means that reluctant progress in the development of renewable electricity can be fueled by implementing a CO_2 tax, making that lower CO_2 emissions can still be realised.

The fact that subsidies on insulation and alternative energy systems are found to be less important in the PRIM analysis, suggests that either these policies have limited effect on the economic feasibility of the implementation of these systems, or that the cumulative reduction of energy use by insulation has a much larger influence than the reduction realised by switching to alternative systems. Hence, further investigation of the effects of policies and uncertainties on the implementation of new energy systems and the effects of these systems on CO_2 emissions will be further analysed in the next section.

12.1.3. The impact of policies and uncertainties on energy systems

Following general analysis of policies that affect CO_2 emissions, is the role of energy systems in accomplishing CO_2 reduction. Figure 12.6 shows the system distributions grouped on different categories of CO_2 emissions, as well as the distributions for the most relevant univariate policy bins. One can observe that with lower CO_2 emissions, the relative share of alternatives to (green) gas does not vary that much. This suggests that the various systems' extra contribution to CO_2 poor outcomes are roughly equal. However, one clear thing, is that use of alternatives over (green) gas has a strong contribution to lowering CO_2 emissions. So what policies and uncertainties influence the development of these systems?

Feature scoring analysis helps to distinguish the most relevant policies and uncertainties for these systems (figure C.2, Appendix C). Three uncertainties strongly affect the use of systems: the cost scenario for heating grids, the maximum share homeowners are willing to invest, and the minimum ROI that heat companies require. Interesting to notice is the fact that the use of LT heating grid is more strongly dependent on the cost scenario than MT heating grids. This makes sense, since in general, the business case for LT heating grids is more dependent on the investment costs, due to the more limited demand for heat in such systems. Heat pumps, on the other hand, are most dependent on the willingness to invest of homeowners, likely because in general, they require both investments in insulation and in the system itself.

On the policy side, all evaluated policies have an influence on the share of systems to some extent, however, the CO_2 tax scheme and multiplier seem to be dominant for heat pump implementation, whereas investment subsidies have a stronger influence than production subsidies on the development of heating grids. This suggests that in general, the investment cost of heating grids is the limiting factor, so that policy on reducing the cost of these investments or sharing the risks may be fruitful.

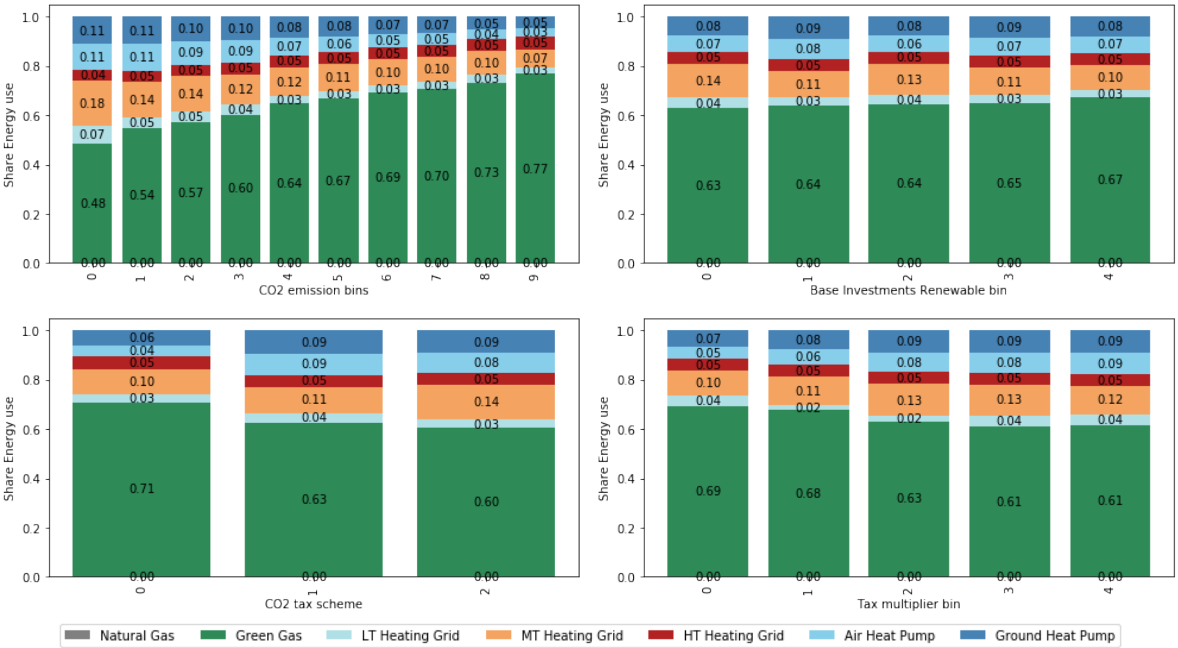


Figure 12.6: Average system distributions for most influential factors in CO_2 emissions

12.1.4. The role of green gas in future heating

As is found in previous analysis, (green) gas is expected to have a significant role in future heating despite the policies and uncertainties evaluated. It appears that subsidies and taxes are unlikely to push demand under 40 per cent of the total demand. In worst-case scenarios, this may even result in final demand of nearly 90 per cent still. Although flexibility exists in how to fill in this demand, utilizing blue or green hydrogen (TNO, 2020a), or through biogasses (CE Delft, 2019b; Rabobank, 2019), a problem with this high green gas demand is that it is both undesirable from a CO_2 perspective (as long as not the entire demand is fulfilled with green hydrogen) as well as because it is very unlikely that we will be able to meet that demand without making use of natural gas and/or large imports. Although the import of green gas from where renewable production thereof is affluent does make sense from a techno-economical perspective, from a political perspective it may be undesirable to create a dependency on this green gas. It is important, therefore, to understand what policies and uncertainties lead to the scenarios which require few gas connections.

Dimensional stacking, figure C.3, helps to find the states that lead to a (green) relatively low gas demand, in this case: under 55 per cent. As with reducing CO_2 emissions, green gas demand can be reduced best by applying a high CO_2 tax. A high willingness to invest of homeowners strengthens this effect by allowing for more houses to be insulated. The construction capacity of municipalities should be taken into account in this since this could be an inhibitory factor in the process. With the right guidance by municipalities, the construction demand for remodelling houses can be spread, reducing the risk of capacity shortages.

A solution that can additionally reduce the demand for gasses is the implementation of hybrid heat pumps where possible. Although not yet implemented as a solution in this model, since it was not considered as a way to become gas independent, may offer an intermediate option in the period that houses are not insulated sufficiently yet to allow for all-electric heating. Natural gas demand for houses with labels higher than label E can be reduced up to 50 per cent with the implementation of hybrid systems (Mileu Centraal, 2020). With a technical lifetime of about 15 years, the period in which insulation to levels higher than label C is not yet economically feasible can be bridged with a semi-sustainable solution for areas in which collective MT heating systems are not feasible. At the moment that better insulation becomes economically attractive, the implementation of that insulation will further reduce gas demand and allow for replacement with all-electric systems following the lifetime of hybrid heat pumps.

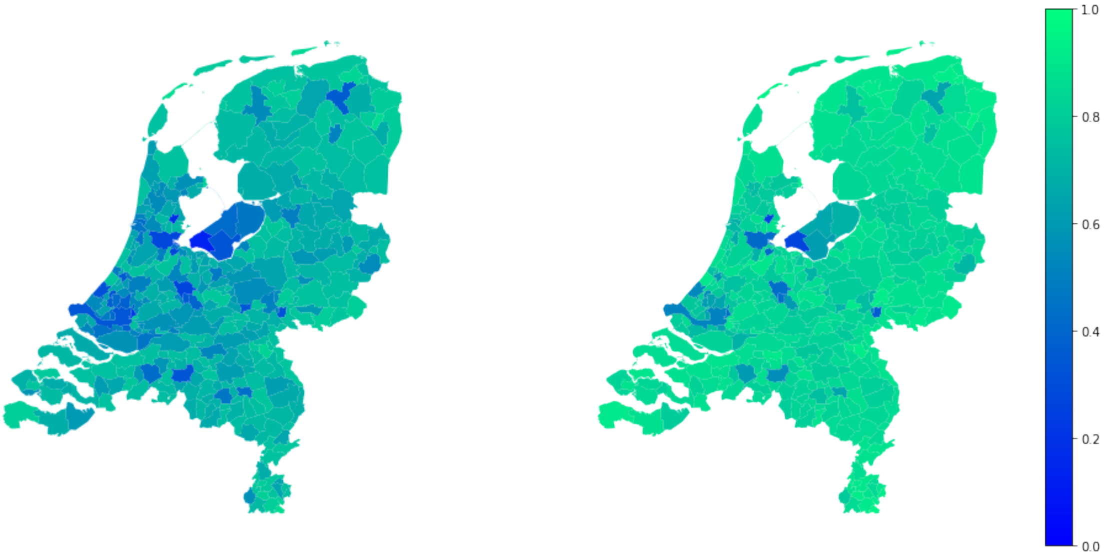
12.2. Intermunicipal Perspective

After investigating the experiments at the national level, the model allows for the inspection of heterogeneous effects of policies and uncertainties. Next to this, the desired insights at the municipal level may be very different from the knowledge necessary at the national level.

To do so, one has to deal with enormous data overload. One way to deal with this is to identify stereotype scenarios which can be used for finding examplar results that fit these scenarios. For this, the cluster analysis from the national perspective will be extended by creating five clusters for CO_2 emissions and selecting the 'best' and the 'worst' case.

From the national analysis, it has been found that the use of (green) gas is likely to play an important role in the energy supply of the future built environment. This is a shame since this system still provides for direct CO_2 emissions, whereas heating grids and heat pumps only do so indirectly. This causal relationship makes that it can be identified that experiments in which CO_2 emissions turn out to be low, are also the experiments in which (green) gas us is limited. This can clearly be observed in 12.7. The left figure gives the mean share of green gas used in 2050, for each municipality in experiments that lead to low emissions, whereas the right shows shares that lead to high emissions.

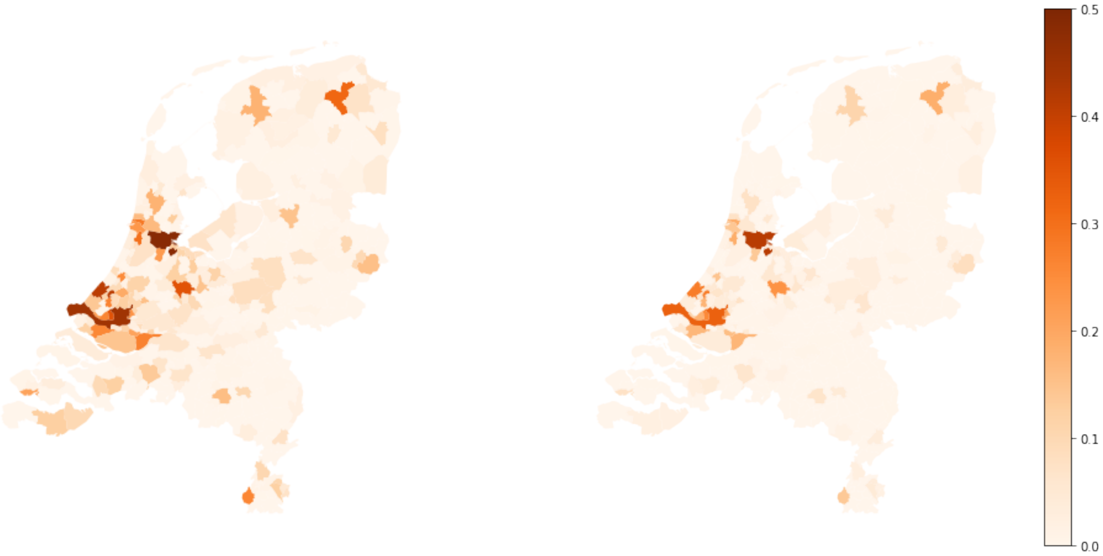
Interesting to notice is that in both clusters urban areas perform better than rural areas. The higher density and availability of industrial clusters for residual heat provision in these regions appear to make that these regions are more robust to scenario influences. The lower demand for insulation that residual heat systems require appears to enable sustainable heating to be proficient in a wide range of scenarios. This would mean that the challenge for realising low CO_2 emissions lie more with the rural areas. Although their limited population would suggest otherwise. This idea is confirmed by fig 12.8, in which residual heat systems are given. Although differences between the high and low CO_2 scenario can be observed outside of the Randstad (main urban area of the Netherlands), the agglomerates in the Randstad, such as Amsterdam and Rotterdam-The Hague make significant use of residual heat in both scenarios.



(a) Low CO_2 emission cluster

(b) High CO_2 emission cluster

Figure 12.7: Mean final (green) gas use for CO_2 clusters



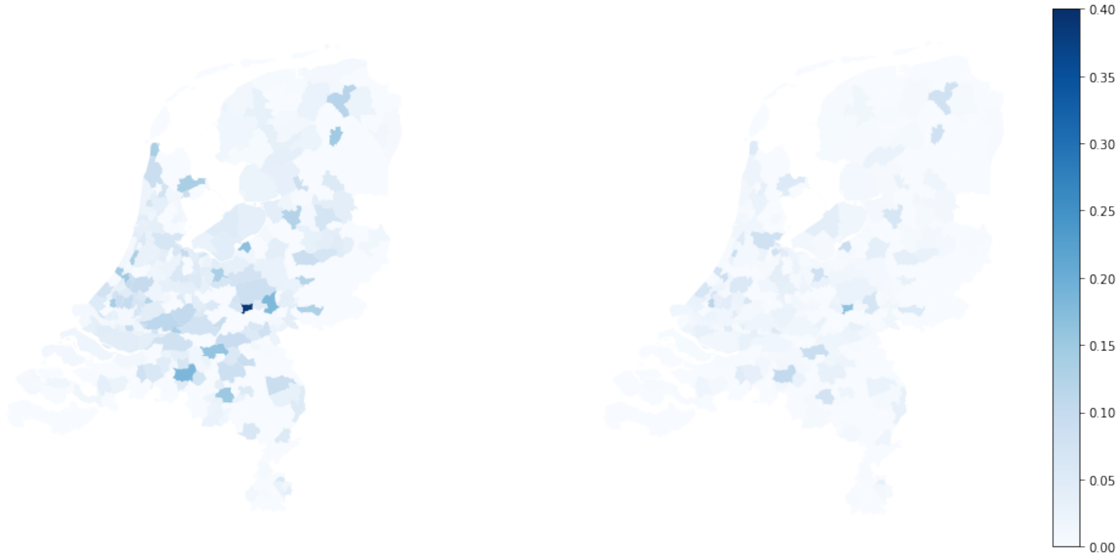
(a) Low CO_2 emission cluster

(b) High CO_2 emission cluster

Figure 12.8: Mean final residual heat systems (MT) for CO_2 clusters

The role of low-temperature solutions such as LT heating grids and heat pumps (figures 12.9 and 12.10 respectively) seems to be strongly correlated with CO_2 emissions. This is partially a direct connection: the use of these systems lead to fewer direct CO_2 emissions. However, this is also true for residual heat systems. This difference can be explained by the fact that the scenarios in which LT systems work well, are the scenarios in which insulation levels are also high since that is a prerequisite for LT systems to function. The decrease of energy demand that the higher degree of insulation provides, appears to have a significant effect on the total CO_2 emissions.

Another explanation for the different roles of MT and LT solutions in the two CO_2 scenarios, may be that high-density areas are less in need of stimulating policies to create feasible business cases for new systems, due to the availability of residual heat. Heat pumps appear to be more dependent on

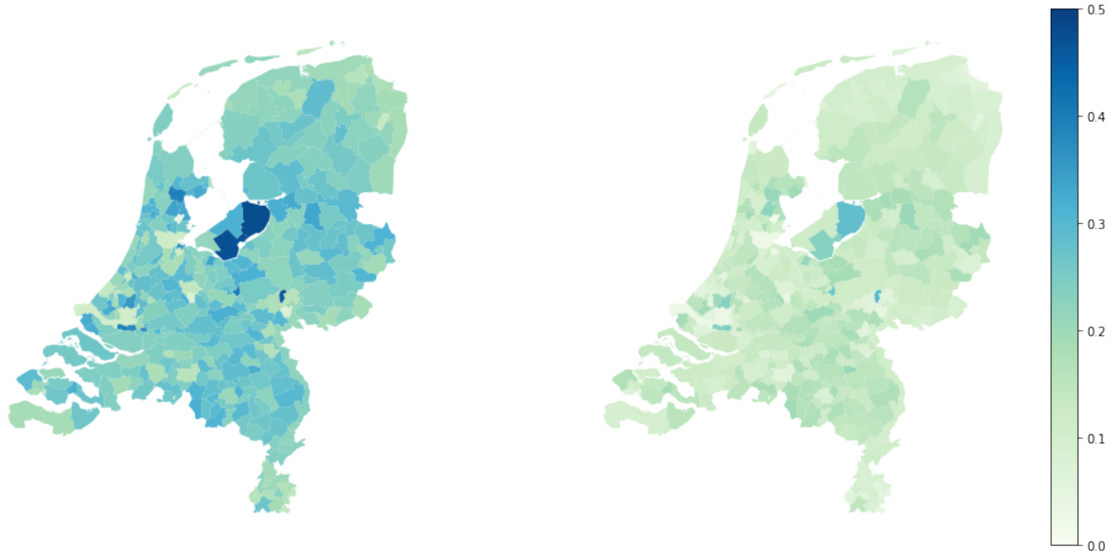


(a) Low CO_2 emission cluster

(b) High CO_2 emission cluster

Figure 12.9: Mean final LT heating grids for CO_2 clusters

the 'right' scenario and policy. This is endorsed by the fact that income strongly influences the final use of heat pumps. By comparing the map with a map showing income distributions, one will find that lower-income areas develop fewer heat pump systems. This trend is illustrated in figure 12.11.



(a) Low CO_2 emission cluster

(b) High CO_2 emission cluster

Figure 12.10: Mean final heat pump use for CO_2 clusters

This can be explained since the lower-income regions have to make relatively large investments to disconnect from the gas grid. Figure 12.12 shows the share of investment cost on property value and annual income, to insulate to level B, which is needed for heat pumps to become a feasible alternative. For most rural areas the relative investment is double the that of urban areas, still excluding the investment that is needed for the heat pump.

All in all, it appears that the development of low-temperature solutions depends more on the specific scenario than the development of medium temperature systems. This is explained by the fact that these systems depend strongly on the degree of insulation, which in general is a costly endeavour. A problem

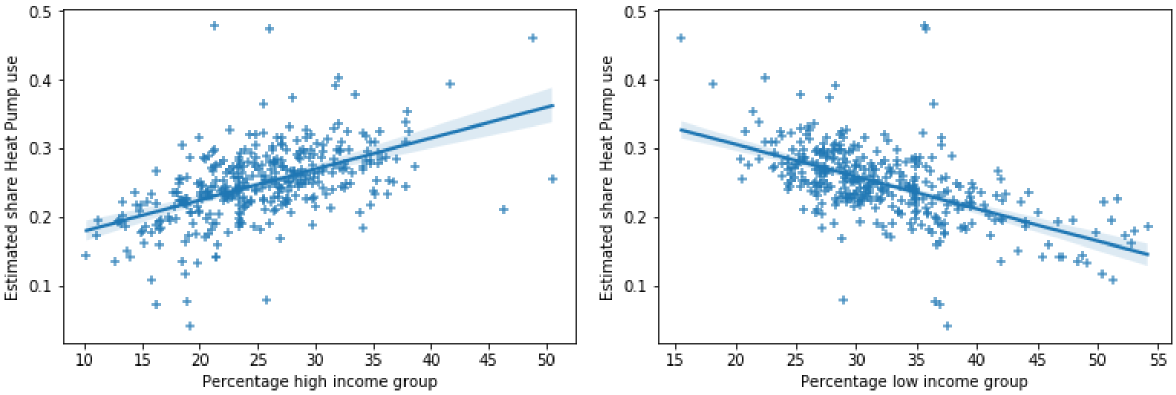
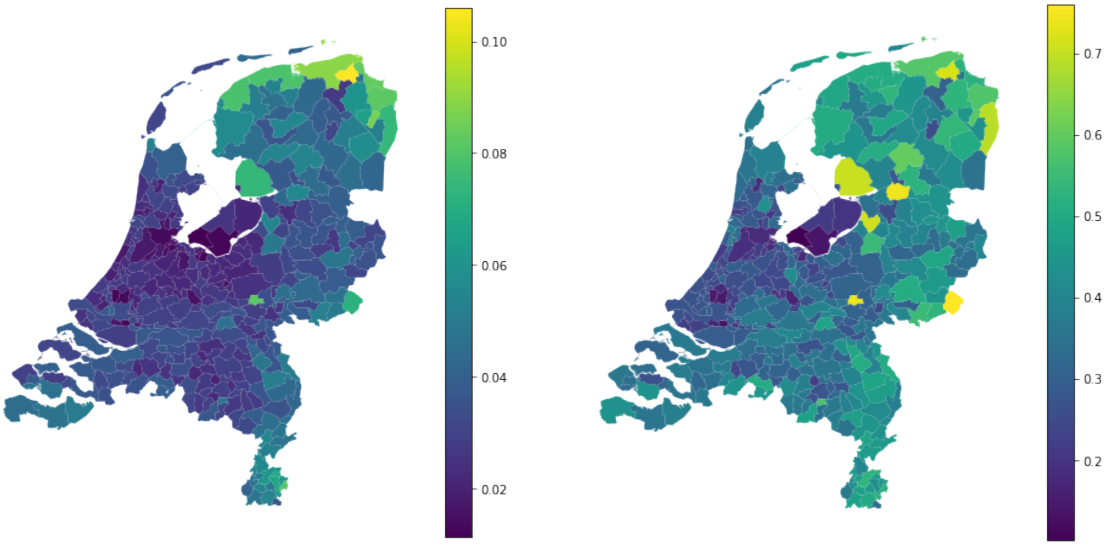


Figure 12.11: Regression plots for income and heat pump use per municipality



(a) Share investment cost insulation to label B: property value

(b) Share investment cost insulation to label B: income

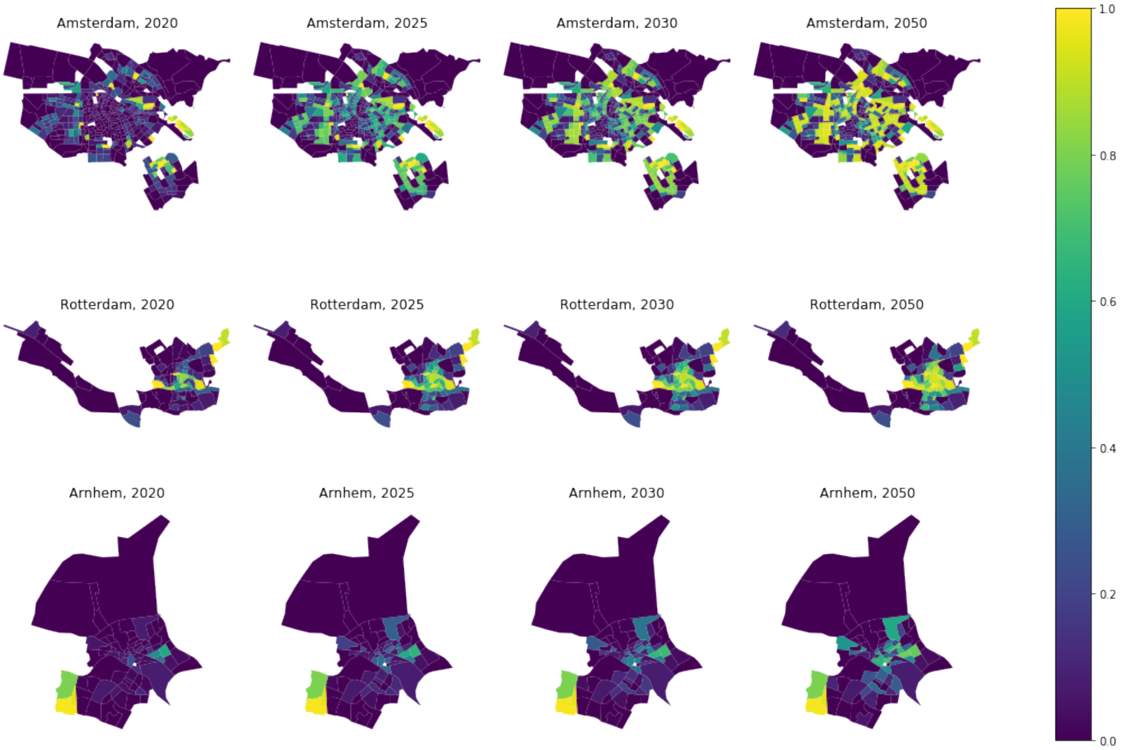
Figure 12.12: Relative investment cost for insulation to label B for property values and income

is that it is precisely the areas that are less wealthy will be dependent on the solutions that require higher investments. This results in the fact that urban areas are more likely to develop alternative systems to natural gas, despite the scenario that will unfold. This means that a bigger struggle is expected in lower-income rural to become independent of gas systems. Without proper financing mechanisms, investing in both insulation and heat pumps turns out to undesirable from an economic perspective in these areas.

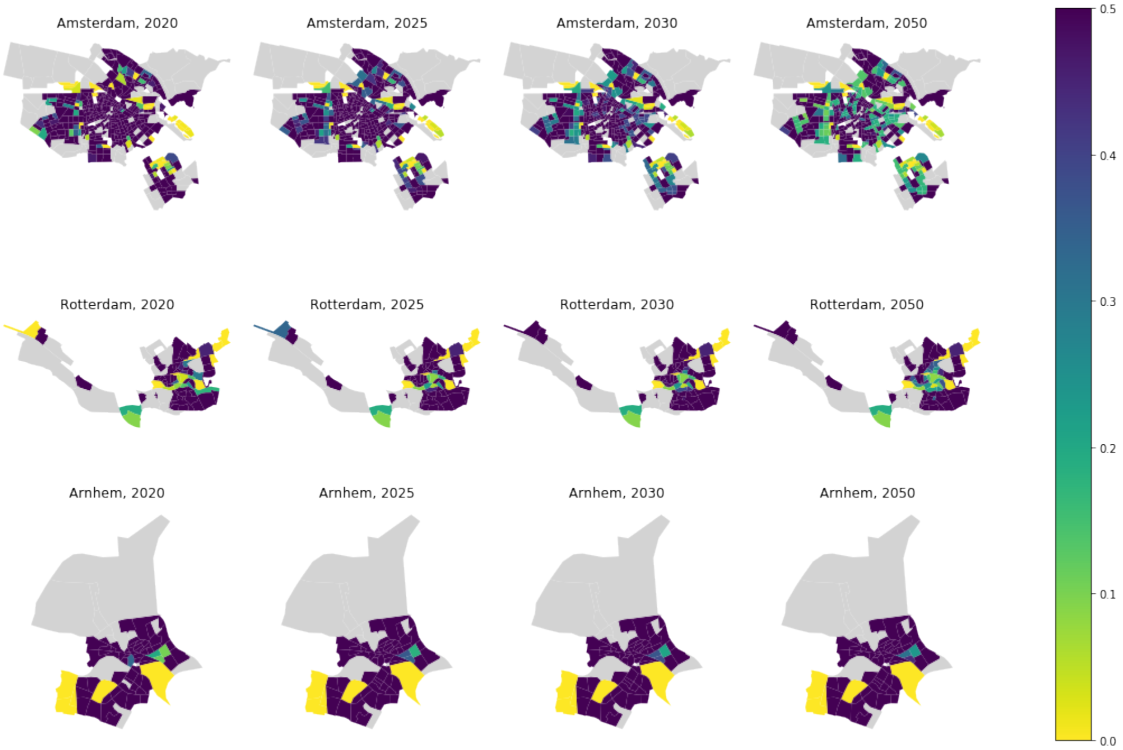
12.3. Intramunicipal Perspective

In this section, I will discuss the model outcomes for three relevant municipalities to inspect the capability of the model to evaluate intramunicipal differences. For this, Amsterdam, Rotterdam, and Arnhem have been chosen to present, because of their potential for heating grids. Heating grids require high investments and long preparation periods, so creating insights about which neighbourhoods are likely to have a positive business case for heating grids and in what period is extremely relevant. Not that rural municipalities are not important, but their lack of potential for heating grids makes that it is harder to provide a clear overview of how the transition in these municipalities may play out, and will hence be discussed following this section.

Rotterdam and Amsterdam are interesting because these two municipalities are likely to play a big role in heating grid development, due to their size, density and location close to industrial clusters.



(a) Average share heating grid use



(b) Coefficient of variation

Figure 12.13: Development of heating grids over time, in Amsterdam, Rotterdam, and Arnhem

Arnhem, on the other hand, may be very interesting, since it is a medium-sized city that from the previous analysis (fig 12.9) appears to have significant potential for low-temperature heating grids, whereas Rotterdam and Amsterdam will likely make use of residual heat.

So what does the development of heating grids look like? Of course, this is dependent on a wide range of uncertainties and the policies by the national government. Hence, it is wise to investigate averages and coefficients of variation for all experiments. In this way, the development of neighbourhoods that come up with high average heating grid use, and a low coefficient of variation, is less dependent on the scenario. It is these neighbourhoods that a municipality wants as an initial starting point for their heat transition, because of the relative certainty of the solutions applied. The average development of heating grids and the corresponding coefficients of variation are given in figure 12.13.

From this figure, those familiar with the three cities can easily identify the areas that are suitable for heating grids. For Amsterdam, the first areas to be suitable to switch to heating grids, are high-density areas just outside of the oldest part of the city centre. Whereas in Rotterdam, neighbourhoods with similar building years are found in the middle of the city centre. The proximity of neighbourhoods connected to heating grids allows for cost reduction by interconnecting these systems, limiting the need for supply pipes. That the inner centre of Amsterdam is unlikely to develop heating grids may be because the monumental status of buildings there makes that insulation to decent levels for MT systems may not be economically or technically feasible, leaving (green) gas as the only available option in such neighbourhoods.

12.3.1. Investment order selection

From figure 12.13 one can identify the neighbourhoods for which the uncertainty of their development is limited, despite the possible scenarios. From this information, it is possible to develop a map that indicates the most likely implementation year for the neighbourhoods that in most scenarios develop a heating grid. For this, only neighbourhoods have been selected that on average develop a participation rate over 50 per cent, to find the most 'certain' neighbourhoods. For all three cases, these are plotted in fig 12.14, and table 12.1 provides detail for Arnhem. The full details for the other cases can be found in the digital appendix.

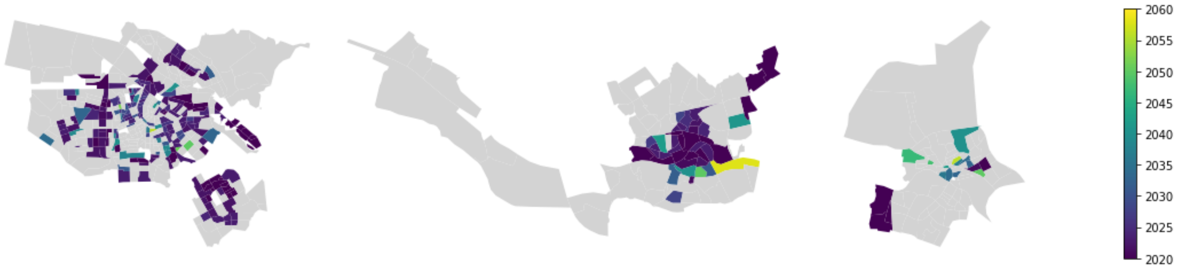


Figure 12.14: Plausible building years for scenario independent heating grids. Fltr: Amsterdam, Rotterdam, and Arnhem

From figure 12.14 one can conclude that most heating grids are likely to obtain feasibility in the next decade. Especially in Rotterdam and Amsterdam. This can be explained because most heating grids there will make use of residual heat, and delivery temperatures at medium level. Fewer investments in insulation make that these grids can be developed first.

In Arnhem, residual heat appears not to be available, or less economically attractive than low-temperature solutions, due to larger distances to industrial clusters. This results in a somewhat wider spread in the proposed building years for grids, since these grids will depend on the degree of insulation that is obtained by renovations.

Unfortunately, such concrete advice is more difficult to formulate for switching to alternative individual solutions. The individuality makes that the process will be incremental per se. Nevertheless, this could also be considered as an opportunity. By stimulating investment in insulation and (hybrid) heat pumps, the decision for whether the neighbourhood should become all-electric, or some mix of heat pumps and gas systems can be made later. A starting point for this is the neighbourhoods that are most likely to invest in insulation so that with the right stimulants, the remodelling of houses in these neighbourhoods can be accelerated. This will allow the implementation for LT systems to be imple-

Table 12.1: Heating grid development for Arnhem

Municipality	Neighbourhood	Building year	Expected participation	Grid Temperature
Arnhem	Presikhaaf I	2021	0.82	LT
	Boulevardwijk	2033	0.77	LT
	Terrein ENKA	2033	0.71	LT
	Markt	2034	0.70	LT
	Velperweg-Noord	2034	0.79	LT
	Weverstraat	2036	0.73	LT
	Klarendal-Zuid	2037	0.69	LT
	Klarenbeek	2040	0.67	LT
	Janssingel	2042	0.62	LT
	Het Dorp/Mariëndaal	2047	0.57	LT

mented as soon as enough houses have been remodelled. The transition of neighbourhoods for which remodelling to label B or higher is difficult or expensive can be postponed for the time being. New technological developments, such as the development of HT heat pumps (Feenstra, 2020) may be a solution for these neighbourhoods in the future. The relative average improvement in LT suitability over the period between now and 2060 is given in figure 12.15, to illustrate the neighbourhoods with high LT potential.

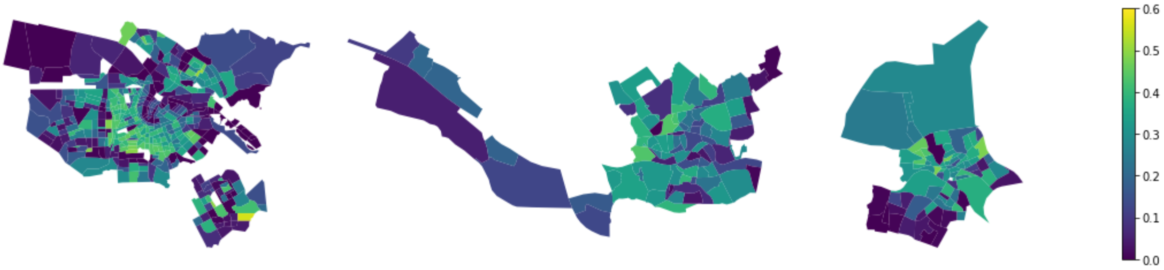


Figure 12.15: Average improvement of suitability for LT systems by insulation investment. Fltr: Amsterdam, Rotterdam, and Arnhem

12.3.2. Transition implementation

After it is clear what solution should be implemented and when, the next step is to determine a suitable project delivery model. As discussed earlier, this selection depends on many factors outside of this model, such as market circumstances and client preference. However, based on project characteristics and expected technology development, project-based advice can be given to provide an initial direction. Four project delivery models have been evaluated, and an estimation of their suitability over time is given in figure 12.16. An important note is the fact that the traditional contract does not appear in the figure. This is because purely based on project characteristics, a traditional contract can always be considered suitable. Hence, to provide a view of relative suitability, the selection model has been altered to prefer other options where possible.

To manage neighbourhood transition from a municipal perspective, agreements need to be made in which the entire neighbourhood is included. In this way, economies of scale can be obtained by combining individual remodelling projects. From figure 12.16 one can identify that for all renovation types, integrated contracts are becoming more suitable over time. This can be explained since with time, experience with similar projects increases, technologies develop further and thus project uncertainties diminish. The strongest integrated form, the life-cycle contract appears to be only suitable for the development and exploitation of heating grids, which can be explained due to the size of such projects. Although its share is small, one should consider the fact that not all neighbourhoods in the graph will be suitable for a heating grid, so that the share of suitable life-cycle contracts for to build heating grids may be larger.

Interesting to notice is the initial decrease of the suitability of integrated contracts for insulation in

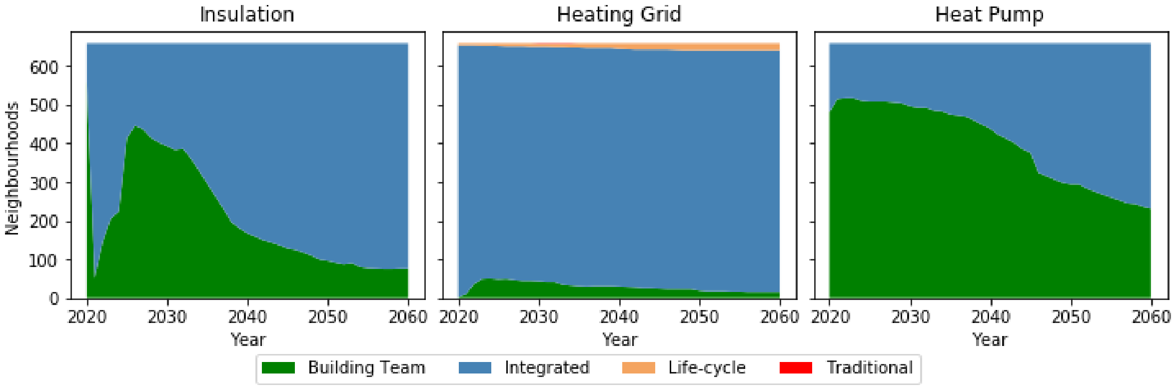


Figure 12.16: Relative project specific contract suitability for neighbourhood transformation

* Note that this graph only portrays the contract suitability for the neighbourhoods of the three municipalities evaluated.

the first decade, after which it shows the same trend as with heating grids and heat pumps. This is likely the consequence of the type of renovations that will be performed in these periods. In the early stages, smaller renovations will be performed, after which larger and more drastic (new) renovations (to label B or higher) will become economically feasible. When more experience with these kinds of projects is obtained and risks decline, integrated contracts will become more attractive again.

Concrete steps that municipalities can take to benefit from these insights is to find neighbourhoods that are likely willing to cooperate or to select neighbourhoods with a high share of housing corporation ownership. This allows for larger contracts to be set up to obtain economies of scale. Based on project characteristics, a suitable contract can be selected. For Amsterdam, Rotterdam, and Arnhem this means that initially small housing renovations can be performed well using integrated contracts, given the smaller risks that these more common projects have. For installation of heat pumps and extensive housing insulation, it is advisable to start with traditional or building team contracts, in which enough room to manoeuvre lays with the municipalities, housing corporations and homeowners. When these types of renovations and heat pump installations become common practice, for insulation around 2035, and heat pumps following 2045, cost reductions may be realised by allowing contractors to fully design the process using integrated contracts.

Based on project characteristics, life-cycle contracts only need to be considered for the development of heating grids. The existing experience with such systems makes that the technical complexity is limited, and the relative size of heating grid projects makes that a life-cycle contract becomes interesting from a contractor perspective. For smaller neighbourhoods, this makes that integrated contracts may be most suitable.

However, apart from project-specific characteristics, there may be other reasons for considering life-cycle contracts for both heating grids and heat pumps. The inequality observed from the intermunicipal perspective may be addressed and remedied using life-cycle contracts. In this way, investment requirements and the associated risks can be transferred from homeowners and housing corporations to 'heat-as-a-service companies'. Preferably state-owned, initially at least, as opted by Zuid-Holland deputy Han Weber for heating grids (Ekker, 2019). This option takes this idea a step further. National arrangements on fair prices for heat supply can take away the differences that various systems may bring to households in terms of investment. This allows for the heat-as-a-service companies to determine the 'best' solution to implement, whilst households no longer have to worry about their heat supply. Key in realising this will be connection obligation, which may be undesirable for fear of monopolist energy suppliers or monopoly formation after privatisation. However, designing a system that is similar to the current electricity and gas networks, in which a neutral grid operator provides the system, and the energy is purchased from energy suppliers in a competitive environment, this problem can be mitigated.

By having grid operators determine and develop the energy system, smart allocation of asset capacities such as the electricity net and gas grids, cost reduction can be realised, and the overall costs of the energy transition can be borne jointly and severally, reducing inter- and intramunicipal differences.

13

Discussion

Sustainable Urban Development, as it is getting ever more complex due to to the need for an Energy Transition (Klimaatakkoord, 2019), climate adaptation (European Commission, 2018b) and ongoing urbanisation (Grubler et al., 2012), is likely to benefit from more and more elaborate models to investigate pathways in that development. This study has provided a multi-model that can provide the initial insights needed for setting up strategies in Sustainable Urban Development. However, as this development proceeds, new and more detailed insights will be needed to keep up with that development.

13.1. Experiment and result expansion

A first step in gaining extra insights in Sustainable Urban Development is to extend the experiments performed in this study as a proof of concept, into fully workable outcomes. A high-performance cluster will be required to perform all the experiments and to store all the data that is generated. The model will best fulfil its purpose when the detailed data is stored for all municipalities, instead of only a few.

In-depth scenario discovery (Bryant & Lempert, 2010) with the extra experiments will help to identify several stereotype scenarios other than CO_2 emissions, to provide a wide range of possible outcomes to consider for policymakers. From there a database should be set up containing the outcomes for all municipalities for each of these scenarios. The model presentation as developed in this study provides a base for setting up an online environment which policymakers can consult to extract the scenarios for their specific jurisdiction. Interactive maps may enable to more efficiently present data about neighbourhoods to municipal policymakers.

Next to this, extra experiments will allow for performing directed search and optimisation algorithms provided by the EMA-workbench (Kwakkel, 2018). In this way, candidate policies can be set up that are likely to outperform other policies, despite scenario input. All in all, the model provides for a much wider range of analyses than have currently been performed due to the limited amount of available experiments. The added analyses, such as many-objective robust decision making (Kasprzyk et al., 2013), may strengthen the model outcomes by not only identifying what policies have an impact but also indicate how these policies should be configured, leading to more detailed and concrete advice, which municipalities strongly need (Straver, 2019).

13.2. Model improvement

Although the model developed in this study can provide valuable insights for the Urban Energy Transition, and has ample potential to be further analysed in its current state, Sustainable Urban Development is a concept that is wider than as interpreted in this study. The fact that Urban Development also faces challenges such as the current housing shortage (ABF Research, 2020) and climate adaptation, the model can be further developed so that it can also provide insights from these aspects of Sustainable Urban Development and evaluate the possibly competing interests between these aspects.

By further developing and endogenising the housing and population model, by for instance integrating property values and the attractiveness of cities, as well as geospatial limitations to the development of cities, the model can be improved. In this way, the housing market can be modelled more realistically, by allowing for insights into the development of new areas, which currently minimally included in the model, although inevitable given the current housing shortage.

Next to this, extended data gathering and parameter estimation were necessary to provide the model with the relevant data. The unavailability of up-to-date detailed information at the house level made that estimations had to be made based on housing characteristics and the average energy demand for such houses. By feeding the model with actual data on energy demand per household, more accurate distributions for investment can be developed. This improvement can be strengthened by including better insights on the expected cost of investments in insulation since these are currently only based on averages per square meter.

13.3. Remaining challenges

A major assumption that had to be made when developing the model, is the main assumption from classic economical theory: the Homo Economicus assumption. Although the concept has been changing over time (Thaler, 2000), the idea that rational agents evaluate their options, assuming complete knowledge of the characteristics of these options, making a well-informed decision, is short-sighted. Nevertheless, so far research has shown that the cost and return on investment are still considered the most important factors for investment decisions in energy solutions (Ameli & Brandt, 2015; Bouwfonds ontwikkeling, 2010). However, this study found that with reasonable subsidies and taxes, the 'Homo Economicus' will not be motivated enough to make the required investments in insulation and heat pumps so that the national goals can be attained. This means that there should either be other reasons than cost and ROI which motivate to make investments or homeowners and housing corporations should somehow be forced to make the required investments. The latter is a challenge given the Dutch history and culture of 'poldering' (Schreuder, 2001). Research into what factors besides cost may drive investors to remodel houses may provide insights in policies that will be strong enough to realise national goals.

A challenge in developing such policies is the fact that whatever policy is developed: it is not likely going to be 'fair'. Skewness in neighbourhood characteristics makes that rural areas will have a significantly harder (read: more expensive) task to get rid of natural gas dependency. Urban areas simply have cheaper solutions, due to the often available option of residual heat. This makes that fewer investments in housing insulation are necessary to switch to CO_2 free solutions. Rural areas will require either green gas, or significant insulation ánd a new energy system, making that affordable gas-free solutions remain difficult to realise.

This skewness is strengthened by the fact that rural areas are also less potent for collective solutions. This is a problem, because of the very fact that a large share of the investment, and thus risk, lays with different stakeholders in such systems. With collective solutions, it is going to be a heating company or the local government that is bearing the investments and risks. Whereas individual solutions that are more often required in less densely populated areas, require investment and risk-bearing by the owners of houses.

13.4. Recommendations

Concrete steps that can be taken under the current policy and law, are to actively guide neighbourhoods to new systems for evaluating the trade-off between systems. Collaboration with grid-operators and potential heat companies should help to make that trade-off. It is imperative that resources are prepared and made available before the economic feasibility of insulation measures changes for the better. From that point, it can be expected that many households want to invest all at once, making that the risk exists that this process will be hampered if resources are insufficiently available.

However, the real problem is that the municipality should not be the party that has to govern the energy transition. Although this model can provide municipalities with useful insights into the possible development of neighbourhoods, it also shows that municipalities do not have the tools and skills to make the right decisions. Just as that it will be difficult to realise economies of scale as long as homeowners and housing corporations are free to act as they like.

Next to this, the stakeholder complexity makes that it is extremely hard to align views and opportunities for implementing optimal solutions. Stakeholder diversity and autonomy makes that the energy transition will result in a patchwork of energy systems, co-operations and individuals, never leading to the desired 'optimal' solution. This is not only true on the neighbourhood level, in which home-owners and housing corporations are not aligned, but also at intramunicipal level, in which control of neighbourhood development will be difficult to maintain. The consequences of path work at the low geographical levels will likely cascade into even less optimal solutions at the national level. Inappropriate allocation of resources and infrastructure will cause overcapacity in one municipality, and undercapacity in others. As the choice of solutions at the house level, in the end, has a strong influence on national requirements and outcomes, this is a task that should simply not be handled at the municipal level.

A solution to this problem may come from a contractual perspective. It would be wise to investigate the possibility of setting up 'heat suppliers' in the broadest version of the term: independent of the type of technology that delivers the heat. A life-cycle construct with 'Heat-as-a-service'-companies (although competing with liberal ideas: maybe even state-owned? Utility companies were after all set up by governments for very good a reason) would be able to create portfolios in which the less economic systems can be compensated by the very lucrative ones. This portfolio diversification allows for the overall risks to be limited and will allow relieving homeowners from high risk and costly investments. By setting up such a system in close collaboration with, or even carried out by grid operators and/or utility companies, it will allow for incorporation of net requirements for these systems into the decision making process. In this way, the lowest 'national costs' as proposed by Vesta MAIS (Planbureau voor de Leefomgeving, 2019c) will be able to be implemented, enabling the 'best' solution to become practicable, at least from a utilitarian perspective.

14

Conclusion

Sustainable Urban Development has proven to be an inherently difficult and complex task (Rotmans & Kemp, 2003; Scipioni et al., 2009; Verbong & Geels, 2007). Often competing interests make that the 'best' solution is something that just does not exist (Aklin & Urpelainen, 2013). However, to provide some direction in what solution should be implemented, the national government has supplied municipalities with a tool that should determine the best (techno-economic) solution (Planbureau voor de Leefomgeving, 2019b). Although presenting the 'optimal' in a very detailed manner, it does however not provide the handles to determine how and when that solution should be implemented. Utilizing multi-modelling (Nikolic, Warnier, et al., 2019), this study has expanded the techno-economic approach with time-dependent outcomes and socio-economic thresholds for implementation. The multi-model approach makes that the outcomes can be presented at both national, as well as municipal level. In this way, policymakers at multiple governmental levels will be able to use the model for gaining the insights needed at their jurisdiction. In the next sections, I will conclude on the major outcomes on these different levels by answering the case-specific research questions.

14.1. National insights

Conclusions on national outcomes and recommendations will be presented by answering the following research question:

What stakeholders and concepts are relevant in Sustainable Urban Development and how are these related?

Homeowners, housing corporations and heat suppliers will play a key role in the urban energy transition. On the one hand, homeowners and housing corporations need to remodel their houses to make them ready for new heating systems, and on the other hand heat suppliers will have to provide these new heating systems in urban areas. From the perspective of homeowners and housing corporations deciding whether or not to invest in insulation and alternative heating systems, will depend strongly on developments on the energy market and developments in insulation technology will. As long as gas prices remain relatively low, and insulation is still expensive, insulation to a label higher than label C is not likely to become economically feasible. This is a serious problem because this makes neighbourhoods that are not suitable for high-temperature heating grids will depend on (green) gas systems. All low-temperature systems will be useless, due to their dependence on housing insulation up to label B at least. Without sufficient housing investing in high degrees of insulation, or significant development into sustainable high-temperature individual systems, the goal to become independent of natural gas will never be reached.

What policies at the national level can contribute to obtaining the CO_2 goals of the climate agreement?

One important finding for realising the goals of the Klimaatakkoord (2019) is that a CO_2-tax is key in realising significant CO_2 emission reduction. Although subsidising investment in insulation, collective heating systems, and individual heating systems will affect the energy performance of the built environment, a CO_2 tax is found to be by far the most effective.

Next to this, it is found that stimulating the use of collective or individual alternatives to natural gas are not competing measures. The characteristics of neighbourhoods make that heating grids are more suitable in highly dense populated areas, whereas heat pumps are more profitable in thinly populated areas. This makes that a larger transition away from natural gas can be realised by stimulating both.

However, with the current stimulating policies evaluated, even in the most optimal scenario, the role of (green) gas is still going to be critical. This is a serious challenge: at this point, prospects suggest that it will simply not be possible to produce such amounts of green gas (CE Delft, 2019b; TNO, 2020a). This means that either natural gas still needs to be used, or that large imports are needed to fulfil demand. Next to this, unless all of the green gas used will be green hydrogen, the share of biogasses will still result in harmful CO_2 and NO_x emissions. The current discussion about the use of biomass (Hakkenes, 2020) shows that public and political opinion about 'bio-solutions' may turn very fast, making it a less reliable solution.

14.2. Municipal insights

To present the capabilities of the multi-model to provide insights at a municipal level as well, three municipalities have been picked based on insights from the national outcomes. The municipalities that have been chosen to use as case studies for evaluating the model's capabilities are Rotterdam, Amsterdam, and Arnhem. As municipalities struggle with setting up their policies (RTL, 2019; Schuttenhelm, 2020; Straver, 2019), valuable insights include what solution to implement in what neighbourhood and when, despite the national policy. These insights will be presented by answering the next research questions.

What are the effects of national policy uncertainty on system developments at the municipal level?

It is found that regional differences exist in various scenario outcomes. Urbanised areas seem to be less sensitive to scenario influences than rural areas. This makes that although most people live in the cities, the transition cannot be made without also transforming rural areas into sustainable living environments. Urban areas close to industrial clusters will be able to draw much of their energy demand from residual heat, although, for areas further away from these clusters this will be more difficult.

By subsidising low-temperature systems and insulation, better performance in rural areas can be realised. Unfortunately, this is not likely going to be enough to reduce the use of (green) gas to an acceptable level, and realise the climate agreements CO_2 goals. Willingness to invest will have its limitations, especially if a lot of money has already been spent. An investment program in which the state provides for the investment needed, and the users repay this investment with lower monthly costs than their energy savings, may be able to motivate substantially to invest in energy-saving solutions. Such a system, however, is a significant risk for the Dutch state. This system would require the state to guarantee for all of these investments, while future developments may form better and newer alternatives that transcend the current investments significantly. Nevertheless, the risks of not facilitating the Urban Energy Transition, and the fact that the state will then not oblige to its own agreement (Klimaatakkoord, 2019), as well as the European agreement (European Commission, 2018b), should preponderate.

How can municipalities coordinate and accelerate the energy transition and what are suitable starting points to do this?

It can be concluded that a suitable strategy to tackle this problem is to start with heating grids since these require high investments and a large number of participating houses. Based on a wide range of experiments, neighbourhoods are found that are minimally affected by the scenario variation and thus provide a no-regret base of neighbourhoods to start with.

Deciding what neighbourhoods need to become all-electric, and which may still make use of (green) gas, is a much more difficult question. Since the process of investment in insulation and alternative individual heating solutions is an incremental process, this allows for postponing the final decision. However, it is advised for policies to be developed that further motivate homeowners and housing corporations to invest in insulation as insulation itself is a no-regret solution. Next to this, fast-developing neighbourhoods can be identified which provide the starting point for neighbourhoods in which to accelerate that development to gain results in the least resistant neighbourhoods.

Economies of scale may be obtained by setting up cooperation between homeowners and housing corporations to remodel entire neighbourhoods at once. Possible contract strategies for implementing this are suggested based on project-specific characteristics. It can be expected that integrated contracts, in which risk is moved from the client to the contractor, become more and more suitable with the ongoing development of neighbourhood remodelling.

More rural municipalities should be prepared to work closely together with their inhabitants to realise the transition. Subsidies and taxes at the national level are not likely going to be enough to transform enough houses into natural gas free establishments. Homeowners and housing corporations need to be motivated for different reasons than economic incentives alone, to move away from gas dependency.

Lastly, this study has tried to incorporate planning for the Urban Energy Transition with the process side of implementation. Although some advice can be given for contract strategies to pre-sort for based on project characteristics, contracting is still going to be a human affair. Because the perfect project delivery model does not exist (Bannet & Grice, 1990; Chen et al., 2011; Mafakheri et al., 2007), it is inherently difficult to provide for a one-size-fits-all strategy. It does help, however, to gain insights into the project-specific characteristics that make one model more suitable than others, before aligning this with context and stakeholder characteristics. In the end, contract strategies may be chosen based on what the client may be most comfortable and/or experienced with. Adapting this comfort by providing insights into the project dependent choices to make, may help policymakers to better choose their preferred project delivery model.

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IV

Synthesis

15

Conclusion and Discussion

In this research, synthesis is acquired by developing a novel method in modelling and simulation and directly applying it to a relevant use case. By focusing on the conceptualisation, and the analysis of the outcomes of the model for the Sustainable Urban Development case, more useful insights into the methodological challenges and opportunities were exposed. In this way, the process enabled the development of insights into the case, as well as into the development of multi-models in general. The research question that is answered by doing so is:

How can multi-perspective insights into Sustainable Urban Development be provided using a System Dynamics and Agent-Based multi-model, and what do these insights imply for the effectivity of national and municipal policies towards the realisation of CO_2 emission reduction in the Built Environment?

Part II has shown that the development of multi-models is not trivial. Although the opportunity to develop model concepts that lie closer to reality is tempting and provide multi-perspective insights, only in specific instances, this opportunity will outweigh the challenges that the method brings. Nevertheless, the case introduced in part III of this dual thesis appeared to be very suitable for, on the one hand, exploring the possibilities of multi-modelling and on the other hand, directly obtaining valuable insights in Sustainable Urban Development.

Multi-modelling has proven to lend itself very well for developing multi-perspective insights since the model is designed in a way that allowed the two model formalisms to provide for each of these perspectives. Although two separate models would also have been able to provide these perspectives, the interaction between the perspectives makes that one can directly view policy options at one level as uncertainties at other levels, better representing the way the system functions.

Even more essential than with traditional modelling methods, the presentation of the results of multi-models is key in delivering the multi-perspective interpretation it allows. The geographical characteristic of the Sustainable Urban Development case enabled the usage of maps, making that this could be done very well. This way of presenting model results allows policymakers to inspect their specific perspective of a region of interest. However, for cases without such a characteristic this may not be that easy.

The challenges posed by developing a new methodology not only forced the consideration of methodological aspects but also resulted in the development of a model that is a better fit for purpose. Better concept development driven by the need to evaluate formalism selection and model integration makes that the model is a closer representation of reality and thus can provide better insights into the Sustainable Urban Development case.

The multi-perspective interpretation has especially proven its value in part III. Without the multi-model, it would have been incredibly difficult to take into account all the relevant aspects and provide these multi-perspective insights. Although producing these insights resulted in enormous data overload, it did show that the model can provide a municipal specific understanding that helps municipalities develop the strategies that are fit for their specific circumstances, while also taking into account national considerations.

Although these theses might suggest that they are written for two different audiences, namely: methodologists (part II) and professionals in the built environment (part III), this is not the case. Especially the combination of both made in this research further allows the integration of modelling and simulation into a field of practice. This research has shown that multi-modelling is very well able to contribute to gaining understanding in Sustainable Urban Development, and has also shown the difficulties that are encountered when developing such models so that future studies can tackle these challenges. This is not only a win for the field of practice, in which models can be improved to provide better and more useful insights. It is also a significant scientific contribution to how modelling and simulation can be further developed to enlarge its application in the field of practice.

After all, one does not model without a purpose. Model method development is dependent on the problems that lend themselves well for modelling. Two separate studies investigating multi-modelling and Sustainable Urban Development would not have borne the same results, since both studies would have needed two elements: the model and the case. The combination of both enables one model and one case. In this way, a better model has been developed that includes many more and more complex elements than the models that would have been developed in separate studies. This does not necessarily result in better models, but in this case, it does. As the case requires a multi-perspective approach and is dependent on so many different elements and behaviours, multi-modelling is the only method capable of grasping that complexity and reducing it to a simplified version of reality in the model. Nevertheless, as with any modelling study, choices had to be made that influence the model's capabilities and possible outcomes strongly. Hence, the next section will discuss what is explicitly not done in this study, to provide clear boundaries on the model and show where methodological, as well as case-specific improvements, can still be made.

15.1. Limitations

The model developed in this research includes a vast range of technical solutions and options for investment behaviour and system development. Nevertheless, as a model is a simplification of reality per definition, the model does omit some elements that could be considered to add to the model in further research or could be investigated separately altogether.

Two salient assumptions made in this study are that no differentiation in types of (green) gasses is made and that shortages in these gasses can be supplemented with imports. Whether this is either desirable and/or even feasible has not been investigated. This research shows, though, that (green) gasses will keep playing an important role in heating the built environment, even after 2050. This means that further research into the feasibility of the goals to become independent of natural gas is necessary to learn more about the consequences of these goals.

The same holds for the implementation of hybrid heat pumps. Although it can be expected that such systems will fulfil an important role in the transition period disconnecting from the gas grid, the system has not been taken along in this study. This is chosen because the choice of investment in hybrid heat pumps will likely strongly depend on the natural replacement moments of current high-efficiency boilers. This makes it puzzling, to develop a concept for the investment behaviour in hybrid heat pumps, as compared to all-electric heat pumps. A similar train of thought is the reason that incremental housing insulation is not taken into account. Although it may be feasible to make incremental improvements to insulation levels, for the majority it can be expected that fixed costs for remodelling prevent incremental renovations.

Following the omission of hybrid heat pumps, other systems not been evaluated and/or differentiated for sustainable heating just yet. These are geothermal heating grids, different types of residual heat, and the sustainability of residual heat sources, due to the unavailability of reliable data about these systems. This is also why the emergence of new technologies, such as high-temperature heat pumps is not considered in this analysis. However, this does not suggest that these systems lack technical, economic or social potential, just that at least one of these items cannot be quantified sufficiently for evaluation in this model.

Another element that is excluded on purpose, is one of the main drivers for this research to propose for grid operators to take the lead: external costs to investment behaviour. In this case, the external costs refer to the (dis)investments that need to be made into energy infrastructure as a result of homeowners and housing corporations making their investment decisions. Costly net investments due to a large increase in heat pump use and/or electric mobility, as well as inefficient asset allocation, may surpass the benefits they bring to the individual, caused by redistribution of the (sub-optimal) national costs. However, the goal of this study was to investigate the consequences of individual behaviour, rather than coordinated change management. The model developed in this research is, therefore, not an extension of Vesta MAIS (Planbureau voor de Leefomgeving, 2019c), which does assume full control. The model aims to provide a realistic perspective on the possibilities given current policies and shows that the solutions offered by Vesta MAIS are not likely to be implemented without a drastic change in policy.

Regarding the methodological development in this research, an important, yet limiting choice has been made to develop a multi-model using System Dynamics and Agent-Based Modelling, splitting the model on a geographical level, whereas a vast range of other options is available also. Not only the model segregation options discussed in part II, chapter 4 influence model capabilities and outcomes but also an entirely different approach would have been viable to provide the multi-perspective insights that are sought for.

A rather unconventional opportunity for the case of Sustainable Urban Development would be to turn the multi-model around by having a System Dynamics model approach behaviour within a neighbourhood, and using that information for guiding investment decisions within the Agent-Based Model. This could significantly speed up the decision-making process in the Agent-Based Model. However, to realise this, the System Dynamics model should be completely integrated into the Agent-Based Model, which was not possible in this research due to the co-simulation approach chosen.

The biggest limitation caused by the multi-modelling approach and strengthened by the co-simulation approach chosen, however, remains the computational requirements. Model interaction is responsible for about half of the total computational time needed for simulation. Although software does exist that allows for multi-formalism multi-modelling, The AnyLogic Company (2020) is the only one, according to their own website, common practice of multi-modelling may be hampered by the fact that nearly no integrated software is available. Vendor dependence and path dependency in the education of modellers make that fewer scholars work on the development of multi-models than desirable, to provide for the right environment for the method to become common practice. However, as this research and other studies demonstrate the great potential of multi-modelling for complex challenges, the field of modelling and simulation cannot miss out on this opportunity any longer.

15.2. Recommendations for policy makers

The multi-perspectivity is what has led to the insight that Sustainable Urban Development should better be managed at a higher level than municipality level so that better trade-offs can be made and regional assets and resources can be allocated efficiently. However, as no government body at the national level has the knowledge and expertise to do this, it is advised that grid operators take a leading role in guiding the energy transition. Although a drastic policy change is required to realise this, I expect that this proposition will enable mitigation of the problems currently hampering Sustainable Urban Development.

The proposition is as follows: make heating a common commodity as natural gas and electricity are now. Have grid operators maintain and operate not only gas and electricity grids, but also manage heating infrastructure. Households will pay for the heat (energy) they consume, and a fixed price for the energy infrastructure that provides that heat, independently from whether this heat is created using gas, electricity or warm water. In this way, grid operators can take into account the current and future state of their grids, to determine cost-effective solutions, and homeowners and housing corporations will remain incentivised to apply insulation measures that will limit their energy bill. At a regional level, this means that inequalities between regions can be levelled, by financing less economically feasibly systems with those that are economically very attractive.

Another major advantage that this solution brings, is that it will prevent a patchwork of small monopolies which will maximise the price for heat and bring significant risk to the security of supply, because of lacking portfolio diversity in small heat companies. Concretely this means that grid operators need to be responsible for every part of infrastructure between the energy delivered by an energy supplier (gas, electricity or heat) and the delivery system for heat in housing (blocks). This means that heat pumps in the case of an all-electric system, or heat pumps for upgrading heating grid temperature need to be included, as well as high-efficiency boilers and heat exchangers.

Following this strategy, one can expect that the inequalities between rural and urban municipalities can be reduced, by bearing the costs of systems in the energy transition jointly and severally, whilst keeping energy savings a personal responsibility. This is safeguarded by having consumers pay a fixed (national) price for their heat-connection, and a variable fee for the energy consumed. Next to this, it will also reduce the inequalities within municipalities and neighbourhoods, and prevent sub-optimal system development due to insufficient and/or inadequate coordination caused by the individuality of the current approach.

After all, although municipalities are willing to tackle Sustainable Urban Development, the issue is just too complex, and the municipalities simply do not have the resources and the expertise to deal with this challenge. Grid operators do have the knowledge and skills to make consideration for different systems and have the capability to take into account the bigger picture, as they have decades of experience in dealing with such infrastructure. Lets no longer burden homeowners, housing-corporations and municipalities with a task they are not capable of handling but leave it to those who can.

Appendices

A

Stakeholder Analysis

In this analysis, the relevant stakeholders, their characteristics and inter-relatedness are investigated. This is done using a stakeholder analysis, of which many methods exist (Bryson, 2004; Reed et al., 2009; Varvasovszky & Brugha, 2000). In this research, a framework by Reed et al. (2009) will be used for setting up the stakeholder analysis. In this framework, three types of analysis are distinguished. The first is to identify the stakeholders that will influence or are influenced by the proposed actions or decisions. The second step is to differentiate between and categorise the stakeholders. The last step is then to investigate the relationships between stakeholders. For each of these steps, Reed et al. (2009) propose several methods, depending on the necessity of different elements and the availability of information and time of the stakeholders involved.

The first step, identification of stakeholders is done by literature research and consulting Witteveen+Bos experts, on what stakeholders are relevant in this task, because of their experience in working with comparable projects. Given the fact that policymakers at municipalities are considered the problem owner, the extra focus lies on which elements are especially relevant to present to these policymakers, so that they can be helped in their decision-making process.

The second step, a differentiation and categorisation of the identified stakeholders will be done during the same focus group meeting as the identification step. This step is important in gaining further understanding of the abilities and disabilities of the involved stakeholders. Estimation of different perspectives on the system and on how it works will be created, which can be used in further conceptualisation of the model. Especially the addition of other agendas of stakeholders will create added value for understanding the behaviours of stakeholders. The findings of this step will be presented in an actor scan and will be summarised in a Power-Interest-Attitude diagram (Murray-Webster & Simon, 2006).

Combining the knowledge obtained with the different elements of the stakeholder analysis, the understanding of the problem and involved stakeholders can be elaborated extensively, and can be used as input for the conceptualisation in the model development. The final product of this research can then be enriched with this stakeholder analysis, by explaining the system boundaries and main assumptions to the end-user, to better steer to correct applicability of its results.

A.1. Stakeholder identification

This section will identify the stakeholders involved in the Energy Transition in the Built Environment. This is done by examining several projects and agreements, to find out what stakeholders are typically involved in similar projects. In this way, an extensive list can be set up of stakeholders that need to be evaluated for including in the conceptual model. The results of this identification can be found in table A.1. The table shows 7 different projects in various cities in the Netherlands, for which the stakeholders actively involved in the process are mentioned. It is important to make the distinction here that they are actively involved because that implies that they have a (positive) interest in the project, whereas opponents to the project may be omitted intentionally. It can be found, that for each project, some stakeholders turn out nearly always to be present, namely: some government organisation, often the municipality. However, various other interest groups and companies are also involved.

Table A.1: Identification stakeholders

Municipality	Amersfoort	Gorinchem	Den haag	Sittard-Geleen	Barneveld (de Glind)	Assen	Arnhem
Object	Declaration of intent Green gas	Declaration of intent Sustainable energy	Programme plan	Declaration of intent residual heat	Wijk van de toekomst	Declaration of intent HCS	Declaration of intent HCS
Reference	Weblog Staphorst (2019)	Provincie Zuid-Holland (2019)	Gemeente Den Haag (2019)	Woonpunt (2019)	De Glind (2019)	Assenstad (2019)	Rijksvastgoedbedrijf (2019)
Stakeholders	Municipality	Municipality	State	Housing corporation (Woonpunt)	Municipality	Energy supplier (Engie)	Energy supplier (Engie)
	Energy supplier (gas) (Rendo)	Province	Province	Energy supplier (Heat) (Het groene net)	Interest group (de Glind)	Hospital (Wilhelmina Ziekenhuis Assen)	Waterschap rivierenland
	Gridoperator (Rendo)	Housing corporation (Poort6)	Municipality	Municipality	Foundation (Jeuddorp, Rudolphstichting)	Rijksvastgoedbedrijf	Grid operator (alliander)
	Process-manager (N-tra - Rendo)	Energy supplier (Heat & Electricity) (HVC)	Energy suppliers		School (Donnerschool)	Foundation (stichting icare)	Housing corporation (Rijsterborgh)
			Energy service suppliers		Youth services (Pluryn)	Municipality	Energy service company (IF technology)
			Grid operators			Province	
			Financing companies			Energy supplier (Gas) (NAM)	
			Knowledge institutes			Social services (vanboejen)	
			Civilian initiatives			Health organisation (GGZ)	
			Companies			Health organisation (Interzorg)	
			Residents Corporations				

A.2. Stakeholder categorisation

In this section, the results found in section A.1 are aggregated into the following stakeholders:

- Home-owners
- Home-owners association
- Tenants
- Tenants association
- Local residents
- Companies (energy consumers)
- Entrepreneurs association
- Housing corporations
- Energy suppliers
- Energy corporations (consumer-owned)
- Energy service companies
- Grid operators (Electricity, heat, internet, sewage etc.)
- Contractors
- Municipalities
- Provinces
- State

After identification of these stakeholders, they can be categorised over two axes. The first being whether the stakeholder is a collective or individual, a second being the type of stakeholder: a consumer, producer or a government institution. This categorisation is displayed in table A.2.

Table A.2: Categorised stakeholders

	Individual	Collective
Consumer	Home-owners Tenants Companies Housing corporations Local residents	Home-owners association Tenants association Entrepreneurs association
Producer	Energy Suppliers Energy service companies Grid operators Contractors	Energy Corporations
Government		Municipality* Province* State*

*The government has a collective role per definition

For each of these stakeholders, several elements have been estimated. These include the goals and interests of the stakeholders, but also their expected attitude to the problem and available resources.

Next to this, it has been investigated whether a stakeholder is a collective entity, and what legal entity it is. Together with the available resources, these elements determine the power of a stakeholder. The higher the resources the higher the power, collectives are expected to have more power than individuals and the legal entity can be a catalyst for this power, where a public legal entity, company, association/foundation and individual are rated from most powerful to least powerful respectively. The results hereof are delineated in table A.3. A summary of these results can be made using a power-interest-attitude diagram. This diagram is shown in figure A.1. This diagram gives a clear insight of which stakeholders are the most relevant to take into account in the conceptualisation of the model to be developed.

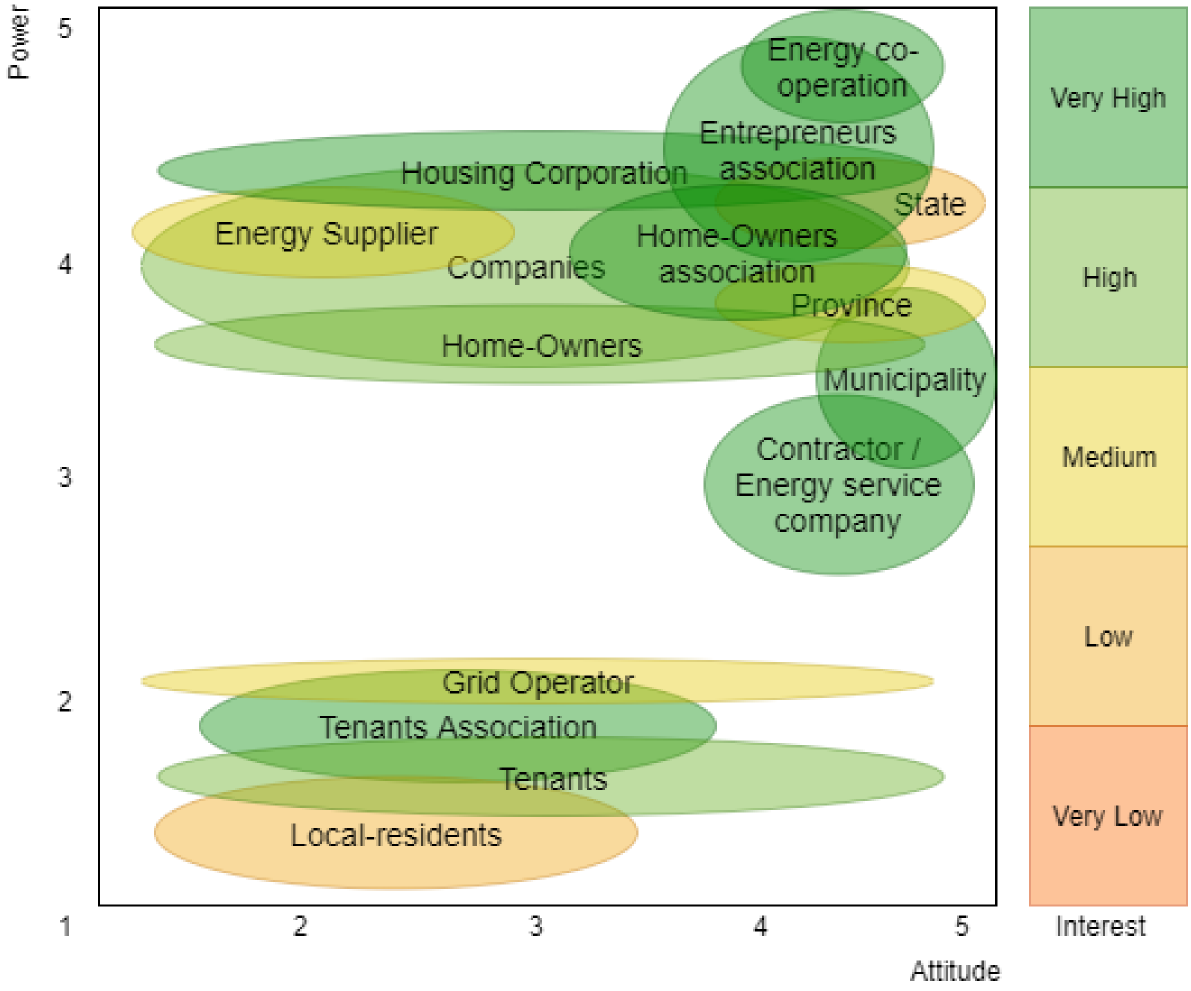


Figure A.1: Power-Interest-Attitude Diagram

Table A.3: Stakeholder analysis

Stakeholder	Goal	Interest	Attitude	Collective?	Legal entity	Resources	Power
Home-owners	Comfortable living environment	Affordable (sustainable) heating & power	Varying, depending household factors	No	Individual	Medium	Medium
Home-owners association	Comfortable living environment	Affordable (sustainable) heating & power	Varying, depending household factors	Yes	Association/ Foundation	Medium	Medium-High
Tenants	Comfortable living environment	Affordable (sustainable) heating & power	Varying, depending household factors	No	Individual	Low	Low
Tenants association	Comfortable living environment	Affordable (sustainable) heating & power	Varying, depending household factors	Yes	Association/ Foundation	Medium	Medium-High
Local residents	Comfortable living environment	Limited nuisance	Neutral to negative	No	Individual	Low	Low
Companies (consumers)	Good value energy	Affordable (sustainable) heating & power	Varying, depending company factors	No	Company	Medium-High	Medium-High
Entrepreneurs association	Good value energy	Affordable (sustainable) heating & power	Neutral to positive	Yes	Association/ Foundation	Medium-High	High
Housing corporations	Profit	Affordable (sustainable) heating & power	Neutral	No	Company	High	High
Energy suppliers	Profit	Affordable (sustainable) heating & power	Neutral to negative	No	Company	High	High
Energy corporations (consumer-owned)	Sustainable energy supply	Independence of Energy suppliers	Positive	Yes	Co-operation	Medium-High	High
Energy service companies	Profit	Selling energy services	Neutral to positive	No	Company	Medium-High	Medium-High
Grid operators (Electricity, heat, internet, sewage etc.)	Profit	Limited and predictable change to grid	Neutral to negative	No	Company	High	High
Contractors	Profit	Construction of energy solutions	Neutral to positive	No	Company	Medium-High	Medium-High
Municipalities	Developing 'Warmte transitie visie'	Stimulating Energy Transition Built Environment	Positive	Yes*	Public legal entity	Medium-High	High
Provinces	Developing RES (Regional Energy Strategy)	Stimulating Regional Energy Transition	Positive	Yes*	Public legal entity	High	High
State	Compliance to Climate Agreement	Stimulating National Energy Transition	Positive	Yes*	Public legal entity	High	High

*The government has a collective role per definition

B

Model

As the model developed in this study is a computational simulation model, fully printing out the model code is not much useful. Hence, the full model has been uploaded to Github and can be found at the following link:

https://github.com/dwolffenbuttel/EnergyTransition_MultiModel.

To give an initial impression of the model components, the interfaces of the System Dynamics model (figure B.1) and the Agent-Based Model (figure B.2) are given. The interface that is used for performing experiments with the multi-model, is shown in B.3.

Figure B.1 shows the full System Dynamics model structure. In this figure, the submodels discussed in part III, chapter 11 can be identified and its interrelatedness can be observed. The legend indicates the factors that are endogenously modelled, as well as the factors that are used as inputs exogenously, either from the Agent-Based Model or as scenario input. Information that may be difficult to read can be found in chapter 11, or in the digital model on Github.

In figure B.2 the Agent-Based Model interface is shown, in which in NetLogo real-time modelling data can be gathered. It shows the relevant graphs that have been used for the verification and validation of model behaviour during the model development phase. The graph in the second row of the second column shows the evolution of cumulative energy labels in the country. This is an important graph that helps verify and validate investment behaviour in insulation. The cumulative must always be one, houses should not be able to invest in lower levels of insulation, and shares of energy labels may not become negative. In the specific experiment shown in the interface, these two conditions hold up fine. The s-shaped behaviour is what could be expected given the theory on the technology s-curve (Foster, 1988).

Similar verification and validation can be performed for other aspects of the model using the other graphs and inspecting agent behaviour in the model environment.

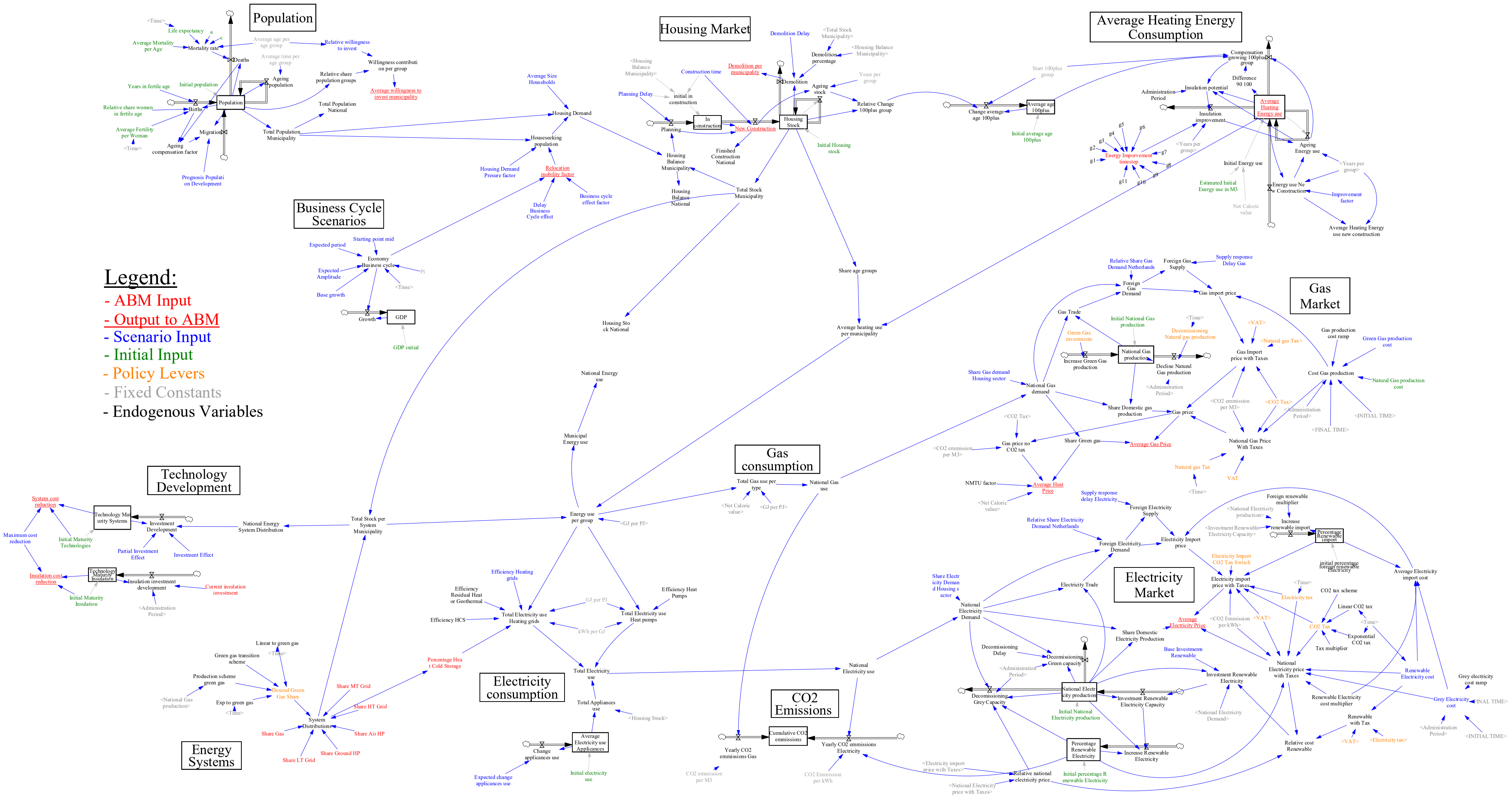
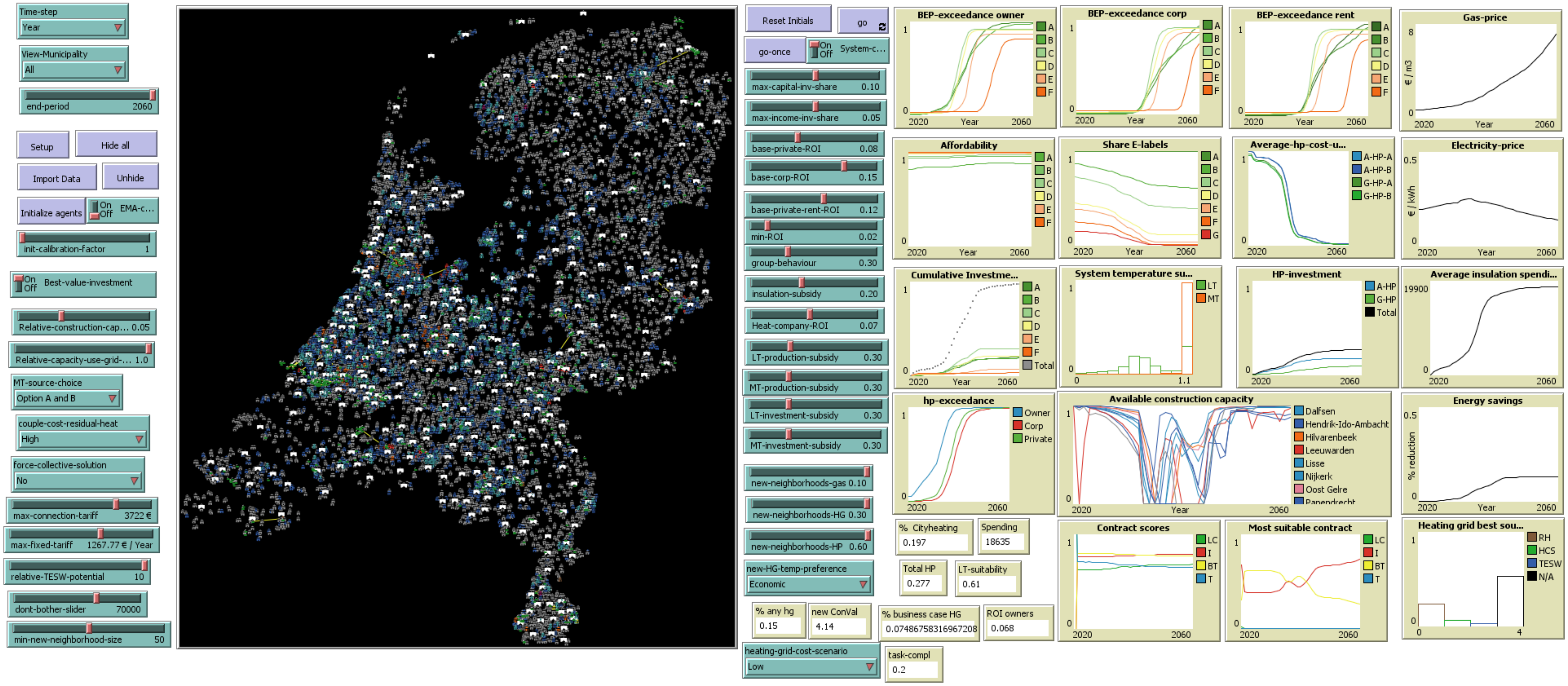


Figure B.1: Full System Dynamics model



Time-step: Year

View-Municipality: All

end-period 2060

init-calibration-factor 1

Relative-construction-cap… 0.05

Relative-capacity-use-grid-… 1.0

MT-source-choice: Option A and B

couple-cost-residual-heat: High

force-collective-solution: No

max-connection-tariff 3722 €

max-fixed-tariff 1267.77 € / Year

relative-TESW-potential 10

dont-bother-slider 70000

min-new-neighborhood-size 50

max-capital-inv-share 0.10

max-income-inv-share 0.05

base-private-ROI 0.08

base-corp-ROI 0.15

base-private-rent-ROI 0.12

min-ROI 0.02

group-behaviour 0.30

insulation-subsidy 0.20

Heat-company-ROI 0.07

LT-production-subsidy 0.30

MT-production-subsidy 0.30

LT-investment-subsidy 0.30

MT-investment-subsidy 0.30

new-neighborhoods-gas 0.10

new-neighborhoods-HG 0.30

new-neighborhoods-HP 0.60

new-HG-temp-preference: Economic

% any hg 0.15

new ConVal 4.14

heating-grid-cost-scenario: Low

% Cityheating 0.197

Spending 18635

Total HP 0.277

LT-suitability 0.61

% business case HG 0.07486758316967208

ROI owners 0.068

task-compl 0.2

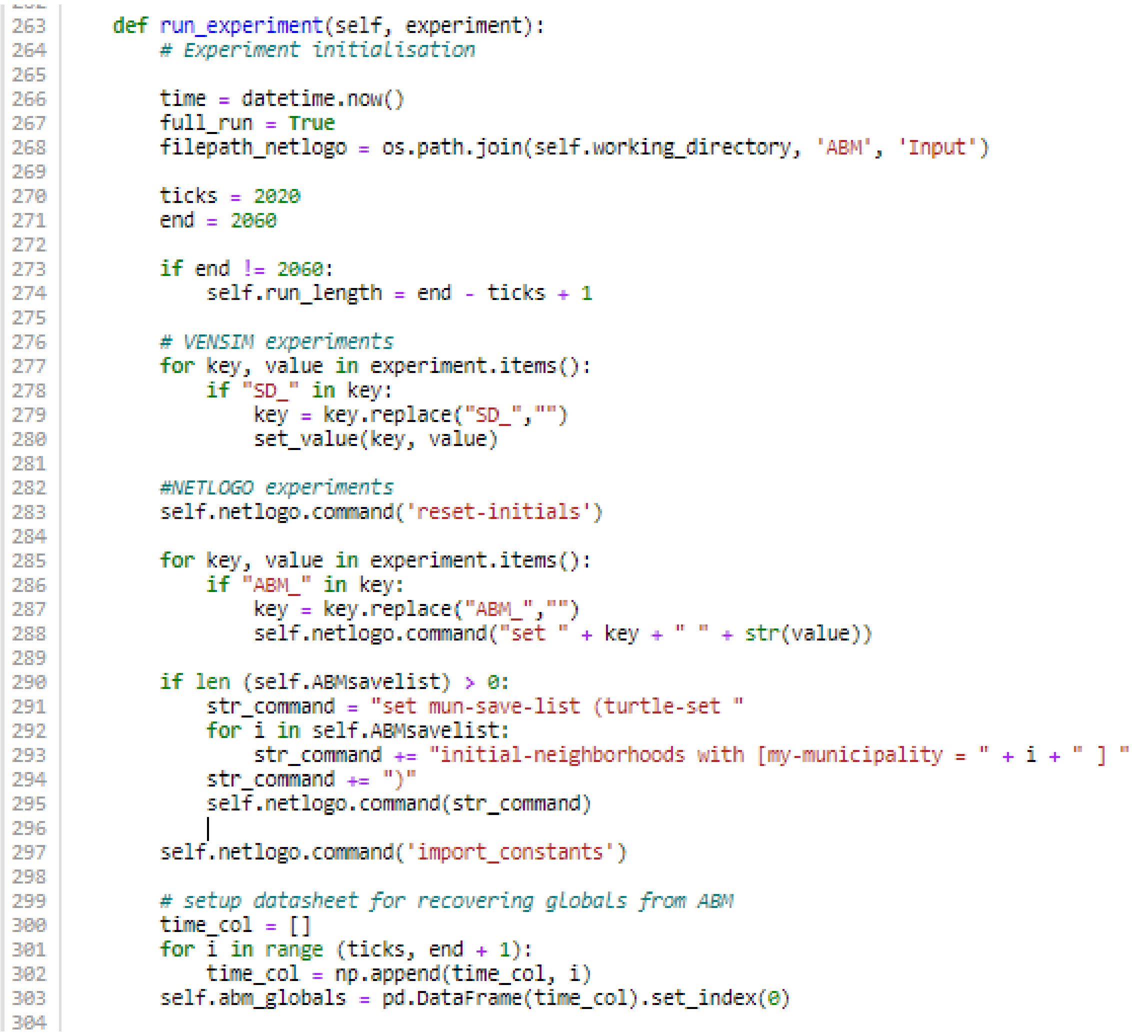
Figure B.2: Agent-Based Model interface

```
multi_model.uncertainties = [
                             # High Level System uncertainties
                             RealParameter('SD_Base Investments Renewable', 0.025, 0.125),
                             RealParameter('SD_Maximum cost reduction', 0.1, 0.5),
                             RealParameter('SD_Green Gas investments', 1e8, 4e8), # current expectation = 1.7 (CE Delft)
                             RealParameter('SD_Gas production cost ramp[Natural Gas]',-0.001, 0.001),
                             RealParameter('SD_Gas production cost ramp[Green Gas]',-0.001, 0.001),
                             RealParameter('SD_Grey electricity cost ramp', -0.001,0.001), #minimum is -0.001
                             RealParameter('SD_Renewable Electricity cost multiplier', 0.5, 2),
                             RealParameter('SD_Foreign renewable multiplier',0.5 , 2),
                             # Economy Scenarios
                             RealParameter('SD_Expected Period', 4, 10),
                             RealParameter('SD_Expected Amplitude', 0.01, 0.05),
                             # People uncertainties
                             RealParameter('ABM_group-behaviour', 0, 1),
                             RealParameter('ABM_Heat-company-ROI', 0.03, 0.15),
                             RealParameter('ABM_Max-income-inv-share', 0.01, 0.15),
                             RealParameter('ABM_Max-capital-inv-share', 0.01, 0.15),
                             # Low level system uncertainties
                             RealParameter('ABM_Relative-construction-capacity', 0.01, 0.1),
                             CategoricalParameter('ABM_heating-grid-cost-scenario', ['"High"', '"Low"']) # Double quotes nee
                             ]


multi_model.levers = [RealParameter('ABM_insulation-subsidy', 0, 0.5),
                      RealParameter('ABM_LT-production-subsidy', 0, 0.5),
                      RealParameter('ABM_LT-investment-subsidy', 0, 0.5),
                      RealParameter('ABM_MT-production-subsidy', 0, 0.5),
                      RealParameter('ABM_MT-investment-subsidy', 0, 0.5),
                      RealParameter('SD_NMTU factor', 1, 2),
                      RealParameter('SD_Tax multiplier', 0, 3),
                      CategoricalParameter('SD_CO2 tax scheme', [0, 1 , 2]),
                      CategoricalParameter('SD_Green gas transition scheme', [0, 1 , 2])
                     ]

 # Specify Municipalties to save neighbourhood data
multi_model.ABMsavelist = ['"Amsterdam"', '"Rotterdam"', '"Arnhem"'] # Double quotes needed for netlogo

multi_model.SD_subscripted_output = [['System Distributions', 'sub_mun-sys'],['Total Electricity use', 'mun_subs']]

                                # subscript options implemented: ['mun_subs','sys_subs','ins_subs','sub_mun-sys']
# FOR ABM: globals only
multi_model.outcomes = [TimeSeriesOutcome('SD_Average Gas Price'),
                        TimeSeriesOutcome('SD_Average Electricity Price'),
                        TimeSeriesOutcome('SD_Average Heat Price'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[Natural Gas]'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[Green Gas]'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[LT Heating Grid]'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[MT Heating Grid]'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[HT Heating Grid]'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[Air Heat Pump]'),
                        TimeSeriesOutcome('SD_National Energy System Distribution[Ground Heat Pump]'),
                        TimeSeriesOutcome('SD_Cumulative CO2 emmissions'),
                        TimeSeriesOutcome('SD_Percentage Renewable Electricity'),
                        TimeSeriesOutcome('SD_CO2 Tax'),
                        TimeSeriesOutcome('SD_Gas Trade[Natural Gas]'),
                        TimeSeriesOutcome('SD_Gas Trade[Green Gas]'),
                        TimeSeriesOutcome('SD_Electricity Trade'),
                        ArrayOutcome('System Distributions'),
                        ArrayOutcome('Total Electricity use'),
                        ArrayOutcome('Neighbourhood Data'),
                        ArrayOutcome('Municipality Data')
                       ]

multi_model.replications = 4
multi_model.nrScenarios = 50
multi_model.nrPolicies = 30

with MultiprocessingEvaluator(multi_model) as evaluator:
    results = perform_experiments(multi_model, multi_model.nrScenarios, multi_model.nrPolicies,
                                 evaluator=evaluator, callback = Extra_dim_Callback)
```

Figure B.3: Python multi-model environment

Figure B.3 shows the multi-model environment, in which the experiments performed are specified. Five different elements can be identified. The first two, model uncertainties and model levels specify the factors that need to be included in the sampling of experiments. The next three, ABM savelist, SD subscripted output and model outcomes specify the data that needs to be saved. As the model can produce enormous amounts of data, it is necessary to define the relevant output. The last element specifies the number of scenarios, policies and replications that will be used for setting up the experiments, followed by the command that starts model experimentation.

Figure B.4 shows how the experiments defined in the multi-model environment will be implemented into the separate models in the multi-model. Input variables are split over the Agent-Based Model and the System Dynamics model, to allocate the right variables to the right model.



```python
    def run_experiment(self, experiment):
        # Experiment initialisation

        time = datetime.now()
        full_run = True
        filepath_netlogo = os.path.join(self.working_directory, 'ABM', 'Input')

        ticks = 2020
        end = 2060

        if end != 2060:
            self.run_length = end - ticks + 1

        # VENSIM experiments
        for key, value in experiment.items():
            if "SD_" in key:
                key = key.replace("SD_","")
                set_value(key, value)

        #NETLOGO experiments
        self.netlogo.command('reset-initials')

        for key, value in experiment.items():
            if "ABM_" in key:
                key = key.replace("ABM_","")
                self.netlogo.command("set " + key + " " + str(value))

        if len (self.ABMsavelist) > 0:
            str_command = "set mun-save-list (turtle-set "
            for i in self.ABMsavelist:
                str_command += "initial-neighborhoods with [my-municipality = " + i + " ] "
            str_command += ")"
            self.netlogo.command(str_command)

        self.netlogo.command('import_constants')

        # setup datasheet for recovering globals from ABM
        time_col = []
        for i in range (ticks, end + 1):
            time_col = np.append(time_col, i)
        self.abm_globals = pd.DataFrame(time_col).set_index(0)
```

Figure B.4: Python multi-model experiment initialisation

The model cycle and the interaction between the two models in the multi-model are defined in figure B.5. Every tick (timestep) a set of calculations is performed. First, the System Dynamics model performs one timestep. The relevant data is extracted and then inserted into the Agent-Based Model. Then, the Agent-Based Model performs one timestep, after which the relevant data is extracted and then saved for use in the System Dynamics model. This process repeats itself until the end of the simulation is reached, followed by saving of the end results.

Following this, a new experiment will be initialised as shown in B.4, until all experiments have been performed.

```
        while ticks <= end:

            # RUN SD until TICKS
            run_partial_SD_model(ticks, self.vensim_model_output)
            #get globals from SD
            output_vars = ['Average Gas Price', 'Average Heat Price', 'Average Electricity Price', 'Relocation mobility factor']
            globals_SD_output = extract_SD_data(output_vars, self.vensim_model_output)

            # Ask netlogo to update globals
            self.netlogo.command('set gas-price ' + str(globals_SD_output.loc[ticks]['Average Gas Price']))
            self.netlogo.command('set electricity-price ' + str(globals_SD_output.loc[ticks]['Average Electricity Price']))
            self.netlogo.command('set heat-price ' + str(globals_SD_output.loc[ticks]['Average Heat Price']))
            self.netlogo.command('set relocation-mobility ' + str(globals_SD_output.loc[ticks]['Relocation mobility factor'] ))

            # Retrieve subscripted output from Vensim and save to be updated in NetLogo
            get_subscripted_data('Demolition per Municipality', self.mun_subs,
                                 self.vensim_model_output).to_csv(os.path.join(filepath_netlogo,
                                                                               'SD_output_demolition.csv'))
            get_subscripted_data('New Construction', self.mun_subs,
                                 self.vensim_model_output).to_csv(os.path.join(filepath_netlogo,
                                                                               'SD_output_construction.csv'))
            get_subscripted_data('Average Heating Energy use new construction',
                                 self.mun_subs, self.vensim_model_output).to_csv(os.path.join(filepath_netlogo,
                                                                                              'SD_output_e-use_new-construction.csv'))
            get_subscripted_data('System cost reduction', self.sys_subs,
                                 self.vensim_model_output).to_csv(os.path.join(filepath_netlogo,
                                                                               'SD_output_systemcost-reduction.csv'))
            get_subscripted_data('Insulation cost reduction', self.ins_subs,
                                 self.vensim_model_output).to_csv(os.path.join(filepath_netlogo,
                                                                               'SD_output_insulationcost-reduction.csv'))

            # Ask netlogo to update all subscipted vars from csv's. Unfortunately directly asking netlogo to update
            # the datafiles doesn't work due to the need for strings in strings.
            self.netlogo.command('update-SD-data-import')

            #RUN once
            try:
                self.netlogo.command('repeat 1 [go]')
            except:
                raise CaseError("Netlogo run not completed at " + str(ticks), experiment)
            # Save Model Output

            save_ABM_globals(self, ticks)

            if full_run == True:
                # Do not overwrite ABM results of full run with partial run
                save_ABM_output(os.path.join(self.working_directory, 'ABM'),
                                os.path.join(self.working_directory, 'SD'))

            ticks += 1

        SD_results = self.get_sd_results(experiment)
        ABM_results = self.get_abm_results()

        results = SD_results
        results.update(ABM_results)
        return results
```

Figure B.5: Python multi-model experiment run

C

Additional results

In this appendix, additional results and analyses can be found, that will provide deeper insight and understanding into the investigated parts of the system. Table C.1 shows the full outcome of the heating grid analysis for Amsterdam, Rotterdam, and Arnhem. For briefness in achieving confidence in the model, rather than extensive analysis of outcomes, only Arnhem was presented in the main text. For those interested in the full outcomes for Amsterdam and Rotterdam, table C.1 provides a guideline for heating grid development in these cities, regarding building year, expected participation and grid temperature. Secondly, analysis of policy and uncertainty influence on KPI's is given by means of feature scoring and dimensional stacking analyses.

C.1. Heating grid development

The following table shows the neighbourhoods in Amsterdam, Rotterdam, and Arnhem for which in all experiments on average at least a participation rate of 50% is achieved. For these neighbourhoods the average building year of the grid is given, as well as the expected average participation and the most common grid temperature. It should be taken into mind that a participation rate of 50% could imply that with a 50% probability, 100% of the households will participate, as well as a 100% probability that 50% of the households will participate, this means that the uncertainty of this aspect decreases with a higher expected participation. Further experimentation and analysis will enable eradication of this uncertainty, but due to limited computational resources and the goal to provide a proof of concept, this analysis has not further been performed.

Table C.1: Suggested heating grid development for case studies

Municipality	Neighbourhood	Building year	Expected participation	Grid temperature
Amsterdam	Amstelkwartier Noord	2020	0.97	LT
	Bijlmermuseum Noord	2020	0.98	MT
	F-buurt	2020	0.94	MT
	K-buurt Midden	2020	0.98	MT
	Olympisch Stadion e.o.	2020	0.99	LT
	Rietlanden	2020	0.96	MT
	Robert Scottbuurt West	2020	0.89	MT
	Staalmanbuurt	2020	0.95	MT
	Valkenburg	2020	0.98	MT
	Zuidas Zuid	2020	0.97	MT
	Banne Zuidwest	2021	0.95	MT
	Buurt 8	2021	0.97	MT
	Delflandpleinbuurt Oost	2021	0.97	MT
	Kolenkitbuurt Zuid	2021	0.97	MT
	Noordoever Sloterplas	2021	0.97	MT

Table C.1: Suggested heating grid development for case studies

Municipality	Neighbourhood	Building year	Expected participation	Grid temperature
Amsterdam	Overtoomse Veld Noord	2021	0.97	MT
	RI Oost terrein	2021	0.97	MT
	Amstelkwartier West	2022	0.95	MT
	Amsterdamse Poort	2022	0.95	MT
	Banne Zuidoost	2022	0.92	MT
	De Klenckebuurt	2022	0.96	MT
	Delflandpleinbuurt West	2022	0.97	MT
	Hakfort/Huigenbos	2022	0.91	MT
	Het Funen	2022	0.86	MT
	Holendrecht West	2022	0.91	MT
	Hoptille	2022	0.96	MT
	Houthavens West	2022	0.91	MT
	Kattenburg	2022	0.93	MT
	Kolenkitbuurt Noord	2022	0.95	MT
	Koningin Wilhelminaplein	2022	0.95	MT
	Kop Zuidas	2022	0.95	MT
	L-buurt	2022	0.91	MT
	Loenermark	2022	0.94	MT
	Lucas/Andreasziekenhuis e.o.	2022	0.94	MT
	Meer en Oever	2022	0.96	MT
	NDSM terrein	2022	0.96	MT
	Oostelijke Handelskade	2022	0.95	MT
	Oosterdokseiland	2022	0.95	LT
	Oostpoort	2022	0.93	MT
	Osdorp Midden Noord	2022	0.95	MT
	Osdorpplein e.o.	2022	0.96	MT
	Overhoeks	2022	0.94	LT
	Overtoomse Veld Zuid	2022	0.96	MT
	Rembrandtpark Noord	2022	0.91	MT
	Riekerhaven	2022	0.95	MT
	Riekerpolder	2022	0.92	LT
	Schipluidenbuurt	2022	0.95	MT
	Science Park Noord	2022	0.95	MT
	Uilenburg	2022	0.97	MT
	Veluwebuurt	2022	0.96	MT
	Venserpolder West	2022	0.96	MT
	Werengouw Midden	2022	0.96	MT
	Westerdokseiland	2022	0.94	MT
	Zeeburgerdijk Oost	2022	0.89	MT
	Zuidwestkwadrant Osdorp Zuid	2022	0.94	MT
	Banne Noordoost	2023	0.84	MT
	Banne Noordwest	2023	0.9	MT
	BelgiÃ«plein e.o.	2023	0.77	MT
	Borgerbuurt	2023	0.94	MT
	Buikslotermeerplein	2023	0.95	MT
	Buitenveldert Zuidoost	2023	0.95	MT
	Buitenveldert Zuidwest	2023	0.88	MT
	Buyskade e.o.	2023	0.96	MT
	Dapperbuurt Noord	2023	0.95	MT
	Dapperbuurt Zuid	2023	0.95	MT
	De Eenhoorn	2023	0.96	MT

Table C.1: Suggested heating grid development for case studies

Municipality	Neighbourhood	Building year	Expected participation	Grid temperature
Amsterdam	G-buurt Oost	2023	0.87	MT
	Gaasperdam Noord	2023	0.92	MT
	Gaasperdam Zuid	2023	0.93	MT
	Gein Noordwest	2023	0.95	MT
	Gein Zuidwest	2023	0.95	MT
	Jacques Veltmanbuurt	2023	0.94	MT
	Julianapark	2023	0.94	MT
	Kadijken	2023	0.96	MT
	Kortvoort	2023	0.95	MT
	Marcanti	2023	0.96	MT
	Marjoleinterrein	2023	0.76	MT
	Medisch Centrum Slotervaart	2023	0.91	MT
	Noordoostkwadrant Indische buurt	2023	0.95	MT
	Oosterparkbuurt Noordwest	2023	0.95	MT
	Oosterparkbuurt Zuidwest	2023	0.95	MT
	Osdorp Midden Zuid	2023	0.95	MT
	Parooldriehoek	2023	0.73	MT
	Reigersbos Noord	2023	0.89	MT
	Sportpark Middenmeer Noord	2023	0.93	LT
	Staatsliedenbuurt Noordoost	2023	0.94	MT
	Weespertrekvaart	2023	0.91	MT
	Westelijke eilanden	2023	0.95	MT
	Wittenburg	2023	0.95	MT
	Woon- en Groengebied Sloterdijk	2023	0.88	MT
	Zeeburgereiland Zuidoost	2023	0.81	MT
	Zuidoostkwadrant Indische buurt	2023	0.95	MT
	Zuidwestkwadrant Indische buurt	2023	0.94	MT
	Zuidwestkwadrant Osdorp Noord	2023	0.94	MT
	Amstel III deel A/B Zuid	2024	0.76	MT
	Anjeliersbuurt Zuid	2024	0.96	MT
	Bedrijvengebied Cruquiusweg	2024	0.84	MT
	Czaar Peterbuurt	2024	0.96	MT
	Haarlemmerbuurt West	2024	0.95	MT
	Marnixbuurt Zuid	2024	0.97	MT
	Noordwestkwadrant Indische buurt Zuid	2024	0.95	MT
	Oostoever Sloterplas	2024	0.84	MT
	Passeerdersgrachtbuurt	2024	0.96	MT
	Spaarndammerbuurt Noordoost	2024	0.95	MT
	Spaarndammerbuurt Zuidoost	2024	0.95	MT
	Spaarndammerbuurt Zuidwest	2024	0.96	MT
	WG-terrein	2024	0.86	MT
	Weesperbuurt	2024	0.96	MT
	Weesperzijde Midden/Zuid	2024	0.96	MT
	Willibrordusbuurt	2024	0.96	MT
	Zeeheldenbuurt	2024	0.95	MT
	Zuiderkerkbuurt	2024	0.96	MT

Table C.1: Suggested heating grid development for case studies

Municipality	Neighbourhood	Building year	Expected participation	Grid temperature
Amsterdam	Bellamybuurt Zuid	2025	0.95	MT
	Driehoekbuurt	2025	0.96	MT
	Elandsgrachtbuurt	2025	0.95	MT
	Erasmusparkbuurt Oost	2025	0.95	MT
	Rapenburg	2025	0.95	MT
	Bloemgrachtbuurt	2026	0.95	MT
	Buurt 9	2026	0.79	MT
	Erasmusparkbuurt West	2026	0.95	MT
	Fannius Scholtenbuurt	2026	0.77	MT
	Filips van Almondekwartier	2026	0.94	MT
	Frederik Hendrikbuurt Zuidwest	2026	0.68	MT
	Nieuwmarkt	2026	0.75	MT
	Sarphatistrook	2026	0.9	MT
	Schinkelbuurt Noord	2026	0.95	MT
	Swammerdambuurt	2026	0.93	MT
	Van der Helstpleinbuurt	2026	0.94	MT
	Anjeliersbuurt Noord	2027	0.76	MT
	Frederik Hendrikbuurt Zuidoost	2027	0.93	MT
	Leidsebuurt Noordwest	2027	0.8	MT
	Noordwestkwadrant Indische buurt Noord	2027	0.92	MT
	Surinamepleinbuurt	2027	0.69	MT
	Bellamybuurt Noord	2028	0.94	MT
	Hercules Seghersbuurt	2028	0.75	MT
	IJplein e.o.	2028	0.57	MT
	Lootsbuurt	2028	0.93	MT
	Spaarndammerbuurt Midden	2028	0.89	MT
	Transvaalbuurt Oost	2028	0.91	MT
	Weteringbuurt	2028	0.89	MT
	De Wester Quartier	2029	0.87	MT
	Don Bosco	2029	0.82	MT
	Kortenaerkwartier	2029	0.71	MT
	Vondelparkbuurt Midden	2029	0.8	MT
	Da Costabuurt Zuid	2030	0.64	MT
	Balboaplein e.o.	2031	0.8	MT
	Buitenveldert West Midden	2031	0.7	MT
	Geuzenhofbuurt	2031	0.66	MT
	IJselbuurt Oost	2031	0.8	MT
	Rijnbuurt West	2031	0.84	MT
	Markengouw Midden	2032	0.65	MT
	Science Park Zuid	2033	0.58	LT or MT
	Sloterpark	2033	0.56	LT
	Kop Zeedijk	2034	0.69	MT
	Westerstaatsman	2034	0.64	MT
	Leidsebuurt Noordoost	2035	0.62	MT
	Frans Halsbuurt	2036	0.63	MT
	Burgemeester Tellegenbuurt Oost	2037	0.67	MT
	Eendrachtspark	2037	0.72	LT
	Frederik Hendrikbuurt Noord	2037	0.55	MT
	Van Brakelkwartier	2037	0.64	LT
	Rijnbuurt Oost	2038	0.62	MT

Table C.1: Suggested heating grid development for case studies

Municipality	Neighbourhood	Building year	Expected participation	Grid temperature
Amsterdam	Zuidas Noord	2038	0.54	LT or MT
	Calandlaan/Lelylaan	2039	0.53	LT or MT
	Frederikspleinbuurt	2039	0.57	MT
	Kromme Mijdrechtbuurt	2039	0.61	MT
	Legmeerpleinbuurt	2039	0.6	MT
	Schinkelbuurt Zuid	2040	0.59	LT or MT
	Vogelbuurt Zuid	2040	0.61	MT
	Oude Kerk e.o.	2041	0.61	MT
	Tuindorp Frankendael	2050	0.53	MT
	Tuindorp Amstelstation	2051	0.51	LT or MT
	Pieter van der Doesbuurt	2052	0.52	LT or MT
	Gerard Doubuurt	2056	0.5	LT or MT
Arnhem	Presikhaaf I	2021	0.82	LT
	Boulevardwijk	2033	0.77	LT
	Terrein ENKA	2033	0.71	LT
	Markt	2034	0.7	LT
	Velperweg-Noord	2034	0.79	LT
	Weverstraat	2036	0.73	LT
	Klarendal-Zuid	2037	0.69	LT
	Klarenbeek	2040	0.67	LT
	Janssingel	2042	0.62	LT
	Het Dorp/MariÃ«ndaal	2047	0.57	LT
	Brouwerijweg e.o.	2048	0.59	LT
	Klarendal-Noord	2056	0.53	LT or MT
Rotterdam	Kop van Zuid	2020	1	LT
	Kop van Zuid - Entrepot	2020	0.96	MT
	Schiemond	2020	0.95	MT
	Stadsdriehoek	2020	0.95	MT
	Struisenburg	2020	0.98	MT
	Katendrecht	2021	0.94	MT
	Rubroek	2021	0.95	MT
	Zuidplein	2021	0.88	MT
	Afrikaanderwijk	2022	0.91	MT
	Oud Crooswijk	2022	0.93	MT
	Agniesebuurt	2023	0.9	MT
	Bospolder	2023	0.91	MT
	Delfshaven	2023	0.92	MT
	Feijenoord	2023	0.87	MT
	Nieuw Crooswijk	2023	0.84	MT
	Noordereiland	2023	0.94	MT
	Oude Westen	2023	0.91	MT
	Provenierswijk	2023	0.9	MT
	Tussendijken	2023	0.91	MT
	Kralingen West	2024	0.82	MT
	Oude Noorden	2025	0.83	MT
	Spangen	2027	0.88	MT
	Liskwartier	2028	0.69	MT
	Pendrecht	2028	0.73	MT
	Hillesluis	2031	0.8	MT

Table C.1: Suggested heating grid development for case studies

Municipality	Neighbourhood	Building year	Expected participation	Grid temperature
Rotterdam	Oud Charlois	2032	0.76	MT
	Tarwewijk	2040	0.58	MT
	Prinsenland	2041	0.63	MT
	Nieuwe Westen	2042	0.61	MT
	Bloemhof	2050	0.55	MT

C.2. Policy and uncertainty influences on KPI's

Figures C.1 and C.2 show the relation between policies and uncertainties, and their effect on national KPI's, such as the shares of the energy systems used and cumulative CO_2 emissions. Regarding policies, figure C.1 shows that for heating grids investment subsidies have a bigger influence on heating grid development than production subsidies. This suggests that the (economic) barriers do not lie with exploitation of heating grids, but that it is the investment cost that is hampering its development. Individual heating solutions appear to be affected most by CO_2 taxes and the tax multiplier. This can be explained due to the double effect this policy has on heat pump systems, because it stimulates both the feasibility of heat pumps and insulation measures. The fact that these policies also have the strongest effect on the cumulative CO_2 emissions suggests that this policy brings something extra regarding CO_2 reductions, as compared to other policies. This is in line with the findings from part III, chapter 12, that heating grids are less scenario dependent than individual solutions.

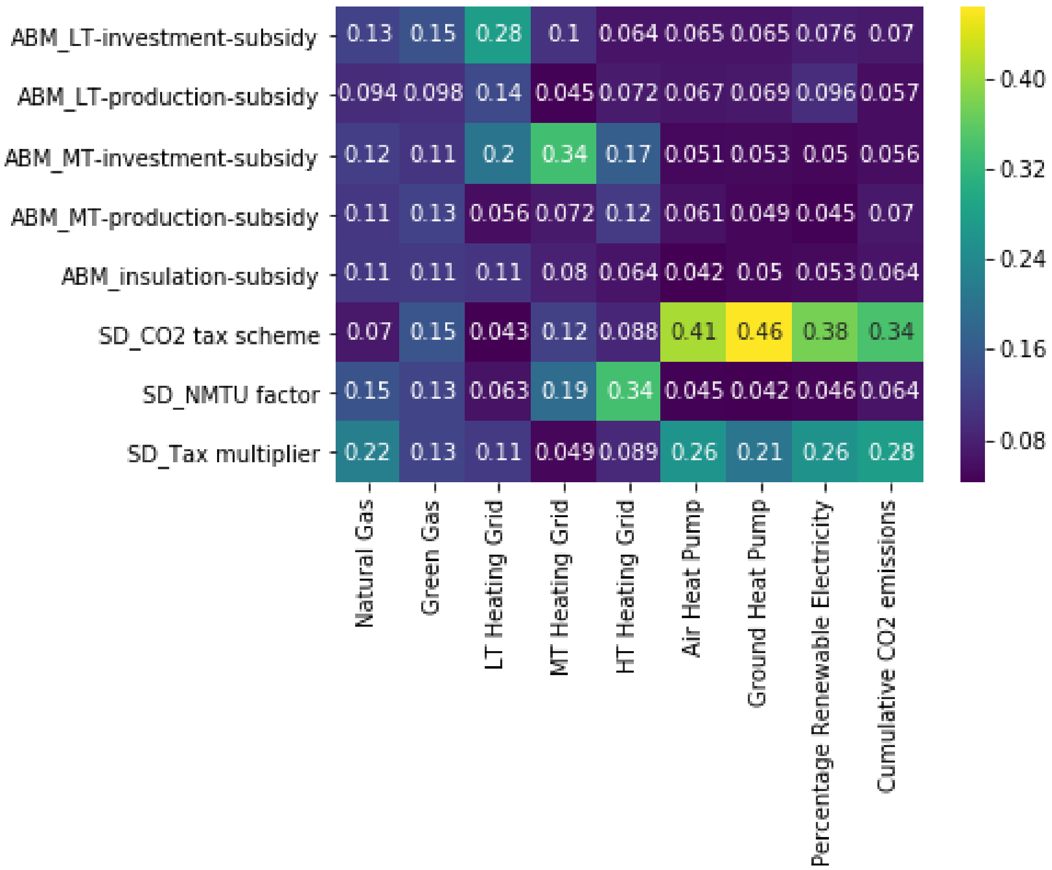
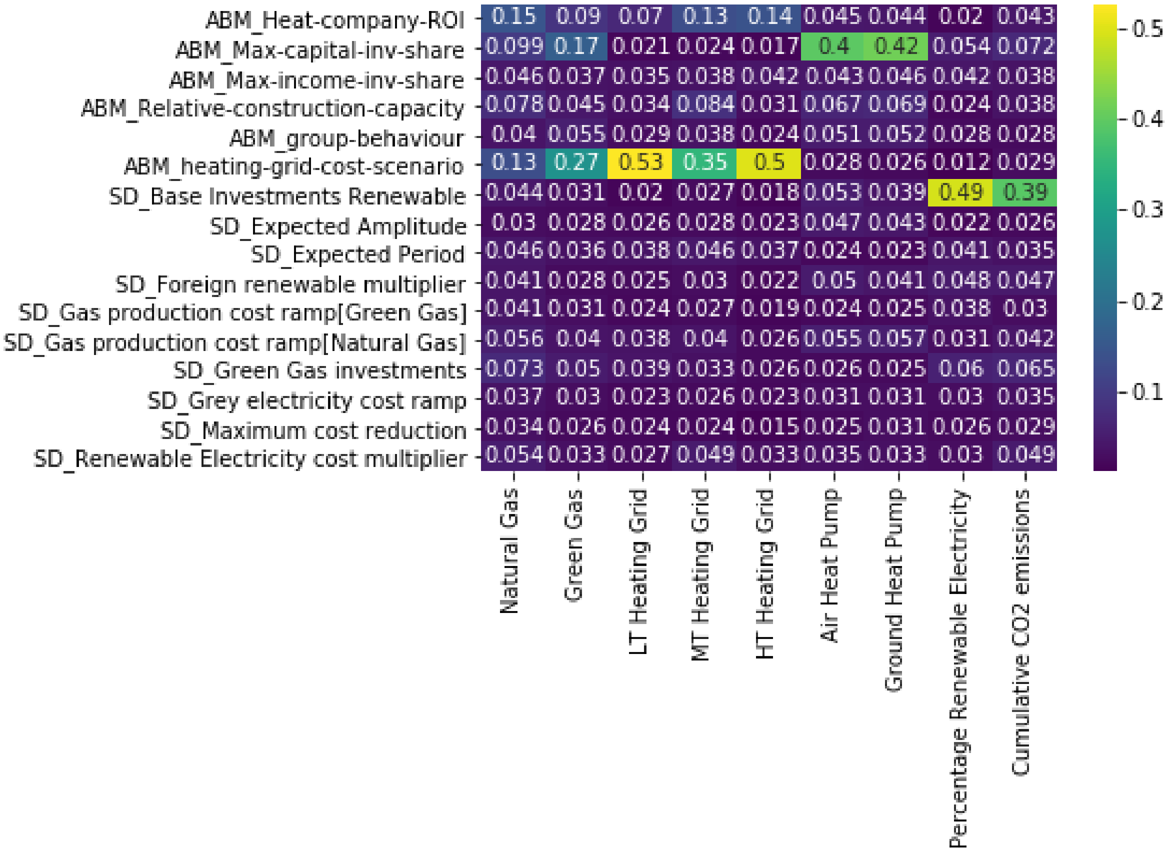


Figure C.1: Feature scoring for policies

As for uncertainties, figure C.2 shows that there is a clear distinction in the types of KPI's that are susceptible to uncertainty influences. Heating grids are primarily influenced by the heating grid cost scenario, and the ROI that heating companies require. Heat pumps are strongly dependent on the maximum share of property value that households are willing to invest. The percentage of renewable electricity produced and the cumulative CO_2 emissions are most dependent on the base level of investment in renewable electricity. The latter suggests that without a significant share of renewable electricity use, realising low CO_2 emissions is going to be unlikely.



	Natural Gas	Green Gas	LT Heating Grid	MT Heating Grid	HT Heating Grid	Air Heat Pump	Ground Heat Pump	Percentage Renewable Electricity	Cumulative CO2 emissions
ABM_Heat-company-ROI	0.15	0.09	0.07	0.13	0.14	0.045	0.044	0.02	0.043
ABM_Max-capital-inv-share	0.099	0.17	0.021	0.024	0.017	0.4	0.42	0.054	0.072
ABM_Max-income-inv-share	0.046	0.037	0.035	0.038	0.042	0.043	0.046	0.042	0.038
ABM_Relative-construction-capacity	0.078	0.045	0.034	0.084	0.031	0.067	0.069	0.024	0.038
ABM_group-behaviour	0.04	0.055	0.029	0.038	0.024	0.051	0.052	0.028	0.028
ABM_heating-grid-cost-scenario	0.13	0.27	0.53	0.35	0.5	0.028	0.026	0.012	0.029
SD_Base Investments Renewable	0.044	0.031	0.02	0.027	0.018	0.053	0.039	0.49	0.39
SD_Expected Amplitude	0.03	0.028	0.026	0.028	0.023	0.047	0.043	0.022	0.026
SD_Expected Period	0.046	0.036	0.038	0.046	0.037	0.024	0.023	0.041	0.035
SD_Foreign renewable multiplier	0.041	0.028	0.025	0.03	0.022	0.05	0.041	0.048	0.047
SD_Gas production cost ramp[Green Gas]	0.041	0.031	0.024	0.027	0.019	0.024	0.025	0.038	0.03
SD_Gas production cost ramp[Natural Gas]	0.056	0.04	0.038	0.04	0.026	0.055	0.057	0.031	0.042
SD_Green Gas investments	0.073	0.05	0.039	0.033	0.026	0.026	0.025	0.06	0.065
SD_Grey electricity cost ramp	0.037	0.03	0.023	0.026	0.023	0.031	0.031	0.03	0.035
SD_Maximum cost reduction	0.034	0.026	0.024	0.024	0.015	0.025	0.031	0.026	0.029
SD_Renewable Electricity cost multiplier	0.054	0.033	0.027	0.049	0.033	0.035	0.033	0.03	0.049

Figure C.2: Feature scoring for uncertainties

At the national level in part III, chapter 12, was found that (green) gasses will remain an important energy carrier even beyond 2050. However, the combination of the goals to no longer make use of natural gas, and be self sufficient, makes that it is unlikely that both these goals will be attained as long as the share of green gas demanded by the built environment is high. Therefore, it is key to understand what factors make that green gas use is limited. Dimensional stacking (figure C.3) helps to find what six factors have the strongest influence on green gas demand in 2050, and whether these factors should score low (0) or high (1) to realise a maximum of 55% green gas use. The CO_2 tax scheme is an exception to this system, there 1 indicated no tax, 2 indicates exponential tax, and 3 indicates a linear tax scheme. The diagram shows that without a CO_2 tax, green gas use lower than 55% is nearly never achieved, as well as that the same holds for a world in which heating grid costs turn out to be very high. This means that, even though heating grids have a smaller effect on CO_2 emissions than heat pumps, due to the fact that heat pumps will only develop in scenarios that are favourable to housing insulation, heating grids are indispensable in the realisation of growing independence of natural gas.

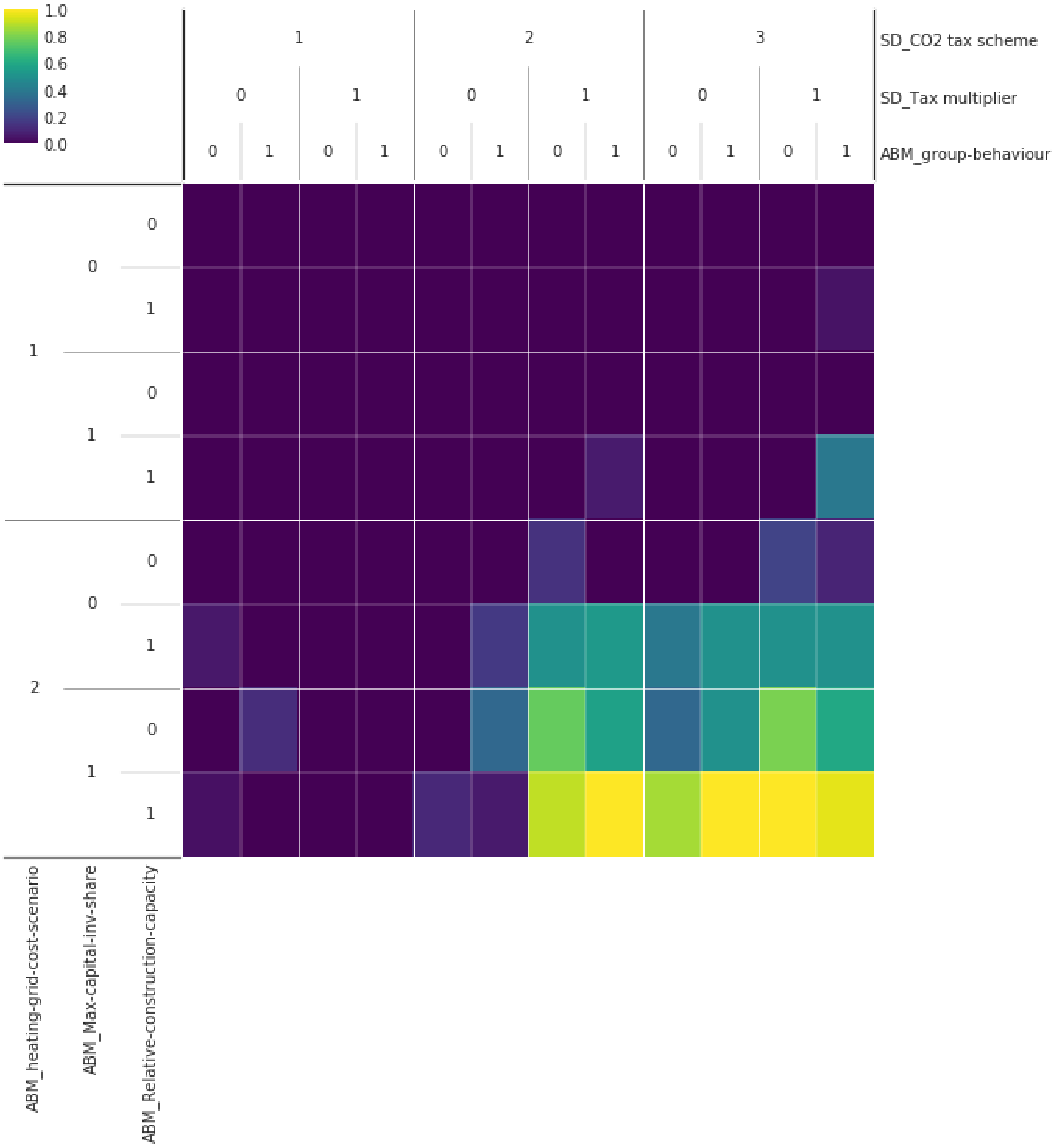


Figure C.3: Contribution of factors for experiments with low green gas use (<55%)

D

Data Gathering

Data gathering and analysis is an extensive task, especially when one opts to build a data-driven multi-model. Raw data tends to be badly organised and containing many mistakes. Next to this, finding a dataset that provides all the information one needs, is hard to find. Hence, I made a combination of several datasets to enrich the information available about neighbourhoods and make more detailed estimations of for instance energy use. The initial step is to gather all the relevant datasets and make sure that outliers, wrong entries, semantic and syntactic errors are resolved. From there, data can be combined into useful information. Table D.1 gives an overview of the datasets used.

Table D.1: Data sources used for model initialisation

Model	Submodel	Data use	Data description	Reference
Base Data	Housing stock characteristics	General information	Base registry addresses and buildings (BAG)	Kadaster (2020)
		Energy Labels	Energy labels Database	RVO (2020b)
		Energy use estimation	Average energy use per characteristic	CBS (2020e)
		Neighbourhood characteristics	General statistics	CBS (2020n)
		Household size estimation	Household size per postal code	CBS (2020h)
		Total cost estimation	Investment cost per label improvement	CE Delft (2018b)
		Potential savings estimation	Potential savings per label improvement	CE Delft (2018b)
		Investment restriction	Monumental buildings	Dataplatform Nederland (2015)
SD	Housing Market	Housing stock initials	Number of houses	Base Data
			Initial energy use	Base Data
SD	Population	Population prognosis	Growth per municipality	ABF Research (2020)
ABM	Neighbourhoods	Housing stock initials		Base Data
		Heating grids	Current distribution	CE Delft (2009)
ABM	Residual Heat Sources	MT sources	Source characteristics	Planbureau voor de Leefomgeving (2019c)
ABM	System cost	Calculation rules	Validated cost functions	Planbureau voor de Leefomgeving (2019c)

The basis for data gathering and enriching is the base registry addresses and buildings (BAG), which contains information about every single building in the Netherlands regarding size, building year, occupancy, location etc. This dataset has been merged with the RVO (2020b) data on energy labels, to get a better overview of energy related characteristics of housing. Energy use, according to European privacy law (European Commission, 2018a), may not be traceable to the individual, making that this information is not publicly available. To deal with this, averages for energy use based on housing characteristics and the average household size (CBS, 2020e, 2020h) have been used to estimate energy demand per house.

Based on this estimate, and the CE Delft (2018b) report, investment cost and expected savings can be estimated per households, which in term is used to estimate the gamma distributions for investment thresholds per neighbourhood. Based on these distributions, investment behaviour is simulated in the Agent-Based Model. Similar data regarding the housing stock is used as input to the System Dynamics model. The full data gathering and analysis process, can be inspected from the python files in the digital appendix at the following link:

https://github.com/dwolffenbuttel/EnergyTransition_MultiModel.

E

Model Initialisation

This appendix shows the initial setup for the multi-model based on the data resources used assumptions. Table E.1 gives the model input variables for all submodels of the System Dynamics model. Depending on the source and the uncertainty of that source, a minimum and maximum is given for each variable. However, due to the limited computational availability, not all these uncertainties have been evaluated. Based on a qualitative assessment of the most relevant factors, the experimental setup has been developed (tables 11.6 and 11.7 in part III, chapter 11). Complete detail can be found in the digital appendix (see appendix B).

Table E.1: System Dynamics model input variables

Submodel	Variable	Type input	Min	Max	Unit	Source
Housing Market	Average Size households (average[a])	Scenario	2.17[a]	2.17[a]	Person / House	CBS (2020n)
	Planning Delay	Scenario	1	5	Year	Assumption
	Demolition Delay	Scenario	1	5	Year	Assumption
	Construction Time	Scenario	0.5	0.5	Year	Assumption
	Size Construction distribution	Policy Lever	Uniform	Uniform	Dmnl	Assumption
	Type Construction distribution	Policy Lever	Uniform	Uniform	Dmnl	Assumption
	Initial Housing Stock (total[a])	Initial	7.93M[a]	7.93M[a]	House	Kadaster (2020)
Business Cycle Scenarios	Base Growth	Scenario	0.01	0.04	1 / Year	Assumption
	Expected period	Scenario	4	12	Year	Assumption
	Expected amplitude	Scenario	0.01	0.05	1 / Year	Assumption
	Starting point	Scenario	2010	2020	Year	Assumption
	GDP initial	Initial	800B	800B	Euro / Year	CPB (2019)
	Business cycle effect factor	Constant	3	5	Dmnl	Assumption
Technology Market	Initial Maturity:					
	- Natural Gas	Initial	1[b]	1[b]	Dmnl	Canon volkshuisvesting nederland (2020)
	- Green gas	Initial	0.18[b]	0.22[b]	Dmnl	GroenGas Nederland (2016)
	- LT Heating grid	Initial	0.4[b]	0.5[b]	Dmnl	CBS (2020b)

Table E.1: System Dynamics model input variables

Submodel	Variable	Type input	Min	Max	Unit	Source
	- MT Heating grid	Initial	0.55[b]	0.65[b]	Dmnl	Assumption
	- HT Heating grid	Initial	1[b]	1[b]	Dmnl	Energiekaart (2020)
	- Hybrid Heat pump	Initial	0.55[b]	0.65[b]	Dmnl	CBS (2020p)
	- Heat pump	Initial	0.4[b]	0.5[b]	Dmnl	CBS (2020p)
	Partial Investment effect	Scenario	0.1	0.3	Dmnl	Assumption
	Investment effect	Scenario	0.05	0.2	Dmnl	Assumption
Population	Life expectancy	Time dependent	82.1	88.16	Year	CBS (2020l)
	Average Mortality	Constant	0.0087	0.0087	1 / Year	CBS (2020k)
	Years in fertile age	Constant	30	30	Year	CBS (2020m)
	Relative share women in fertile age	Constant	0.5	0.5	Dmnl	Assumption
	Average Fertility per Woman	Time dependent	1.609	1.75	Dmnl	CBS (2020m)
	Initial population (total[a])	Initial	17.28M[a]	17.28M[a]	Person	CBS (2020c)
	Prognosis Population Development (average[a])	Initial	0.096%[a]	0.63%[a]	Dmnl	ABF Research (2020)
	a	Constant	0.3	0.3	1 / Year	Assumption
	c	Constant	0.02	0.02	1 / Year	Assumption
Energy systems	Initial distribution Gas systems	Initial	0.99	0.01	Dmnl	Netbeheer Nederland (2018)
	Initial percentage Heating grids (average[a])	Initial	0.05[a]	0.05[a]	Dmnl	Data merge[d]
	Initial Distribution Heating grids	Initial	0.6[c]	0.1[c]	Dmnl	Assumption
	Distribution Heat pump age groups	Initial	0.4[c]	0[c]	Dmnl	Assumption
	Initial percentage Heat pump	Initial	0.05	0.05	Dmnl	Alliander (2018)
	Initial Distribution Heat pump	Initial	0.024	0.976	Dmnl	CBS (2020p)
Average Energy consumption	Estimated initial Average Energy Use in M^3 (average[a])	Initial	1415[a]	1415[a]	M^3 / House / Year	Data merge[d]
	Initial electricity use (average[a])	Initial	2944[a]	2944[a]	kWh / House / Year	Data merge[d]
	Initial Average age 100plus	Initial	156[a]	156[a]	Year	Data merge[d]
	Improvement factor	Scenario	0.001	0.03	1 / Year	Assumption
	Efficiency Heating grids:					
	- Low temperature	Constant	0.9	0.9	Dmnl	Saxion (2019)[e]
	- Medium temperature	Constant	0.75	0.75	Dmnl	Saxion (2019)[e]
	- High temperature	Constant	0.65	0.65	Dmnl	Saxion (2019)[e]

Table E.1: System Dynamics model input variables

Submodel	Variable	Type input	Min	Max	Unit	Source
	Efficiency Residual heat or Geothermal	Constant	20	20	Dmnl	CE Delft (2018b)
	Efficiency Heat cold storage	Constant	3.5	3.5	Dmnl	CE Delft (2018b)
	Efficiency Air Heat Pumps	Constant	3.7	3.7	Dmnl	CE Delft (2018b)
	Efficiency Ground heat pumps	Constant	4.4	4.4	Dmnl	CE Delft (2018b)
	Expected change applicances use	Scenario	0.98	1.01	1 / Year	Assumption
	CO_2-Tax	Policy Lever	0.30	3.55	Euro / Kg	Klimaatakkoord (2019)[f]
Gas Market	Share Gas Demand Housing sector	Scenario	0.32	0.32	Dmnl	CBS (2020d)
	Initial National Gas production:					
	Natural Gas	Initial	35B	35B	M^3 / Year	Schoots and Hammingh (2019)
	Green Gas	Initial	300M	300M	M^3 / Year	CE Delft (2019b)
	Green Gas Investments	Policy Lever	56.66	56.66	M^3 / $Year^2$	CE Delft (2019b)
	Relative Share Gas Demand Netherlands	Scenario	0.072	0.072	Dmnl	Index Mundi (2020a)
	Supply response delay gas	Scenario	5	10	Year	Assumption
	Domestic Natural Gas production cost	Constant	0.15	0.15	Euro / M^3	Forstrom (2020)
	Domestic Green Gas production cost	Scenario	0.17	0.17	Euro / M^3	Rabobank (2019)
	Foreign Natural Gas production cost	Constant	0.15	0.15	Euro / M^3	Same as domestic
	Foreign Green Gas Production cost	Scenario	0.17	0.17	Euro / M^3	Same as domestic
	Natural Gas Tax	Scenario	0.29	0.29	Euro / M^3	Rijksoverheid (2020a)
Electricity Market	Share Electricity Demand Housing sector	Scenario	0.25	0.25	Dmnl	CBS (2020d)
	Initial percentage Renewable Electricity	Initial	0.074	0.074	Dmnl	CBS (2020g)
	Base Investment Renewable	Scenario	0.05	0.1	1 / Year	CBS (2020g)
	Initial National Electricity production	Initial	100B	100B	kWh / Year	Schoots and Hammingh (2019)
	Relative Share Electricity Demand Netherlands	Scenario	0.0307	0.0307	Dmnl	Index Mundi (2020b)
	Supply response delay electricity	Scenario	5	10	Year	Assumption
	Domestic Grey Electricity production cost	Constant	0.04	0.04	Euro / kWh	Ecofys (2018)

Table E.1: System Dynamics model input variables

Submodel	Variable	Type input	Min	Max	Unit	Source
	Domestic Renewable Electricity production cost	Scenario	0.09	0.09	Euro / kWh	Ecofys (2018)
	Foreign Grey Electricity production cost	Constant	0.04	0.04	Euro / kWh	Same as domestic
	Foreign Renewable Electricity production cost	Scenario	0.09	0.09	Euro / kWh	Same as domestic
	Electricity import tax switch	Policy Lever	0	1	Dmnl	

[a] In the model data is subscripted on multiple categories, for clarity in this table, the aggregate of these categories is given.

[b] The initial values for maturity of systems is relative to the number of years a technology has been in use compared to natural gas, which has been commonly used for 58 years (Canon volkshuisvesting nederland, 2020), plus or minus 10% for sensitivity analysis.

[c] For these distribution the biggest and smallest share are given, for full distribution see model.

[d] Data in the datamerge contains datasets from CBS (2020a, 2020e, 2020f), Kadaster (2020) and RVO (2020b). How this merge has been performed can be found in the data gathering section.

[e] Authors of report: Papa et al. (2019)

[f] Policy concerning CO_2-Tax is extrapolated in line with current trend.

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