Transitioning from natural gas to carbon-free households in the Netherlands

The influence of behavioral characteristics and policy conditions in the heat transition

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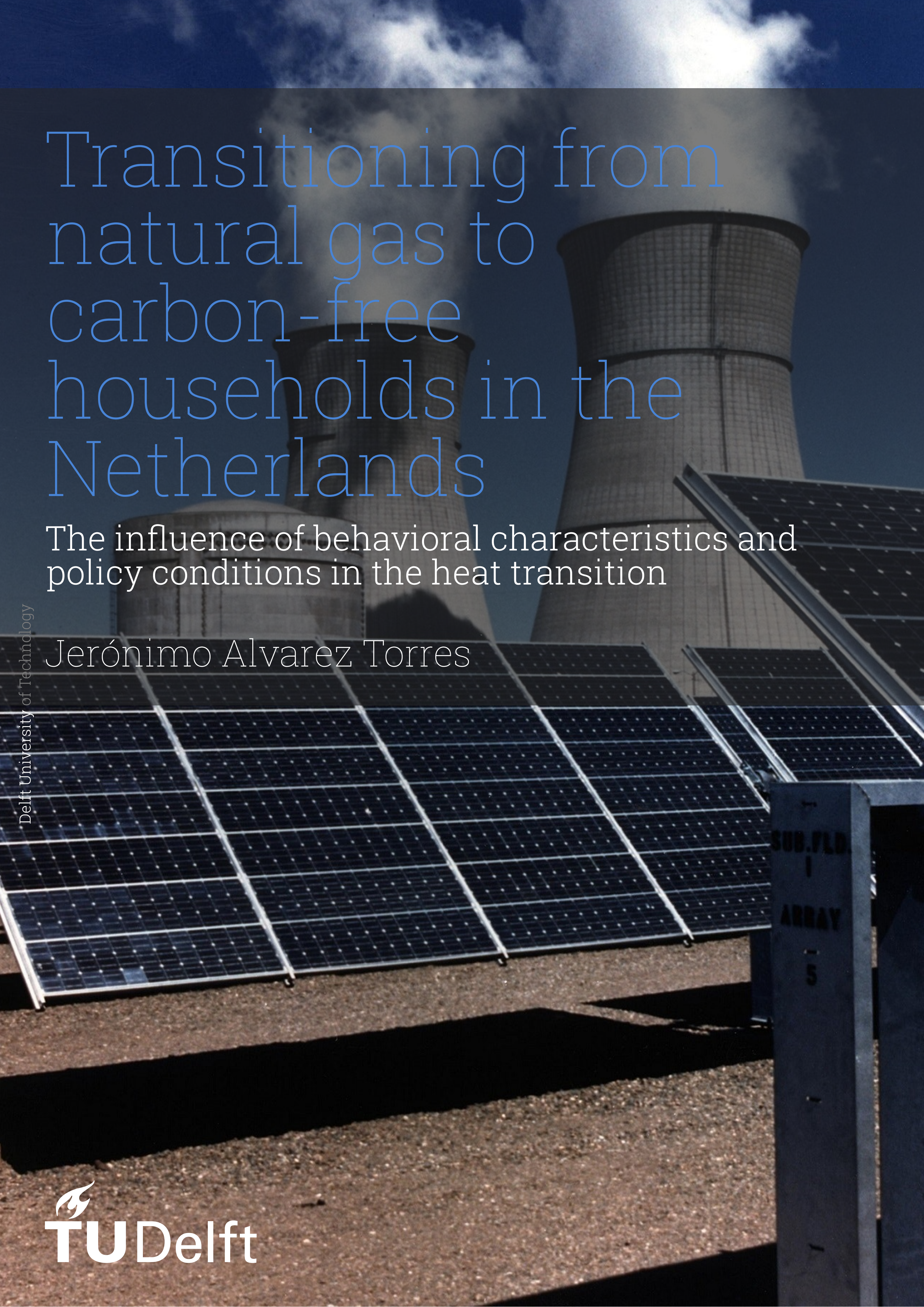
Delft University of Technology



TU Delft

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by

Jerónimo Alvarez Torres

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Jerónimo Alvarez Torres
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Summary

In the face of the current environmental crisis led by the extended use of fossil fuels to cover society's energy needs, sustainability objectives have been defined around the world. In the European Union, the European Green Deal has emerged as a leading guideline for its member states to achieve energy neutrality by 2050. The Netherlands has acted accordingly establishing its Climate Act, and setting ambitious objectives for this same year. Among these objectives, a full halt in natural gas use finds its way. Considering that the building sector, and specifically households, present a high consumption of energy, it results important to analyze how this sector can reduce its gas consumption and migrate towards the use of renewable heat systems.

The importance of behavioral characteristics and policy conditions that surround households regarding this transition has not been studied in depth in the documented literature and therefore stands as an opportunity area that this thesis covers. For achieving this, an agent-based model was developed using NetLogo, taking into account the characteristics of the Dutch population, being represented in the form of a sample neighborhood. The technical settings available in the model represent mature technologies that are currently in use in the Netherlands, and that can be used collectively or individually. Complementing and supporting these technologies, the Dutch government has made available a series of policy instruments, namely subsidies and credits, that financially support households in acquiring them. The availability of these subsidies is mainly dependent on the type of household ownership and additional factors, which are included in the model.

A behavioral theory known as the theory of planned behavior was implemented to define the households' behavior. This theory links three elements, namely attitude, subjective norms, and perceived behavioral control, to the final intention of households to execute an action. Regarding this specific topic, the study found out that the main beliefs that influence attitude are environmental friendliness, awareness of gas-saving measures, energy independence and economic drive. The subjective norms, which relate to social influence, are represented through the concept of belief dynamics, which develops the idea that social connections can shape a household's set of beliefs. Finally, perceived behavioral control, which is a measure of the apparent facility to execute a certain action, is reflected in four main external elements, namely the availability of subsidies, the municipality efforts, time availability, and financial capability of households.

The results of the model showed that with the current conditions, the Netherlands would be able to achieve a total of 55% of gas-free households by 2050. This, in turn, would represent a reduction of 45% of the current natural gas being used. To evaluate the extent to which behavioral characteristics and policy conditions influence the heat transition, additional scenarios were developed, where random behavioral attributes were assigned. Following the same line, additional scenarios were defined where the number of available subsidies and the amount awarded per subsidy varied, in addition to a scenario with a higher gas price. These scenarios showed that behavioral characteristics are a very relevant factor and can shape the extent to which the heat transition can be achieved. The policy conditions showed an influence, both in the extent of the heat transition and on the uptake of specific technologies. However, the amount awarded per subsidy and the price of gas showed no relevant differences in gas consumption or technology choice.

The results provide insights into the possibilities for policymakers to ensure that this transition is fulfilled. Policies should target the beliefs of society, either by inducing people into them or by reinforcing them. Besides this, technology choice seems to be directly influenced by the number of subsidies available for each specific technology, which could be useful to target specific technologies that might result more promising than others. Finally, considering that varying the amount awarded per subsidy did not generate a substantial difference, there is a possibility to redefine the subsidy schemes and reallocate this financial means to support the tenants, which is currently the group with the most restricted access to subsidies.

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1 Introduction

1.1. Research context

Global energy-related CO_2 emissions reached a total of 36.8 Gt CO_2 in 2022, which represents an increase of 0.9% in comparison to 2021 (International Environment Agency, 2023). According to the United Nations climate science panel, a reduction of 43% of greenhouse gases emissions must be achieved by 2030, relative to 2010, to constrain the global increase of temperature to 1.5°C and avoid disastrous ecological and social consequences (Abnett, 2022).

Globally, almost half of the consumed energy is related to heating purposes, leading to 40% of the carbon emissions (Cole, 2020). This number has been similar for over a decade within the European Union (Agency, 2023). Energy used for heating purposes in buildings, namely space and water heating, represented around half of the global energy demand of buildings in 2021. This led to a total of 2.5 Gt CO_2 emitted, which represented 80% of the total direct emissions related to buildings (Goodson, 2022).

The households sector in the European Union, specifically, is responsible for 28% of the final energy consumption. Space and water heating, which accounts for 78% of the final energy use in households, is in its majority supplied by fossil fuels, with renewable energy sources supplying only a quarter of this required energy (Agency, 2023). It is important to acknowledge the households sector as an important energy consumer and promote improvements in its energy efficiency levels (B. Gao et al., 2023).

In the Netherlands, 92% of the households still use natural gas for heating (Cole, 2021), due to the historical dependence on natural gas since the discovery of the Groningen gas field in 1956 (Palomo-Vélez et al., 2023). Nevertheless, the Netherlands has been pushing for a reduction of emissions, achieving in 2022 a level below 30% from that one in 1990 for the first time (CBS, 2023b). This emissions level can be partially attributed to a decrease in natural gas consumption, in the face of the disruption of the natural gas supply from Russia due to the war in Ukraine and the resulting increased prices (Williams, 2023). Nevertheless, it can also be attributed to an improvement in the used technologies' efficiencies (Goodson, 2022).

The Dutch government has set up the objective of reducing 95% of the carbon emissions by 2050 (Ministerie van Economische Zaken, n.d.), with an intermediate goal of 55% reduction by 2030 (CBS, 2023b). A set of measures and commitments to achieve these goals were laid down by the government through the "Klimaatakoord" or "Climate Agreement", published in 2019 (de Kluizenaar et al., 2020). Special attention is put towards the built environment, with strategies such as available funding for implementing sustainability measures in existing households. This has the goal of adapting around 7 million households to be properly insulated and heated using renewable heating systems (Government of the Netherlands, 2019). This combination of proper insulation and renewable heating generation has the ability to reduce the overall consumption of energy, while at the same time, reducing emissions due to the use of renewable sources to meet this demand (European Environment Agency, 2021).

With technologies such as heat pumps, solar thermal systems and different forms of district heating systems already proven and providing heat for households (Achtnicht et al., 2017), and different policies in place for facilitating their adoption (Government of the Netherlands, 2019), it results interesting to perform an integral assessment to evaluate the fulfillment potential of the goals set through the Climate Agreement, taking into account the Dutch households' own behavioral characteristics.

Considering the urgency of achieving the heat transition, ongoing academic research is focused on assessing the implementation of renewable heating systems in the household sector. However, it is possible to see that documented research mostly emphasizes the technical and economic aspects of their implementation, overlooking the influence of **behavioral characteristics** of households, especially in combination with given **policy conditions**. This was therefore identified as an important **academic knowledge gap** in this topic, due to its relevance as a complement to the existing documented studies, adding an additional dimension to these types of assessments.

The study presented in this thesis attempts to cover this academic knowledge gap by **exploring** how these behavioral characteristics shape the way in which households in the Netherlands are able to take part in the heat transition and to what extent they are able to influence this process.

1.2. Research questions

Considering the research gap mentioned in the previous section, the main question of this thesis was composed. This main question has the objective of providing insights regarding the adoption of renewable heating systems and how the behavior of households and institutional context affect this process in the Netherlands:

"What behavioral characteristics and policy conditions, under specific assumed technical and economic settings, are most effective in transitioning a significant proportion of Dutch households away from natural gas by 2050?"

To answer this main question, three sub-questions were composed. The first sub-question looks into the technical and economic settings of the implementable renewable heating systems available in the country:

SQ1: "What are the technical and economic settings for implementation to achieve natural gas–free households in the Netherlands?"

The second sub-question aims at identifying key behavioral household characteristics, along with relevant policy conditions, in the context of the heat transition and how they can be connected to the technologies identified in SQ1. This will also lead to the identification of core concepts that influence the households' behavior:

SQ2: "How can the different behavioral characteristics and policy conditions be combined with the technical and economic settings in transition scenarios?"

The third sub-question addresses the performance of the scenarios developed through SQ2 and aims at providing insights regarding the achievement of the natural gas reduction goals for households:

SQ3: "To what extent can the different behavioral characteristics and policy conditions achieve natural gas-free households?"

As mentioned before, the contribution of this thesis is strongly related to the inclusion of the behavioral characteristics of households within the models that explore heat transition. This, in addition to the inclusion of existing and implementable policy conditions, permits the identification of insights regarding the households' heat transition that help to answer the main question.

1.3. Systems perspective and link to CoSEM program

Energy systems are highly **complex** in nature, due to their composition and the different dynamic relationships taking place within them (Ridha et al., 2020). Essentially, the energy system is a technical system where actors such as generators, system operators, energy providers and end-users interact, however, with different interests and stakes (Cherp et al., 2011). This inclusion of different stakeholders turns the technical energy system into a **socio-technical** one. Besides, energy **transitions**, such as the one currently taking place, add an additional layer of complexity to the system due to the paradigm change in terms of energy supply, sources, and its corresponding feedback on policies that support this transition (Pruyt et al., 2011). This added complexity is reflected in the technical subsystem in the form of new renewable energy technologies being integrated, decentralized generation, and bidirectional energy flow, among others. The social subsystem is impacted by new stakeholders and new policy instruments that support the transition such as regulations, codes, and incentives.

In the system framed within this thesis, two subsystems are easily identifiable: the human one and the technological one. The human subsystem is made up of households, with individual behavioral patterns and intricate networks between them. The technological subsystem is constituted by the different technologies that can be used to generate heat in a clean manner. The interaction between both subsystems is promoted by its overarching context: the development of climate change and the consequential resulting ecological and energy regulations, where different public and private bodies play a role. This interaction between scales of space and time defines the system as a **complex adaptive system** (Kraan et al., 2016). Properties of this kind of system include emergence, non-linearity, interconnectedness and adaptation (Van Dam et al., 2012), and therefore should be considered. It is therefore possible to say that the topic of this thesis aligns with the **CoSEM** program, as it is focused on understanding the influence of technology and human behavior within the complex adaptive system of the heat transition.

1.4. Research approach

System studies can be performed in different ways, as shown in Figure 1.1. Due to the nature of this study and the size and complexity of the system, it results difficult to perform experiments with the actual system. Therefore, a model of the system has been chosen as the most appropriate option. Similarly, physical models are out of the question as they require the use of physical constructions that represent the system, which in contrast to mathematical models, can be costly and time-consuming (Sparling, 2016). Given that the knowledge gap presented in section 1.1 reflects a **lack of understanding** of the effect the behaviors by the households and policies can have regarding the adoption of renewable heating systems, the choice has been made towards a **simulation** of the model. This way, it can be possible to study the relationship between variables, and the effect variations in the values of these variables can have on the overall behavior of the system (Birta and Arbez, 2013). Like this, it can be possible to explore the extent to which different combinations of behavioral characteristics and policy conditions can contribute towards achieving the heat transition.

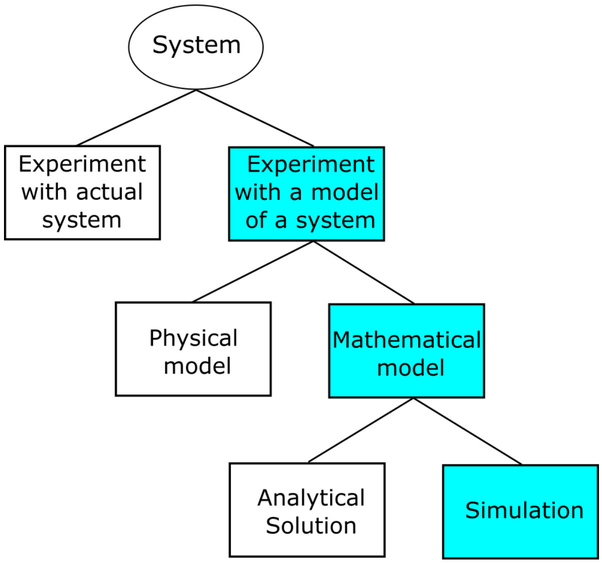

Figure 1.1: Different ways of studying a system (Eduard and Ming, 2010)

As mentioned before, due to its characteristics, the studied system can be categorized as a complex adaptive system (Kraan et al., 2016). These types of systems can be best studied through the use of **agent-based models**, as they are successful at capturing the system's complex structures and dynamics (Van Dam et al., 2012). They also allow for the construction of models when one only has information on the behavior of the individual components or when one knows very little or nothing about the behavior of the entire system (Borshchev and Filippov, 2004). In other words, they work from a **bottom-up** perspective, having the capability of representing emergent system properties (Van Dam et al., 2012).

Some advantages and disadvantages of using agent-based models have been described in the literature (Bonabeau, 2002; Van Dam et al., 2012). Advantages include 1) the possibility of capturing emergent phenomena, 2) providing a natural description of the system, making it seem closer to reality, and 3) providing high flexibility for configuration activities such as adding more agents, adjusting their complexity, or having various levels of aggregation. On the contrary, disadvantages include 1) the necessity for the model to have the right amount of description and detail, 2) the difficulty of quantifying and justifying the behavior of human agents, and 3) large systems having computationally intensive requirements for modeling.

Additionally, agent-based models have an important trait: they allow to represent all the different characteristics of social agents, namely **behavior**, **motivations** and **relationships** between them (Bankes, 2002). They may also simulate **belief dynamics**, including cognitive and social network elements, and produce predictions that can be empirically tested (Galesic et al., 2021). This makes them a very convenient tool to make use of while studying social sciences, or systems that present human interactions (Helbing, 2012).

1.5. Outline

The rest of the document is structured as follows: Chapter 2 describes the research approach carried out in this thesis and links it to the presented model; Chapter 3 presents the theoretical background, which elaborates on the general topic areas of this thesis and explains key concepts; Chapter 4 further elaborates on the topics presented in Chapter 3 but with a focus on the Dutch heat transition, Chapter 5 discusses the model itself, from conceptualization to implementation; Chapter 6 presents the results of the model, their discussion and reflection, and Chapter 7 presents a conclusion and discusses the relevance of the work performed.

2
Research Design

This section describes the conceptual framework of the research. It covers how the knowledge gap that this thesis attempts to cover was defined, and provides an overview of the methodological definition and structurization of the research.

2.1. Research gaps in energy transition agent-based models

As presented in the introduction, the academic knowledge gap that this thesis covers is supported by the fact that the documented studies do not assess the extent to which the behavioral characteristics of the households affect the heat transition. This section documents the performed procedure that made this academic knowledge gap evident.

2.1.1. Assessment research gap

An initial **systematic literature review** was conducted on 10 March 2023, with the intention of exploring the different existing studies that covered the implementation of a certain kind of renewable heating system and a corresponding assessment of some sort. An overview of the implementation and structure of this literature review and the selected articles can be found in Appendix A.

All the selected articles present and discuss the implementation of a certain type of renewable heating system, including an assessment of performance. This assessment can be categorized into four main areas: economic, technical, environmental, and social. Single category evaluations were presented by five articles in the social (Freyre et al., 2021; Hecher et al., 2017), environmental (Mahon et al., 2021), economical (Roben et al., 2022), and technical (Haller et al., 2013) areas. The remaining six articles performed a more elaborate analysis as they evaluated two or more categories.

Regarding the different areas, six articles present an economic analysis. Economic factors like capital expenditure, operational costs and cost of energy are compared by Pokhrel et al. (2022), Roben et al. (2022) and Durga et al. (2021) for different renewable heating systems configurations and natural gas or other conventional systems. Two articles (Ashfaq and Ianakiev, 2018; Chen et al., 2021) consider initial investment and operating cost for determining the optimal sizing of different renewable heating system components while minimizing carbon emissions. The behavior of investment, fuel and operational costs for RHS in buildings is evaluated by Haase and Torio (2021) under different policy scenarios.

Five articles present a technical analysis. Sizing, performance and efficiency calculations are presented by Pokhrel et al. (2022) and Durga et al. (2021) for different renewable system configurations and compared to natural gas systems. Two more articles (Ashfaq and Ianakiev, 2018; Chen et al., 2021) present calculations for optimally sizing heat generation and storage for a system throughout a year. Finally, Haller et al. (2013) tested different elements and control methods for a renewable heating system to evaluate its dynamic behavior.

Two articles present an environmental analysis. Mahon et al. (2021) analyze global warming, eutrophication, human toxicity potentials, and fossil fuel depletion for a district heating system throughout its lifecycle. Similarly, Walmsley et al. (2015) evaluate energy return on investment ratios, emission factors and availability of resources for a renewable heating system.

The remaining three articles present a social analysis. Two of them (Freyre et al., 2021; Hecher et al., 2017) determine the drivers and the decision-making process for household owners to install renewable heating systems, while Haase and Torio (2021) present a study to determine the effect of recent policy changes and subsidy schemes on the heating market.

It is important to consider that the implementation of renewable heating systems depends on the site-specific availability of resources and the existing conventional heating systems. It is, therefore, necessary to keep in mind that the geographical scope plays a big part in the results of the analyses performed (Pokhrel et al., 2022).

It is possible to see that the previously presented studies cover different aspects of the implementation of renewable heating systems, with a stronger emphasis on the economic and technical aspects, as four articles evaluate these two criteria at the same time. This can be explained by understanding that the studies evaluated the actual implementation of a renewable system in place of an existing conventional heating system, which therefore reinforces the conception that the two biggest challenges are the technical coupling and the economic implications, as has been shown (Alabid et al., 2022; H. Du et al., 2019). Environmental aspects, on the other hand, are the least covered aspect, possibly due to the existing idea that renewable energy technologies decrease emissions simply due to their reliance on renewable energy sources, which have been already proven to produce no emissions while generating heat or electricity (Shafiei and Salim, 2014).

The social assessments covered by the articles can be categorized into two areas: the effect of policy implementation and the positions of households regarding renewable heating systems. The two studies that covered the positions of household owners mainly based their studies on exploring the reasons that made them switch to a renewable-based system. Both studies were based on surveys from household owners that had already switched systems. However, it was possible to see that none of the studies analyzed two important factors: the influence of the behavioral characteristics of the end-users on the process of acquiring renewable heating technologies, and the influence of policy conditions on the motivation of the end-users.

Existing studies **neglect** the influence of behavioral characteristics and the effect of policy conditions on the heat transition for households. Including them, in combination with specific technical and economic settings, can provide a more complete image of the situation, broadening an academic area currently in research and providing a reference for policymakers. This was therefore identified as the **main research gap** that this thesis is covering.

2.1.2. Behavioral theory research gap

As described in Chapter 1, agent-based models have an edge over other modeling techniques when it comes to modeling complex adaptive socio-technical systems, mainly due to their capability of showing emergent properties of systems that were defined from a bottom-up perspective (Kraan et al., 2016). Due to the characteristics of the system that is being studied and the main research gap that was identified, the more appropriate modeling technique to implement is to construct one of these models. Considering that the foundation of such a model is the entity of an **"agent"** (Dam et al., 2013), it seems appropriate to base the behavior of the agents of the model, in this case households, on a **behavioral theory**. Behavioral theories are explained further in Chapter 3. However, it is worth mentioning here that the **theory of planned behavior** by Ajzen (1991) stands out as a practical and popular theory for modeling behavior.

Taking the above into consideration, a second **systematic literature review** was conducted on 1 April 2023 in order to determine the existing research gap in agent-based models that model the behavior of agents within the heat or energy transition context. Again, the results of this literature review can be found in Appendix A.

The results showed that several studies do not make use of a behavioral theory, even if they are modeling human behavior. However, among those studies that made use of one of these theories, a variety of theories were used. The theory of planned behavior was used to model agent behavior in three different studies. Interestingly, all three models were studying the adoption of photovoltaic systems (Caprioli et al., 2020; Caprioli et al., 2019; Moglia et al., 2022), with one of them additionally studying the implementation of retrofit systems, namely double glazing, envelop insulation, and ventilation systems (Caprioli et al., 2019).

None of the results described the implementation of an agent-based model to study heat transition, specifically with the scope that this thesis has. The results that made use of the theory of planned behavior were focusing mainly on implementing photovoltaic systems, and the single result that included heat-saving measures was not evaluating their adoption in the face of achieving a full heat transition for households. Therefore, this knowledge gap, along with the theory characteristics commented on in Chapter 4 support the possibility of using the theory of planned behavior to model the behavior of the households for this thesis.

2.2. Agent-based models

Complementing what was already mentioned in Chapter 1, agent-based modeling is a computational method used to model social systems (Miller and Page, 2009). They are able to represent the different structures and interactions taking place in complex adaptive systems (Van Dam et al., 2012), as well as characteristics of complex adaptive systems like evolution, aggregated behavior, anticipation of the future and decentralized control (Nava Guerrero et al., 2019). There are three main components that constitute agent-based models: agents, environment and time (Dam et al., 2013).

Agents are the representations of the actors in the real socio-technical system. According to van Dam et al. (2013), and adapted from Jennings (2000), agents have characteristics that include:

- They are easy to identify due to their defined boundaries.
- They are placed in a specific environment, and can receive information from it and act in response.
- They can answer to changes and anticipate them.
- They have control over their own state and behavior.
- They are designed to fulfill a purpose.

The environment is defined as the place where agents are located. The environment provides the agents with information and a space where agents can interact (Dam et al., 2013). As mentioned before, the environment provides the agents with a variety of information that allows them to adapt their behavior. The environment can be shaped by the agent in response to the context it provides (Macal and North, 2009).

Interactions among agents in real systems occur parallelly in a continuous way. However, due to computational constraints, time can only be modeled in a discrete way, with parallel interactions limited by the computational power of the software and hardware specifications (Dam et al., 2013). This is therefore important to keep in mind, to be able to produce a model that can represent reality in spite of these limitations (Hammond, 2015).

2.3. Research framework

Once the research methods to be used and the system of study have been determined, it becomes crucial to establish a clear structure for the research. The purpose of this structuring process is twofold: first, to define the relationships between various elements of the research, and second, to provide a framework for approaching each stage of the research process.

A **series of steps** have been proposed by Nikolic et al. (2013) to create agent-based models of socio-technical systems. The steps have been formulated as a practical approach, and have been used as a guide for performing the research detailed in this thesis.

Looking forward to achieving a correct and detailed description of the developed model, a structured framework known as **”ODD protocol”** (Overview, Design concepts, Details) has been chosen as an appropriate guide to explain the different elements of the model and its functioning. This model was developed by Grimm et al. (2020) with the idea of facilitating a common framework for describing agent-based models, and its structure is shown in Figure 2.1.

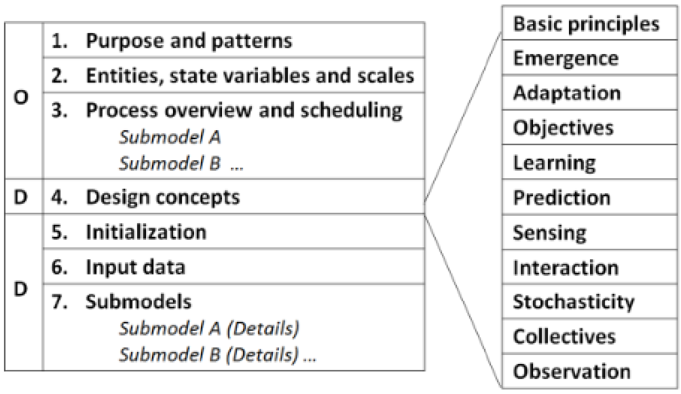

Figure 2.1: Structure of the ODD protocol (Grimm et al., 2020)

The steps, in combination with the ODD protocol, are listed below with a description of their implementation within the model:

Problem formulation and actor identification: two systematic literature reviews were conducted at the beginning of the investigation to identify the research gaps around the study of the households within the heat transition. The results of both reviews can be found in Appendix A, and their discussion was presented earlier in this chapter. This allowed the formulation of the research questions and the selection of the research approach, described in Chapters 1 and 2, respectively. The identification of actors could be done afterward: Chapter 5 includes a description of the households based on the ODD protocol, with its characteristics and the relationships between them.

System identification and decomposition: in this phase, the different elements that form the system are identified and characterized. We can identify three main components: the household component, the renewable heating technologies component and the policies component. Research on the household component was more extensive and elaborate, given the scope of the research. Household characterization was performed on the basis of 1) the Dutch demographic and socio-economical characteristics, 2) behavioral characteristics around the energy transition and renewable heating systems acquisition, and 3) household interaction and information exchange dynamics. The renewable heating technologies component characterization included the collection of pieces of information regarding the current status of installed technologies and the economic and technical settings of these technologies. The information gathered here was used to answer sub-question 1. For understanding the policies component, information regarding the different clean energy objectives and support programs available for Dutch households was compiled and analyzed. At last, links and relationships between the three components were established and their dynamics were defined. This process resulted in the answer to sub-question 2. A detailed description of all these can be found in Chapter 4.

Concept and model formalisation: using the output of the second step, it was possible to construct a conceptual model through a series of flow diagrams that show how the interactions within the system occur and how the different decision points for the households lead them to the next steps. These flow diagrams are detailed and explained in Chapter 5. After an iterative process of verification and validation of the conceptual model, the formal model was created. This formal model has the form of pseudocode and a variable definition and is included in Chapter 5.

Software implementation: the formal model was translated into a computational model using NetLogo 6.2.1 (Wilensky, 1999). NetLogo is a programming language that is suited for education and research and is especially useful for modeling complex systems that evolve over time. It has certain characteristics that made it ideal for using it to implement the model described in this thesis. First, it enables setting up different independent agents at the same time, each with a set of instructions that model their behavior. Second, it permits users to simulate the model under different conditions using variables that can be easily configured using the built-in interface and the simulation environment. Third, it has been proven since 1999 with multiple applications and therefore is mature enough to be stable and fast. Finally, its documentation is extensive and detailed and comes with a collection of sample models that can be used for reference (Tisue and Wilensky, 2004).

Model verification and validation: Verification and validation of models are two techniques that provide confidence in the functioning of the model and its results (S. Robinson, 1997). Model verification ensures that the model is correct and performs as intended, while model validation refers to the process of making sure that the functioning of the model matches the functioning of the real system (Carson, 2002).

Robinson (1997) mentions that both techniques should be performed throughout the entirety of the modeling process. The objective of this is to achieve a continuous assessment of the model's functioning. This was the case for the model presented in this thesis. A thorough description of the different activities carried out in this regard can be found in Chapter 5.

Experimentation: an experimental campaign was carried out using the NetLogo model. An initial sensitivity analysis was performed to determine the set of initial variable values that were able to capture the largest amount of detail of the outputs. Afterward, the model was run using different scenarios to analyze the differences in results. A detailed description of the experimental campaign can be found in Chapter 6.

Data analysis: the results of the experimental campaign are presented and discussed in Chapter 6, which ultimately leads to answering sub-question 3, and after integration of the answers to the first two sub-questions, also the main question. The analysis is focused on one hand, on the behavioral characteristics of households and what their effect is towards the achievement of gas-free households. On the other hand, the influence of the available policy conditions is also reflected in their influence on the behavioral characteristics of the households and the achievement of gas-free households as well.

Model use: in Chapter 7 insights are presented on the elaboration of policies that support the acquisition of renewable heating technologies by households and on the possibilities of further study and exploration regarding this topic.

Figure 2.2 shows a diagram with the structure of the research. The structuring process was based on the previously mentioned steps by Nikolic et al. (2013). The diagram shows relationships between the different elements of the study and links the content of the different steps with the chapters in this document. Besides, annotations regarding the answers to the proposed sub-questions are included to show where they can be found.

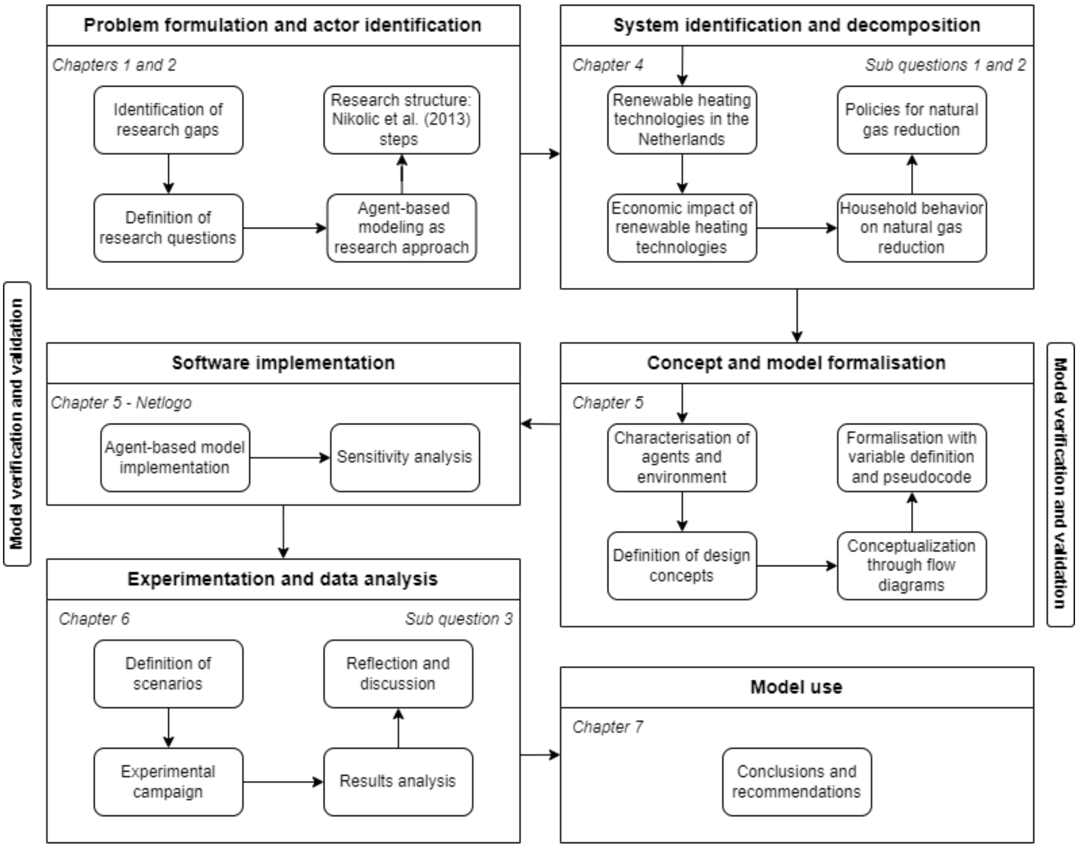

Figure 2.2: Research flow diagram

2.4. Case study scope

For developing this thesis, a **case study** has been selected as the appropriate research method to combine the selection of applying an agent-based model. This particular case study covers the development of households in the Netherlands around the heat transition.

Case studies are useful when attempting to study specific systems with delimited boundaries. As described by Flyvbjerg (2011), selecting a case study targets the research direction of an individual unit, thus defining the boundaries of what this unit entails. In the particular case of this thesis, the ”unit” is delimited within the geographical scope of the Netherlands, represented through a sample neighborhood.

As commented by Njie and Asimiran (2014), a case study has as its objective to analyze the background and factors that have an impact on the theoretical topics being investigated. Therefore, the particular characteristics of the system under study need to be defined. In the precise case of this thesis, the general demographic, institutional, technological and behavioral characteristics present around the Dutch household demographic are present in the characteristics configured for the sample neighborhood developed in the agent-based model.

The Netherlands forms an interesting case to study the processes and factors around the heat transition in households. First, as was already mentioned, 92% of the Dutch households are still connected to the natural gas grid, which makes the Netherlands the European country with the highest proportion of gas-connected households (Cole, 2021). Besides, there is a possibility that this household transition can set foot towards a larger energy transition, considering that the country is one of the European countries with the lowest share of renewable energy generation in its energy system (Cole, 2022).

Another factor makes this choice for the case study interesting: in 1959, the Groningen gas field, one of the largest in the world and particularly the largest in Europe, was discovered (EBN, 2023). This drove a fast change in the energy system: infrastructure for transporting and using this gas was developed, first in the Netherlands and soon after throughout Europe. This was a tipping point in the Dutch economy, as the country was able to swiftly base its energy system on natural gas, while at the same time raising its living standards derived from the economic benefits that this discovery brought along (Whaley, 2009). In a certain way, it is possible to still see a degree of path dependence - the conception that past acts or decisions influence the course of present and future states, acts or decisions (Page et al., 2006), considering the huge dependence the country still has on this resource. However, with factors discouraging the use of natural gas such as continuous extraction-induced earthquakes in the Groningen region affecting citizens and damaging buildings (Alliance, 2021) and sustainability objectives that look to disconnect seven million households and one million buildings from the natural gas infrastructure by 2050 (Government of the Netherlands, 2019), it naturally results interesting to research on the possibilities for the country to achieve this transition.

Additionally, and considering that the implementation of a case study through an agent-based model requires the use of data specific to the system at study (Macal and North, 2009), it results conveniently that for this specific system, data is widely available. First, a study known as ”Woononderzoek” (Rijksoverheid, 2022), which is a housing survey in the Netherlands performed every three years, provides insights into the demographic characteristics of households and their situation. The most recent available results correspond to the 2021 study and are publicly available. Second, information regarding public policies for supporting the adoption of renewable energy technologies in the Netherlands is available on several websites, which is the same case for information on the different available technologies in the country. Finally, a study presented by Koirala et al. (2018) presents the results of a survey among 599 Dutch citizens, which provides insights on different personal factors and positions around the willingness to acquire renewable energy technologies and participate in community energy systems. All these information sets are used to characterize the system of study that is represented through the agent-based model developed.

2.5. Conclusion

In order to complement the existing studies on heat transition, it is valuable to construct an agent-based model that includes the behavioral characteristics and the policy conditions that surround Dutch households regarding the heat transition and adoption of renewable heating systems, using the theory of planned behavior as behavioral theory. This could address an academic knowledge gap that has been overlooked in documented studies, regarding both the behavioral assessment and the use of the mentioned theory for modeling heat transition. Besides, the specific case of Dutch households is interesting due to the historical dependence on natural gas and the relatively low penetration of renewable heating systems, in combination with the ambitious 2050 decarbonization objectives.

A set of steps for modeling purposes based on the work by Nikolic et al. (2013) are used as guidelines to decompose the system, build a conceptual model and translate it into a formal model to implement it using NetLogo as a modeling software.

3

Theoretical Background

This section examines some important topics connected to the different areas the main question tackles, providing a synthesis of key concepts and theories that lay the foundations of the work presented in this document, and that allow for a better understanding of the performed research.

3.1. Socio-technical systems

The concept of a ”socio-technical system” refers to the integration of technical components and social elements within a complex whole (Bauer and Herder, 2009). This term was first introduced in labor studies during the late 1950s, given the then-changing context between workers and their working environment (Trist, 1981). However, according to the suggestion by Ropohl (1979), technology, in general, should be explained using this concept due to the intrinsic relationship it has with humans.

A central aspect to consider is that a socio-technical system comes to be when the relationship between both subsystems, the social and the technical, is so closely linked to each other that its design or optimization should be performed taking both subsystems into account (Bauer and Herder, 2009). Social elements like values, norms and even cultural structures influence the design of the technical subsystem, while at the same time, the technological infrastructure and work procedures influence individual and group behavior (Emery, 2016).

The interaction of humans with technology, the social subsystem with the technical subsystem, is dynamic in nature and constitutes an evolving process (Ropohl, 1999). Bauer and Herder (2009) comment on the different time frames where this shaping process comes to be, from continuous adjustments present in the resources allocation process to changes every one to ten centuries to the informal values inherent to the technologies people use.

3.2. Complex adaptive systems

Complex adaptive systems are systems constituted by agents that are in constant interaction with one another (Holland, 1992). These agents have defined behavioral characteristics. However, the behavior of the system as a whole is emergent and aggregated from the agents' interactions through their individual behaviors (Lansing, 2003).

Holland (1992) argues that complex adaptive systems have three main characteristics that are always present, regardless of the nature of the system: evolution, aggregate behavior, and anticipation.

Agents in complex adaptive systems are constantly looking to improve measures of goodness, also known as ”fitness”, based on their environment and the other agents. This process is what constitutes evolution, which occurs according to two key principles: order emerges, rather than being preset, and the state of the system is irreversible and most of the times unpredictable (Dooley, 1997).

The behavior of the system, as mentioned before, emerges from the behavior of the constituent parts and their interactions (Dam et al., 2013). Therefore, the global behavior of the system is an aggregated behavior, which can only be understood by studying the behavior at a system level (Li et al., 2006).

Knowing that agents are constantly looking to improve their fitness, they engage in anticipation practices, which according to Holland (1992), is due to agents trying to adapt to changing circumstances even before they occur. Naturally, this leads to changes in the aggregate behavior that keep on shaping the context in which the agents develop, which further makes them try to improve their fitness.

These processes of action and reaction of agents embedded within a network lead to a highly decentralized control across multiple levels of aggregation, which in turn lead to dynamic emergent patterns at local and system levels (Dam et al., 2013). All this is a reflection of the complexity that complex adaptive systems exhibit.

3.3. Heating systems

As commented in section 1.1, almost half of the world's energy consumption is allocated to heating tasks (Cole, 2020). Currently, that heating demand is mainly covered directly by the use of energy sources like coal, gas and oil, or indirectly by the use of electricity (Ramos Cabal et al., 2017). However, burning fossil fuels releases carbon dioxide into the atmosphere, which is the main driver of climate change (Lackner et al., 2010).

It is possible to define and study heating systems through a socio-technical systems perspective. Technologies, users, and the environment can be seen as different subsystems that form a network where interactions between them take place. Additionally, the presence of policies such as subsidies and regulations influence this network and shape it (Nava Guerrero et al., 2019).

Renewable heat systems are systems that rely on local renewable resources to generate heat and electricity for their functioning (Chen et al., 2021). They are often combined with electrical and heat storage systems, that allow for autonomy due to the intermittent nature of these renewable resources, namely solar and wind (Rämä and Wahlroos, 2018).

Renewable sources like solar and geothermal energy can be used to produce heat (Herzog et al., 2001). As their use to generate heat or even electricity, does not lead to the emission of greenhouse gases, they are considered sustainable in the long term (Kothari et al., 2010). In 2020, 11% of the world's heating demand was met by using renewable sources, with a projected increase to 13% in 2026 (IEA, 2023a).

The use of biomass is an interesting one, as it is usually considered a renewable and sustainable source (Herzog et al., 2001), although its combustion actually generates emissions into the atmosphere (Obaidullah et al., 2012). Its use in developing countries is more widespread than in developed ones, and it is usually done there through direct combustion (Herzog et al., 2001).

Technically, heat production throughout history has been done in a decentralized way. Heat is usually produced by the end-user close to the consumption point, such as domestic hot water produced in houses or buildings, or heat for cooking, for example (Stryi-Hipp, 2015). However, centralized systems that serve several end-users have also been present since the Roman Empire (Stryi-Hipp, 2015), with different types of sources, like geothermal (Torné et al., 2023), aqua thermal (Goossens et al., n.d.) and bioenergy (He et al., 2013) systems currently in use.

In the last years, there has been an important development of technologies for supplying renewable heat to buildings, namely households (Kranzl et al., 2013). Some of these technologies include solar thermal systems, heat pumps, and modern biomass boilers (Yang et al., 2018).

Integrating these new technologies in the existing built environment and infrastructure poses several technical challenges: sources like solar energy present daily and seasonal variations that lead to intermittent generation (Yin et al., 2020). Heat storage might be required to guarantee a constant and reliable supply in moments where renewable heat production is low (Weitemeyer et al., 2015). Retrofitting existing buildings to accommodate new technologies can be challenging, expensive, and cause disturbances to the existing heat provision systems (Ferrante and Semprini, 2011).

Some of the social challenges include the high upfront costs that acquiring new technologies might represent for some users (Egli et al., 2018); public perception of renewable heating technologies can hinder their adoption due to misconceptions on their benefits in the short and long-term (Devine-Wright, 2007). A way to sort these social challenges is through the implementation of public policies that support renewable energy development, as has been shown by social scientists (Patel and Parkins, 2023).

3.4. Human behavior and energy use

As was noted previously, a broad range of household energy behaviors needs to be significantly modified to achieve the energy transition goals (Steg et al., 2015). Existing research shows that energy consumption amongst households varies according to socio-demographic factors such as building characteristics (Al-Shargabi et al., 2022; Santin et al., 2009), including type, size and age, local climate (Lauzet et al., 2019), the existence of heating and ventilation systems (Santin, 2011), and occupant characteristics such as type of ownership, age, income and behavior (Dietz et al., 2013; Gaspari et al., 2021).

The psychological characteristics of household occupants are another determining factor in shaping their energy use patterns (Frederiks et al., 2015). Research shows that aspects like environmental knowledge and awareness (Pietrapertosa et al., 2021), values, attitudes and beliefs (Brounen et al., 2013), motives, intentions and goals (Bishoge et al., 2021; Lee et al., 2020), personal norms and perceived responsibility (Frederiks et al., 2015; Ibtissem, 2010), perceived behavioral control (Pals and Singer, 2015; Ru et al., 2018), perceived cost-benefit ratio (Attari et al., 2010; Frederiks et al., 2015), need for personal comfort (Frederiks et al., 2015), and normative social influence (Jain et al., 2013; Schultz et al., 2008) also have an impact on the final amount of energy people use to fulfill their daily activities.

Studies have looked into how people developing a certain level of environmental concern and possessing environmental awareness and knowledge leads them to engage in pro-environmental behavior at different levels (Huddart Kennedy et al., 2015; Kollmuss and Agyeman, 2002; Ru et al., 2021). Stoknes (2014) reported a widening gap between the declining public concern and support for bold and successful climate policies, and the growing scientific consensus that human-caused climate change exists, which he dubbed the ”psychological climate paradox”. A survey conducted by BCG during the COVID-19 pandemic to more than 3,000 people across eight countries reported that 70% of the participants were more aware at that time than before the pandemic started, of the importance of tackling environmental problems, with only 40% committing to engaging more actively in pro-environmental behavior (Kachaner et al., 2023).

As noted by Stoknes (2014), more environmentally friendly practices appear to be seriously hampered by this discrepancy between people’s environmental awareness and their response to climate change. This gap between a person’s values and the performed actions that might reflect those values is called the ”value-action gap” (Barr, 2006). This value-action gap, put into the context of energy efficiency, relates to how consumers avoid engaging in actions that lead to a reduction in their energy consumption (such as acquiring more technologically efficient products or products that use renewable energies as power source), even though they are available in the market and have a faster return on investment due to their consequent energy savings (Brown and Sovacool, 2018).

Brown and Sovacool (2018) compiled a list of 23 behavioral theories that are able to address this value-action gap in the context of energy efficiency, and that take into account contextual factors, social norms, beliefs, attitudes and values. These theories have been widely used in different studies regarding the energy transition, namely and among others the theory of planned behavior (J. Du and Pan, 2021; L. Gao et al., 2017; Macovei et al., 2015), the attribution theory (Febriani and Avicenna, 2022), the focus theory of normative conduct (Bergquist and Nilsson, 2016), the social learning theory (Glad, 2012), the theory of reasoned action (Alzahrani et al., 2019; Bang et al., 2000; Lei et al., 2011), the values-beliefs-norms theory (Fornara et al., 2016; Ibtissem, 2010; Van der Werff and Steg, 2016) and the diffusion of innovations theory (Franceschinis et al., 2017; Völlink et al., 2002). As noted by Ertz et al. (2016), taking into account the existing research, the theory of planned behavior has been the most prominent framework when it comes to taking into account intra-personal aspects like attitudes, norms and beliefs.

3.5. The theory of planned behavior

Ajzen (1991) developed this model seeking to explain how human behavior gets influenced by individual attitudes, beliefs and intentions in the face of behaviors under ”non-volitional control” - behaviors whose performance depends to some extent on external factors such as availability of opportunities or resources. This model is an improvement from the theory of reasoned action developed by Ajzen and Fishbein (1980), as it manages to include the influence of these external factors on both the intention and the behavior itself (Ajzen, 1991).

Figure 3.1 shows a diagram of how the different elements of the theory interact with each other.

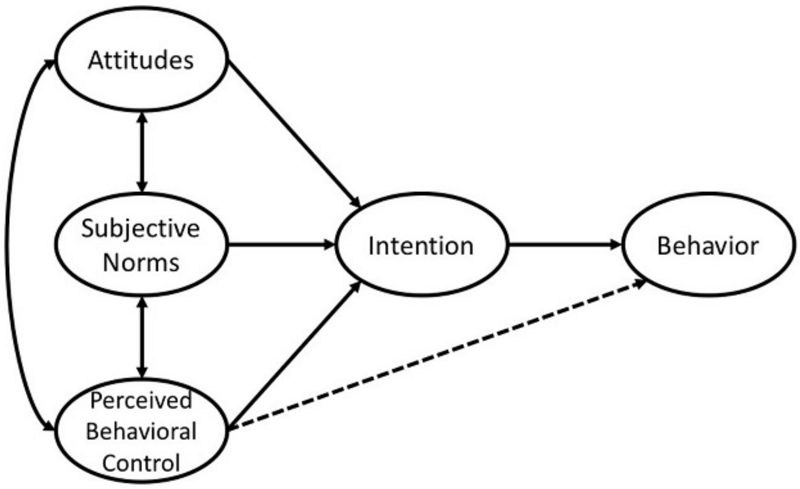

Figure 3.1: The theory of planned behavior (Ajzen, 1991)

It is possible to see that a person’s intention to carry out a specific behavior is a key component of the model: it is the precursor of people behaving in a certain way (Ajzen, 1991). Intentions encompass the driving forces for motivation: in other words, they show how hard people are willing to attempt to execute the behavior (Conner, 2020). This behavior must be defined in terms of its target, the action involved, its context, and its time frame. This definition will have an influence on the rest of the elements in the model as these should match the behavioral definition, thus fulfilling the ”principle of compatibility” (Ajzen, 2005).

Three factors are the ones that exert an influence on the intention: attitudes toward the behavior, subjective norms in the face of the behavior and perceived behavioral control (Ajzen, 1991).

The attitudes towards a certain behavior are directly linked to the beliefs that the performance of said behavior will bring along a set of consequences upon which a preconceived idea exists (Ajzen, 2020). In other words, attitudes represent the feelings that a person might have about performing certain behavior and the impact this behavior might have.

Subjective norms encompass the pressure of performing a certain behavior due to social expectations. They can be related to either the expectation that a pressure individual or group (people that the individual deems as important) will approve of the behavior, or that the pressure group in question performs the behavior themselves and expects the same from the individual (Ajzen, 2020). The significance or importance that the reference pressure individual or group has over the individual affects proportionally the degree to which the subjective norm has an influence on said individual (Conner, 2020).

The third element, perceived behavioral control, has both an influence on the aggregate intention, and contributes as a facilitator of the behavior, complementing the intention itself (Ajzen, 1991). This element refers to the existence of factors that can contribute to the fulfillment of the action or conversely, impede it. These factors include internal factors like skills or intelligence and external factors like financial means or legal barriers (Ajzen, 2020).

It is usually the case that the higher the intention value, the higher the chance for the person to execute the behavior (Ajzen, 2020).

According to Ajzen (2020), factors such as demographic characteristics, character qualities or life values intrinsically influence each of the three precursors of intention, therefore having an effect on the ultimate behavior.

Like it was mentioned previously, this theory has been used to model behavior in a wide variety of study areas, with around 2,000 different papers (Ajzen, 2023) citing it.

3.6. Social norms and belief dynamics

Subjective norms within the scope of the theory of planned behavior imply a degree of influence of the social structure that is inherent to the individual: social norms - expectations of proper behavior that takes place in a collective setting - are the foundation of the pillars of human essence like culture, language, social interaction, among many more (McDonald and Crandall, 2015).

The degree of social influence that social norms are able to exert on the attitudes and behaviors of the individual varies according to the type of social norm (McDonald and Crandall, 2015). According to Kelman (1961), descriptive norms - norms that show the way a group behaves (Deutsch and Gerard, 1955) - lead to a genuine and unstrained change in beliefs and behaviors, while injunctive norms - the approval or disapproval perception of a particular behavior within the group (Deutsch and Gerard, 1955), only achieve resulting beliefs and behaviors that are deemed as managed and less genuine.

This process of how beliefs are influenced, ”belief dynamics”, relies on a structure composed of two elements: the individual’s own beliefs and the way they are linked, and the individual’s social network and the strength of the different connections (Galesic et al., 2021).

The first element relates to any assumptions or views relating to a particular topic. The level of agreement towards them can be measured in different scales, including dichotomous, point scales, or probability distributions. These beliefs usually experience changes over time (Galesic et al., 2021).

The second element is concerned with the data derived from a person’s social surroundings. The network under which the connections are included and its underlying characteristics have a strong influence on belief dynamics, with characteristics such as centrality (M. Granovetter, 1985) or the links’ weight and length (M. S. Granovetter, 1973) influencing the way the information flows and consequentially influences the individual.

In case of differences between an individual’s own beliefs and new information that he might be in contact with, coming for example from another individual in his network, a discomfort state known as dissonance might occur (Heider, 1982; McGrath, 2017). Research has shown how individuals are able to deal with dissonance mainly by updating their beliefs to fit better with the new information (Balcetis and Dunning, 2007; Schelling, 1969; Van Harreveld et al., 2009). Another reported way they are able to resolve dissonance is by updating their social network (Heider, 1982).

Galesic et al. (2021) propose a framework where they are able to quantify the impact that this belief update has on the original belief. They achieve this by making use of three integration techniques: simple averaging, weighted averaging (in the function of the connection’s link strength), or simply by taking the most important belief.

3.7. Key Concepts

An overview of the most important concepts coming from this chapter can be seen in Box 1 below. It serves as a guide to a synthesized understanding of the topics described in it, and as background for the purpose of improved comprehension of this thesis.

Box 1: Key concepts arising from this chapter.

Socio-technical transition: ”set of processes that lead to a fundamental shift in socio-technical systems” (Markard et al., 2012).
Energy transition: ”a change in the primary form of energy consumption of a given society” (*Dictionary of Energy*, 2015).
Renewable heating: generation of energy using renewable resources to power end-use applications such as heating water for pools, domestic consumption or space heating (EPA, 2022).
Centralized generation: the energy system paradigm where electricity or heat is produced at large generation facilities and afterward distributed to the end-consumers (Martin, 2009).
Decentralized generation: also known as ”distributed generation”, refers to the production of electricity or heat at smaller generation facilities close to the consumption points (Martin, 2009).
Intermittent generation: a characteristic of generation using uncontrollable energy sources such as solar or wind, that leads to a non-predictable, non-constant output due to the resource availability (Wu and Kapuscinski, 2013).
Environmental policy: regulation that encourages behavior through the setting up of goals in regard to environmental conservation. Conventional approaches allow little flexibility in enforcing pollution limits; market-based policies use market signals as motivators (Stavins, 2003).
Subsidy: payment by a giver body, for which this giver body receives no retribution. They are usually awarded on the basis of fulfilling a set of requirements. If the giver body is the government, they are ”essentially similar to taxes except for the difference in sign” (W. C. Robinson, 1967).
Pro-environmental behavior: ”such behavior which is generally judged in the context of the considered society as a protective way of environmental behavior or a tribute to the healthy environment” (Krajhanzl, 2010).
Value-action gap: ”discrepancy between the values and attitudes of an individual and his or her actions” (Brown and Sovacool, 2018).
Behavioral theory: *theory that connects the way a* person behaves to the different factors that influence that person’s decision-making process (Kwon and Silva, 2020).
Theory of planned behavior: theory that establishes the intention to execute a specific behavior in terms of the attitudes towards this behavior, the subjective norms in the face of the behavior and the perceived behavioral control (Ajzen, 1991).
Belief dynamics: the process through which an individual’s beliefs are shaped and influenced through the interactions with his surroundings (Galesic et al., 2021).

3.8. Conclusion

It is important to consider that a heating system, due to its composition and interactions, can be categorized both as a socio-technical system and a complex adaptive system. This is a reflection of the intrinsic complexity of the system, given the dynamic interaction of households amongst them and with the technologies that make up this system. Households, as individual and unique agents, have particular socio-demographic and behavioral characteristics that have an impact on their energy consumption. With such an intricate causal relationship, it is worth making use of a behavioral theory to explain how these factors affect the ultimate behavior of a household. The theory of planned behavior stands out as an important theory to model behavior while taking into account the attitudes, social influence and external facilitating factors.

In such complex networks, the interaction between agents can lead to a change in beliefs due to belief dynamics: contrasting beliefs can lead to an individual updating his beliefs to assimilate new information. This is a factor that should be considered and that can be computed using weighted averaging in proportion to the level of importance of the second agent, the one providing information.

4 The Renewable Heat Transition in the Netherlands

This chapter builds on the information described in the previous section and focuses on the Netherlands, with the intention of generating an applied theoretical basis on which it is possible to conceptualize the model. In addition, an answer to **sub-questions 1 and 2** is provided.

4.1. Renewable heat technologies in the Netherlands

The Dutch government set up a guide within the Klimaatakkord for achieving the natural gas-to-renewable heat transition in the built environment, where a set of technological options are displayed as options to reduce the consumption of natural gas (Delft, 2022; van Economische Zaken en Klimaat, 2019). In this guide, both **collective** and **individual** options are included and are outlined in detail below.

4.1.1. Centralized heat systems

Centralized heat systems, also known as collective heat systems, provide heat to several end-users by using a large generation facility and a distribution system. Currently, the state-of-the-art of these systems, also called ”district heating systems”, make use of pressurized water circulating through buried pipes and compact substations (Lake et al., 2017). The Dutch government's approach is to heat this water using different sources, namely geothermal energy, aqua thermal energy, renewable residual heat, and renewable electricity (Delft, 2022).

Geothermal energy Geothermal energy refers to the energy stored as heat in the interior of the Earth, generated due to the physical processes taking place there (Barbier, 2002). Even though it could be said that the amount of existing geothermal energy contained within the Earth is unlimited, the depths at which it becomes available and the uneven distribution across the different regions of the Earth make its exploitation difficult (Dickson and Fanelli, 2013). In the Netherlands, the potential for geothermal energy to be used as a renewable source within the built environment is projected at 20 PJ per year for 2030, the equivalent of heating up 400,000 households throughout the year (Geothermie, 2018).

Aqua thermal energy Aqua thermal energy refers to the extraction of heat from bodies of water (Deltares, 2023). Three sources of aqua thermal energy are identified: surface water, wastewater, and drinking water (CEDelft, 2021; Deltares, 2023). Regarding the surface water, considering that the geographical conditions of the Netherlands cause a large amount of it to be present in the country, over 40% of future heat demand in the urban area is predicted to be covered by the economically extractable potential, which is anticipated to be over 150 PJ annually. Wastewater heat could be extracted at different points in the water treatment chain, such as sewage pumping stations or treatment plants, and has a potential of around 56 PJ annually. Finally drinking water production generates heat, which can be recovered with a potential of between 4 and 6 PJ per year (CEDelft, 2021). In the Netherlands, the promotion of aqua thermal energy has not been very thorough compared to other sources of renewable energy, even though research has shown that it has the potential to cover around half of the built environment's heat requirements (Aquathermie, 2023).

Residual heat The recovery of residual heat is based on the possibility to use technologies such as heat exchangers to capture generated heat product of a process (Zhang et al., 2013). Certain industries, such as steel or cement, run processes at high temperatures with a high potential for residual heat recovery (Campana et al., 2013). In the Netherlands, for example, residual heat from Shell's refinery in Pernis is used to provide heat to 16,000 households (Port of Rotterdam, 2018). Residual heat is an energy source that due to its origin, is difficult to control. This is, it depends on an external party for its supply frequency and quantity. This reliability is therefore a factor that makes its use difficult for a household's collective energy system.

Renewable electricity Renewable electricity can be used to provide carbon-free heat based on the possibility to power devices that can produce heat such as heat pumps or electric heaters (Ruhnau et al., 2019). Renewable electricity can be generated at facilities using wind turbines (Gipe, 2004) or photovoltaic modules (Parida et al., 2011).

4.1.2. Decentralized heat systems

Decentralized generation can be achieved by the use of individual technologies installed closely or directly at the consumption point (Stryi-Hipp, 2015). The Dutch government has identified a series of these technologies, that can be installed directly in the consumer's households, that make use of renewable sources of energy to generate heat for domestic consumption (Delft, 2022). These technologies span from **active** technologies - technologies that make use of devices to convert one source of energy into another usable energy carrier (X. Hu et al., 2021), to **passive** technologies - technologies that minimize the loss of energy by reducing the thermal conductivity of a building to the environment (X. Hu et al., 2021). Active heat generation technologies include heat pumps, solar boilers, biomass/biogas boilers and solar PVT, while passive technologies include roof, floor, walls and facade insulation (Delft, 2022).

Heat pumps A heat pump is a technology that is able to absorb heat from one location and release it in a second one by using electricity to perform mechanical work (Chua et al., 2010). This makes this technology very versatile, as it can be used to heat the inside of a building during the winter or to cool it during the summer (Staffell et al., 2012). Commercial models can extract this energy either from the air (air source heat pumps) or from the ground (ground source heat pumps) (Omer, 2008). One particularity of heat pumps is that they are able to achieve very high efficiencies: commercial air source heat pumps have a coefficient of performance, the ratio between extracted energy and energy used to run the system (Ommen et al., 2014), between 3.2 and 4.5, while this value for ground source heat pumps is located between 4.2 and 5.2 (Fischer and Madani, 2017). The reason for this is that the only energy being consumed is the one used to power the pumps to move the refrigerant fluid (Omer, 2008). In the Netherlands, the installation of heat pumps has been growing in recent years and it has been set as the new standard, starting from 2026, to replace gas boilers in households (Dutch News, 2022).

Solar boilers Solar boilers are hybrid systems, that make use of solar collectors to convert solar irradiation into thermal energy and transfer it to a fluid, which is usually in the form of water (Tian and Zhao, 2013). These collectors usually work together with a storage tank, where the heated water is stored. In households, it is possible to connect the collectors to the existing gas-fired boilers, thus having direct access to the piping system, making installation easier. This also leaves the boiler as a backup heat-generating system, which can be handy during winter time (Milieu Centraal, 2023d). Solar collectors are fabricated using heat-absorbing coatings or materials, which allows them to retain heat (Suman et al., 2015). Two types of solar collectors can be used: flat plate, which consists of a flat glass plate with a metal collector underneath, or the more efficient heat pipe, which is made up of several glass vacuum tubes (Milieu Centraal, 2023d; Tian and Zhao, 2013).

Biomass boilers Biomass boilers work just like regular gas-fired boilers: they burn fuel, in this case, biomass, to supply heat (Milieu Centraal, 2023b). Biomass fuels are produced using agricultural waste, forest waste, or sawdust (Huang et al., 2022). Wood is the most common form of biomass used in boilers, usually in the form of chips or pellets (Chau et al., 2009). Biogas is produced from the anaerobic fermentation of wet biomass, through a process called anaerobic digestion. It can also be used directly as fuel in boilers (Niemczewska, 2012). One aspect to keep in mind is that, given that the content of biomass is very diverse and variable, the same variability will be present in its heating value. Factors such as its elemental composition, moisture and ash content will determine this (Sheng and Azevedo, 2005). In the Netherlands, biomass is the most prominent renewable energy source currently in use (Milieu Centraal, 2023b).

Solar PVT The term solar PVT stands for ”photovoltaic-thermal”, and refers to a group of technologies that utilize solar radiation (Chandrasekar and Senthilkumar, 2021). PVT collectors work with a photovoltaic module that converts sunlight directly into electricity (Al Tarabsheh et al., 2016), and a thermal module directly underneath that absorbs the excess heat produced by the photovoltaic module and works in the same way as a solar collector (Shakouri et al., 2020). These processes are complementary: removing excess heat from the photovoltaic module increases its overall efficiency, while this heat removal permits the thermal module to provide heat to the water flowing through it (Vittorini et al., 2017).

Insulation As mentioned before, insulation stands as a possibility, not to produce heat, but to improve the energy efficiency of buildings by reducing the amount of heat lost to the exterior in winter and of heat absorbed to the interior during the summer (Delft, 2022). The retrofitting of buildings with the so-called ”thermal envelopes” includes insulating outer walls, roof, foundation, windows and doors (El-Darwish and Gomaa, 2017). Insulation of buildings is common in the Netherlands, and retrofitting studies report a heat demand reduction of 15% if a house is insulated to a passive house standard (Alavirad et al., 2022); Macjen et al. (2016) reported reductions on the heat demand of 11.6% and 16.9% for one and two insulation measures, respectively. Sarihi et al. (2021) reported that for heating-dominated climates (climates where heating households is more common than cooling them), reductions in heat demand account for 20.1% for insulation retrofitting measures, with an additional 8.6% measured from glazing windows.

4.1.3. Available technologies in the Netherlands: technical and economic settings

Being aware of the characteristics of the technologies previously discussed, it was possible to take a decision regarding the most appropriate technologies for implementation in the model. Most of these technologies are being currently subsidized. For this model, a selection has been made on the basis of the **maturity** of the technologies, the **possibilities for implementation**, and the **subsidies availability**, which are all described in this Chapter.

A total of five **collective** technologies were chosen. Technical and economic characteristics were collected from sustainable wood pellet boilers (Fouladvand, 2022), aqua thermal with seasonal storage (Fouladvand, 2022), aqua thermal from surface water (Fouladvand et al., 2022), geothermal (Fridriksson et al., 2017; IRENA, 2020a, 2020b; Mines et al., 2015; Pinto and da Graça, 2018; Schoof et al., 2018; Trinomics, 2020) and solar photovoltaic-thermal (ConvertEnergy, 2023; Good, 2016; Smets et al., 2015; ZonCo, 2023). This can be seen in Table 4.1.

Table 4.1: Collective technologies with their characteristics

Collective technologies	Investment costs [euro/kW]	Fixed OPEX [euro/kW/year]	Variable OPEX [euro/kWh]	CO2 intensity [kg/kWh]	Average Capacity [kW]	Load [hours/year]	Lifetime [years]
Sustainable wood pellet boiler	825	55	0.003	0.26	950	3000	20
Aqua thermal with seasonal storage	1600	113	0.0019	0.152	800	3500	30
Aqua thermal from surface water	2364	170	0.0019	0.138	10000	6000	30
Geothermal	2000	46	0.014	0.122	20000	6000	40
Solar PVT	1340	0	0	0.3	1278	1095	30

Similarly, the **individual** heat technologies selected include ground source heat pump (Fouladvand, 2022), solar boiler, wood pellet boiler and solar photovoltaic-thermal. Figure 4.2 shows an overview of the technologies along with their characteristics.

Table 4.2: Individual technologies with their characteristics

Individual technologies	Investment costs [euro/kW]	Fixed OPEX [euro/kW/year]	CO2 intensity [kg/kWh]	Average Capacity [kW]	Load [hours/year]	Lifetime [years]
Ground source heat pump	1770	35.4	0.14	5	1500	15
Solar boiler	1666	22.5	0	4.4	700	30
Wood pellet boiler	415	140	0.35	20	2000	20
Solar PVT	1340	0	0.3	1278	1095	30

Finally, **insulation** was also included in the model as a technology that increases the efficiency of buildings, as it reduces the thermal convective coefficient with the exterior. Insulation can be installed on the façade, roof, and floor of the household. High-efficiency glass is also included for the windows. Their characteristics (Milieu Centraal, 2023a) can be seen in Figure 4.3 below.

Table 4.3: Insulation technologies with their characteristics

Insulation technologies	Investment costs [euros]	Lifetime [years]
Façade insulation	2350	75
Roof insulation	5400	75
Floor insulation	2350	75
HR+ glass	3900	75

Insulation efficiency gains have been reported in the literature for different configurations of insulation measures within a household (Alavirad et al., 2022; Majcen et al., 2016; Sarihi et al., 2021). Considering the available information, it is possible to say that façade, roof and floor insulation are considered equivalent in terms of efficiency improvement, but not HR+ glass. Their contribution towards the efficiency gain can be seen in Table 4.4.

Table 4.4: Efficiency gain by number or type of insulation technologies

Number of insulation measures	Heat demand reduction
1	11.6%
2	16.9%
3	20.1%
HR+ glass	8.6%

4.2. Policy instruments in the European heating transition

In December 2019, the European Commission published what is known as the ”European Green Deal”, a policy framework that lays out a number of objectives to make the EU into a ”circular, low-carbon, sustainable economy” (European Commission, 2023). The main sustainability goal encompassed within the European Green Deal is to achieve zero net emissions of greenhouse gases by 2050 (Hainsch et al., 2022).

However, in comparison to policy instruments that facilitate the use of renewable sources of electricity, financial backing for zero carbon heat is significantly less widespread and less well-developed (Harvey-Scholes et al., 2022). An overview of the current **financial instruments** supporting energy renovations in the EU is shown in Figure 4.1, as published by Bertoldi et al. (2021).

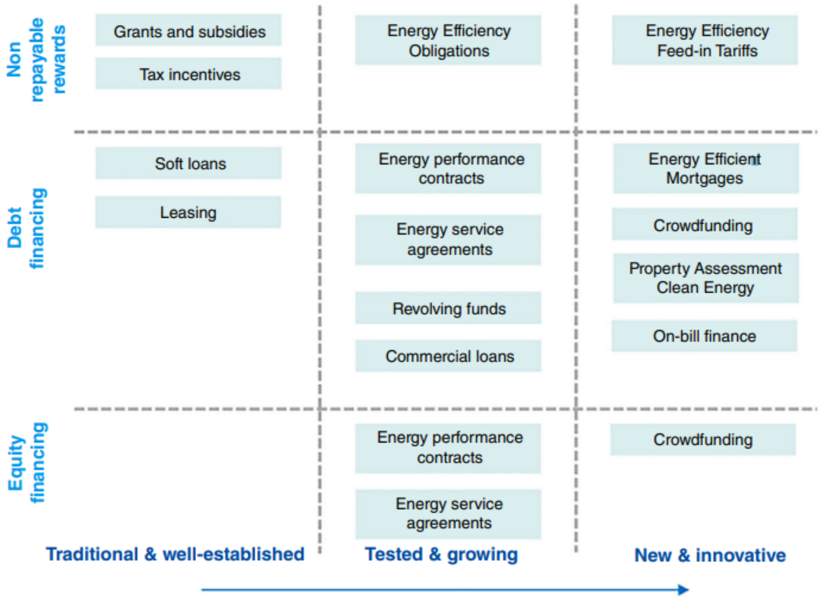

Figure 4.1: Financial instruments in place in the EU that support energy renovations (Bertoldi et al., 2021)

It can be seen that these financial instruments vary in type. Instruments labeled as ”traditional and well established” grant customers in a new market help by offering liquidity and easy access to funds (Meyer, 2011). ”Tested and growing” instruments encompass those that are directed towards letting users improve the efficiency and performance of existing installations (Bertoldi et al., 2021). As it can be inferred, they have been in place in the EU for a while (Fawcett et al., 2019; Rosenow and Bayer, 2017; Tupikina and Chernov, 2016). Finally, ”new and innovative” instruments have the particularity of allowing loans to be returned by energy savings, but through different actors such as utility companies or local governments, which obviates the need for an initial capital (Bertoldi et al., 2021).

Existing research argues that the application of a combination of policy instruments is more effective when dealing with sustainability transitions (Markard et al., 2012). This combination of policies, or ”policy mixes” should be aimed towards pushing the innovation of new technologies, while at the same time displacing those that are already mainly in place (Kivimaa and Kern, 2016).

The urgency related to pushing and achieving a faster energy transition is complemented by the continuous development of sustainable policies that integrate environmental, social and developmental factors with political and economic approaches (Byrne, Lund, et al., 2017; Hersh, 1999). According to Krause (2013), decision-makers within municipalities have four main motivations to engage in the development of policies that support energy transitions: environmental concerns, economic benefits, social integration and development of resilient systems. This is consistent with the principles that make up a sustainable city: environmental management, economic development, social development and urban governance (Dizdaroglu, 2017), with the only difference being urban governance, which represents the unifying pillar that connects the other three principles.

A coordinated exercise of policy development is required in the following years in order to motivate an organized change in behavior from all agents that interact with the heating system (Harvey-Scholes et al., 2022). This will ensure that fair policies are developed, which for example do not neglect the existing distributional conflicts around housing (Grossmann, 2019) and that while maintaining social justice, invest in practical technical solutions, empower citizens, and coordinate action in crucial sectors like research, industrial policy or finance (EC, 2018).

4.3. Policy instruments in the Netherlands

Several strategies have been developed by the Dutch Government in terms of policies that permit this clean energy transition, which has as an ultimate goal a full decarbonization by 2050 (Rijksoverheid, 2023c). The roadmap to this energy transition can be found in the Energy Agenda, which describes main strategies such as the further development of offshore wind, increasing the energy efficiency of buildings and practices, the reduction of greenhouse gas emissions through carbon pricing mechanisms, and the adoption of renewable energy technologies, promoting innovation in the field and establish international collaboration to achieve shared energy transition goals (Ministry of Economic Affairs, 2017).

In order to promote the use and further installation of technologies that generate energy in a clean way, the government has allocated a budget to grant **subsidies** and **loans** to Dutch households that have an interest in installing renewable energy technologies through different programs (Rijksoverheid, 2023c). These include:

- Stimulering Duurzame Energieproductie (SDE++)
- Investeringssubsidie Duurzame Energie (ISDE)
- Subsidiregeling verduurzaming voor verenigingen van eigenaars (SVVE)
- Stimuleringsregeling aardgasvrije huurwoningen (SAH)
- Subsidieregeling Verduurzaming en Onderhoud Huurwoningen (SVOH)
- National Warmtefonds

It is important to note that Dutch households are only allowed to receive one national subsidy at a time. Local subsidies can be combined if more financing is required. Local subsidies vary by municipality in type and in the amount they grant (Rijksdienst voor Ondernemend, 2023).

4.3.1. Stimulering Duurzame Energieproductie (SDE++)
(Netherlands Enterprise Agency, 2021)

The SDE++, or "Stimulation of sustainable energy production and climate transition", is a program directed towards incentivizing the installation of large, clean energy production projects or carbon capture facilities. It is an operating subsidy, which means that it directly subsidizes the production of energy or the capture of emissions.

Figure 4.2 shows a schematic of the way this subsidy works. Each technology has a base rate, which corresponds to the cost price for the production of energy or the reduction of emissions, and sets the lower limit for the maximum receivable subsidy. The application amount is the rate of subsidy that is being applied for and sets the upper limit for the receivable subsidy. In the case of a heat-generating facility, revenue will be made when it sells its production. This is represented as the "correction amount" on the graph and shows the price fluctuation due to the market's natural equilibrium.

When this revenue per unit (kWh) is located below the base energy price, the program will grant the full difference between the application amount and the base energy price. If the revenue per unit is located anywhere between the lower and upper limits, the subsidy amount will be equal to the difference between the application amount and this revenue. Finally, if the revenue per unit is higher than the application amount, no subsidy will be granted.

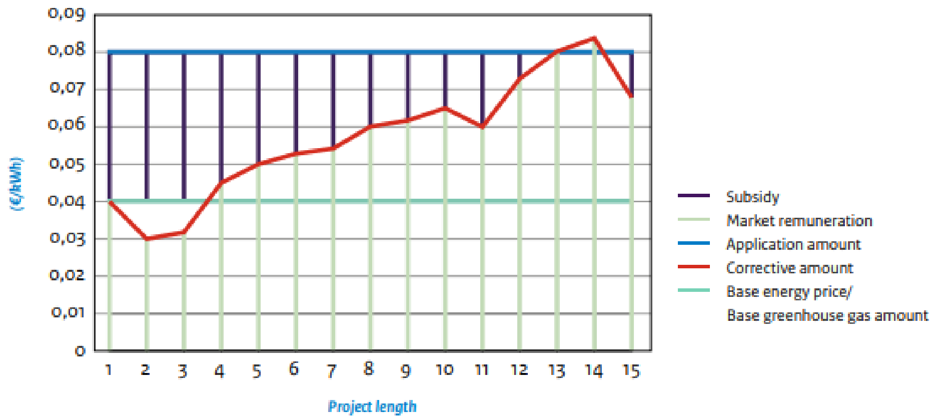

Figure 4.2: Example of an SDE++ contribution (Netherlands Enterprise Agency, 2021)

Each technology has 5 application phases, based on its subsidy intensity per ton of emissions reduction. The base energy price increases with every phase (reducing the maximum amount of receivable subsidy), which allows projects with a less amount of emissions to be supported first.

This subsidy term varies between 12 and 15 years and is capped to a certain amount of maximum full-load hours per year. Only an organization or business that sets up and operates the facility can apply for this.

4.3.2. Investeringssubsidie Duurzame Energie (ISDE)

(Rijksdienst voor Ondernemend, 2023)

The ISDE or "Sustainable energy investment subsidy scheme" is a program that provides applicants with a certain amount of money to assist them in paying for a specific energy-saving technology. Applicable technologies include passive ones like insulation, and active ones, namely heat pumps, solar boilers, solar panels, and connection to a heat network.

A particularity of this program is the possibility to increase the amount of the receivable subsidy if the applicant installs more than one technology. The type of technology, model and capacity of the different technologies set their energy efficiency level, and consequently, the subsidy amount.

This program is open to owner-occupied households, housing corporations, and household owners' associations.

4.3.3. Subsidieregeling verduurzaming voor verenigingen van eigenaars (SVVE)

(voor Ondernemend, 2023c)

This program is specifically directed toward household owners' associations and provides subsidies across three lines: energy advisory, installation of sustainability measures, and advisory for electric vehicle charging points.

Both of the energy and charging point advisory lines are based on the opportunity to get professional advice to help determine the best options for insulation and energy-saving technologies in a building, or for installing charging stations for electric vehicles.

Installation of sustainability measures is also covered, and works in a similar way to the ISDE, as it grants the applicant a certain amount to cover the upfront costs of installing energy-saving measures. The technologies taken into account include different types of insulation, heat pumps, solar boilers and a connection to a heat network.

4.3.4. Stimuleringsregeling aardgasvrije huurwoningen (SAH)

(voor Ondernemend, 2023a)

The objective of this program is to grant households with interest in disconnecting from the natural gas supply network and connecting to a renewable heat network a maximum of 5,000 euros to make the corresponding adaptations within the property. This includes indoor adaptations and the connection to the network.

This subsidy program applies to household owners' associations or landlords with one or more rental properties, which can be private, corporations, or investors.

4.3.5. Subsidieregeling Verduurzaming en Onderhoud Huurwoningen (SVOH)

(voor Ondernemend, 2023b)

This program grants applicants an amount of money to cover the upfront costs of installing measures like insulation, ventilation and receiving professional advice. The maximum amount accounts for 6,000 euros, which can be received if at least two measures are carried out. Otherwise, the subsidy would only account for half of the amount. The amounts vary per technology.

Applicability is limited to private landlords for supporting them in improving the sustainability and efficiency of their rental properties. There is no limit to the number of properties that the landlord can own, although the total subsidy is capped at 400,000 euros.

4.3.6. National Warmtefonds

(Warmtefonds, 2023)

This program provides low-interest loans, called "energiebespaarlening" (EBL), to applicants to finance the installation of renewable heat systems. Applicability is limited to owner-occupied households and household owners' associations.

Owner-occupied households can get up to 65,000 euros in financing to install different types of insulation, heat provision systems like electric boilers, heat pumps and solar boilers, solar photovoltaic modules, and ventilation systems.

Household owners' associations can get up to 65,000 euros per household to install the same measurements as owner-occupied households, in addition to high-capacity electric boilers and hydronic balancing and flue ducts.

4.3.7. Technologies and their subsidies

The technologies presented in Tables 4.5 and 4.6 are the ones that have been selected as the most appropriate for their incorporation in the model. These technologies were included because they figure within the most promising technologies identified by the Dutch Heat Expertise Centrum for the Netherlands (Fouladvand et al., 2022). Similarly, all of them except for individual bio-pellet boilers and solar photovoltaic-thermal are applicable to a subsidy for their implementation. Additionally, they do not rely on external factors that might compromise their constant supply, like residual heat, for example.

Table 4.5 provides an overview of the technologies, the total amount of subsidies available for them, and the maximum receivable amount that can be granted.

Table 4.5: Number of subsidies and maximum amount per technology

Technology	Maximum subsidy (€)	Amount of subsidies
Sustainable wood pellet boiler	167010	1
Aqua thermal with seasonal storage	169120	1
Aqua thermal from surface water	2616000	1
Geothermal	3912000	1
Solar PVT	21418	1
Ground source heat pump	2700	6
Solar boiler	2090	6
Sustainable wood pellet boiler	0	0
Solar PVT	0	0
Façade insulation	38 / m2	6
Roof insulation	30 / m2	6
Floor insulation	11 / m2	6
HR+ glass	26.5 / m2	6

Table 4.6 provides a summary of the different technologies and the available subsidies that are currently available for them in the Netherlands.

It is important to note that *connection to a heat network* was included in the table, but was not mentioned before in the previous technologies section. The reason for this is that it does not precisely represent a technology, but a household can apply for this subsidy if this household looks forward to connecting to an existing heat network. This heat network can be managed by the owner's association, for example. In this case, it would be possible for the respective household to use this subsidy to supply renewable heat into its house and therefore was considered within the available subsidies.

Table 4.6: Applicable subsidies by technology and applicant

Technology	Type	Owners' association	Owner - occupied	Private Landlord	Corporation landlord	Tenants
Sustainable wood pellet boiler	Collective	SDE++	-	-	-	-
Aqua thermal with seasonal storage	Collective	SDE++	-	-	-	-
Aqua thermal from surface water	Collective	SDE++	-	-	-	-
Geothermal	Collective	SDE++	-	-	-	-
Solar PVT	Collective	SDE++	-	-	-	-
Ground source heat pump	Individual	ISDE, SVVE, EBL	ISDE, EBL	-	ISDE	-
Solar boiler	Individual	ISDE, SVVE, EBL	ISDE, EBL	-	ISDE	-
Sustainable wood pellet boiler	Individual	-	-	-	-	-
Solar PVT	Individual	-	-	-	-	-
Facade, Roof, Floor, HR+ glass	Insulation	ISDE, SVVE, EBL	ISDE, EBL	-	ISDE	-
Connection to a heat network	Combined with collective	ISDE, SVVE, SAH, EBL	ISDE, EBL	SAH, SVOH	ISDE, SAH	-

4.4. Integration of behavioral characteristics and policy conditions with technical and economic settings

Considering the information presented before, it results interesting to analyze the way in which the Dutch household's behavior plays a role in the process of acquisition of renewable heat technologies. As was presented before, subsidies and loans are available for a wide range of technological options. However, it results interesting to analyze the extent to which these policy conditions motivate households to acquire the technologies, and what other factors play a role in this, from the perspective of the theory of planned behavior.

Regarding the **attitude** component, and after consulting some literature (Balcombe et al., 2013; Ghorbani et al., 2020; Koirala et al., 2018; Meiklejohn et al., 2018), the following values and beliefs were regarded as the most decisive when it comes to households deciding to reduce their natural gas consumption and adopt renewable heating technologies.

- **Environmental Friendliness:** refers to a positive attitude regarding the conservation of the environment. A household is environmentally friendly when it engages in practices that do not harm the environment.
- **Awareness:** the household's level of knowledge regarding practices that allow them to reduce their gas consumption. The higher this value, the more knowledgeable the household is.
- **Energy Independence:** the household's level of desire to become self-sufficient regarding energy supply. If this value is high, the household will favor engaging in practices that permit it to generate its required energy supply locally.
- **Economic-Driven:** the level of importance a household gives to spending money. The higher this value, the higher the chance that the household will prefer performing behaviors that do not represent a high economic impact.
- **Attitude:** an attribute that comprises the values of the four previous elements, and that serves as a measure of how positive a household is towards the reduction of gas consumption and the adoption of renewable heating system.

When it comes to defining the Dutch households' **perceived behavioral control** component and after a literature consultation (Asante et al., 2020; IEA, 2023b; Viardot, 2013) the following factors were considered as the most relevant in terms of facilitating or hindering the adoption of measures to reduce gas consumption:

- **Availability of subsidies:** the number of subsidies that support the adoption of renewable heating systems that are available for each type of household.
- **Municipality efforts:** the number of support schemes in pro of reducing gas consumption that is made available by the municipalities in the Netherlands.
- **Financial capability:** a measure of the amount of money that the household possesses. The value is proportional to the economic power the household has.
- **Time availability:** the amount of time to spare the household has, time that can be dedicated to activities other than work or unpaid work.
- **Perceived behavioral control:** an attribute that comprises the values of the four previous elements, and whose value is proportional to the facility perception of a household to implement strategies to reduce its gas consumption and to acquire renewable heating systems.

Considering the **subjective norm** component, no punctual characteristics have been appointed. This is a decision that is further explained in Chapter 5, but that can be understood through the **belief dynamics** explained before. However, the following attributes are deemed relevant for defining this component:

- **Connections:** the different households with whom an individual household has a relation.
- **Connection's weight:** a measure of how strongly related two households are between them.

It is important to understand that social influence is able to affect the households' beliefs, proportionally to the household's connection's weight. This is a process that results after periods of information exchange, and that ultimately affects the household's perception of topics, including the behavioral characteristics previously mentioned.

Finally, the **intention** encompasses the three components of the theory of planned behavior and serves as an indicator of the commitment a household has towards adopting a measure to reduce its gas consumption.

It is possible to see that the policy conditions, namely the **availability of subsidies**, are a factor that shapes the way in which households behave. Additionally, a high level of local support, namely the **municipality efforts**, can result in an increased level of perceived behavioral control, which can ultimately lead to the household acquiring a technology.

This determination of relationships between the technical and economic settings, along with the behavioral characteristics and policy conditions, sets a precedent to conceptualize the model, which is further presented in Chapter 5.

4.5. Conclusion

Household heating in the Netherlands is currently done mainly by means of burning natural gas. However, the heating transition can be accomplished using a variety of technologies. Centralized systems, which generate heat for multiple users, can make use of sources like geothermal, aqua thermal, biomass, and solar energy. Decentralized, or individual systems, are focused on providing heat to one household at a time and include heat pumps, solar boilers, wood pellet boilers, and solar PVT, in addition to the insulation possibilities that can reduce the amount of consumed heat.

The Dutch government has made available a series of subsidies and loans to support households in acquiring these technologies, in line with their 2050 decarbonization goals. The eligibility for these depends on certain households' characteristics, mainly on the type of ownership and the belongingness to an owner's association. Owner-occupied households have access to the highest number of subsidies, while tenants are completely dependent on their landlords, which in turn have access to the least amount of subsidies themselves.

In terms of behavioral characteristics, it seems that the four most relevant attitudes that shape a household's heat consumption include environmental friendliness, awareness, energy independence and economic drive. The perceived behavioral control component, on the other hand, is mainly shaped by a household's availability of subsidies, time availability, financial capability, and the municipality's efforts. Finally, the subjective norm component depends on the household's own connections and the weight of those same connections, which have a dynamic effect on the attitude attributes.

5

Modeling the Heat Transition for Households in the Netherlands

This section describes the model, from conceptualization until its implementation, following the structure of the ODD protocol (Grimm et al., 2020) visible in Figure 2.1, in combination with the modeling steps outlined by Nikolic et al. (2013), described in Chapter 2.

5.1. Purpose of the model

The **purpose** of the model is to explore the extent to which certain behavioral characteristics of Dutch households, along with the policy conditions in the Netherlands, are able to influence the heat transition in the country. In this sense, it is an explanatory model, as it looks into the **"causal process"** (Shram, 1994), the way these behavioral characteristics and the policy conditions shape the behavior of the households, and how this individual behavior ultimately aggregates to a certain amount of households achieving a complete gas-to-fully renewable heat transition.

Considering the extent to which the model is able to capture the different influence factors, this model can be useful for **academics** that might be interested in behavioral analysis and its relationship with the environment. This is due to the possibility of relating certain behavioral characteristics and belief dynamics of individuals to the construct of intention, and how this intention is ultimately translated into a behavior. On the other hand, this model can also be useful for **policymakers**, as the model is able to explore how different policy conditions affect this transition.

5.2. Entities, state variables, and scales

5.2.1. Entities

Households constitute the only entities present in the model. They have certain **demographic** and **economic** related characteristics that are representative of the Dutch population, which include:

- **Household type:** refers to the ownership status of the house. It can be of three types, as categorized by the Rijksoverheid (2022) in its study "Woononderzoek", namely **"owner-occupied"** (household owned, inhabited by the owner), **"rental-private"** (privately owned, inhabited by a tenant) and **"rental-corporation"** (corporately owned, inhabited by a tenant).
- **Belongingness to a VvE:** refers to whether the household is part of the owners' association of its neighborhood or not. This has a direct influence over the availability of some subsidies, as mentioned in Chapter 3.
- **House area:** refers to the physical surface of the house inhabited by the household.

- **Energy label:** a certificate that indicates the level of thermal quality of the building (Brounen and Kok, 2011). This level is a ratio between the gas consumption of the household and the house area (Architecten, 2020).
- **Annual salary:** the total amount of money that the household receives due to the work-related activities performed by their members.
- **Money savings:** the total amount of money that the household is able to save; the difference between the income and the expenses.
- **Annual expenses:** the yearly amount of money that the household requires to cover its needs.

Similarly, households have some characteristics that show their inclination towards being part of the community they belong to and how this feeling influences their inclination to engage in a community energy system. These are also representative of the Dutch population and include:

- **Community orientation:** indicates how likely the household is to engage in activities that benefit the community as a whole.
- **Community trust:** a measure of the household´s belief in the reliability of its community.
- **Community energy system participation willingness:** a measure of the likeliness for the household to participate within a collective system arranged by its community.
- **Community tendency:** an attribute that comprises the values of the three previous elements, and that measures how strong the household's feelings are towards its community.

As mentioned in Chapter 2, the households' **behavior** in this thesis is modeled using the theory of planned behavior. An extensive description of the specific behavioral characteristics, external factors, and social relationships that permit to describe the behavior of households through this theory is included in Chapter 4. Further on in this Chapter, a description of the implementation of this theory for modeling purposes is described.

Households in the model are able to acquire a set of **technologies** that allow them to reduce their gas consumption, either because these technologies generate heat in a renewable, clean manner, or because they reduce the total heat consumption of the household. These technologies can be categorized into three areas, namely:

- **Collective renewable thermal energy:** these include bio-pellet boilers, aquifer thermal energy storage systems, residual heat from surface water systems, geothermal and solar photovoltaic-thermal systems.
- **Individual renewable thermal energy:** these include heat pump systems, solar boiler systems, bio-pellet boilers, and solar photovoltaic-thermal systems.
- **Individual insulation:** these include different types of insulation like facade, roof, and floor, as well as high-efficiency glass for windows.

It is important to mention that regarding **collective** systems, households are only able to have their heat supplied by such a system if they decide to join an existing community or start a new one. Details on this are specified further in this chapter.

5.2.2. State variables

In the model, the households are able to reflect their status at different points of the simulation using a set of variables, described below:

- **Will to install:** this is a binary variable that shows if the household has the desire to acquire a renewable heating system. It is based on comparing the intention level of the household with a preset intention threshold. If the household's intention is higher than the threshold, this value becomes a 1.
- **Want to install a collective system:** this is a binary variable that indicates if the household would be part of a collective system rather than acquiring an individual system at that point in time. This is based on the household's own characteristics, and its value becomes a 1 if the household prefers a collective system.

5.2.3. Scales

The choice of a temporal and spatial scale is important for the conceptualization of the agent-based model because these two factors have an influence on how the interactions take place and to what extent they are able to impact the agents' attributes and interactions. Lippe et al. (2019) stress the importance of a correct definition of these two elements, especially when it comes to modeling a case study, and specifically, if the objective of the model is to obtain insights on the application and impact of policies. This is due to the complex dynamics of the current society, where individuals can be part of different social groups whose interactions are spatially and timely different: households, groups of friends, and neighborhoods, among others (Whitehead, 1995). Taking this into account, some assumptions were made regarding the definition of time and space scales in the model.

Temporal scale

Time is an intrinsic property of the environment where the entities in a model exist (Dam et al., 2013). In this model, the assumption was made so that every time step would represent a year in the real system. This was decided like that considering that households' interaction patterns, adjustment of beliefs, decision-making, and installation of any renewable heating system can be best represented with a yearly granularity.

The model has as starting point the year 2022. This was deemed as the most appropriate choice, considering that the majority of the input data was collected at the end of the year 2021.

The model was set up to finish after 28 time steps, which in the model is equivalent to the year 2050. The reasoning behind this is that 2050 is a target year for the heat transition in the Netherlands: the European Green Deal expects to achieve net zero emissions by then (Hainsch et al., 2022), and the Netherlands has explicitly committed to this objective with its Klimaatakkord (Government of the Netherlands, 2019).

Spatial scale

The model represents a sample neighborhood in the Netherlands. The environment within the model respects the spatial distribution of households. This means that when households are created and located around the environment, households on one edge are not close neighbors of households that are located on the opposite edge (the environment does not wrap around). This has no real influence over the behavior of the model, however, it is important to mention it to show that the model was made as realistic as possible.

5.3. Design concepts

5.3.1. Basic principles

Behavior of households

As previously mentioned, the model is able to simulate the behavior of the households making use of the theory of planned behavior (Ajzen, 1991). In this model, the *intention (I)* is the result of a weighted average of the *attitude (A)* and the *perceived behavioral control (PBC)* components, with their corresponding weights w_A and w_P. The equation that computes the *intention* variable looks as follows:

$$I = w_A * A + w_P * PBC$$

Attitude (A) in this model is calculated using again a weighted average influenced by four behavioral attributes, namely *environmental friendliness (EnFr)*, *awareness (Aw)*, *energy independence (EnIn)* and *economic driven (EcDr)*, along with its corresponding weights w_{A1}, w_{A2}, w_{A3} and w_{A4}. The equation that computes the *attitude* component is the following:

$$A = w_A1 * EnFr + w_A2 * Aw + w_A3 * EnIn + w_A4 * EcDr$$

Perceived behavioral control works in a similar way to *attitude*. It involves the factors *availability of subsidies (AvSu)*, *municipality efforts (MuEf)*, *financial capability (FiCa)* and *time availability (TiAv)*, along with its corresponding weights w_{P1}, w_{P2}, w_{P3} and w_{P4}.

$$PBC = w_P1 * AvSu + w_P2 * MuEf + w_P3 * FiCa + w_P4 * TiAv$$

The social influence that the households are subject to, known as the *subjective norms* in the theory of planned behavior (Ajzen, 1991), is taken into account with a different approach in this model. Making use of the concepts arising from the belief dynamics theory presented in Chapter 3, households incorporate the social element by updating their beliefs after exchanging information with their connections. This belief-updating process can be measured using a weighted average, as presented by Galesic et al. (2021), considering that the extent of this influence depends on the strength and importance given to the connection.

The following equation shows how a household's belief attribute *environmental friendliness* $(EnFr_i)$ is updated to *EnFr*, influenced by one of its connection's regard to that same attribute, $EnFr_j$, after exchanging information.

$$EnFr = w_i * EnFr_i + w_j * EnFr_j$$

It is important to notice that w_j represents the importance that the household gives to its connection. Therefore, w_i is calculated as follows:

$$w_i = 1 - w_j$$

Institutional dimension

It is worth making clear that in the model, the institutional dimension only considers **subsidies and loans** that are currently available from the Dutch government. As it was mentioned in Chapter 4, there is a wide variety of subsidies and loans available that target different technologies and household groups. In the model, each household is particularly profiled based on its demographic characteristics and therefore has access to a particular set of subsidies and loans. This distinction is reflected in the perceived behavioral control of the household and in the technologies ranking.

Network

The households in the model are connected through a **small-world network** (Watts and Strogatz, 1998). These types of networks are the usual choice when it comes to modeling individuals adopting renewable energy technologies (Fouladvand, 2022; Ghorbani et al., 2020; Y. Hu et al., 2020). Small-world networks are able to closely resemble the network dynamics within a neighborhood, given their characteristic that even though most nodes in the network might not be connected to each other, most nodes can be reached after a small number of steps (Watts and Strogatz, 1998).

In the model, the households are arranged in a small-world network using the Watts and Strogatz model (Watts and Strogatz, 1998). In this model, shown in Figure 5.1, it is possible to start with a regular ring lattice of *n* nodes, where each node is connected to *k* direct neighbors. Without altering the number of nodes or edges, a node is selected, along with one of the edges that connect it to one of its nearest neighbors. That edge is reconnected with a probability *p* to a random node, making sure that the newly formed edge does not yet exist. Watts and Strogatz (1998) found that for intermediate values of *p*, the resulting network is a small-world network.

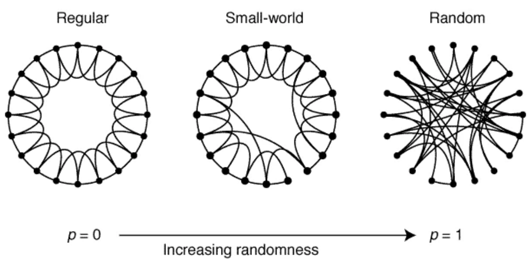

Figure 5.1: Rewiring process to achieve a small-world network

Technologies grading

Households in the model are able to represent their technology preferences by assigning a grade to particular characteristics of each technology on the basis of the level of alignment of these technologies with their behavioral characteristics. Households can achieve this by making use of a set of formulas that link particular technical and economic settings (see *Input data*) of the technologies with their behavioral characteristics.

Environmental impact (EnI), which refers to the perception each household has on the effect of the use of the technology, is related to the CO_2 *impact* of the technology and the *environmental friendliness (EnFr)* of the household, and can be calculated using the following formula:

$$EnI = EnFr * CO_2 \text{ impact}$$

Economic impact (EcI) refers to the household's perception of how beneficial installing a given technology can be to its financial situation. It is proportional to the *economic driven (EcDr)*, *financial capabilities (FiCa)* and *annual salary* attributes of the household, and inversely proportional to the *upfront costs* and *annual operational expenditure (OPEX)* of the technology.

$$EcI = \frac{EcDr + FiCa}{2} * \frac{\text{upfront cost} + \text{annual OPEX}}{\text{annual salary}}$$

Subsidy support (SS) refers to the household's perception of the usefulness of the existing subsidies per technology. This factor is proportional to the *economic driven (EcDr)* and *financial capabilities (FiCa)* attributes of the household, and the *highest subsidy* amount of for each technology, and inversely proportional to the *annual salary* of the household.

$$SS = \frac{EcDr + FiCa}{2} * \frac{\text{highest subsidy}}{\text{annual salary}}$$

Lifetime impact (LI) is related to the household's perception about the time that the system will be functional and how that will affect its economy and need to be supplied by gas to make up for the reduced renewable generation if the system reaches this lifetime. This factor is proportional to the *economic driven (EcDr)* and *energy independence (EnIn)* attributes of households and to the *lifetime* of the technology.

$$LI = \frac{EcDr + EnIn}{2} * \frac{lifetime}{15}$$

Technology's noticeability (TN) refers to the degree to which the household is aware of the existence of each particular technology and the possibilities for its implementation. This factor is proportional to the *awareness (Aw)* attribute of each household, the *municipality efforts (MuEf)*, and the *available subsidies* per technology.

$$TN = \frac{Aw + MuEf}{2} * \text{available subsidies}$$

Considering that households are able to make a choice between individual and community technologies, it might be the case that certain households have a particular inclination for a specific type of technology. The attribute ***tendency for community technologies (TC)*** is a behavioral characteristic that shows to what extent a household is inclined to get involved with its community. It comprises the average of three behavioral attributes, namely *community orientation (CO)*, *community trust (CT)*, and *community energy system participation willingness (CPW)*.

$$TC = \frac{CO + CT + CPW}{3}$$

Finally, it is possible to compute the overall grade of each technology by combining the grades of each attribute. Considering that the factor *TC* is based on behavioral characteristics that specifically show the tendency for households to get involved in community initiatives, it makes sense to include the influence of this factor only while grading collective technologies. This factor has been included as a ratio between the household's particular *TC* value and the mean *TC* value of the households. Then while grading individual technologies, as this value does not necessarily imply an influence on individual technologies, this ratio will be equal to 1. The ***overall grade*** G_t for each technology is calculated as follows:

$$G_t = (-EnI - EcI + SS + LI + TN) * \frac{TC}{\overline{TC}}$$

Assignation of energy labels

The most important indicator used in the model to show the level of energy efficiency of households comes in the form of its energy label. As previously mentioned, they provide a clear signal of the amount of energy used in the household that has a fossil fuel origin (Brounen and Kok, 2011).

The procedure to calculate a particular household's energy label has been detailed by the Dutch agency Rijksdienst voor Ondernemend (2022). The factor has been named "BENG2", and stands for *"bijna energieneutrale gebouwen"*, or *"nearly zero-energy buildings"*. This factor is calculated using the following formula:

$$BENG2 = \frac{\textit{primary fossil energy use}}{\textit{house area}}$$

The procedure calls to perform this calculation using the measure of *primary fossil energy use* in *kWh*, and the *house area* in m^2. Knowing the *BENG2* value for a particular household, it is possible to compare it with the established range scale, shown in Figure 5.2 below, to assign the corresponding energy label. Energy labels are assigned with letters and go from "G" (worst energy performance) to "A" (best energy performance). Within the "A" label, there are various levels, with the "A++++" corresponding to the best possible energy efficiency in the form of a building that has a neutral or negative net consumption (it has an excess of renewable energy generation that delivers to the grid).

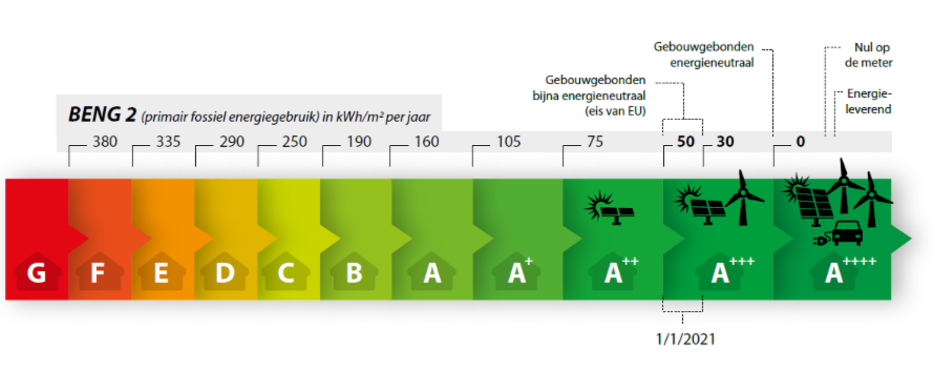

Figure 5.2: BENG2 scale (Architecten, 2020)

5.3.2. Emergence

In the model, households decide upon adopting measures that allow them to reduce their natural gas consumption based on behavioral characteristics that are intrinsic to the household, in addition to external factors that facilitate or complicate this process, to a certain extent. However, due to interaction among households taking place in the model, these beliefs experience a change over the course of time. This can lead to different patterns of adoption of measures, that would probably not occur if this collective dynamics of interaction were not taking place. Besides, the agents have the possibility to organize and start a collective system or join an existing one, which also showcases emergent behavior.

5.3.3. Adaptation

Achieving adaptation could be considered the desired outcome of the model. If households adopt any technology that allows them to reduce their gas consumption, they would be reacting to the stimuli of the environment. The availability of subsidies is a reflection of this stimuli: in this case, it is environmental change and the need to reduce emissions. The number of households that become gas-free would be an indicator of the effectiveness of the measures in place that were designed to let households adapt to these changes.

5.3.4. Prediction

It is possible to say that the model achieves to predict whether the households will adopt any measure to reduce their gas consumption, given a set of values and interactions that influence their intention, and that ultimately shape their behavior.

Arguably, the model is also able to predict what type of measures the households are more likely to acquire, considering their behavioral characteristics and the degree to which each technology is able to match their behavioral profile.

At last, the model can also be used to predict to what extent the households are able to translate their intention into behavior, considering that not all households who have the intention to acquire any measures might be able to do so.

5.3.5. Interaction

As mentioned before, interaction is an important component of the model. Every time step, households interact randomly with one of its connections. This leads to an information exchange process where the behavioral characteristics that shape the attitude, and the beliefs of the household, undergo an update process. This does not only have an effect on the intention level that the household will have at the next time step but also affects the preference for the different available technologies. Considering that this interaction is randomized, as well as the strength and importance level of the connection, interaction can be a very relevant factor in the outcome of the model.

5.3.6. Stochasticity

The model described in this thesis is a stochastic model. This implies that every time that the model runs, even with the same initialization parameters, different outcomes are expected on the basis of the probabilities for those results to occur (Pinsky and Karlin, 2010). This was achieved by integrating randomness within the model.

In the setup of the model, households populate the environment, and their location is assigned randomly. These households are then assigned certain characteristics (as described in the *Entities* subsection in this chapter) based on real-world data for the Dutch population. However, the assignation procedure is randomized as well: every run, a certain household will have a different house type, a different attributes profile, and access to different subsidies, energy labels, and installed technologies. Every run, a household will be connected to different households with different connection weights for all of them.

As the model progresses beyond the setup, stochasticity is also present. Every time step households establish contact with one random connection from their network. Given the specifications of the modeling environment used, this process happens simultaneously, but the order in which the different households carry out this interaction process is randomized. Considering that as a result of this interaction the behavioral characteristics of the households are influenced, it can be said that in every run, the amount of influence will be completely different. This is not only due to the different weights of the connection, but because the influence will also depend on whether the connection already carried out this belief update process or not yet.

Clearly, as these processes are based on a probability distribution, it can be the case that given two runs, certain parameters might have the same values. However, it is precisely the inclusion of this random assignation factor that provides the model with stochasticity that permits the model to generate a set of different outcomes after performing multiple runs. That is the reason for carrying out multiple runs of a single scenario and analyzing all outcomes at once: that way, the range of possible results is increased and all possibilities are observed.

5.4. Initialization and narrative

The model, as it has been mentioned before, represents a sample neighborhood in the Netherlands. Figure 5.3 shows the main flow diagram of the model.

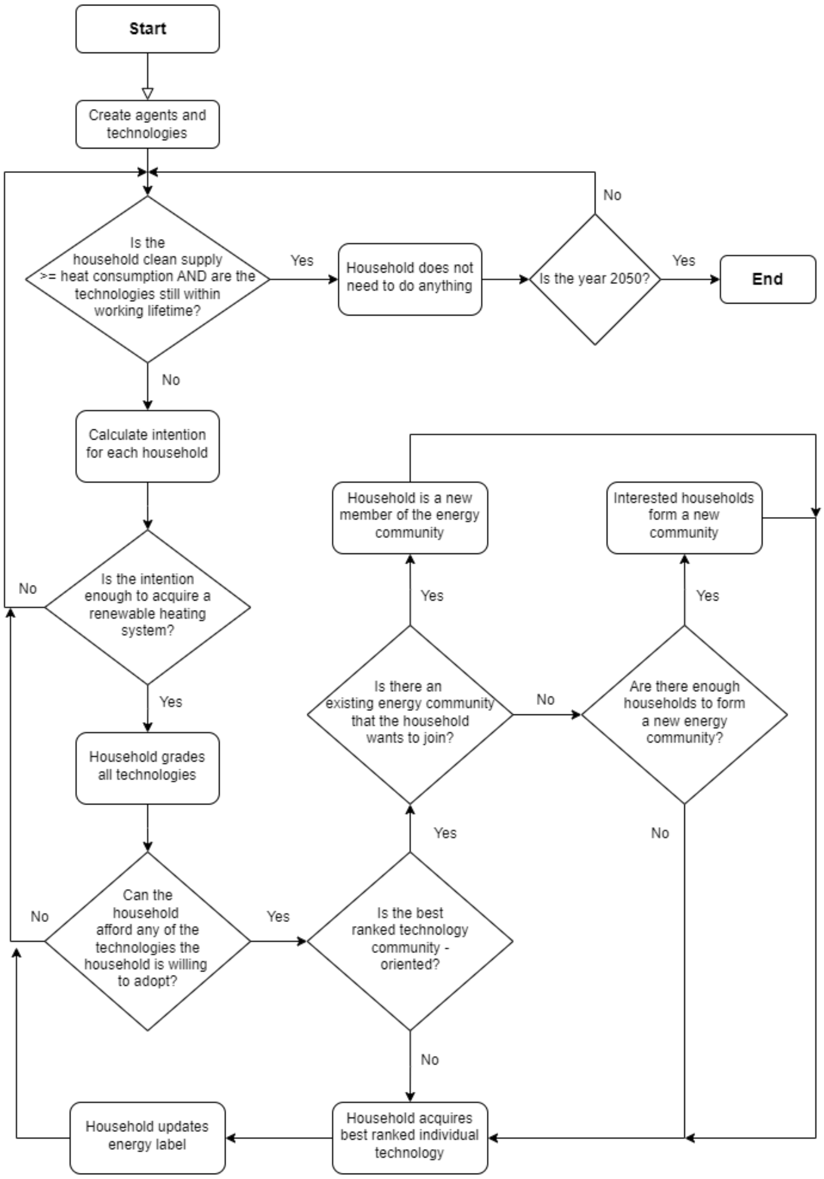

Figure 5.3: Main flow diagram

At the beginning of the simulation, the households are created and placed randomly throughout the environment. These households have a certain level of gas consumption, based on their household type, house area, and technologies already installed. It is assumed that every household has access to the gas grid, even if they are already being supplied fully renewable-based, and that gas is the only energy carrier they have access to apart from what they are able to generate in a renewable way.

Every time step and based on the household's gas consumption, the household **evaluates** whether it should consider installing a renewable heating technology. If the household at that particular time step is being supplied fully by renewable heat, then it does not need to do anything. However, if that is not the case, then the household will evaluate whether its **intention is high enough** for it to want to install any measure. Considering that in this model the lifetime of the technologies is being taken into account, it can be the case where a household increases its gas consumption due to its installed technologies reaching the end of their functional lifetime.

The process of determining how high the household's intention is is represented in the diagram in Figure 5.4. Every household will **interact** randomly with one of its connections, and as a result, the household's beliefs will be **updated**, which will have an influence on its *attitude* component. After computing the *perceived behavioral control* component, it will be possible to calculate the value for the *intention* of every particular household.

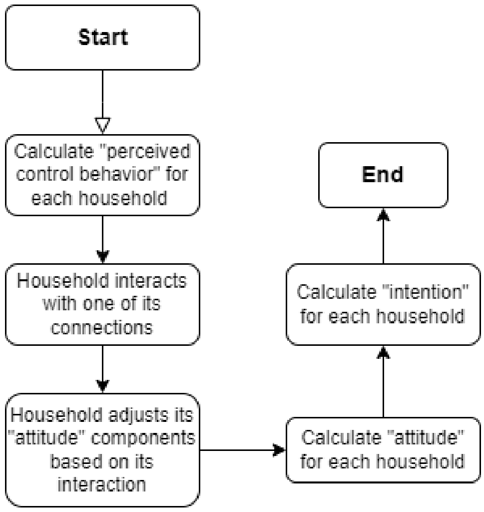

Figure 5.4: Intention calculation flow diagram

In case the intention of a household is high enough to acquire a renewable heat technology, the household will then proceed to **rank** all available technologies based on the grades awarded to each technology considering the household's particular behavioral profile and the characteristics of each technology. This process is shown in Figure 5.5.

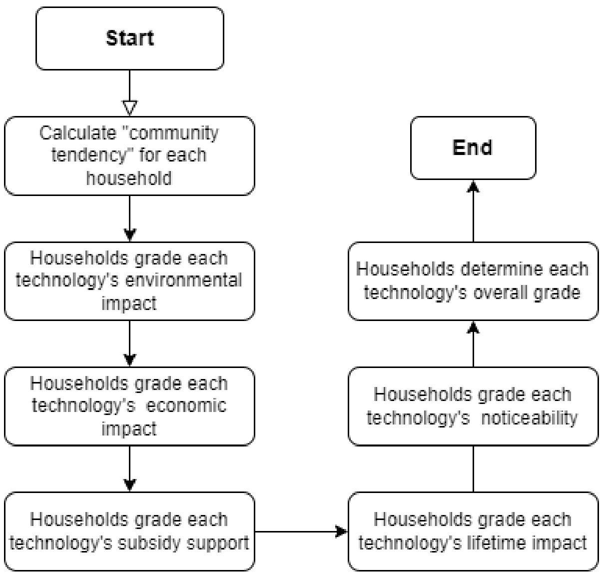

Figure 5.5: Technologies grading flow diagram

It is important to notice that **subsidies** play a role in the technologies ranking for each household, given that the ranking takes into account the maximum subsidy amount per technology and the amount of subsidies that are available per technology and household type.

Using the ranking, the household checks whether any of the technologies it is willing to adopt is **affordable** in a sequential manner. This is, the household prioritizes the highest-ranked technology, and acquires it given the case that it is able to pay for it. If not, then it proceeds to check the second-highest-ranked technology. This process keeps on until the household acquires one technology, or until the household has checked all the technologies it is willing to adopt and realizes it is not able to afford any.

If the chosen technology is an **individual** technology, then the household acquires it and implements it. However, if the technology is **community-based**, there are two options. The first option is that an existing community energy system exists that makes use of that particular technology. If so, then the household is **able to join** the community system with the only requisite that it can afford to join it. The second option is that the chosen technology is different than the one being used by the existing energy community. In that case, a **new energy community** would be formed only if there are enough households interested. For this, two conditions should be met: that each household expresses its interest in the particular technology through the ranking, and that each household is able to afford the technology. If the minimum amount of households covers these two conditions, then it is possible for a new thermal energy community to emerge in the neighborhood. Otherwise, each household would then acquire its best-ranked individual technology.

It is important to notice that for this specific model, the assumption was made that households are able to acquire only **one technology per time step**.

Once all the households that had the intention to acquire a measure to reduce their gas consumption and that were able to afford it did so, the energy label of the house gets updated. This process is shown on the diagram in Figure 5.6.

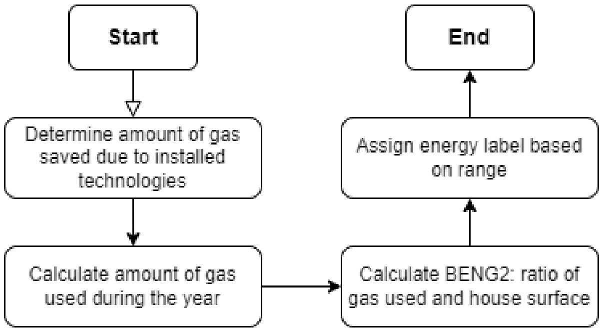

Figure 5.6: Energy label calculation flow diagram

5.5. Key performance indicators

A set of indicators were selected to be able to measure the performance of the simulations. They are the following:

- **Gas-free households ratio**: the proportion of households that generate enough renewable energy to satisfy their energy demand without the necessity of natural gas. In other words, the number of households that achieved an energy label "A++++". *A differentiation by household type is included.*
- **Average gas consumption per household [kWh]**: the average value of the individual households' energy consumption that is made using natural gas.
- **Number of community energy systems**: the total number of community energy systems present in the neighborhood.
- **Households in a community energy system ratio**: the proportion of households that decided to join a community energy initiative and have energy delivered to them from a collective energy

system.

- **Selection of technologies**: the selection of thermal technologies performed by the households.
- **Average number of individual technologies per household**: the average number of individual technologies that the households possess in the year 2050 in the simulation.
- **Average total money savings per household [€]**: the average amount of money a household was able to save until the year 2050 in the simulation.

5.6. Input data

This section presents the real system information used to build the model. This includes information related to the technologies that can be used by households to achieve their heat transition. This section also describes the characterization of households, from their demographic to their behavioral characteristics.

5.6.1. Data requirements

Due to the variety of information used in the model, it is important to have in mind the data requirements for the different variables considered. The data for characterizing the households is primarily quantitative, as it mainly relates to population percentages. However, there are some qualitative data sets used, such as the household type and energy label.

It is crucial to emphasize that the selected data set must meet specific requirements before considering its use in the model. Firstly, the data should originate from a reputable and reliable source. Secondly, it must contain up-to-date information, preferably aligned with the year 2022, which serves as the model's reference year. Additionally, the data should demonstrate logical coherence and be presented in a clear manner to minimize the risk of misunderstandings and the use of erroneous information.

Table 5.1: Variables and respective data sets used

Variable	Data set used	Reference
Population	”Kerncijfers wijken en buurten 2022”	CBS, 2023a
Owners' association belongingness ratio	”Transitiepaden: VvEs”	Ringelberg, 2020
Household type	”Woononderzoek Nederland”	Rijksoverheid, 2022
House area	”Woononderzoek Nederland”	Rijksoverheid, 2022
Energy labels A, B, C by household type	”Woononderzoek Nederland”	Rijksoverheid, 2022
Energy labels by house	”Energielabels van woningen”	Rijksoverheid, 2023a
Annual salary	”Woononderzoek Nederland”	Rijksoverheid, 2022
Annual expenses	”Aandeel woonlasten in inkomen”	CBS, 2022a
Environmental friendliness	Empirical survey, sample of Dutch population	Koirala et al., 2018
Awareness	Empirical survey, sample of Dutch population	Koirala et al., 2018
Energy independence	Empirical survey, sample of Dutch population	Koirala et al., 2018
Economic driven	Empirical survey, sample of Dutch population	Koirala et al., 2018
Available subsidies	Compendium of existing subsidies	See Chapter 4.
Financial capability	”Woononderzoek Nederland”	Rijksoverheid, 2022
Time availability	Time use in the Netherlands	Roeters, 2019
Municipality effort	Subsidies per municipality	Vattenfall, 2020
Attitude weight	Survey, sample of Dutch population	Okur and Fouladvand, 2023
Perceived behavioral control weight	Survey, sample of Dutch population	Okur and Fouladvand, 2023
Community orientation	Empirical survey, sample of Dutch population	Koirala et al., 2018
Community trust	Empirical survey, sample of Dutch population	Koirala et al., 2018
Community energy system participation willingness	Empirical survey, sample of Dutch population	Koirala et al., 2018
Total heat requirement	”Woononderzoek Nederland”	Rijksoverheid, 2022

The data used was obtained using publicly available information. The census ”Woononderzoek” (Rijksoverheid, 2022) resulted highly useful, as it contained very recent information regarding the household's demographic and economic situation. Similarly, the study published by Koirala et al. (2018) included a survey answered by 599 individuals from the Netherlands, whose answers were used to model certain parameters, mainly related to the beliefs of the population. A second survey, conducted by Okur and Fouladvand (2023) was used to obtain the weights of attitude and perceived behavioral control towards the final intention of households. The rest of the data was retrieved from different publicly available sources, namely research papers and websites. Table 5.1 shows the different variables, with a description of the data set used and corresponding reference.

5.6.2. Technological characteristics

As mentioned previously in Chapter 4, a selection of technologies was made on the basis of a list of factors. Tables 4.1, 4.2, 4.3 and 4.4 summarize the technical and economical settings of these technologies, which are considered in the model.

The data used to profile the households regarding their technical characteristics is presented in Appendix B. The data presented includes information on the distribution of energy labels, gas consumption, and installed technologies.

5.6.3. Household characterization

Like it was mentioned before, the households in the model represent a sample of Dutch households. Therefore, their demographic and behavioral characteristics, along with their technical and economic settings, are those particular to the Dutch population.

Demographic characteristics

The data used to profile the households according to the Dutch demographic characteristics is presented in Appendix B. It is worth mentioning that the majority of this information was taken from the most recent Dutch household census ”Woononderzoek” (2022). This data includes information on household types, house area, salaries, and living expenses.

Behavioral characteristics

As mentioned before, the households' behavior was profiled using the theory of planned behavior by Ajzen (1991). The characterization of the different attributes that make up each component of the theory is described below.

Attitude component First, the attitude component's behavioral attributes were all assigned making use of the results of a survey conducted by Koirala et al. (2018) on Dutch households' motivations to join an energy community. It is understood that the model presented here not only includes collective energy systems within its technological scope but also technologies that can only be installed in one household at a time. However, considering the type of information compiled in the survey and the description of the motivations presented there, the assumption was made that these motivations could also be applicable to individual technologies and therefore usable within the scope of this model.

Table 5.2 shows an overview of the values for the four attributes that make up the attitude component of each household. As can be seen, values for mean and standard deviation are presented. These correspond to the mean and standard deviation of a continuous normal distribution.

Table 5.2: Values for the attitude component attributes

Behavioral attribute	Mean	Standard deviation
Environmental friendliness	7.91	2.21
Awareness	4.49	2.43
Energy independence	5.17	2.67
Economic driven	7.41	2.2

The range for these values is established between 0 and 10. In the model, the values are generated using a command that generates a random value with the given distribution characteristics. In the event that this value is less than 0 or greater than 10, the value will be readjusted to 0 or 10, as the case may be.

Available subsidies Regarding the perceived behavioral control component, the attribute *available subsidies* was assigned based on the information on subsidies presented in Chapter 3. A value between 0 and 10 was assigned for each household profile and represents a proportion of the available subsidies to every particular household and the total amount of available subsidies. Table 5.3 provides an overview of these values.

Table 5.3: Values for the available subsidies attribute

Household type	Owner's association	Available subsidies	Value
Owner-occupied	No	8	2.42
Owner-occupied	Yes	26	7.88
Rental-private	No	2	0.61
Rental-private	Yes	20	6.1
Rental-corporation	No	5	1.52
Rental-corporation	Yes	23	6.97

Municipality efforts The attribute *municipality efforts* was assigned on the basis of the number of municipalities in the Netherlands that conduct programs that promote the use of renewable energy technologies. In this sense, it represents a measure of how involved every particular municipality is in the heat transition. According to a study by Vattenfall (2020), around 41% of the municipalities in the Netherlands promote actively the acquisition of renewable heat technologies. Therefore, the value for this was set to *4.1*.

Financial capability The attribute *financial capability* of each household is directly related to its annual salary. Table 5.4 shows how the values were assigned. It is possible to see that the annual salary ranges are those shown in Table B.3. In this case, every range was assigned a particular range of values, which depend on how the annual salary of the household compares to the mode salary, which for the Netherlands corresponds to 40,000 € per year (Randstad, 2023).

Table 5.4: Values for the financial capability attribute

Annual salary	Financial capability
<Mode salary	0.1 - 2
1x - 1.5x mode	2 - 4
1.5x - 2x mode	4 - 6
2x - 3x mode	6 - 8
3x - 4x mode	8 - 10

Three assumptions were made here:

- The lowest value for this attribute corresponds to 0.1, which is equivalent to the minimum wage for the age range "21 years and older", a total of € 21,074.1 per year (Rijksoverheid, 2023b).
- Households with a mode salary were assigned a value of 2.
- Regarding the upper limit of the 8 - 10 range, a value of 10 corresponds to a salary 4 times higher than the mode salary.

Time availability The values for the last attribute integrating the perceived behavioral control component, *time availability*, were assigned taking into account the information shown in Table B.5 regarding the amount of leisure time the members of the different Dutch households have. The values for this attribute reflect the proportion of leisure time in contrast to the "theoretical" maximum amount of leisure time that an average person could have, which accounts for 72 hours (8 hours per day during the weekdays and 16 hours per day during the weekend days). The values were assigned using ranges that show the variability in leisure time that men and women can have. Table 5.5 shows this information.

Table 5.5: Values for the time availability attribute

Household size and age group	Rental	Owner - occupied	Time availability
1 person, 18 - 65	40%	16.50%	5.8 - 6.4
1 person, 65+	19%	6.50%	7.6 - 8.2
Couple, 18 - 65	13.60%	26%	5.6 - 5.8
Couple, 65+	6.40%	10%	6.5 - 7.7
Family	21%	41%	4.5 - 4.7

The four characteristics that integrate the attitude and perceived behavioral control components are integrated into two single attributes, whose value is calculated using a weighted average, as mentioned before. In both cases, the weights were defined at 0.25 for every component, as shown below:

$$A = 0.25 * EnFr + 0.25 * Aw + 0.25 * EnIn + 0.25 * EcDr$$

$$PBC = 0.25 * AvSu + 0.25 * MuEf + 0.25 * FiCa + 0.25 * TiAv$$

Attitude The definition of the weights for the *attitude* component was based on a survey conducted by Okur and Fouladvand (2023) on the public perception towards alternatives for energy consumption and the use of natural gas. The results of this survey were compared to the information used in this model, and the matching questions' values were normalized to identify to what extent each of them influenced the final attitude component. In this case, given that the resulting normalized weights were all very close to 0.25, and considering that the difference in the result value was negligible, the decision was made to set all weights at 0.25.

Perceived behavioral control Regarding the definition of weights for the *perceived behavioral control* component, a decision was taken to set these weights to 0.25 as well, setting all four attributes as equally important towards the definition of the component. This was due to the unavailability of information in this regard.

Intention For calculating the *intention*, a weighted average was used again. In this case, the results from the same survey were considered, where two sets of questions were used to assign values to the two components. In this case, the values were 3.78 for attitude and 2.945 for perceived behavioral control. These two values were normalized and the weights were calculated, resulting in the following equation used in this model:

$$I = 0.56 * A + 0.44 * PBC$$

Subjective norms The influence that households have on other households' behavioral attributes is the basis of the way *subjective norms* play a role in this model, as mentioned before. In the model, weak and strong connections can be identified, each with their respective level of influence over a given household's behavioral attributes. Table 5.6 shows the weights per type of connection.

Table 5.6: Weights for connection's influence over behavioral attributes

Connection's influence	Weight
Weak	0.25
Strong	0.75

Community-related values Some attributes that do not play a direct role in building up the behavior of households, but that have an influence on the household's technology preference are the ones related to the households' feelings towards their community. To integrate these within the model, the values were taken from the survey presented by Koirala et al. (2018). In a similar way to the attributes for the attitude component, the values also follow a normal distribution, with mean and standard deviation values for each attribute shown in Table 5.7.

Table 5.7: Values for the community attributes

Community attribute	Mean	Standard deviation
Community orientation	5.43	2.46
Community trust	6.68	2.56
Community energy system participation willingness	6.78	1.96

5.6.4. Modeling assumptions

During the modeling phase, certain assumptions were made where real data could not be found, in order to integrate the input data, combine different data sets, and compatibilize the software capabilities with the routines in the flow diagram. Some of these assumptions were already presented throughout the description of the household characterization for achieving a better understanding of these sections. However, they will be included again here to include all of them in one single section. These assumptions are listed below:

- Each time step represents one year. This consideration is based on documented agent-based models on the heat transition (Caprioli et al., 2020; Caprioli et al., 2019; Moglia et al., 2022).
- The minimum house area is 15 m^2, the maximum is 150 m^2. This consideration is based on the available information on the Dutch census ”Woononderzoek” (2022), which states that 12% and 18% of the rental and owner-occupied houses, respectively, have a house area higher than 100 m^2. As no upper limit was specified, 150 m^2 was selected.
- Financial capability value: 0.1 corresponds to minimum wage (Rijksoverheid, 2023b), 2 corresponds to mode salary (Randstad, 2023), 10 corresponds to 4 times the mode salary (Rijksoverheid, 2022). This consideration was taken following the income distribution presented in the Woononderzoek (Rijksoverheid, 2022), where five ranges are presented in the income distribution.
- Community oriented, community trust and community energy system participation willingness have equal weights towards the overall *community tendency* attribute. This consideration was done given the unavailability of information to determine the actual weights.
- Available subsidies, municipality efforts, financial capability and time availability all contribute equally towards the *perceived behavioral control* attribute. Again, this consideration was done given the unavailability of information to determine the actual weights.
- The economic impact of installing any collective technology for a household is equal to the total amount divided by 140, which corresponds to the average number of households per community system in the Netherlands (Reijnders et al., 2020).
- Values for one, two and three insulation technologies (facade, roof and floor) contribute to a reduction of 11.6%, 16.9% and 20.1% in a household's heat consumption, respectively, regardless of the type. This consideration is based on the fact that the documented studies (Alavirad et al., 2022; Majcen et al., 2016; Sarihi et al., 2021) with available information did not differentiate between different insulated house sections.
- The influence of strong connections in a household's network has a weight of 0.75, and weak connections have a weight of 0.25. The rationale for this decision is twofold: it follows the consideration of the weighted average (Galesic et al., 2021), and it is a way of distinguishing levels of importance in contacts without having specific information about them.
- Each tick, every household exchanges information with one household within its network. This decision was taken in order to evaluate in a more detailed manner the way in which connections

affect the process.

- A household will only consider installing the technologies with a higher ranking than the minimum grade for each household, which is calculated as follows: (intention * 6 / 5), which is a translation of the intention into a [0 - 10] scale for the technologies rank. This follows the idea that the more motivated a household is, the higher number of technologies it will take into consideration for installation (Bergek and Mignon, 2017).
- A household can only have one collective technology installed at a time. This is due to infrastructure constraints and resource availability in a delimited area (Zwickl-Bernhard and Auer, 2021).
- A household can only have one technology of each type. This is due to the way in which technologies are taken into account in the model.
- A household can only install one technology per time step.
- Due to infrastructure constraints and resource availability, at the beginning of the simulation the neighborhood has a single collective energy system (Zwickl-Bernhard and Auer, 2021). The households that are not part of it can organize a second collective system only if half of the neighborhood's population is interested in doing so.

5.6.5. Sensitivity analysis

A "one-factor-at-a-time" sensitivity analysis (Ten Broeke et al., 2016) was performed to examine how performance indicators vary with different values of uncertain parameters. The procedure is to select a base configuration of these parameters and run simulations varying one parameter at a time. Every parameter will have a set of different values, which will permit us to see the way they affect the outcome of the performance indicators. The selected values for these parameters will be used as inputs in the model.

The parameters for which the sensitivity analysis was performed are *number of connections per household*, *population*, *rewiring probability in the network*, and *intention threshold*.

Table 5.8 shows the parameters with the assigned values after performing the sensitivity analysis.

Table 5.8: Parameter values after sensitivity analysis

Parameter	Value	Unit
Number of connections per household	6	connections
Population	500	people
Rewiring probability in the network	0.4	-
Intention threshold	5.5	-
Ratio households in owners' association	0.2	-

5.7. Model formalization

Once the conceptual model has been defined, it is possible to formalize the model by defining the set of parameters that will be used in it. Additionally, a pseudocode is presented, which represents how these variables intervene and what the coding flow should look like.

5.7.1. Model variables

After conceptualizing the model, gathering input data, setting assumptions and performing the sensitivity analysis, a definition of variables was performed. These variables represent certain characteristics of the agents and the environment. Figure 5.7 and Figure 5.8, respectively, show the global and household parameters and their descriptions, along with the names used in the model, and the values they can adopt.

Name in code	Global variables	Definition	Value
year	Year	The year the simulation is running on	*[2022 - 2050]*
population	Population	The size of the modeled neighborhood	*500*
municipality_effort	Municipality effort	The level of support from Dutch municipalities towards the heat transition	*4.1*
VvE_Belongingness_Ratio	Owners' association belongingness ratio	The proportion of population that forms part of an owner's association	*0.2*
Number_Collective-Heating-Systems	Number of collective heating systems	The initial amount of collective heating systems present in the neighborhood	*1*
min_members_energy_community	Minimum members for new energy community	The minimum required amount of interested households to start a new system	*0.5 * population*
intention_threshold	Intention threshold	The minimum intention required to be interested in installing a technology	*5.5*
technologies	Technologies	The technical and economical characteristics of the considered technologies	*See ODD protocol*
group	Collective technology interest group	The group of households interested on installing a collective technology at a certain time step	*Group set of households*
best_graded	Best graded collective technology	The collective technology that the interest group has decided upon installing	*0 - 4 (see ODD protocol)*
number_collective_systems	Number of collective systems	The total amount of collective energy systems present in the neighborhood	*[1 - 2]*
number_connections	Number of connections	The number of network neighbors the connection has	*6*
probability	Rewiring probability	The probability that a connection in the initial ring lattice network gets rewired	*0.4*
attitude_weight	Attitude weight	Attitude's weight towards intention	*0.56*
pbc_weight	Perceived behavioral control weight	Perceived behavioral control's weight towards intention	*0.44*

Figure 5.7: Global variables

Name in code	Household variables	Definition	Value
htype	Household type	The ownership status of the household	*owner-occupied", "rental-private", "rental-corporation*
vve	Owners' association belongingness	Shows if the particular household is part of the owners' association	*(0) not part, (1) part*
harea	House area	The surface of a house, measured in m2	*[15 - 150]*
energy_label	Energy label	The energy label of each household	*(see ODD protocol)*
annual_salary	Annual salary	The annual income of each household	*[21074.1 - 160000]*
money_savings	Money savings	The total amount of money that each household owns at a given time step	*[0 - inf.]*
annual_expenses	Annual expenses	The annual living expenses of each household	*[0.175 - 0.455] * annual salary*
attitude	Attitude	The integrated attitude component of each household	*[0 - 10]*
environmental_friendliness	Environmental friendliness	The level of environmental friendliness of each household	*[0 - 10]*
hawareness	Awareness	The level of environmental / technology awareness of each household	*[0 - 10]*
energy_independence	Energy independence	The level of desired energy independence of each household	*[0 - 10]*
economic_driven	Economic driven	The extent to which a household looks for maximising its economy	*[0 - 10]*
perceived_behavioral_control	Perceived behavioral control	The integrated perceived behavioral control component of each household	*[0 - 10]*
available_subsidies	Available subsidies	The total amount of subsidies that each household has access to	*[0 - 10]*
financial_capability	Financial capability	The level of economic capacity of each household	*[0 - 10]*
time_availability	Time availability	The level of leisure time that each household has.	*[0 - 10]*
connections	Connections	The list of connections of each household	*Group set of households*
connect_weights	Connection weights	The strength of each household's connections' links	*(0.25) weak, (0.75) strong*
current_connection	Current connection	The connection with whom the household exchanges information in a particular time step	*One household*
wj	Current connection weight	The link weight of the current connection	*(0.25) weak, (0.75) strong*
new_intention	Intention	The integrated intention component of each household	*[0 - 10]*
community_oriented	Community orientation	A household's level of engagement with its community	*[0 - 10]*
community_trust	Community trust	The level of reliability a household perceives from its community	*[0 - 10]*
ces_participation_willingness	Community energy system participation willingness	The household's likeliness level to take part in a community system	*[0 - 10]*
tendency_community	Community tendency	The integrated opinion of a household towards its community	*[0 - 10]*
installed_renewable_technologies	Installed technologies	The technologies that each household owns and their respective grades	*[0 - 12] for technologies, grades depend on calculations*
collective	Collective	The collective installation status of each household	*(0) not part of system, (1) part of system*
collective_tech	Collective technology	The collective system's technology that a household is part of, if any	*[0 - 4]*
individual	Individual	The amount of individual tecnologies that a household owns	*[0 - 7]*
new_gas_consumption	Gas consumption	The amount of gas that a household consumes at a particular time step	*[0 - 1] * total heat requirement*
installed_renewable_capacity	Installed renewable capacity	The total installed renewable capacity of each household	*[0 - x), depends on calculations*
installed_renewable_generation	Renewable generation	The yearly generated renewable heat of each household	*[0 - x), depends on calculations*
total_heat_requirement	Total heat requirement	The yearly heat requirement of each household	*[0 - x), depends on calculations*
beng2	BENG2 factor	The ratio between gas consumption and house area	*[0 - 425]*
ranking_techs	Ranking technologies	The technologies preference ranking of each household	*Group set of technologies*

Figure 5.8: Household variables

5.7.2. Pseudocode

A pseudocode is presented in Appendix C, where it is possible to see the logic behind the code. The pseudocode has been divided into two main routines and various separate functions to facilitate its comprehension. The variables presented in the previous subsection are included with their *name in code*.

5.8. Verification and validation

As it was noted in Chapter 2, verification and validation techniques were performed throughout the modeling process to ensure that the current progress of the model was at all times correct and was performing as it was intended to. Cooley and Solano (2011) note three stages within the process: model verification, model validation, and sensitivity analysis.

5.8.1. Verification

Model verification ensures that the model works according to how it was conceptualized (Olaru et al., 2009). Sargent (1991) mentions that using a special-purpose simulation language can result in fewer programming errors and less programming time. This was done, as the NetLogo environment is especially suited for multi-agent models (Wilensky, 1999).

Whitner and Balci (1989) identify several verification techniques that can be used throughout the programming process to verify the model.

Informal analysis (Whitner and Balci, 1989) was constantly applied throughout the coding campaign. This type of analysis relies on the modeler being aware of how the code's logic is working and how the modeling decisions are shaping the outcomes of the model. *Desk checking* was constantly done, revising the code to ensure that the sequence of commands and logic behind its structuring was logical and followed the order set up in the conceptual model.

Static analysis (Whitner and Balci, 1989), which examines the characteristics of the code, was also constantly performed throughout the coding campaign. Naturally, *syntax analysis* is performed by the NetLogo environment every time the code is compiled. *Structural analysis* was constantly applied, as the code was written using modules. This is, the full code was subdivided into different functions, each performing a different task. This organizes the code in a structured way, allows for better identification of errors, and permits testing individual functions of the code to check their functioning. Finally *consistency checking* was also constantly performed to avoid misassigning values to variables. This was helped by in-code comments next to the functions that provided an overview of the variables that were being manipulated and what the intention of the commands was.

Dynamic analysis was the most frequent analysis performed while coding the model. This refers to checking the behavior of the model while it is being executed (Whitner and Balci, 1989). *Bottom-up testing* was the main technique used. As it was mentioned before, the code is structured in functions, each of which performs a separate task. Every time a new function was fully coded, the individual function was independently tested to the extension of its possibilities, depending on how reliant the function was on inputs coming from other functions. Afterward, this new function was tested in combination with the existing code. This was useful to identify two types of errors: in-function errors, or function-connection errors. *Stress testing*, using extreme variable values to see the response of the code, was always a part of the testing procedures. This ensured that the code would work in all conditions, with all ranges of values.

In case of errors, *debugging* and *execution tracing* (Whitner and Balci, 1989) were used to identify the error and solve it. Given that NetLogo does not have features like breakpoints or stepping that make debugging easy, tracers had to be used when errors appeared, especially in the case of conditional routines that did not provide any printed argument in the output monitor.

5.8.2. Validation

Model validation makes sure that the behavior of the model accurately reflects the behavior of the real-life system (Cooley and Solano, 2011). The techniques described below were carried out to make sure that the model is a valid one, and therefore the results are valid and representative of the real system.

Face validity (Sargent, 1991) was constantly used to determine the validity of the conceptual model. Consultations took place with experts Dr.ir. Özge Okur and Dr. Javanshir Fouladvand on both the translation of the real system into the conceptual model, and on the application of the behavioral theory into the model. This led to a proposal-feedback cycle that allowed the model to be constantly reviewed.

Internal validity (Sargent, 1991) is useful with stochastic models, as it refers to analyzing the distribution of results coming from the same initial parameterization. Variability is expected, but too much variability can be an indication of wrong model behavior (Sargent, 1991). To ensure an appropriate level of variability, a ”one-factor-at-a-time” *sensitivity analysis* was performed. The results of this are included in Appendix B.

Additionally, confidence intervals were used to further validate the model. As outlined by Petty (2012), this is a way to ensure with a certain level of confidence that certain parameters provide valid outputs.

A confidence level of 95% was used, as this is the most common confidence level in practice, and utilizing it is likely to pose no methodological issues (Balci and Sargent, 1984; Petty, 2012). The model was run 50 times with a base parameterization (see Chapter 6), and five performance indicators were measured. Based on Petty (2012), a Student *t* distribution should be used considering that for the generated values the sample size is larger than 30, the population distribution is unknown and the population standard deviation is also unknown. Table 5.9 shows these results.

Table 5.9: Confidence interval validation for base parameterization with confidence level = 0.95

Key Performance Indicator	Lower Limit	Upper limit	Simuland value
Gas-free households ratio	0.545	0.565	0.546
Average money savings of households	1365495.376	1372160.746	1368569.29
Households in community system ratio	0.038	0.043	0.042
Average gas consumption per household	6107.591	6400.481	6179.6
Average number of individual technologies	3.681	3.746	3.686

5.9. Conclusion

This chapter looks into the translation of the system into a conceptual model, and further on into a formal model. This translation is supported by the technologies, subsidies, and behavioral characteristics identified in the previous chapter. It is important to emphasize the importance of the process of identification of the demographic and social characteristics of Dutch households, in addition to the definition of design concepts, as these form the basis of the conceptual model.

The definition of the conceptual model is a very critical step, as this represents the preamble of formalizing the model, which will later be the base upon which the software will be implemented. This stresses the importance of validation and verification practices as the model is developed, in order to achieve an accurate representation of the real system.

Data collection, interpretation, and use is another important step within the process of developing the model, especially when the sources of the data are variate, as in this case. This is due to the necessity of integrating the different data sets, which most of the time might not accurately reflect the same information. Therefore, it is necessary to consciously reflect on how the integration should be done and how the software implementation might need to use this information. Based on this, a decision can be made on what the best integration strategy is.

Finally, it is important to take into account that going from the formal model to the software implementation needs to consider the software that will be used. Different types of software have different capabilities, and therefore the implementation will vary. The formalization was performed taking into account that the software NetLogo would be used, in order to facilitate the transition process.

6 Results and discussion

This chapter provides an overview of the experimental campaign carried out, with the different designed scenarios and the reasoning behind them. The results of the campaign are included and discussed, with the intention of answering sub-question 3.

6.1. Experimental setup

Considering that the intention of this model is to analyze the way in which behavioral characteristics and policy conditions are able to influence the transition of households toward having a ”gas-free” status, a set of parameters were defined to run the model with different values and see how the ”base” behavioral characteristics and policy conditions perform against other parameterizations.

Behavioral characteristics Regarding the behavioral characteristics, it results interesting to see how the model would perform with different values assigned to the behavioral attributes, this is, the attributes that relate directly to the beliefs of the people. These include the four behavioral attributes related to attitude (environmental friendliness, awareness, energy independence and economic driven) and the three community attributes (community orientation, community trust and community energy system participation willingness). For this, two different batches were defined: 1) the base Netherlands batch, with attributes that correspond to the Dutch population, and 2) a randomized batch, with the attributes taking random values between 0 and 10.

Policy conditions Considering the policy conditions, it resulted interesting to analyze how the base Netherlands scenario performs against different configurations of available subsidies and subsidy amounts. Two different parameters were selected and assigned four different values each, as shown in Table 6.1.

Table 6.1: Values for the policy conditions parameters

Parameters	Values
Availability of subsidies	”Base”, ”owner-occupied”, ”rental-private”, ”rental-corporation”
Subsidy amount	”Base”, ”highest”, ”lowest”, ”average”

Availability of subsidies, as mentioned previously, refers to the amount of subsidies that are available for each household. After performing the review of policy options, it was possible to see that there was a big difference in terms of availability by household type. Therefore, it seems interesting to see how the model would behave if these subsidies were made available in a different way.

In the base scenario, the availability is dependent on the household type, as it is now. With the ”owner-occupied” value, all households have access to the different subsidies that owner-occupied households currently have. The same happens with ”rental-private” and ”rental-corporation”, where all households have access to the subsidies currently available for rental-private and rental-corporation households, respectively.

The subsidy amount refers to the monetary sum granted for each technology if a subsidy is awarded. In this case, in the "base" scenario the amounts considered are the ones that are being currently awarded. However, if this parameter has the "highest" value, then the technologies are awarded the maximum amount possible by the type of technology: this means that the maximum amount currently being awarded among the different collective technologies, for example, will be awarded to every collective technology. The same will happen with the individual and insulation technologies, respectively. Similarly, if this parameter is set to "lowest", the lowest amount per type of technology will be selected and assigned to every technology of the same type.

If the parameter is set to "average", the current subsidies per type of technology will be averaged, and this average will be assigned to every technology of the same type. This will simulate a redistribution of the amounts currently awarded.

Gas price variability In view of the variability in natural gas prices due to events such as the war in Ukraine and gas shortages, it is interesting to analyze the results with a different price than the one considered in the model. An additional scenario was developed, where the gas price presented an increase of 30%, going from an average for 2021 of 42.51 €/MWh (Aizarani, 2023), to 55.3 €/MWh. This value was considered as a way of modeling a controlled worst-case scenario, keeping in mind that natural gas prices are difficult to predict due to their volatility (Cochintu, 2023). However, this percentual increase is similar in magnitude to the decrease experienced from 2022 to 2023 (Cochintu, 2023), and therefore was selected as the value to use.

In the model, the gas price has a direct effect only on the amount of money saved, although it can indirectly affect the technology acquisition process.

Taking then into account the two batches that represent the different behavioral attribute scenarios, the two parameters with four variations each that represent the different policy scenarios, in addition to the scenario with the higher gas price, with a total of 100 runs per combination as suggested by Nikolic et al. (2013), sums up for a total of (2 x 4 x 4 x 100 + 100) = 3300 runs.

It is important to note that all performance indicators are reported over the entire simulation run, this being, the final values by the simulation year 2050.

6.2. Results

The results of the different runs are presented as follows: first, the results of the base Netherlands scenario, as it is the one that represents the current status in terms of behavioral characteristics and policy conditions. Second, a comparison between the Netherlands and the random batch is done, with the intention of analyzing the influence of the behavioral characteristics on the performance indicators. At last, an analysis of the influence of the policy conditions is done by comparing the results of the "availability of subsidies" and "subsidy amount" parameter variations to the base Netherlands scenario.

6.2.1. Results of the base Netherlands scenario

Table 6.2 shows an overview of the results achieved by the base Netherlands scenario in the performance indicators. It is possible to see that on average, at the end of the simulation 54.8% of the households in the neighborhood achieved a gas-free status. Owner-occupied households achieved the largest proportion of gas-free households with a total of 69.3%. Rental-corporation and rental-private households achieved 40.3% and 35.7% of gas-free households, respectively. These results were expected, as higher values, not only in the available subsidies but also in financial capability attributes, are the more evident factors that permit owner-occupied households to achieve a higher proportion of gas-free households.

Table 6.2: Results of the Netherlands base scenario at the end of the simulation

	Min	Average	Max
Gas-free households ratio	0.472	0.548	0.610
Gas-free owner-occupied ratio	0.602	0.693	0.773
Gas-free rental-private ratio	0.227	0.357	0.545
Gas-free rental-corporation ratio	0.320	0.403	0.480
Gas consumption per household [kWh]	5317.13	6310.20	7748.13
Amount of collective energy systems	1	1	1
Households in a CES ratio	0.03	0.04	0.06
Individual technologies per household	3.43	3.69	3.93
Money savings per household [€]	1348732	1371068	1403859

On average, each household possessed 3.69 individual technologies at the end of the simulation. This was an increase from the initial 2.47 individual technologies per household. As a consequence of this, the total gas consumption in the neighborhood was reduced by almost 45%, as can be seen in Figure 6.1.

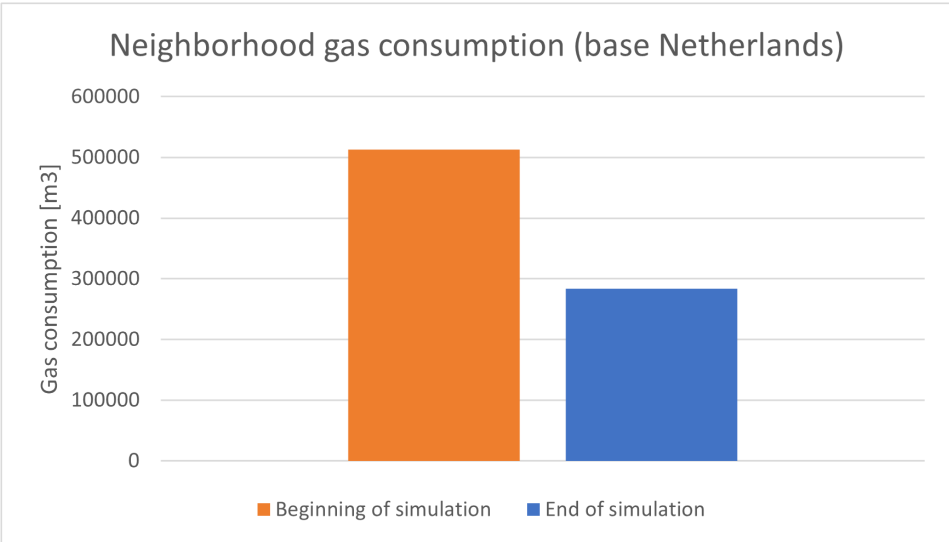

Figure 6.1: Neighborhood gas consumption in the base Netherlands scenario

Regarding the technology-related aspects, none of the runs presented the formation of a second collective energy system. This was expected in a certain way, as the number of interested households required to achieve this was high, and therefore the probability for this to happen was low. Therefore, in all the runs, the total amount of collective energy systems was equal to 1.

The measure of households that belong to a community energy system also showed a small variation, jumping from 3% at the beginning of the simulation to an average of 4%, which corresponds to 5 households. This is related directly to the choices that households make in terms of technology preference, both collective and individual. The households' preference for individual technologies over collective ones can be explained by the higher upfront costs that need to be covered by households to be part of the collective energy system, the lower amount of subsidies available in comparison to some individual technologies, and the existence of alternatives with similar energy potential fulfillment throughout similar lifetimes.

The technology choices for collective and individual technologies can be seen respectively in Figures 6.2 and 6.3.

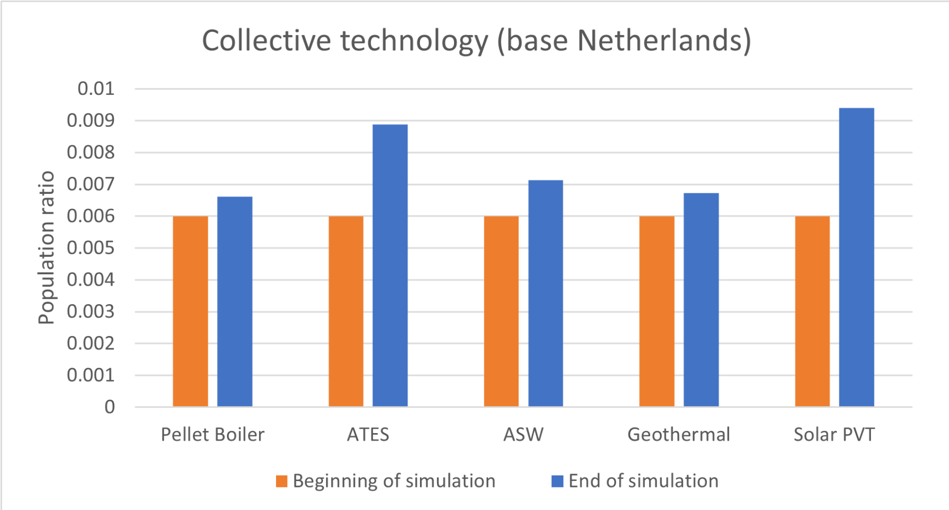

Figure 6.2: Collective technology choice in the base Netherlands scenario

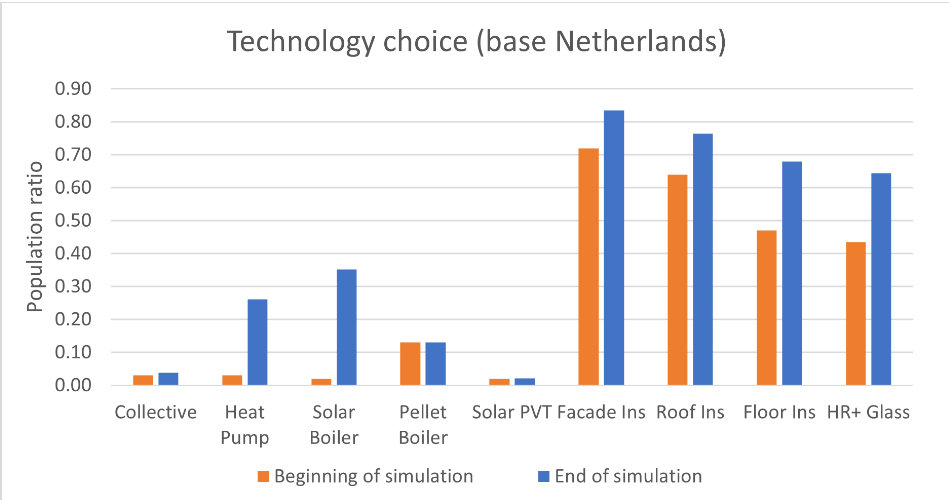

Figure 6.3: Technology choice in the base Netherlands scenario

Regarding the collective technologies, the most popular one was the solar PVT, with ATES falling shortly behind. The pellet boiler was the least selected option. Nevertheless, the difference (0.28%) between the best performing and the worst performing collective technologies is so small that can be practically considered negligible.

If considering the technology choice, the insulation technologies are present in the largest proportion of households, with all of them in a little more than 60% of the households in the model neighborhood. This was expected, given that at the start of the simulation they already were present in a large proportion of households.

Considering active heat generation technologies, solar boilers, and heat pumps were the most popular, with presence in 35% and 26% of the households, respectively. Pellet boilers and solar PVT modules showed no difference between their initial values and the ones at the end of the simulation. It was expected that these two technologies would be the least selected, as they are currently not subsidized.

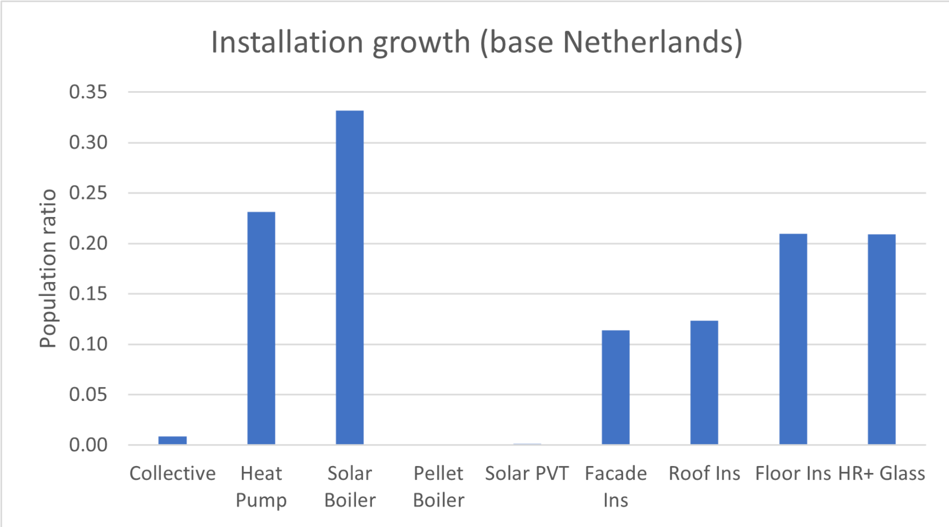

Figure 6.4: Installation growth in the base Netherlands scenario

It is possible to see which technologies were the most and least selected throughout the simulation in Figure 6.4. Solar boilers and heat pumps had the highest installation numbers, considering that they are active generation technologies with lower upfront costs and the highest number of available subsidies. Besides, this was also pushed by the low percentage of households with these two technologies already installed at the beginning of the simulation.

Floor insulation and HR+ glass were more installed than the other two types of insulation technologies, given the households' overall preference for insulation technologies due to their lower upfront costs, long lifetime, absence of emissions, and a high number of available subsidies, and the lower proportion of households with those two types of insulation technologies already installed at the beginning of the simulation.

6.2.2. Results according to the batch type

It is interesting to compare the achieved performance indicator results with the random batch configuration to the presented results of the base Netherlands scenario. Overall, the performance of the random batch was poorer, which can be observed in the lower values achieved in every performance indicator.

Regarding the achievement of gas-free households, Figure 6.5 shows a comparison between batches. Nearly 50% fewer gas-free households were obtained overall in the random batch than in the Netherlands batch. The difference is more pronounced with owner-occupied households, possibly due to the fact that these households are the ones with the higher gas consumption and financial capability, and therefore the higher potential to acquire a technology. If their intention is not high enough, then this larger number of households that otherwise would have acquired a technology, did not find themselves motivated enough to do so. Rental-private and rental-corporation households in the random batch scenario performed almost equally, which is expected after observing the reduced overall amount of gas-free households.

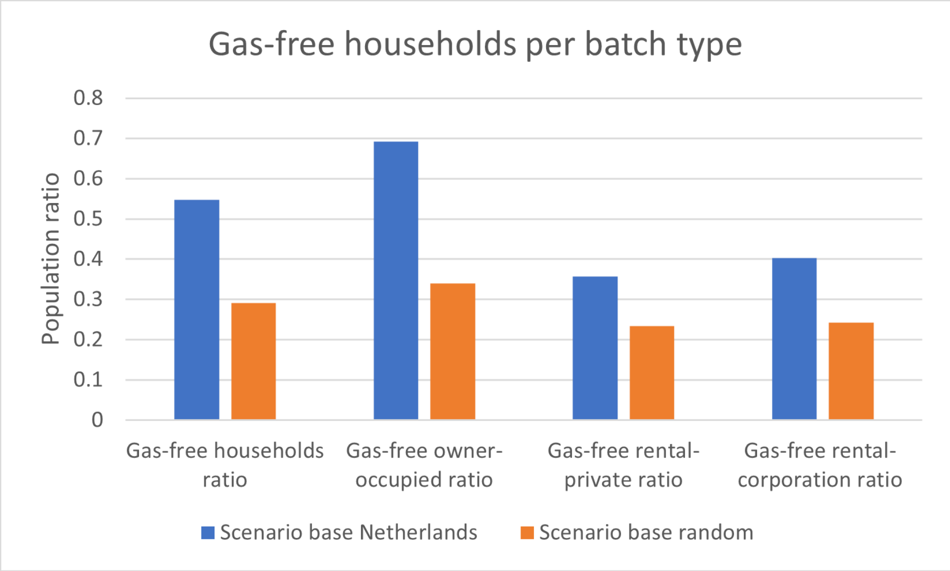

Figure 6.5: Gas-free households per batch type

Additional performance indicators are shown in Table 6.3. Gas consumption in the neighborhood increased 1.6 times with the random batch, which is understandable as the number of individual technologies in this scenario was inferior to the base Netherlands scenario in almost one full technology, from 3.7 to 2.8.

Variations for the amount of households in a collective system between the two scenarios were so small that they can be practically considered non-existent. This therefore shows that the community-related attributes did not play a major role in defining the preference of households between collective and individual technologies.

Table 6.3: Additional performance indicators results per batch type

	Scenario base Netherlands			Scenario base random		
	Min	Avg	Max	Min	Avg	Max
Gas consumption per household [kWh]	5317.128	6310.197	7748.127	9225.989	10056.17	10740.59
Households in a CES ratio	0.03	0.03876	0.062	0.03	0.03298	0.042
Individual technologies per household	3.432	3.68562	3.932	2.662	2.78352	2.932
Money savings per household [€]	1348732	1371068	1403859	1331180	1378653	1409988

As the number of installed technologies was significantly lower in the random batch, this has a repercussion as well on the technology choice. Comparing the collective technology choice, it can be seen that all technologies apart from ATES perform very similarly in both batches. However, as mentioned before, the difference is still so small that this does not represent a paradigm shift. This is represented in Figure 6.6.

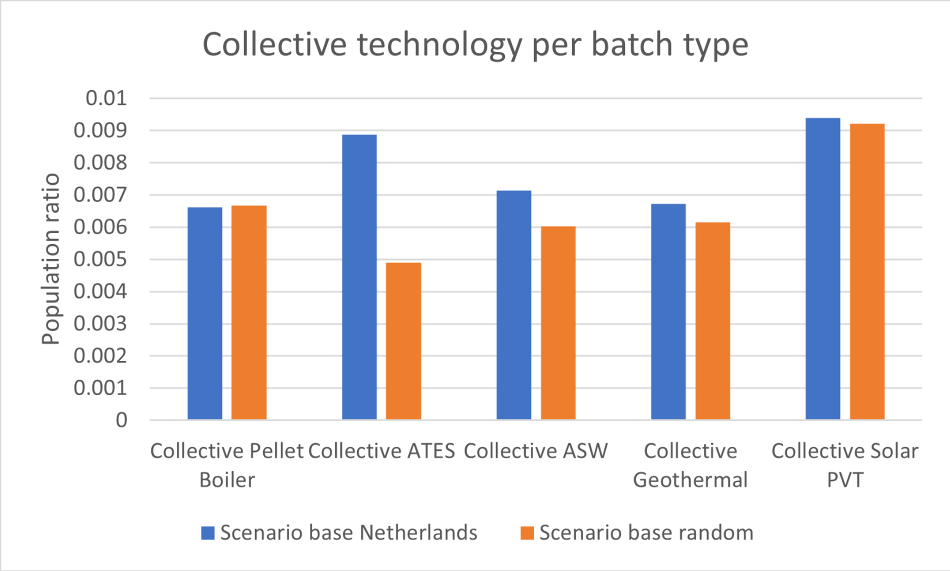

Figure 6.6: Collective technology choice per batch type

Figure 6.7 shows the technology choices per batch type, and Figure 6.8 the installation growth per batch type. The trend in both batches is similar to the insulation technologies, but this is due to the high existing installation numbers at the beginning of the simulation. Solar boilers did not experience an increase as large as in the base Netherlands scenario, but still high enough to make it the most selected technology throughout the simulation. With the random batch, the floor insulation and HR+ glass achieved higher installation numbers than heat pumps, which have a similar number to facade insulation. There is no change with pellet boilers and solar PVT, as in neither of the scenarios they get selected.

It is important to mention that the difference between batches in terms of installed solar boilers is the highest one among the different technologies, with the base Netherlands scenario managing to cover an additional 25% of the households with a solar boiler. In the case of the heat pumps, this number is equal to almost 19%. Both technologies achieve important installation growth numbers in the base Netherlands scenario, which makes the difference in gas-free households between both scenarios understandable.

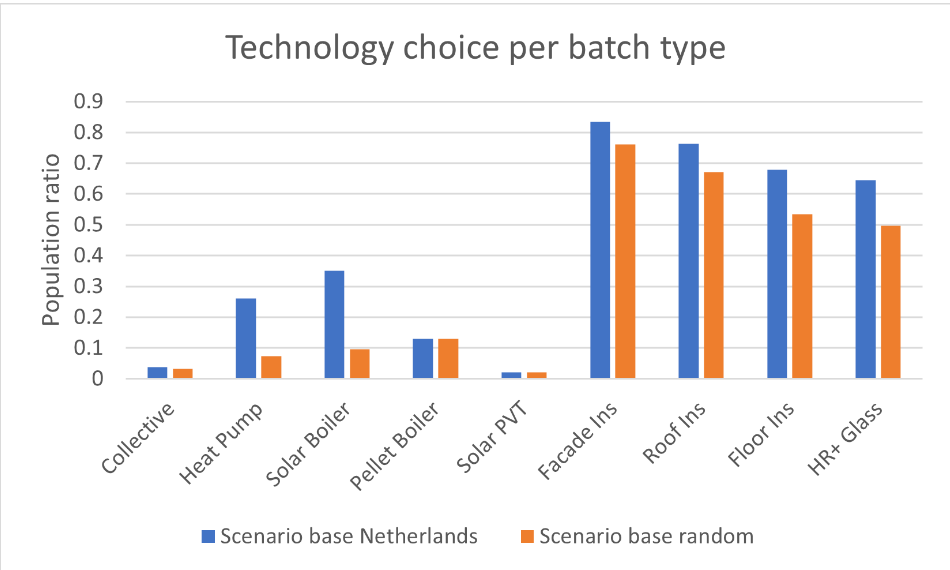

Figure 6.7: Technology choice per batch type

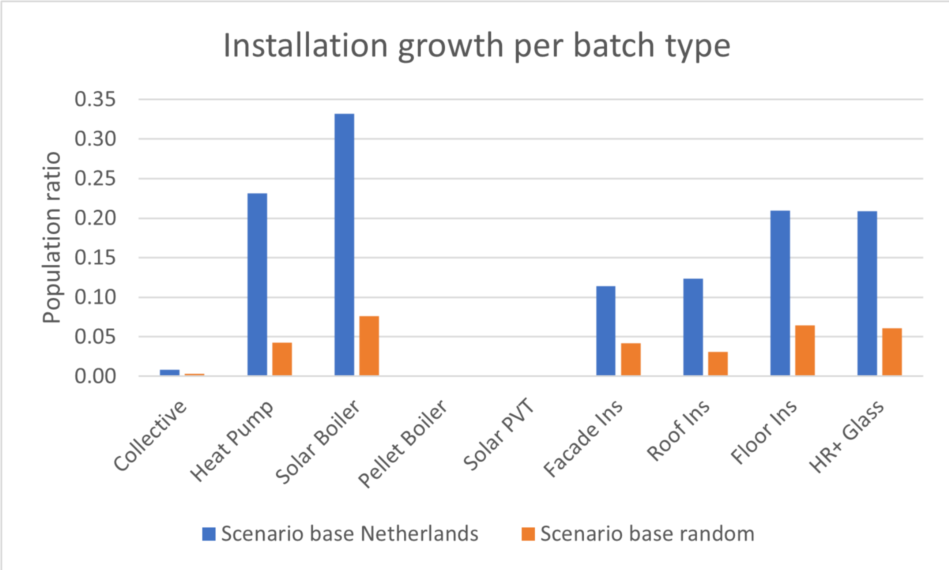

Figure 6.8: Installation growth per batch type

It is possible to see that behavioral characteristics actually play an important role in the uptake of renewable heat technologies in the model neighborhood. One defining factor around this is the value of the intention threshold, which was set to 5.5 after performing the sensitivity analysis. In the random batch scenario, the assignation of values leads households to have an initial average attitude value of around 5.0, which leads to a high percentage of them not having enough intention to acquire technology. In contrast, in the base Netherlands scenario, this average initial attitude value is equal to 6.1.

Regarding the community tendency value, the average value in the Netherlands scenario is 6.2, while the random batch scenario has an average value of 5.0. However, this turned out not to be a defining value, as the number of households in a community energy system, if indeed slightly superior in the Netherlands scenario, was practically equal.

6.2.3. Results according to the availability of subsidies

The results with the different subsidy configurations are presented below. Regarding the amount of gas-free households achieved, the "owner-occupied" subsidies availability was able to achieve the highest amount in all household types except for the owner-occupied households, where the base configuration performed equally well. Overall, the "owner-occupied" subsidies scenario performed 1.06 times better than the base one. The "rental-corporation" subsidies scenario achieved a performance equal to 0.94 times that of the base, with the "rental-private" achieving it by 0.83 times. This can be seen in Figure 6.9.

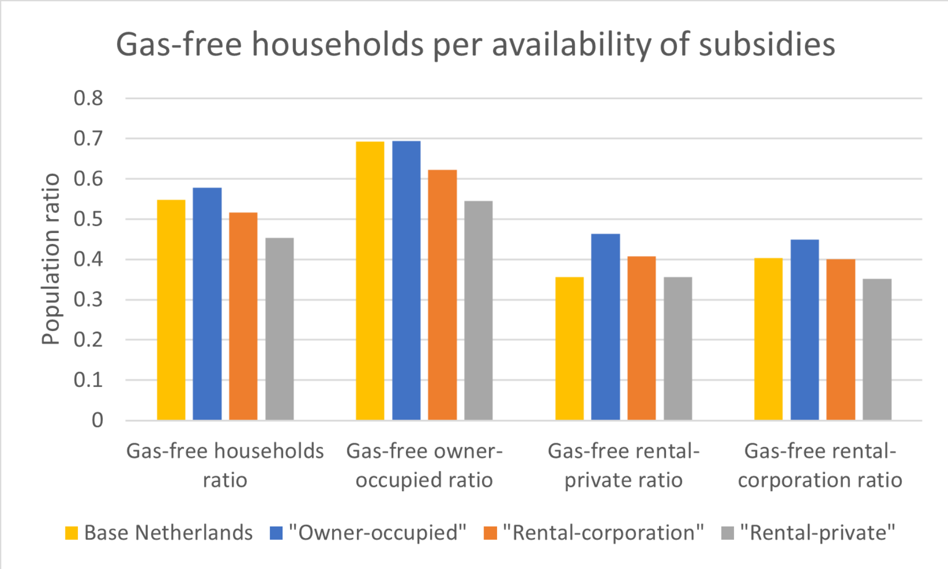

Figure 6.9: Gas-free households per availability of subsidies

It is interesting to see that the base Netherlands scenario achieves the worst performance in the gas-free rental-private households ratio, and is tied in performance with the ”rental-corporation” subsidy scenario for the rental-corporation households ratio. However, considering the totality of gas-free households, the results are in line with what was expected, as the gas-free households achieved per scenario follow the amount of available subsidies in each scenario.

Additional performance indicators are shown in Table 6.4. The gas consumption for each scenario follows the same pattern as the gas-free households ratio. The ”owner-occupied” subsidy configuration achieved 93% of the consumption presented by the base configuration. The ”rental-corporation” and ”rental-private” configurations presented a higher consumption, around 1.07 and 1.2 times higher than the base configuration, respectively.

The amount of individual technologies per household is similar among scenarios but also follows the pattern seen in the amount of gas-free households. The amount of households in a community energy system is practically the same in all scenarios.

The money savings, following their performance per batch type, performed very similarly in all four subsidy configurations. The ”rental-private” configuration achieved the highest money savings, and the ”owner-occupied” configuration achieved the lowest ones. Nevertheless, the percentage difference between them is practically negligible (less than 0.4%).

Table 6.4: Additional performance indicators per availability of subsidies

	Base Netherlands	**”Owner-occupied”**	**”Rental-corporation”**	**”Rental-private”**
Neighborhood gas consumption [m3]	283987.3	263881.3	305035.6	346118.5
Individual technologies per household	3.686	3.792	3.579	3.359
Households in a CES ratio	0.030	0.039	0.036	0.039
Money savings per household [€]	1371068	1368219	1369827	1372675

Regarding the collective technology choice, the preferences among scenarios vary in different ways, as shown in Figure 6.10. However, as it was the case while varying the batch type, the differences here are minimal and can therefore be considered non-existent. Nevertheless, the collective solar PVT was again the preferred option, followed by the ATES technology.

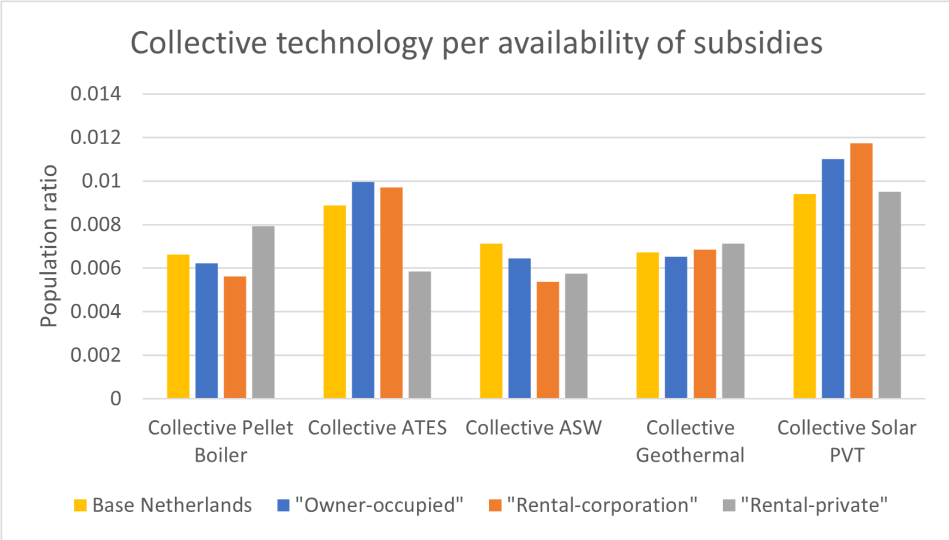

Figure 6.10: Collective technology choice per availability of subsidies

Figures 6.11 and 6.12 show the technology choice and installation growth per availability of subsidies, respectively. As expected, both graphs follow the same pattern that was shown with the amount of gas-free households, with the ”owner-occupied” subsidy availability achieving the highest amount, followed by the base availability, ”rental-corporation” availability, and finally the ”rental-private” availability. The technology preferences have the same order as when varying the batch type, with solar boilers and heat pumps being the preferred option. The patterns with pellet boilers and solar PVT are still the same, as none of them recorded any additional installations throughout the simulation.

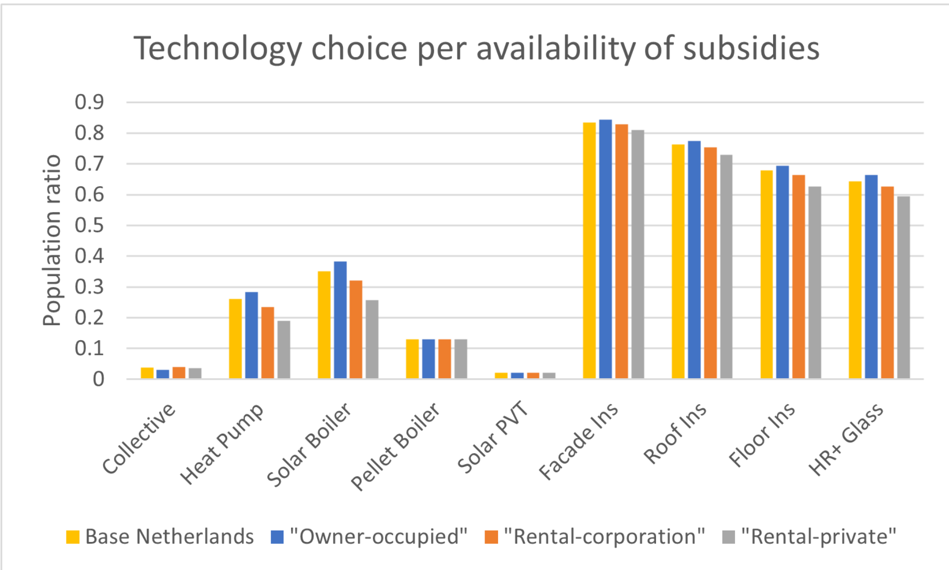

Figure 6.11: Technology choice per availability of subsidies

It is however interesting to notice that when the amount of subsidies is higher (”owner-occupied” being the highest, for example), the installation growth also presents the larger differences between the technologies. With ”rental-private” subsidies availability, the differences are much smaller: heat pump, floor insulation, and HR+ glass achieve practically the same installation rates and the same for facade insulation and roof insulation.

This can be explained by the fact that lower amounts of subsidies bring along a lower intention to households. If the amount of households with enough intention to acquire technology is not too high, then there will not be a high rate of installation across technologies, and the different installation rates will be closer together.

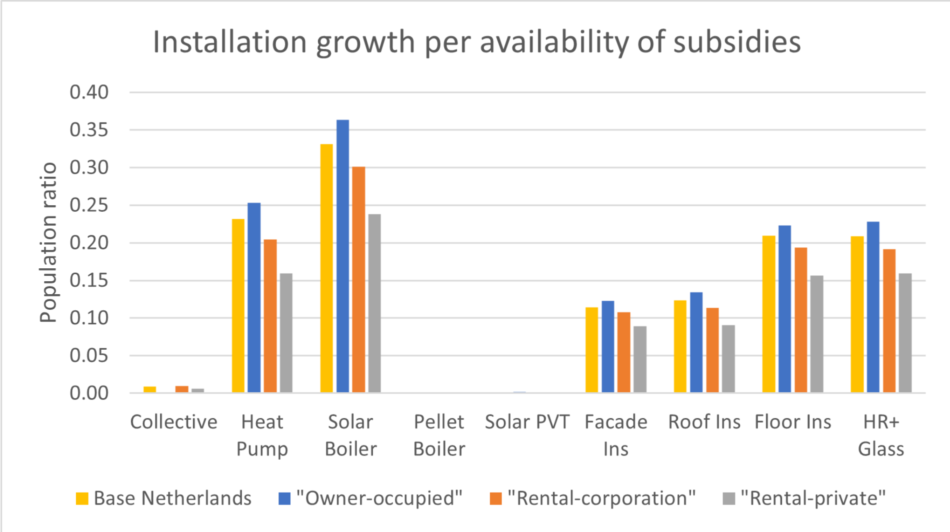

Figure 6.12: Installation growth per availability of subsidies

The effect of varying the amount of subsidies available for households does affect the uptake of renewable heat technologies and consequently has an impact on the amount of gas-free households achieved. Nevertheless, this effect is much less pronounced than while varying the behavioral attributes of households.

It is important to take into account the economic impact while comparing the performance of the different scenarios. While the performance of the ”owner-occupied” subsidies scenario is better, this also represents allocating an additional amount of money to financial support. If comparing the ”owner-occupied” scenario to the ”rental-corporation” scenario, the ”owner-occupied” has additional access to the credit ”energiebespaarlening” across three technology groups. If comparing it to the ”rental-private” scenario, then it is necessary to additionally allocate €4790 for individual technologies and €105.5/ m^2 for insulation measures per household. This additional allocation resulted in a gas consumption reduction of 23.8% achieved by the ”owner-occupied” scenario, in comparison to the ”rental-private” scenario.

Comparing the best performing ”owner-occupied scenario” to the base scenario, then the reduction of gas consumption is equal to 7%, to the expense of allocating the additional financial resources to be available in the form of subsidies and credits to the households.

6.2.4. Results according to the subsidy amount

When varying the amount of subsidy, the results in all performance indicators are extremely similar. In the case of gas-free households achievement, it can be seen in Figure 6.13 that the differences are practically non-existent. However, the base subsidy amount is the only one that does not perform the best in any category, with the ”average” amount scoring highest in the gas-free households ratio and gas-free owner-occupied ratio. The ”highest” amount scored best in the gas-free rental-private ratio, and the ”lowest” amount did the same in the gas-free rental-corporation ratio. Nevertheless, these margins that make a technology achieve a higher performance are so subtle that again, can be considered non-existent.

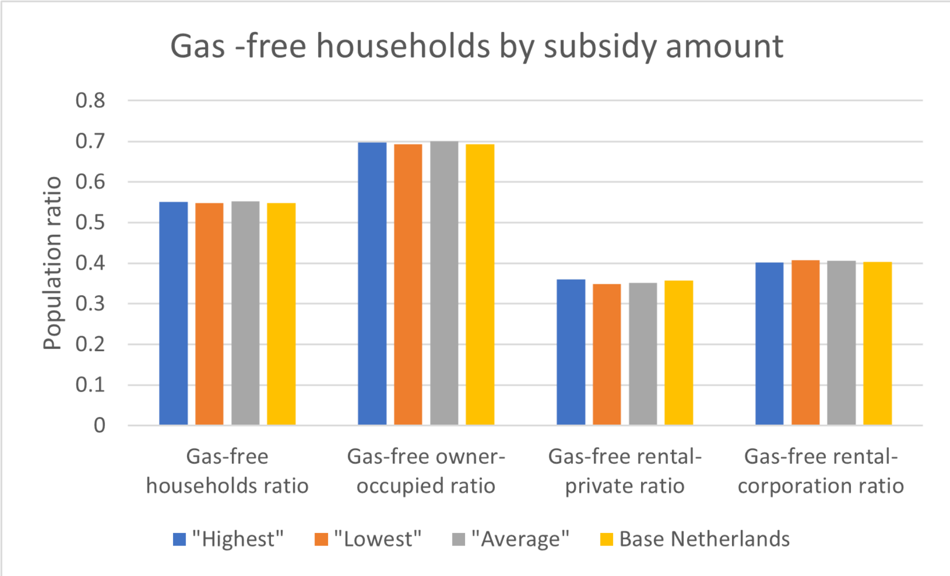

Figure 6.13: Gas-free households per subsidy amount

The rest of the performance indicators presented a very similar pattern in terms of performance, with minimal differences between the results of all four subsidy amounts. Therefore, they are not further included as they can be compared to the results obtained in the base Netherlands scenario.

6.2.5. Results varying the gas price

The results for the performance indicators of the scenario with the higher gas price can be seen in Table 6.5 below.

Table 6.5: Performance indicators with higher gas price

	Min	Average	Max
Gas-free households ratio	0.488	0.551	0.596
Gas-free owner-occupied ratio	0.631	0.700	0.770
Gas-free rental-private ratio	0.212	0.365	0.470
Gas-free rental-corporation ratio	0.287	0.398	0.503
Gas consumption per household [kWh]	5566.78	6248.12	7225.26
Amount of collective energy systems	1	1	1
Households in a CES ratio	0.03	0.04	0.06
Individual technologies per household	3.50	3.69	3.88
Money savings per household [€]	1431499	1528889	1844086

Comparing these results to the ones obtained from the base Netherlands scenario, it is possible to say that minimal variations exist throughout all indicators except for the money savings per household. Households in the scenario with the higher gas price were able to save an average of 11.5% more money, which can be explained by understanding that a higher price allows households to increase their savings if they manage to cover their gas consumption with renewable heat generation. Considering additionally that the annual gas consumption per household in the scenario with the higher gas prices was slightly inferior, then it results understandable that this additional amount was able to be saved by households.

The rest of the performance indicators, which show the uptake of the different technologies, presented practically identical patterns to the ones obtained through the base Netherlands scenario. Therefore, they are not further included.

6.3. Discussion

The results of the model showed that with the current strategy, the Netherlands would be able to achieve around 55% of gas-free households by 2050, reducing its total gas consumption by 45%. This stays short of the target of achieving a full heat transition in households by the same year. However, there are some interesting takeaways from the obtained results that are discussed further below.

Results by household type A significant disparity was observed between owner-occupied households and rental households concerning gas-free achievement. This disparity highlights the impact of the discrepancy in available subsidies, in addition to the existing differences in economic capabilities.

It is crucial to emphasize that tenants lack access to any form of subsidies, making it notably challenging for them to adopt renewable heat technologies. As a result, the progress of rental households toward achieving a complete heat transition in the model was hindered. Considering that they make up 40% of the households in the country, it might be a good strategy to enable support programs and subsidies that facilitate their access to different types of renewable heat technologies. Another possibility could be to impose required minimum energy labels for rental households, which would force the landlords to adequate the houses with renewable heat technologies, benefiting tenants with a reduced demand for heat and landlords with the possibility to increase the rent.

Technology choice The specific uptake of technologies such as heat pumps and solar boilers, in addition to the different insulation technologies, shows that households are willing to acquire specific technologies more than others with the current conditions. This could serve as a reference to policymakers and technology companies that are willing to participate and push this transition, to design support schemes that allow these specific technologies to be diffused in a faster way.

Clearly, insulation technologies have an edge over the rest of the technologies due to their long lifetime and low expenses. However, they need to be combined with active technology to cover the full heat demand of the household.

In the model, heat pumps and solar boilers were the two most acquired active technologies by a big margin. Solar boilers are interesting given their longer lifetime, although given the weather conditions in the Netherlands, a large storage unit might be required. Heat pumps, on the other hand, can be more useful in the country given their high efficiencies.

Additionally, the average number of technologies showed that combining technologies is the general trend among households. Considering only the households that achieved a gas-free status, the average number of installed technologies is equal to 4.6 (compared to the current number of 2.47 technologies per household). This number is usually made up of combinations of insulation technologies and one active heat technology. It is therefore important to motivate households to adopt more than one technology at a time. The current subsidy schemes allow households to receive a larger subsidy amount if they decide to install more than one technology in a lapse of 24 months. This seems to be the right choice and should be further encouraged.

Collective systems Collective systems did not perform as it was expected. The expectation was that, given the possibility to join an existing system, households would react in a positive way as these systems have generally lower costs per installed capacity than individual technologies due to economies of scale, and have higher capacity factors throughout a year. Nevertheless, in the model that was not the case, and can be attributed directly to the way in which the households rank the different technologies, more specifically, to the *technology noticeability* factor. As described in Chapter 5, the grade that every household awards to each particular technology is a function of five different factors that connect the household's own behavioral characteristics, access to subsidies, and the technical and economic characteristics of each technology. Collective technologies were scored on *technology noticeability* on average almost 6 times lower than individual technologies (except for individual pellet boilers and solar PVT). This can explain the general preference of individual technologies over collective ones, given that for the remaining four factors the scores were competitive to a certain extent, especially between collective technologies and active individual technologies.

The SDE++ is the only current subsidy program accessible for collective technologies, hence it is plausible to link this underperformance of collective technologies to the lack of other subsidy programs. Comparatively, individual technologies can benefit from a wider range of subsidies, which inevitably raises household awareness of and propensity to purchase individual technologies.

The emergence of new collective energy systems did not occur. As mentioned before, the model had as a requirement a minimum amount of households, equal to half of the neighborhood population, which clearly made it easier for the interested households to join the existing community system rather than forming a new one. However, this was expected, as in the real system it is the case that neighborhoods have access to only one type of collective system due to infrastructure constraints and availability of resources. Besides, behavioral tendencies benefit options that are already available rather than options that require higher transaction costs, simply due to the easiness and the exertion of less effort. The results in the model, therefore, comply with the behavioral trend in the real system.

General overview The results showed that behavioral characteristics can play a very relevant role when it comes to transitioning to gas-free households. The differences in performance between both batches are important and clearly show that it is necessary to continue informing people about the benefits of implementing renewable heat technologies, both for them and for the environment. It is important to consider that motivated people can serve as disseminators of ideas through their social network, which can speed up the adoption of renewable heat technologies through the population as well.

Additionally, municipalities can become key players in this regard, as they have the possibility to use their channels to spread information regarding the heat transition. This can allow people to adopt or reinforce pro-environmental attitudes, while at the same time increasing the people's perceived behavioral control due to the consideration of municipalities as facilitators.

However, it is impossible to neglect the influence of the availability of subsidies on the uptake of technologies, and on the performance of the gas-free transition of the different household types. This shows that subsidies can be game changers, as they actually provide households with a push to acquire technologies, or certain technologies to be more selected than others. However, the level of success of subsidies also depends on the level of awareness people have over them, and the perceived easiness of applying and being awarded them.

It was not expected that varying the subsidy amounts would not result in any differences in terms of performance, especially regarding the technology choice. However, this can be attributed to the way the subsidy amounts play a role in shaping the households' intention. Actually, they only affect the households' decision towards their technology preference, but do not directly affect the intention level of the households. However, the "average" subsidy amount technically achieved the highest performance out of all of them. It would clearly be interesting to have a look into the actual influence of subsidy amounts on the perceived behavioral control of households, as they must surely affect the perceived easiness of achieving the transition.

Regarding the technology selection, it is possible to see the effect that the lack of subsidies has on the technologies the households decided to install. Clearly, the availability of subsidies is not the only factor that affects the technology preference, but it showed a direct effect on the model. Technologies with a high amount of available subsidies, such as solar boilers, heat pumps, and insulation technologies were the most installed technologies. Individual pellet boilers and solar PVT were not adopted in any of the simulations, and correspond to the only two technologies that are currently not subsidized. Therefore, this reinforces the idea that subsidies really manage to influence households on their decision to install certain technologies, and therefore should be used to promote the most promising technologies.

Policymakers should be careful while delineating support schemes, as there is a trade-off between the increase in gas-free households and the additional amount of money that should be made available to achieve this gain in performance. However, subsidies can also be used to push certain technologies to be adopted more widely, which can be used to promote more efficient or promising technologies.

Finally, it is important to say this process is holistic in nature, and a full heat transition requires the combination of a series of factors to succeed. Subsidies by themselves cannot get the job done, and it is the same case with pro-environmental attitudes. People need favorable conditions with both elements, and also with additional ones such as the rest of the perceived behavioral control factors considered in this model, in order for them to actively and effectively participate in the heat transition. This is the reason why several stakeholders such as households, municipalities, national governmental institutions, and even technology manufacturers need to be aligned in terms of objectives in order for this transition to take place.

6.4. Limitations of the research

As with every model, the one presented here has several limitations. It is important to notice that the objective while building a model is to represent as faithfully as possible the system in question. This was attempted while building the model presented here, to the extent of the possibilities in terms of available data on technologies, household characteristics, and relationships between the different elements.

Input data First, it is worth mentioning that the available demographic data on households was very detailed and provided a strong base upon which it was possible to build up the model. Nevertheless, the information linking the type of households with the installed technologies per type of household was missing. Had this information existed, the model could have been more detailed and could have provided better insights into the performance per type of household.

The survey implemented by Koirala et al. (2018), whose information was used to partly build the profile of the Dutch households, was answered with the assistance of students, who passed the survey on to their adult relatives and acquaintances. There is a high chance that this procedure led to a non-representative sample of the Dutch population, and therefore the results can be biased. This represents a limitation of the study and has an effect on the obtained results, given the possibility that they might not reflect the whole spectrum of beliefs and attitudes of the Dutch households.

The considered assumptions are relevant, as they affect the outcomes of the model. It is important to consider that assumptions were made on the implementation of the behavioral characteristics, relationships between variables, and dynamics between agents and input data. There is a level of uncertainty with some of the values that were considered in the model. The one-factor-at-a-time sensitivity analysis was performed with these variables to increase the spectrum of results that the model could be able to show. However, it is still possible for the results to be biased due to this selection.

Behavioral theory The approach in which the theory of planned behavior was used slightly differs from the approaches published in the literature. While attitude and perceived behavioral control are in line with what has been published, no precise attributes were considered for building up the subjective norm component of the households, as this component relied purely on the belief dynamics. This leaves out certain important aspects that can shape a household's behavior such as social pressure.

Technical factors Some technicalities were not considered, such as daily and seasonal generation and consumption patterns, which are known to be relevant when it comes to renewable energy generation and heat consumption, as they might have an impact on the capacity of the generation system and the complementary use of a heat storage system.

Some currently in-use heat generation technologies like residual heat recovery and waste-to-energy were not considered due to the reliance on an external party or source. Besides, the integration of newer upcoming technologies into the system such as hydrogen is not included either, which given the time frame selected, will also play an important role in the coming years and shape the achievement of gas-free households.

The price of gas was not considered a factor that affected the intention of households. However, considering the way in which gas prices have affected the gas use pattern in the Netherlands in recent times, it is clearly an important factor that can affect the uptake of renewable heat technologies.

Economic factors The model does not take into account variations in economic factors like salaries, living costs, technology costs, or factors like the increase in technologies' performance, lifetime, or capacity factors. Given the time horizon of the model, these are all factors that change over time and that can affect the outcome of the model.

Complex system attributes Certain factors like the effect of path dependence are not being considered. This relates to how households would have a tendency to adopt technologies that have already been used by them before, especially if the technology leads to a positive outcome. This could have had an impact on the technology choice and even on the intention level, if the household was satisfied with the performance of its technologies.

Another factor that is not entirely considered is how robustness and resilience play a part within the system. As an example, this could be related to how households consider redundant or backup systems to provide them with their required heat, in case the main system fails to do so. Currently, this robustness is provided by the possibility to be permanently connected to the gas network. However, in the future system, storage systems might be needed to provide this security.

Finally, the system only manages to consider two levels of aggregation: the individual household and the neighborhood. In the real system, it is possible to identify different levels of aggregation, going further from a city to the whole country. However, the system in the model is bounded to a single neighborhood. Nevertheless, it is important to keep in mind that higher levels of aggregation can be explored.

6.5. Conclusion

This chapter presents the definition of the different modeling scenarios, the corresponding performance indicator results, and a discussion of the results and the limitations of the research performed.

The intention of this study is to define the relevance of behavioral characteristics and policy conditions within the context of the households' heat transition in the Netherlands. Therefore, it was deemed important to evaluate the model with the particular set of behavioral characteristics of the Dutch population against a randomized characterization. Similarly, conditions of subsidy availability and awarded amount were varied to have a clearer image of the role subsidies can play in this. At last, gas prices were also varied to see the effect this could have on the performance indicators.

The results provided a very insightful image, as it was possible to see to what extent this heat transition could be achieved given the current conditions, and assess the influence of the different elements towards it. Both behavioral characteristics and policy conditions resulted very relevant and had an influence over the amount and type of households that were able to achieve a full transition. Policy conditions not only had an influence over this but also over the selection of technologies. Regarding the technology selection, it was interesting to see how the different characteristics of the households, together with the technical and economic characteristics of the technologies, were able to influence their uptake. This showed that even factors like awareness can result very relevant for this process.

Finally, it is important to acknowledge that the various limitations of the study play a very relevant part in the results obtained. It is clear that the more complex a system is, the more elements need to be considered. This, in turn, adds a layer of difficulty while bringing the model together given the possibility of access to certain values, combining data sets, and even possible lack of information. A modeler needs to be capable of assessing and determining the best way to overcome these assumptions and address the existing limitations, to consider to what extent the model can be helpful.

7 Conclusion

7.1. Answering the main research question

In order to be able to provide an answer to the main research question, it is necessary to recapitulate and reflect on the answers to the three sub-questions.

The answer to **SQ1: "What are the technical and economic settings for implementation to achieve natural gas–free households in the Netherlands?"**, comes in the form of a series of collective and individual technologies that allow households to cover their heat demand with renewable sources. Regarding the collective systems, and taking into consideration the state of technology and the availability of resources in the Netherlands, the most important technologies include: sustainable wood pellet boilers, aqua thermal with seasonal storage, aqua thermal from surface water, geothermal and solar photovoltaic-thermal. Due to the geographical characteristics of the country and the resulting high density of water bodies, both aqua thermal systems are very promising. The rest of the technologies make use of resources that to some extent can be found in the majority of the countries, with the corresponding specifications that allow their use for low-medium temperature heat networks.

The individual options include active and passive technologies. Among the active technologies, there are heat pumps, solar boilers, wood pellet boilers, and solar photovoltaic-thermal systems. The passive technologies include insulation in the facade, roof and floor, and the use of high-performance "HR+" glass for the windows.

These are all technologies that have been used already for some time, and that can be considered mature technologies. Their economic characteristics are variable and particular to every technology. Collective and active individual technologies are similar in terms of lifetimes, with insulation technologies having the longest lifetime and being the most economical in terms of upfront costs. A detailed overview of their economic characteristics can be found in Tables 4.1, 4.2, 4.3 and 4.4.

The answer to **SQ2: "How can the different behavioral characteristics and policy conditions be combined with the technical and economic settings in transition scenarios?"** has two facets. On the one hand, there is a wide range of policy conditions that can permit the acquisition of the technology options described in the previous sub-question, where the most prevalent are subsidies. The Dutch government has made available a variety of subsidies that support the acquisition of renewable heat technologies, with varying availability based on some characteristics of the household such as ownership type (owner-occupied, rental-corporation, and rental-private), and belongingness to an owners' association. These subsidies support the acquisition of different technologies and award different amounts based on eligibility.

The other facet comes in the form of the elements that have an influence over the households' perception and ultimate intention of acquiring any form of renewable heat system. Using the theory of planned behavior as an explanatory framework, it is possible to identify relevant elements in the three dimensions of the theory: attitude, subjective norms and perceived behavioral control. Beliefs regarding the transition make up the attitude component. Four belief attributes have been regarded as the more influential: environmental friendliness, awareness, energy independence and economic drive. Social influence integrates the subjective norms component. This relates to the extent to which a household's connections are able to persuade the household to acquire a renewable heat technology or participate in the heat transition. In this case, belief dynamics play a huge role. A household's beliefs update after interacting with other households with different views on the same topic, proportionally to the connection weight, - the level of importance the household places on its connection. Finally, there are external elements affecting the apparent easiness of acquiring a technology, which make up the perceived behavioral control component. Four were identified as the most relevant: availability of subsidies, municipality efforts, financial capability, and time availability.

Having determined the behavioral characteristics and policy conditions, it is possible to relate them to the existing technical and economic settings, to evaluate the way and magnitude in which households are able to adopt them. Setting up a time frame, in this case, the year 2050 due to the heat transition objectives, allows us to determine the extent to which households reduce their gas consumption and become gas-free.

The answer to **SQ3: "To what extent can the different behavioral characteristics and policy conditions achieve natural gas-free households?"** comes from the results of the model. In this case, the current Dutch behavioral characteristics and policy conditions were successful in reducing natural gas use by 45%, resulting in the gas-free status of about 55% of the households.

There was a notorious difference in performance by household type. Around 69% of the owner-occupied households achieved a gas-free status, compared to 40% of the rental-corporation households and 35.7% of the rental-private households. This difference in performance relies on external factors such as the availability of subsidies and the financial capability of the households.

Regarding the technology choice, the setup of behavioral characteristics and policy conditions allowed some technologies to be more selected than others. Solar boilers were the most selected technology, with a total of 33% of the households selecting one throughout the simulation. Heat pumps were the second most selected technology, with 23% of households selecting them. Insulation technologies were overall the most widespread technologies, given their initial high rates of presence in households, with all of them being in use by more than 60% of households at the end of the simulation.

Households rarely decided to take part in the existing energy community. This was due to the households' preference for individual technologies over community technologies, especially due to the community technologies' noticeability. However, the most popular community technology was solar PVT, followed by ATES. New communities were not formed, as there was never a moment when enough households would be interested at the same time in establishing a new energy community.

Behavioral characteristics played a very important role in shaping the final intention of households to acquire a technology. Comparing the performance of the scenario with the characteristics of the Dutch households, to a scenario with randomly assigned characteristics, it was possible to see a big difference in performance between the two scenarios. There were almost 50% more households with the gas-free status in the Netherlands scenario than in the random one. This represented a gas consumption 1.6 times higher in the random scenario compared to the Netherlands scenario.

However, beliefs around the community did not seem to have an important effect on the decision of households to join an existing energy community. In this particular area, both scenarios had equal performance.

Considering the policy conditions, the amount of subsidies was a more decisive factor than the amount awarded through the subsidy. This could be seen throughout the scenarios, where owner-occupied households, which have access to a larger amount of subsidies, always had better performance in terms of natural gas reduction. Additionally, within the scenarios that awarded the same amount of subsidies to all households, the "owner-occupied" scenario performed the best out of all scenarios, including the base Netherlands scenario. Varying the amount awarded turned out to be a factor that did not really have an influence over the intention of households to acquire a technology, nor the technology choice. Likewise, the performance of the scenario with the higher gas price only varied the amount of money saved.

Finally, this permits answering the main research question of this thesis: **”What behavioral characteristics and policy conditions, under specific assumed technical and economic settings, are most effective in transitioning a significant proportion of Dutch households away from natural gas by 2050?”**.

The heat transition is a process that involves the alignment of different factors, to set up the correct conditions under which the use of natural gas can be substituted by heat-providing technologies that make use of renewable sources. For households, these conditions are internal and external.

Internal conditions relate to the households’ beliefs around the topic of the heat transition. The more relevant beliefs have been identified, and are integrated by a household’s level of environmental friendliness, awareness of gas-reducing practices, energy independence, and economic drive. These four beliefs are interconnected and are considered equally important by the Dutch demographic.

These beliefs can be influenced by the network that surrounds each particular household. The information exchange between two entities naturally leads to a reshaping process of beliefs, that can have different levels of strength based on the relative importance one of these entities places on the other one. Households are therefore susceptible to changes in opinion, which has a direct effect on the beliefs described previously and consequently affects the heat transition.

External conditions are variate in nature. On the one hand, there is an array of technological possibilities to generate renewable heat that is available to the Dutch population. These technologies have particular technical and economic characteristics that can shape the preference of the households, based on what each particular household deems as more important.

On the other hand, there are factors that affect a household’s perception of the level of easiness to participate in the heat transition. These factors can be intrinsic to the household, such as its time availability or financial capability. However, other factors can be extrinsic and therefore context-dependent, such as the availability of subsidies and the number of support schemes promoted locally, - the municipality efforts.

As mentioned before, these factors shape the behavioral process of households by defining their intention to acquire a technology. This intention is translated into a behavior when the correct conditions fall into place. In this case, the most important condition comes in the form of the affordability of the preferred technology, given that the main detractor from renewable heat technology adoption is precisely the economic barrier.

Similarly, subsidies can improve the perceived easiness level of households to acquire a technology. The current subsidy offer by the Dutch government supports households with a monetary sum to acquire renewable heat technologies and reduce their gas consumption. However, this subsidy offer is currently skewed in favor of owner-occupied households, leaving tenants completely unable to have access to any subsidy or loan.

Apart from that, subsidies are also able to shape the technological preference of households. The results of the simulation showed that technologies with a higher amount of available subsidies were more commonly selected than others with a lower amount of applicable subsidies. The amount awarded through the subsidy seems to be less relevant, given that it did not have a particularly noticeable effect on either the amount of gas-free households achieved or the selection of technology.

The simulation results showed that behavioral characteristics play a very important role in defining the final intention of households, as motivated households can push the transition both by acquiring the technologies themselves or influencing other households into acquiring technologies.

Finally, it is important to say that Dutch households consider beliefs to be more relevant than external factors when it comes to defining their intention to acquire a technology. Policies should take all this information into account to ensure that a full heat transition by 2050 is accomplished.

7.2. Policy recommendations

Knowing that households’ beliefs are very relevant when it comes to technology adoption, it is then important to design policies that are able to exert an influence over these beliefs. Policies that allow the spread of information regarding the benefits of acquiring renewable heat technologies or the disadvantages of the continuous use of gas are beneficial on two different fronts. On the one hand, they are able to influence households' beliefs by making use of the theory of belief dynamics, especially if special attention is put on the frequency, reach, and impact of the information distribution. They can have an effect on the environmental friendliness levels of a household, their awareness level, energy independence level, and even their economic-drive level.

On the other hand, households will also perceive a higher degree of effort by the local or national government, which will increase the perceived easiness level of acquiring technologies or engaging in practices that reduce their gas consumption. These types of policies are commonly known as "boosts" (Nova and Lades, 2022), and could be able to increase a household's level of information and skills required to adopt renewable heat technologies.

Information campaigns are not the only policies that allow exerting an influence over the beliefs of households. Considering that groups are able to reinforce individual beliefs (Millner and Ollivier, 2016), and that social pressure can generate a change in opinions (Galesic et al., 2021), municipalities could develop focus groups or other types of group dynamics where household members could get involved with highly motivated individuals to spread the benefits of using technologies to alleviate the consumption of gas and to invite other households to join the heat transition. This could again provide external incentives for households to adopt technologies and drift their beliefs towards the pro-heat transition side.

Information campaigns can also be related to the benefits of using certain technologies over others, especially when it comes to making use of more efficient or novel technologies where path dependence plays an important role in redefining use trends. This is related to the results of the simulation where the technologies that had the higher amount of subsidies were the ones that were adopted the most. If a certain technology gets more attention than others, households could be able to form predefined ideas about which technology to adopt. Another type of policy that could help to establish certain technologies over other are nudges. They are based on defining certain aspects as default options (Nova and Lades, 2022), which could be beneficial to allow defining certain technologies as the main option.

Policymakers should also evaluate whether the current distribution of subsidies is optimal. The results showed that a higher amount of subsidies leads to a lower amount of gas consumed. However, making more subsidies available has an economic repercussion that perhaps does not result beneficial in the long run. Nevertheless, this can be used to target specific technologies. Besides, knowing that the effect of having a higher amount awarded through a subsidy is not as defining as the amount of subsidies that are available, there could be a possibility to redistribute the amounts and allow certain members of the population such as tenants of rental-private households to have access to a higher amount of subsidies than they currently have. This is relevant considering that tenants are the group with the lower financial capability and whose living expenses represent the highest percentage of their total salary.

Finally, it might be worth considering regulatory measures such as renewable heat mandates for households given the results achieved with the model, where the objective of 100% gas-free households was not achieved by 2050. Renewable heat mandates have been proven successful (Germeshausen et al., 2022) and can go from making households replace obsolete systems with new renewable heat systems, to forcing households to achieve a specific energy label or cover a specific percentage of their heat demand with renewable heat.

It is important to keep in mind that a relevant aspect for these policies to work is to ensure that trust in government institutions remains high and that households are not obliged to install technologies. It has been shown that trust in the government is directly related to how successful policies can be and that allowing citizens to have self-determination is a more persuasive technique than making a certain action compulsory (Bowles, 2021).

7.3. Scientific relevance

The conducted study manages to successfully incorporate variables that have been identified as relevant in previous studies regarding the adoption of renewable heating systems by households and in their participation in the heat transition and complement their contribution by assessing them through an agent-based model.

Selvakkumaran and Ahlgren (2019), for instance, elaborated a framework to explain the uptake of technologies that can lead households to participate in the energy transition. Herein, they identified and stressed the importance of elements like household characteristics, namely household type and house size, and economic factors such as upfront costs, in the process of renewable heating systems uptake.

Cornago (2021) highlights the relevance of behavioral trends and attitudes over the energy consumption of households; specifically in the case of the Netherlands, Bal et al. (2021) showed that beliefs and attitudes play a big role in a household's motivation to participate in the energy transition. However, they do not manage to measure the extent to which the transition can be achieved given this representative profile of Dutch households' beliefs and attitudes.

Considering a more holistic perspective, Steg et al. (2018) recognize the importance of individual factors like values, identities, and beliefs around the energy transition and their role in shaping the policies that can push it. Attitudes and values are specifically appointed by them as the main motivators for individuals, while subjective norms are also assumed as relevant to shaping the behaviors of individuals.

As it was mentioned in Chapter 2, documented studies have not covered the influence of behavioral characteristics and policy conditions on the heat transition of households, especially not in the Netherlands. The studies cited in the previous paragraphs emphasize the role of these two elements in the heat transition and set a precedent to quantitatively evaluate their influence on the heat transition. As shown in the results, these two dimensions are very relevant in terms of the level of gas use reduction and achievement of gas-free households.

Additionally, the use of an agent-based model that implements the theory of planned behavior within the heat transition context in the Netherlands has not been documented either and therefore complements the research currently being done in this area.

Specifically regarding the way in which the theory of planned behavior was used, a variation that this thesis brings along is the incorporation of belief dynamics into the subjective norm component. It is important to acknowledge its relevance, as this is a process that actually occurs with networks and the exchange of information and that has an impact on the outcome of the model.

The academic contribution of studying this topic is in line with the current academic trend of energy transition modeling, which addresses the current world energy crisis. Similarly, it has the potential of expanding the available knowledge in this field, setting relationships between behavioral characteristics, policy conditions, end-user motivations, and the transition progress.

7.4. Societal relevance

7.4.1. Social impact

Households, as a fundamental part of society, are able to contribute towards the heat transition given their importance within the energy sector and their influence in the different social spheres. Acknowledging the importance of beliefs in the heat transition is key to achieving the established sustainability objectives. Therefore, shaping this set of beliefs can have a direct impact on different social characteristics. Education might be the most evident: as households engage in activities that promote this transition, they might get informed about the topic and develop a level of interest in it. This can lead to the implementation of gas-saving measures at household or community levels, that might influence other households into engaging in the transition.

Income is another social factor that is relevant to this topic. The uptake of renewable heat technologies has the potential to reduce the expenses made in regard to energy. Besides, with the fluctuating and unstable prices of gas, especially during the last years, these technologies provide a certain level of energy and financial security for a medium period of time.

Social connections are a key part of this. Realizing their relevance, especially regarding the diffusion of information, is key to promoting the heat transition.

7.4.2. Environmental impact

The importance of studying this topic is mostly environmental. The United Nations' sustainable development goals, namely "7 - affordable and clean energy", "11 - sustainable cities and communities" and "13 - climate action" are all impacted by the topic covered in this thesis (United Nations, n.d.). The extent to which society is able to achieve this transition directly affects the prices of energy, the energy generation's impact on the environment, the sustainability level of cities, and in a general way the work done towards reducing emissions and reversing the environmental impact already exerted on the planet.

The current dependence on natural gas leads to a high amount of carbon emissions being generated and released into the atmosphere. Accelerating the rate at which households acquire technologies that supply this heat in a clean way using renewable sources will speed up the decarbonization process and reduce the toll the planet takes because of heat generation.

7.4.3. Economic impact

The relevance of this topic can also be extended to the area of economics. At a higher level, the current reliance on natural gas to produce heat is a process that is based on an existing mature industry that supplies the natural gas, and on another mature industry that supplies the technologies to produce heat using this gas. However, with the development of new technologies, new industrial directions can be opened. The diversification of technologies promotes competition among industries, which in turn offers lower costs to end-users and achieves higher efficiencies in the technologies. This, in turn, allows end-users to have access to cheaper energy and brings them economic security. Besides, defining subsidy programs accessible for everybody to push the uptake of technologies to the maximum supports the economies of households and permits them to have equal opportunities.

7.5. Recommendations for future work

After completing this study, a process of reflection allows us to identify improvement areas for future work. Possibly, the most important of them is the use of a survey to obtain information. Future models, after defining the way in which the behavior will be modeled, could develop a survey with specific questions targeting the different attributes taken into account, to obtain a more concise view of how these are rated in the perception of a sample population representative of the one intended to be modeled.

Future studies making use of the theory of planned behavior should explore different ways in which the belief dynamics can be incorporated into the theory. This is relevant as this process is overlooked to a certain extent by the theory, but indeed happens. Besides, beliefs are not the only aspects that are dynamic over time. Certain attributes such as time availability or financial capabilities evolve over time. A recommendation is made to integrate this variation into the models developed, as societies tend to evolve over time.

This model incorporates the price of gas only as an economic factor. However, it is important to recognize its relevance as a factor that actually motivates households to acquire renewable heat technologies. Future studies should include this in the list of external elements that shape a household's behavior.

Additionally, future work could explore the use of some technologies that were not included in this work, such as hydrogen, mainly due to their potential in the heat networks of the future.

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A
Literature Review

A.1. Assessment research gap

An initial systematic literature review was performed to analyze the existing studies surrounding the implementation of renewable heat technologies. Figure A.1 shows an overview of the search process and selection of results.

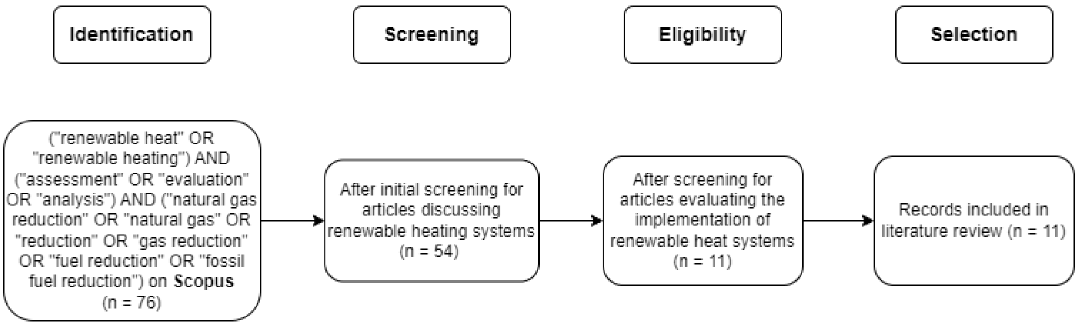

Figure A.1: Search and selection process for the assessment literature review

Table A.1 below presents the selected studies, with an indication of the type of assessment presented.

Table A.1: Overview of selected articles and assessment areas after assessment literature review

Article	Authors	Area	Technical	Economic	Social	Environmental
Life cycle assessment of Irish district heating systems: a comparison of waste heat pump, biomass-based and conventional gas boilers	Mahon et al. (2022)	Ireland				X
Renewable heating solutions for buildings; a techno-economic comparative study of sewage heat recovery and solar borehole thermal energy storage system	Pohkrel et al. (2022)	Canada	X	X		
Decarbonization of the Heating Sector in Hamburg Grid Constraints, Efficiency and Costs of Green Hydrogen vs. Heat Pumps	Röben et al. (2022)	Hamburg		X		
Optimal Sizing of a Grid Independent Renewable Heating System for Building Decarbonisation	Chen et al. (2021)	UK	X	X		
Techno-economic analysis of decarbonizing building heating in Upstate New York using seasonal borehole thermal energy storage	Durga et al. (2021)	USA	X	X		
Cost-minimised design of a highly renewable heating network for fossil-free future	Ashfaq et al. (2018)	Denmark	X	X		
Pinch Analysis Techniques for Carbon Emissions Reduction in the New Zealand Industrial Process Heat Sector	Walmsley et al (2015)	New Zealand	X			X
The Impact of the Climate Action Programme 2030 and Federal State Measures on the Uptake of Renewable Heating Systems in Lower Saxony's Building Stock	Haase et al. (2021)	Germany		X	X	
How to improve effectiveness of renewable space heating programs by better understanding homeowner – installer interactions	Freyre et al. (2021)	Switzerland			X	
The trigger matters: the decision-making process for heating systems in the residential building sector	Hecher et al. (2017)	Austria			X	
Dynamic whole system testing of combined renewable heating systems: the current state of the art	Haller et al. (2013)	Switzerland, Sweden, France	X			

A.2. Behavioral theory research gap

A second systematic literature review was performed to explore the existing studies surrounding the implementation of behavioral theories within agent-based models, with a special focus on studies that made use of the theory of planned behavior. Figure A.2 shows an overview of the search process and selection of results.

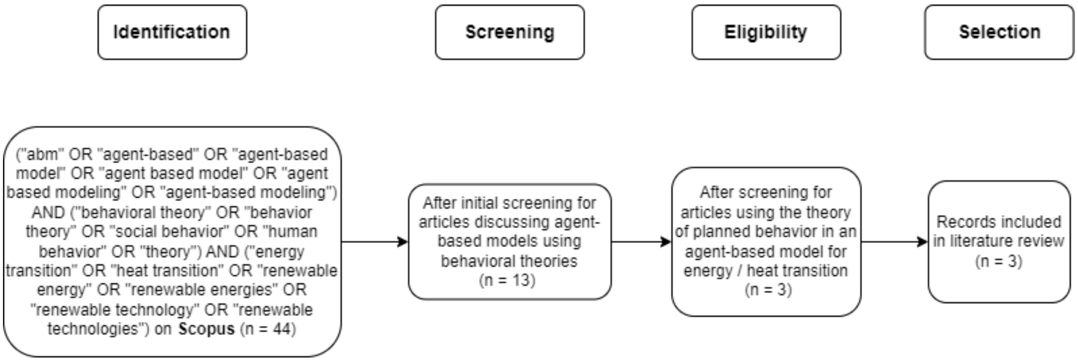

Figure A.2: Search and selection process for the behavioral theory literature review

Table A.2 below presents the selected studies, with an indication of the scope of the study.

Table A.2: Overview of selected articles and scopes after behavioral theory literature review

Article	Authors	Scope
Hybrid Approach for Modelling the Uptake of Residential Solar PV Systems, with Case Study Application in Melbourne, Australia	Moglia et al. (2022)	Adoption of photovoltaic systems
Supporting policy design for the diffusion of cleaner technologies: A spatial empirical agent-based model	Caprioli et al. (2020)	Adoption of photovoltaic systems
An Agent-Based Model (ABM) for the Evaluation of Energy Redevelopment Interventions at District Scale: An Application for the San Salvario Neighborhood in Turin (Italy)	Caprioli et al. (2019)	Temporal diffusion of photovoltaic systems and adoption of retrofit systems

B

Model Input Data

This appendix presents the information used to characterize the agents in the presented model. All this information is particular to Dutch households. Refer to Chapter 5 for extended context on the characteristics here presented.

B.1. Demographic characteristics

Table B.1: Household type distribution (Rijksoverheid, 2022)

Household type	Percentage
Owner-occupied	60%
Rental-private	13.33%
Rental-corporation	26.67%

Table B.2: House area by type of ownership (Rijksoverheid, 2022)

House area	Rental	Owner-occupied
<25 m2	9%	5%
25-50 m2	32%	35%
50-75 m2	29%	28%
75-100 m2	19%	15%
>100 m2	12%	18%

Table B.3: Income by type of ownership (Rijksoverheid, 2022). As a reference, the mode salary is equivalent to € 40,000 per year (Randstad, 2023)

Income	Rental	Owner-occupied
<Mode salary	61 %	12 %
1x - 1.5x mode	21 %	19 %
1.5x - 2x mode	9 %	19 %
2x - 3x mode	7 %	28 %
>3x mode	2 %	23 %

Table B.5: Leisure time by household size and type (Rijksoverheid, 2022; Roeters, 2019)

Household size	1 person		Couple		Family	
Age group	18 - 65	65+	18 - 65	65+	1 parent	2 parents
Rental	40%	19%	13.6%	6.4%	10%	11%
Owner - occupied	16.5%	6.5%	26%	10%	11.5%	29.5%
	Leisure time [hours]					
Men	46.00	58.70	41.3	55.90	33.70	
Women	42.10	54.40	40.6	46.90	32.70	
Average	44.05	56.55	40.95	51.40	33.20	

Table B.4: Living expenses as a percentage of the income by income group and ownership type (CBS, 2022b)

Income group	Rental	Owner-occupied
1 quintile	45.50%	45.50%
2 quintile	34.60%	28.10%
3 quintile	29.70%	24.20%
4 quintile	23.50%	21.20%
5 quintile	18.20%	17.50%

B.2. Technical characteristics

Table B.6: Energy label distribution (Rijksoverheid, 2023d; ten Teije, 2020)

Energy label	Percentage
A++++	11.10%
A	21.00%
B	16.70%
C	25.30%
D	11.10%
E	6.70%
F	4.20%
G	4.00%

Table B.7: A, B or C label by household type (Rijksoverheid, 2022)

Household type	Percentage
Owner-occupied	69%
Rental-private	75%
Rental-corporation	65%

Table B.8: Average yearly gas consumption per household type (Rijksoverheid, 2022)

Household type	Average yearly gas consumption [m3]
Owner-occupied	1270
Rental-private	801
Rental-corporation	912

Table B.9: Percentage of installation by technology (Garnier, 2022; Milieu Centraal, 2023c; Rijksoverheid, 2022)

Technology	Installation percentage
District heating	3%
Heat Pump	3%
Solar boiler	2%
Pellet boiler	13%
Solar PVT	2%
Facade insulation	72%
Roof insulation	64%
Floor insulation	47%
HR+ glass	43.50%

B.3. Sensitivity analysis

A ”one-factor-at-a-time” sensitivity analysis was performed to set up the values for different parameters used in the model. Each parameter configuration was run 50 times, and the results were used to build box plots, which are included below. Table B.10 shows an overview of the parameters and the range of values used.

Table B.10: Parameters and ranges for sensitivity analysis

Parameter	Range	Unit
Number of connections per household	4, 6, 8	connections
Population	400, 500, 600, 700, 800	people
Rewiring probability in the network	0.3, 0.4, 0.5, 0.6, 0.7	-
Intention threshold	5, 5.25, 5.5, 5.75, 6, 6.5, 7, 7.5	-
Ratio households in owners’ association	0.15, 0.2, 0.3, 0.5	-

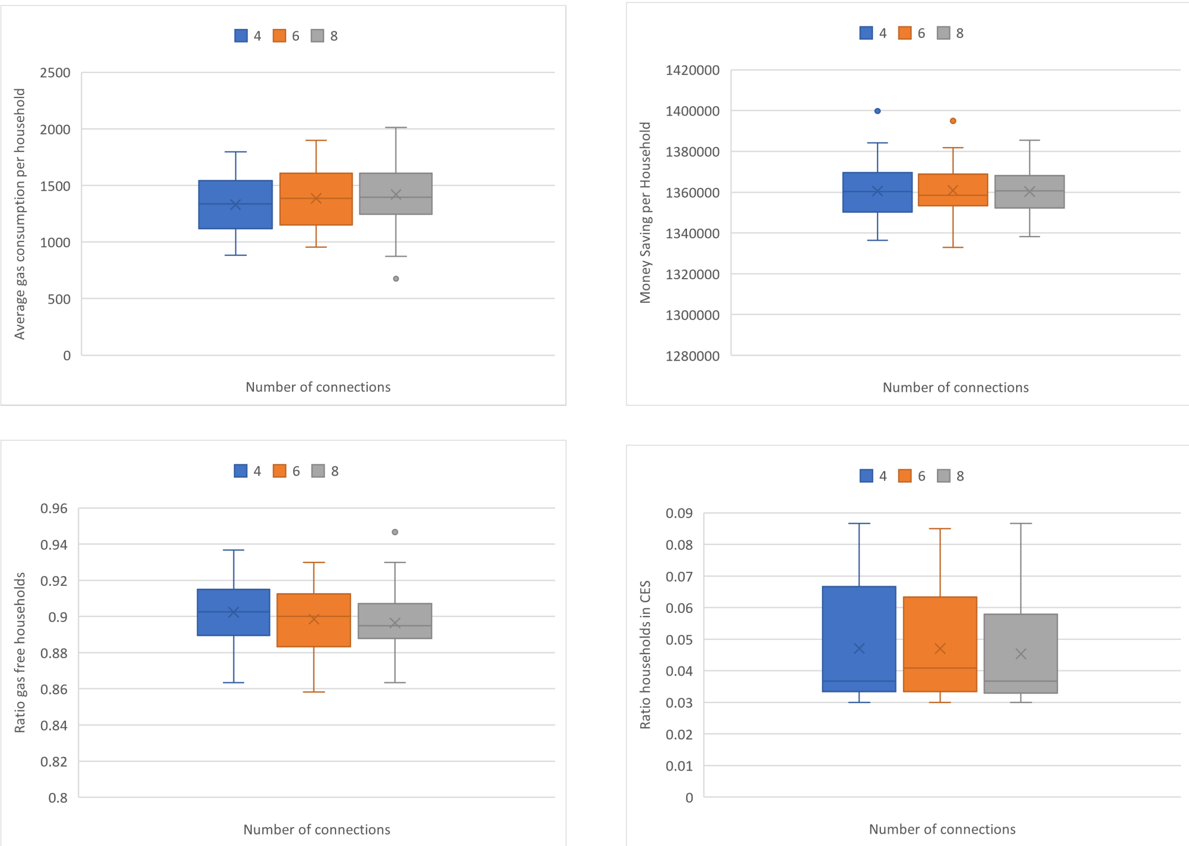

Figure B.1: OFAT sensitivity of KPIs to number of connections per household in the network

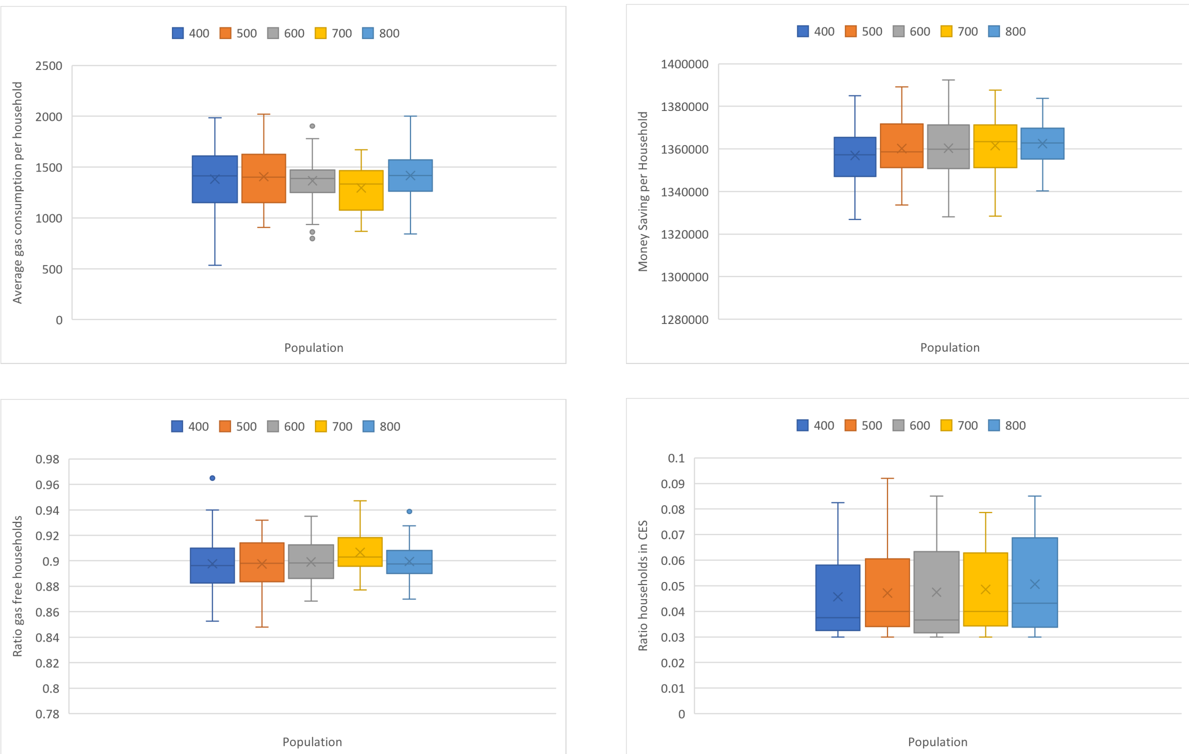

Figure B.2: OFAT sensitivity of KPIs to population

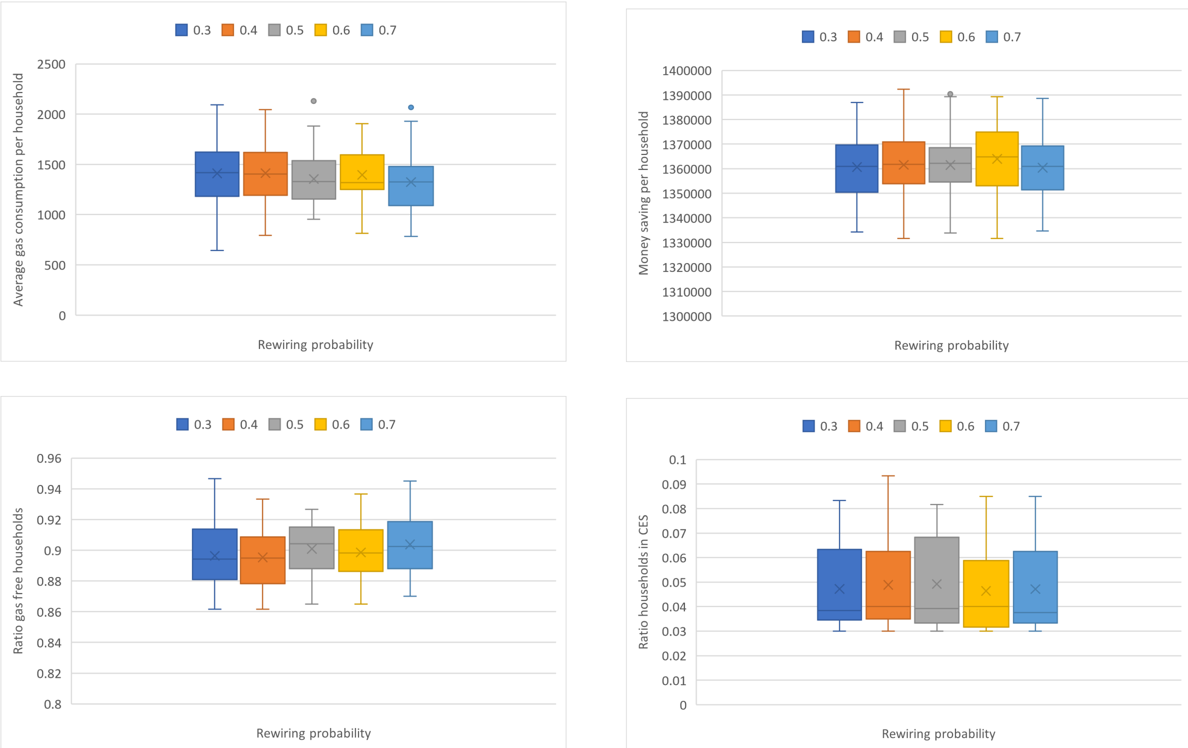

Figure B.3: OFAT sensitivity of KPIs to rewiring probability of the network

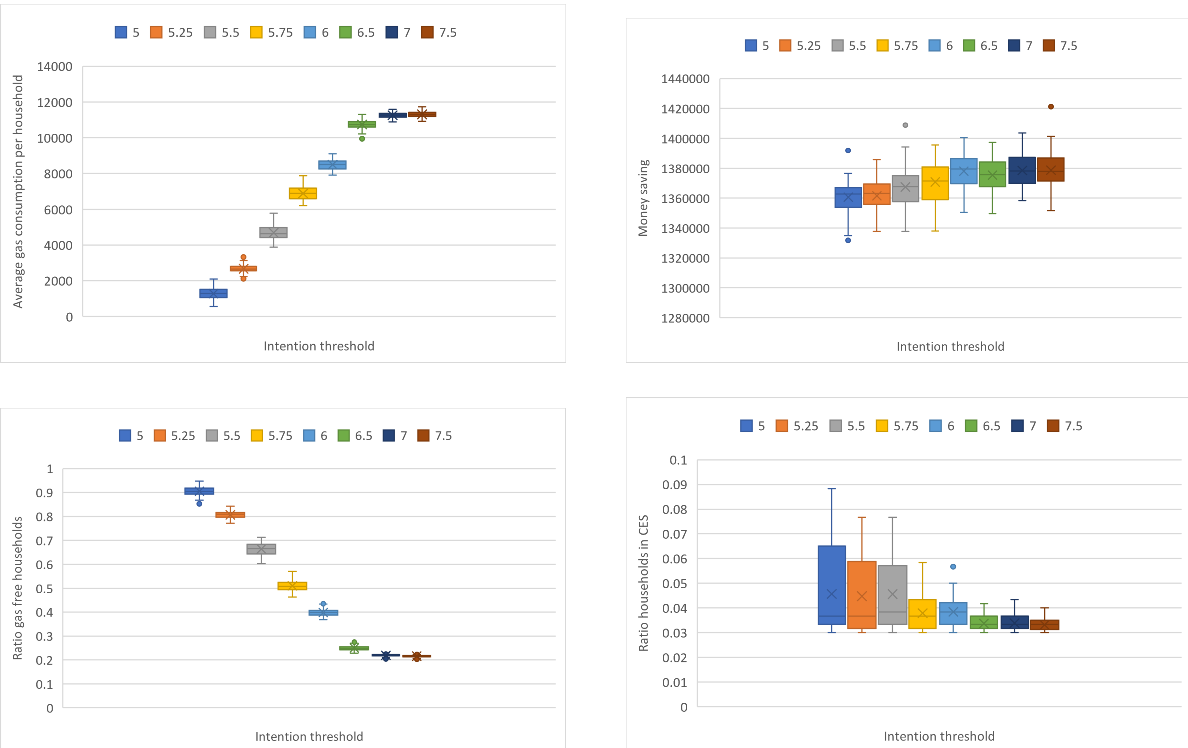

Figure B.4: OFAT sensitivity of KPIs to intention threshold

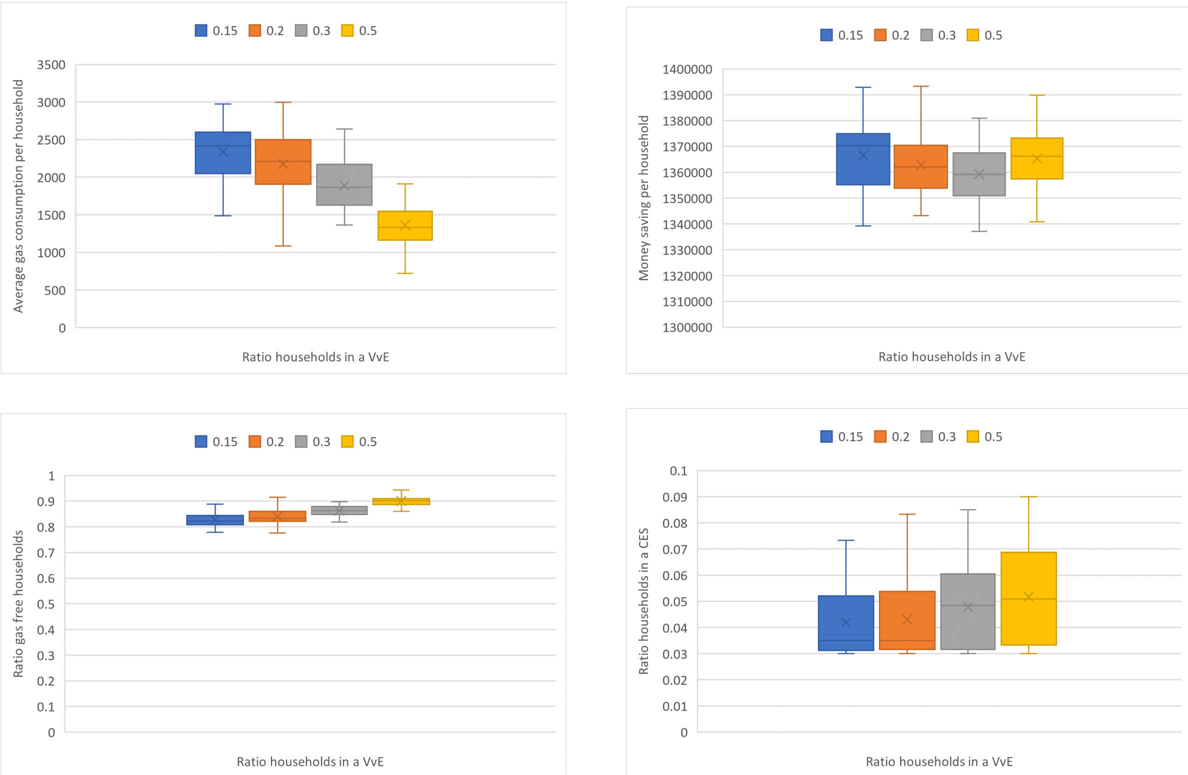

Figure B.5: OFAT sensitivity of KPIs to ratio of population in an owner's association

C

Pseudocode

The pseudocode for this model is included in this Appendix. The pseudocode is divided into functions, or subroutines, for a better understanding. The main routines in the pseudocode are ”setup” and ”go”, which follow the naming used in the NetLogo code. Within these main routines, subroutines are included. All these subroutines are focused specifically to achieve certain parts of the system dynamics.

The main routine code looks as follows:

```

Setup
    Set year = 2022
    Set environment
    Create and characterize households
    Configure attitude characteristics
    Configure perceived behavioral control characteristics
    Configure community characteristics
    Assign technologies to households
    Calculate generation and gas consumption
    Configure network

Go
    Set year = (year + 1)
    Set installed_technologies_age = (installed_technologies_age + 1)
    IF installed_technologies_age = technology_lifetime:
        installed_technology gets uninstalled
    Calculate money_savings = money_savings + annual_salary - annual_expenses -
        installed_technologies_OPEX
    Calculate intention
    IF any household has (new_gas_consumption > 0 AND new_intention > intention_threshold):
           Set will_to_install = (will_to_install + 1)
    Grade technologies
    Install technologies
    IF number of households with want_install_collective > min_member_energy_community:
           Evaluate collective installation
    Calculate generation and gas consumption
    Recalculate energy labels
    IF year is 2050:
           Stop simulation
```

The subroutine *Set environment* configures all the global variables, and sets variables that have constant values. The *set technologies* is not further described to keep the code brief. However, this is a variable that contains the different technologies' technical and economic characteristics, which were presented in Chapter 4.

```
Set environment
    Set population = 500
    Set VvE_Belongingness_Ratio = 0.2
    Set Number_Collective-Heating-Systems = 1
    Set min_members_energy_community = 250
```

```
    Set probability = 0.4
    Set number_connections = 6
    Set intention_threshold = 5.50
    Set technologies
```

The subroutine *Create and characterize households* assigns the households' own demographic and technical characteristics, which are based on the information presented in Chapter 5 and on Appendix B. These characteristics usually vary by household type, which is specified below.

```
Create and characterize households
    Create population households
    Assign htype (Owner-occupied: 60%, Rental-private: 13.33%, Rental-corporation: 26.7%)
    Assign VvE_Belongingness_Ratio * population number of households vve = 1
    Assign harea (
        Rental: 15 - 25 m2 (9%), 25 - 50 (32%), 50 - 75 (29%), 75 - 100 (19%), 100 - 150
            (11%).
        Owner:  15 - 25 m2 (5%), 25 - 50 (35%), 50 - 75 (28%), 75 - 100 (15%), 100 - 150
            (17%))
    Assign annual_salary (
        Rental: <40000 (61%), 40000 - 60000 (21%), 60000 - 80000 (9%), 80000 - 120000 (7%),
            120000 - 160000 (2%).
        Owner: <40000 (12%), 40000 - 60000 (19%), 60000 - 80000 (19%), 80000 - 120000 (28%),
            120000 - 160000 (23%).)
    Assign energy_label, beng2 (
        Owner-occupied: A++++ (11.1%), A (18.8%), B (15.5%), C (23.5%), D (13.3%), E (8%), F
            (5%), G (4.8%)
        Rental - private: A++++ (11.1%), A (21.4%), B (16.9%), C (25.6%), D (10.7%), E (6.5%)
            , F (4%), G (3.8%)
        Rental - corporation: A++++ (11.1%), A (17%), B (14.6%), C (22.2%), D (15%), E (9%),
            F (5.7%), G (5.4%))
    Assign total_heat_requirement  = beng2 * harea  + installed_renewable_generation
    Assign annual_expenses by income group as a percentage of the income (
        Rental: 45.5% (1 quintile), 34.6% (2 quintile), 29.7% (3 quintile), 23.5% (4 quintile
            ), 18.2% (5 quintile).
        Owner: 45.5% (1 quintile), 28.1% (2 quintile), 24.2% (3 quintile), 21.2% (4 quintile)
            , 17.5% (5 quintile))
```

The subroutine *Configure attitude characteristics* assigns the specific attitude attributes to the households based on the information provided in Chapter 5 and calculates the attitude component as an average of the four attributes.

```
Configure attitude characteristics
    Assign environmental_friendliness (normal distribution: mean 7.91, standard deviation
        2.21)
    Assign hawareness (normal distribution: mean 4.49, standard deviation 2.43)
    Assign energy_independence (normal distribution: mean 5.17, standard deviation 2.67)
    Assign economic_driven (normal distribution: mean 7.41, standard deviation 2.20)
    Calculate attitude = (environmental_friendliness + hawareness + energy_independence +
        economic_driven) / 4
```

The subroutine *Configure perceived behavioral control characteristics* assigns the specific perceived behavioral control attributes to the households based on the information provided in Chapter 5, and calculates the perceived behavioral control component as an average of the four attributes.

```
Configure perceived behavioral control characteristics
    Assign available_subsidies (
          Owner-occupied: 2.42 (IF vve = 0), 7.88 (IF vve = 1)
          Rental-private: 0.61 (IF vve = 0), 6.1 (IF vve = 1)
          Rental-corporation: 1.52 (IF vve = 0), 6.97 (IF vve = 1))
    Assign municipality_effort = 4.1
    Assign financial_capability (0.1 - 2 (IF annual salary < 40000), 2 - 4 (40000 <
        annual_salary < 60000), 4 - 6 (60000 < annual_salary < 80000), 6 - 8 (80000 <
        annual_salary < 120000), 8 - 10 (120000 < annual_salary < 160000)
    Assign time_availability (
        Rental: 5.8 - 6.4 (40%), 7.6 - 8.2 (19%), 5.6 - 5.8 (13.6%), 6.5 - 7.7 (6.4%), 4.5 -
            4.7 (21%).
        Owner: 5.8 - 6.4 (16.5%), 7.6 - 8.2 (6.5%), 5.6 - 5.8 (26%), 6.5 - 7.7 (10%), 4.5 -
            4.7 (41%))
    Calculate perceived_behavioral_control = (available_subsidies + municipality_effort +
        financial_capability + time_availability) / 4
```

The subroutine *Configure community characteristics* assigns the specific community-related attributes to the households based on the information provided in Chapter 5 and calculates the community tendency component as an average of the three attributes.

```
Configure community characteristics
    Assign community_oriented (normal distribution: mean 5.43, standard deviation 2.46)
    Assign community_trust (normal distribution: mean 6.68, standard deviation 2.56)
    Assign ces_participation_willingness (normal distribution: mean 6.78, standard deviation
        1.96)
    Calculate tendency_community = (community_oriented + community_trust +
        ces_participation_willingness) / 3
```

The subroutine *Assign technologies to households* makes a random assignation of technologies to the different households based on the percentages of an installation presented in Appendix A and assigns them a randomized age.

```
Assign technologies to households
    Assign collective_system = randomized choice of sustainable wood pellet boiler,
        aquatermal with seasonal storage, aquatermal from surface water, geothermal or solar
        PVT
    Assign installed_renewable_technologies (collective system (3%), heat pump (3%), solar
        boiler (2%), pellet boiler (13%), solar PVT (2%), façade insulation (72%), roof
        insulation (64%), floor insulation (47%), HR+ glass (43.5%))
    Assign installed_renewable_technologies_age (randomized value between 0 and technology
        lifetime)
```

The subroutine *Calculate generation and gas consumption* calculates the generation coming from the installed technologies, and calculates the gas consumption based on this.

```
Calculate generation and gas consumption
    Calculate installed_renewable_generation = SUM (FOR all installed_renewable_technologies,
         calculate installed_renewable_technologies_capacity *
        installed_renewable_technologies_load)
    Calculate installed_renewable_capacity = SUM (FOR all installed_renewable_technologies,
        installed_renewable_technologies_capacity)
    Calculate new_gas_consumption = total_heat_requirement - installed_renewable_generation
```

The subroutine *Recalculate energy labels* uses the gas consumption value calculated previously to recalculate the beng2 factor and assigns the corresponding energy label to the household after comparing the value to the ranges.

```
Recalculate energy labels
    Calculate beng2 = new_gas_consumption / harea
    Assign energy_label = A++++ (beng2 <= 0), A (0 < beng2 <= 160), B (160 < beng2 <= 190), C
         (190 < beng2 <= 250), D (250 < beng2 <= 290), E (290 < beng2 <= 335), F (335 < beng2
         <= 380), G (beng2 > 380)
```

The subroutine *Configure network* sets up the network, starting from a regular lattice where each household has six neighbors. Afterward, it rewires the connections with a probability of 0.4 to random households, to set up the small-world network. This procedure is explained in detail in Chapter 5.

```
Configure network
    Assign number_connections households as connections per household = [n-3, n-2, n-1, n+1,
        n+2, n+3]
    FOR each element in connections, rewire each link with a probability = probability to a
        random household
    FOR each element in connections, assign wj with probability = 0.5 (0.25 or 0.75)
```

The subroutine *Calculate intention* sets up the current connection of the households, carries out the information exchange procedure, and recalculates the behavioral attributes based on the connection's level of influence. After this, the intention is calculated.

```
Calculate intention
    Select a random household from connections
    Calculate influence on behavioral attributes:
        environmental_friendliness = (1 - wj) * environmental_friendliness of household + wj
            * environmental_friendliness of connection
        hawareness = (1 - wj) * hawareness of household + wj * hawareness of connection
```

```
        energy_independence = (1 - wj) * energy_independence of household + wj *
            energy_independence of connection
        economic_driven = (1 - wj) * economic_driven of household + wj * economic_driven of
            connection
    Calculate attitude = (environmental_friendliness + hawareness + energy_independence +
        economic_driven) / 4
    Calculate new_intention = 0.56 * attitude + 0.44 * perceived_behavioral_control
```

The subroutine *Grade technologies* performs the grading of the different technologies based on the technologies' technical and economic characteristics, and the household's own attributes. After this, the final grade of each technology is calculated, and that allows the grades to be ranked based on this factor.

```
Grade technologies
    Calculate per technology and household:
           technologies_environmental_impact = - environmental_friendliness * CO2_impact
    technologies_economic_impact = - (economic_driven + financial_capability) / 2 * (
        upfront_cost + annual_OPEX) / annual_salary
    technologies_subsidy_support = (economic_driven + financial_capability) / 2 *
        highest_subsidy / annual_salary
    technologies_technology_noticeability = (hawareness + municipality_effort) / 2 *
        available_subsidies
    Calculate technologies_grade = SUM (all factors) * (tendency_community / mean of
        tendency_community)
    IF technology is individual, then (tendency_community / mean of tendency_community) = 1
    Rank technologies based on technologies_grade
```

The subroutine *Install technologies* checks the affordability of the technologies that the household is willing to install in the ranking order. If the first affordable technology is an individual one, the household installs it and updates its money savings. If the technology is collective, then it shows its interest in organizing to install a collective system.

```
Install technologies
    FOR technologies with a higher rank than (6 * 5 * new_intention), check ordered by rank:
    IF technology_upfront_cost < money_savings AND technology is individual: acquire
        technology
           Set money_savings = money_savings - technology_upront_cost
    IF technology_upfront_cost < money_savings AND technology is collective:
        IF collective_tech exists in the neighborhood:
            Join the energy community
        ELSE
            Set want_install_collective = 1
```

The subroutine *Evaluate collective installation* organizes the households that are interested in installing a collective system. It decides on the type of collective system, and if enough households are able to afford it, then a new energy community is created. Otherwise, the households install their next best-ranked individual technology, if they are able to afford it.

```
Evaluate collective installation
    Set group = interested households in installing a collective system
    Set best_graded = mode collective technology with best rank from households
    IF at least min_members_energy_community households afford the best_graded technology:
           Households acquire the best_graded technology.
           A new energy community is created
                  Set number_collective_systems = number_collective_systems + 1
    ELSE
        Households check their next best ranked technologies with rank higher than (6 * 5 *
            new_intention)
        Households acquire their next best ranked individual technology, IF technology_capex
            < money_savings
```