Master Thesis

A warm welcome or a poor pick?
Exploring energy poverty and inequality in the transition to a heat network in Delft

A thesis submitted in fulfilment of the
requirements for the Master of Science degree in
INDUSTRIAL ECOLOGY

by

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"Hope, in this deep and powerful sense, is not the same as joy that things are going well, or willingness to invest in enterprises that are obviously headed for early success, but rather an ability to work for something because it is good, not just because it stands a chance to succeed. The more unpromising the situation in which we demonstrate hope, the deeper that hope is. Hope is not the same thing as optimism. It is not the conviction that something will turn out well, but the certainty that something makes sense, regardless of how it turns out. In short, I think that the deepest and most important form of hope, the only one that can keep us above water and urge us to good works, and the only true source of the breathtaking dimension of the human spirit and its efforts, is something we get, as it were, from 'elsewhere.' It is also this hope, above all, that gives us the strength to live and continually to try new things, even in conditions that seem as hopeless as ours do, here and now."

Vaclav Havel

Disturbing the Peace, pp. 181-182

Preface

This is a master thesis report that concludes my master's programme in Industrial Ecology at Delft University of Technology and Leiden University. Industrial Ecology is a field that lies at the interface of the systems that surround us: technology, the environment, and society. This thesis reflects the interdisciplinary nature of this programme by combining theories and methodologies from different fields, from ethics and social sciences to engineering and programming. In this thesis, the effect of the implementation of a heat network on energy poverty and inequality in energy access is explored for two neighbourhoods in Delft that are vulnerable to energy poverty. The findings of this study can be used to support policy making and facilitate stakeholder discussions on the societal effects of the energy transition.

Since this thesis integrates multiple disciplines and is relevant for people in different fields, not every section is as relevant to each interested reader. To help you understand this report, each chapter starts with a brief synopsis that highlights the essential elements of the chapter. In the remainder of this preface, we recommend relevant sections for each potential group of readers. Readers are also invited to view the summary to get an overview of the contents of this thesis.

Policy makers might find the following sections interesting:

- Chapter 3 introduces three frameworks – the capability approach, energy justice, and energy poverty – that can be used to assess policy in the context of the energy transition, focusing on justice aspects of the policy. These frameworks can help in designing more just policies, which is especially important for protecting vulnerable groups in society in volatile and uncertain times such as these. Later in this chapter, policy interventions that can be used to alleviate energy poverty are also described, including a discussion on the positioning of these interventions.
- Chapter 8 presents key findings and recommendations to ensure a just heat transition. These findings and recommendations could be used to inform policy decisions.

Scientists and modellers might find these sections interesting:

- Chapter 3 describes a theoretical background consisting of three frameworks that can be used to investigate energy poverty and inequalities caused by an energy technology. This combination of frameworks might also be useful for future studies related to this topic.
- Chapter 4 describes an agent-based model that can be used to examine inequalities in energy poverty in the context of the heat transition in a specific neighbourhood. This model could be used and expanded to further study these and related issues.
- Chapter 7 provides a discussion on the use of this model, its further development, and the limitations of the research approach. These sections provide indications for follow-up research and could serve as a handle for relevant research on the topic of energy poverty and inequality effects of the energy transition.
- Chapter 8 gives recommendations for researchers studying the topic of energy poverty and energy justice and using agent-based modelling.

Heat network developers and other energy sector professionals are recommended these sections:

- Chapter 8 presents key findings and recommendations to ensure a just heat transition. These findings and recommendations could be used to design more just and inclusive energy systems and improved energy poverty indicators.

Acknowledgements

This thesis was written during a challenging time, both for the world – during a pandemic and a war on the European continent – and for me personally. It would not have been possible without the help of the following persons.

Firstly, I would like to thank my supervisors: Tristan, who provided helpful support and encouragement; Amineh Ghorbani and Niek Mouter for providing constructive feedback and for their patience and understanding.

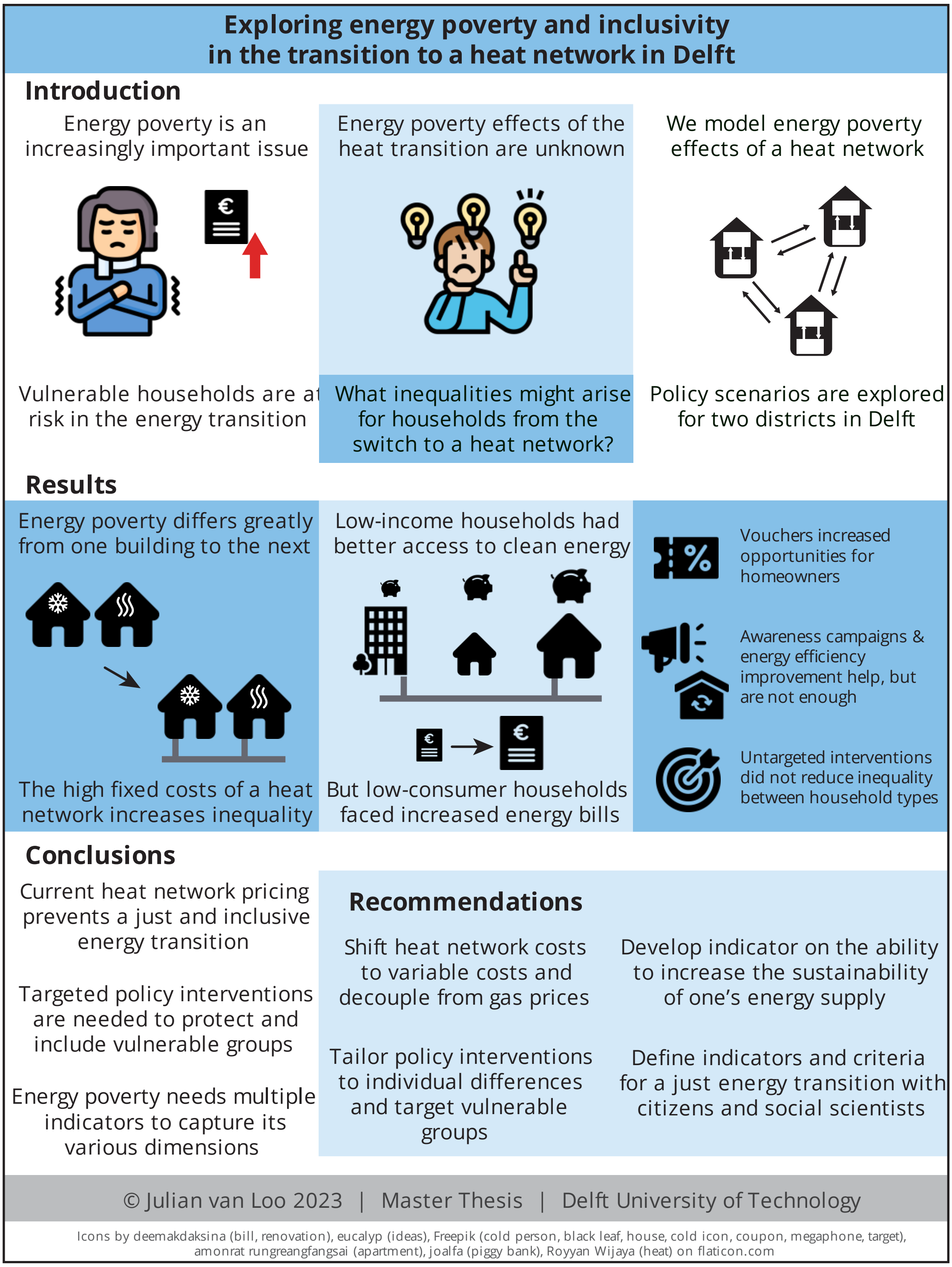
Secondly, my gratitude goes to Serge Santoo, who introduced me to the field of geothermal energy, citizen participation, and consultancy in the energy transition. I look forward to having further interesting conversations and hope to collaborate in the future.

Furthermore, I would like to thank psychologist Martine Efting Dijkstra for exploring eco-anxiety together. In extension, my gratitude goes to all who are working to address eco-anxiety. If you ever struggle with these feelings of anxiety, do not hesitate to talk about this with friends or family, or contact a professional. Discussing these feelings really helps, and you will be surprised to hear how many others are having similar thoughts and worries.

I am especially grateful for being part of student association AEGEE-Delft and the international community of AEGEE-Europe. Being a member of such a diverse and open association allowed me to make friends in Delft and Europe, extend my horizon, and ultimately led me to put on my *geitenwollensokken* and study Industrial Ecology.

Lastly, I would like to thank my friends and family. Their empathy, support and the endless board game nights gave me the energy and motivation to finish my studies. Special thanks go to Nelleke, who has always reminded me to take care of myself and respect my own boundaries.

Visual abstract



Summary

We must rapidly decarbonise our current fossil fuel-dependent energy system. With space heating as the major end-use of energy consumption in the Netherlands, a 'heat transition' is being started. In Delft, a district heating network based on geothermal energy is planned. However, the effects of implementing a novel heat network on the current, especially vulnerable, residents are unknown. At the same time, energy poverty is an issue made urgent by rising energy prices and the uncertainty of the effects of a rapid energy transition. A research gap on energy poverty in varying household types exists, especially in the context of the current volatile energy market. In addition, energy justice aspects of the energy transition remain largely unexplored. Vulnerable households are therefore not sufficiently protected in the heat transition. The heating transition is thus both an opportunity and a threat for vulnerable households.

In this thesis, an agent-based model is developed to explore inequalities in energy poverty and access to energy that might arise from the switch to a heat network. The thesis aims to explore the scenarios in which these inequalities can occur and for what types of households, and to determine policy interventions that contribute to a just and inclusive heat network.

This thesis addresses the following research question:
What inequalities might arise for households from the switch to a geothermal heat network in the Voorhof and Buitenhof districts in Delft and how can these be reduced?

Conceptual framework and key theories

In this thesis, we combine elements of the frameworks *Capability Approach*, *Energy Justice,* and *Energy Poverty* to capture the different dimensions of inequality in the energy transition. The *capability approach* is a framework that focuses on individuals' ability to achieve the things they value. We use this framework to examine the opportunities households have to fulfil their energy services requirements and participate in the heating transition, and what interventions affect these opportunities. *Energy justice* focuses on the distribution of benefits and burdens in relation to energy systems. We use this framework to identify and address the unequal distribution of energy benefits and burdens between different groups of households as a result of a new heat network. *Energy poverty* concerns households' inability to access or afford adequate energy services and emphasises the negative impacts of this on one's quality of life. We use this framework to measure the prevalence and severity of energy poverty before and after the implementation of the heat network and to examine policies that aim to reduce energy poverty.

These frameworks are combined with the Consumat framework of consumer decision making (Jager 2000) and literature on household energy behaviour in an agent-based model of household energy consumption. The model is applied to the case of Open Warmtenet Delft, which will supply heat to households in the Voorhof and Buitenhof districts, which are vulnerable to energy poverty.

The agent-based model

The agent-based model consists of two types of agents, buildings and households, which represent a district using building and address datasets. Households consume energy based on their characteristics, a heat network is implemented for specific buildings, and homeowners adopt one of four decision-making strategies – repetition, deliberation, imitation, or social comparison – to decide whether to switch to the heat network. The model output is a spatially explicit representation of GIS and socio-economic data, the distribution and extent of energy poverty among various groups, and the distribution of heat network connections.

Results

The model was used to explore the extent and distribution of energy poverty in multiple energy price contexts. We explored the following scenarios for policy interventions in Voorhof and Buitenhof:

- Implementation of a heat network.
- Low energy tax for gas use below 1000 m^3 and high energy tax for gas use above 1000 m^3.
- Vouchers to cover upfront costs of heat network connection.
- Renovation of dwellings with labels G, F, E, and D to label B.
- Awareness campaigns to reduce energy use.

Key model results on energy poverty, inequalities, and accessibility of the heat network

1. Within districts, high inequality occurs in the distribution of energy poverty.
2. When gas prices are low, switching to a heat network increases energy poverty.
3. Renters and low-income groups are affected most in changes in energy expenses.
4. The distribution of income groups or household types among the energy-poor is unaffected.
5. Low-income households are affected most by high heat network prices.
6. High heat network prices increase inequality in energy expenses.
7. Building renovations are most effective in decreasing energy use and energy poverty.
8. Vouchers increase accessibility of the heat network.
9. Awareness and energy efficiency interventions reduce the fraction of HEQ households in all income groups except the lowest, when energy prices are high.
10. Tested interventions did not reduce energy poverty inequalities between household composition groups.
11. Building renovation decreases inequality in energy expenses, other measures do not.
12. Low-income renters have good heat network access; vouchers increase access for homeowners.

Discussion and recommendations

A model was used that produced detailed results on the distribution and extent of energy poverty across different households in various scenarios. It showed that the transition to a heat network is both an opportunity and a threat for vulnerable households. While the model did not include factors such as other alternatives for sustainable heating systems, useful insights could be gained on the effect of heat network implementation on energy poverty and access to clean and affordable energy.

Recommendations to reduce energy poverty and inequalities caused by heat networks

1. Shift the balance from fixed heat network costs to variable costs.
2. Determine maximum district heating prices considering differences in energy demand.
3. Develop policy for energy poverty and the energy transition in tandem.
4. Consider household differences when creating policy.
5. Target tailored policies at specific socio-economic groups vulnerable to energy poverty.
6. Collaborate with housing corporations to lead the just energy transition.
7. Support households that cannot achieve housing cost neutrality.
8. Develop a national framework for energy poverty and a just transition that recognises regional and local differences.
9. Measure and monitor energy poverty using multiple indicators.
10. Develop an energy policy indicator on the ability to increase the sustainability of one's energy supply.
11. Use household-level microdata to capture local spatial inequalities in energy poverty.
12. Collaborate with social scientists and psychologists for more human models and policy.

List of abbreviations

ABM	Agent-based modelling
CAS	Complex adaptive systems
CBS	Statistics Netherlands
GIS	Geographic Information System
GTD	Geothermie Delft
HEQ	High Energy Quote
IE	Industrial Ecology
LIHC	Low Income and High energy Costs
LILEQ	Low Income & home with Low Energetic Quality
oLEQ	Homeowner with a dwelling of Low Energetic Quality, unable to improve sustainability
ODD+D	Overview, Design Concepts and Details + Decision
OWD	Open Warmtenet Delft
PBL	Netherlands Environmental Assessment Agency
rLEQ	Renter with a dwelling of Low Energetic Quality, unable to improve sustainability
RVO	Netherlands Enterprise Agency
SDG	Sustainable Development Goal
STS	Socio-technical systems
TNO	Netherlands Organisation for Applied Scientific Research

Glossary

To ensure clarity of key terms, the definitions used in this thesis are given below.

Capability approach
A framework that focuses on individuals' ability to achieve the things they value. It emphasises the importance of expanding people's capabilities in order to improve their wellbeing (Sen 1992).

Capability
The opportunity one has to achieve one's doings and beings (Sen 1992), such as bodily health or control over one's environment (Nussbaum 2003).

Distributional justice
Core tenet of energy justice on the distribution of energy costs and benefits (McCauley et al. 2013).

Energy consumption/use
Actual meter consumption of energy used for heating and appliances by a household, considering heating system efficiency and personal characteristics such as awareness of energy use and environmental attitude.

Energy demand
Average functional energy demand for heating and appliances of a household according to energy label, dwelling size, dwelling category, and household composition (PBL 2021).

Energy justice
A framework that focuses on the distribution of benefits and burdens in relation to energy systems (McCauley et al. 2013). It is often conceptualised using three tenets: distributional justice (assessing where injustices emerge), procedural justice (ensuring fair procedures that engage all stakeholders) and recognition justice (ensuring no individual or group is ignored, misrepresented, or disrespected).

Energy poverty
Households' inability to access or afford adequate energy services (Walker and Day 2012).

Evaludation
Method for evaluating, testing and verifying computational models (Augusiak et al. 2014).

Housing cost neutrality
Also known as living cost neutrality (*woonlastenneutraliteit*), the notion that total expenses for housing or rent, renovations and energy should not increase as a result of sustainability improvement or the switch to a new energy supply (Rijksoverheid 2019).

Inequality
Inequalities in access to energy services is a result of distributional inequalities – in income, energy prices, and housing and technology energy efficiency – procedural injustices and injustices in recognition of differences in vulnerability, needs and culture (Walker and Day 2012).

Just transition
The process of moving towards a low-carbon economy in a way that prevents and reduces inequality in society using energy, environmental and climate justice principles (Heffron and McCauley 2018).

Low income
A household that earns less than 130% of the social minimum (UWV 2022).

Vulnerable household
A household that is at higher risk of experiencing issues such as energy poverty, exclusion, or being left behind in the energy transition.

Warmteplans
'Heating plan' towards gas-free districts made by each Dutch municipality (Rijksoverheid 2019).

Warmte-uitvoeringsplan
Execution plans for the heat transition in a specific neighbourhood (Rijksoverheid 2019).

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Chapter 1.
Introduction

Synopsis

Sustainable heating systems are needed for rapid decarbonization

This chapter introduces two interrelated challenges municipalities currently face: the **transition to a low-carbon energy system** and **energy poverty**. The current fossil fuel-dependent energy system needs to decarbonize rapidly to reach the climate goals of the Paris Agreement and to reduce Europe's dependence on (non-democratic countries for) fossil fuels. With space heating as the major end-use of energy consumption in the Netherlands, a '**heat transition**' is being started. The local heat transition is planned by municipalities and implemented at neighbourhood level in cities such as Delft. Here, the most favourable option is determined per neighbourhood. For the districts of Voorhof and Buitenhof, a district heating network based on geothermal energy is planned. However, the effects of implementing a novel heat network on the current residents, especially the vulnerable households, are unknown.

Energy poverty should be addressed in a just and inclusive energy transition

At the same time, **energy poverty** is an issue that has come into focus in recent years. Rising energy prices and the uncertainty of the effects of a rapid energy transition, with concerns for who will be able to take part in this transition and who will be left behind, make energy poverty an urgent topic. A 'just and inclusive' transition is aim of the Dutch government and Gemeente Delft, and affordability is one of the key requirements of the heat transition.

Energy justice is a framework used to assess the distribution of benefits and burdens of energy systems and the justness of the procedures used in the development of energy systems. The aim is to provide all individuals with safe, affordable, and sustainable energy, and is therefore an important framework to assess novel developments in the energy transition.

Problem statement

Currently, vulnerable households are not sufficiently protected in the heat transition, and energy justice is needed as a framework to assess the available options. A knowledge gap exists on examining energy poverty in the heating transition, at the neighbourhood level, and between household groups. The switch to a heat network might lead to increased inequalities in energy poverty and accessibility to a sustainable and affordable heating system. This thesis uses **agent-based modelling** to explore the effects of the transition to a heat network on energy poverty in two neighbourhoods in Delft and assess which groups could experience increased **inequalities in energy access and affordability**. Understanding these distributive justice aspects of a novel heat network is essential for ensuring a fair and inclusive energy transition and obtaining social acceptance.

1.1 Sustainable heating systems are needed for rapid decarbonization

Decarbonization of the world's economy calls for a rapid energy transition. This transition requires a major overhaul of our energy infrastructures, which will affect households that currently depend on fossil energy. To orchestrate the transition, the European Union mandates its member states to adopting national strategies for decarbonisation. These plans should include the foreseen socio-economic effects, including social impacts and just transition aspects of the proposed policies (European Parliament, 2018). Ensuring "access to affordable, reliable, sustainable and modern energy for all" is Sustainable Development Goal (SDG) 7 of the United Nation's 2030 Agenda for Sustainable Development (United Nations 2015).

The major end-use of energy is heating, with space heating accounting for 60-80% of energy consumption in most EU countries (Eurostat 2019). In the Netherlands, most households rely on natural gas for heating. In fact, 93% of energy for space heating is obtained from natural gas (Rijksoverheid 2016). Not only does this cause a large carbon footprint, but it also causes a dependence on other countries, such as Russia, for the energy supply. In 2021, 90% of gas consumed in the EU came from imports, with Russia providing 45% of those imports (European Commission 2022a). Following Russia's invasion of Ukraine starting February 2022, the European Commission announced the REPowerEU plan to reduce the EU's dependence on fossil fuels from Russia before 2030 (European Commission 2022a). The plan aims to do so by proposing actions to save energy, diversify supplies, substitute fossil fuels by forwarding the clean transition and combining investments and reforms. The decarbonization of the energy supply for heating, also referred to as the heat transition, is a key part of this strategy and essential to reach the 1.5-degree goal of the Paris Agreement. Geothermal energy is seen as a way to replace fossil fuels in heating, and the Commission encourages member states to accelerate the deployment and integration of district heating systems (European Commission 2022b).

Ultimately, the implementation of the energy transition and the distribution of its affects takes place on the local level. In the Dutch municipality of Delft, geothermal energy is also seen as a source of clean energy. It will be used to heat buildings in the Voorhof and Buitenhof districts through a heat network. Affordability of the energy transition for households has the highest priority of Delft's city council and the city council strives to make adequate financial tools available so that everyone can participate in the transition (Gemeente Delft 2021a, 2020).

1.2 Energy poverty should be addressed in a just and inclusive energy transition

While policy makers are facing the major challenges related to a rapid energy transition, the closely related issues of energy poverty and inequality are becoming increasingly important (Feenstra et al. 2021; Oxfam International 2023). Energy poverty is generally referred to as "a level of energy that is insufficient to meet certain basic needs" (González-Eguino 2015). Multiple dimensions can be considered when in assessing energy poverty, such as the affordability of energy, the energetic quality of the home, and the choice and opportunity to participate in the energy transition (Mulder et al. 2021a, 2021b). While the REPowerEU plan mentions that "fairness and solidarity are defining principles of the European Green Deal", it also recognises that a rapid reduction in Russian energy imports can lead to higher and more volatile energy prices (European Commission 2022b). On top of this, the high costs related to the heating transition may lead to an increase in the share of households that spend more than 10% of disposable income to energy (Schellekens et al. 2019). Though various financial arrangements to encourage households to invest in sustainability measures are available, especially households that experience energy poverty face barriers in making use of these. This could undermine the social acceptance of the energy transition, slowing down its progress (Straver et al. 2020b).

Energy poverty affects specific types of households more than others. In the Netherlands, it occurs more often in rural areas than in urban areas, even more so if measuring energy poverty in terms of low-income combined with having a low energetic quality house; in single-person households, especially single-parent families; and in housing corporation buildings. 75% of energy-poor households live in a corporation-owned dwelling. In addition, 48% of households experiencing energy poverty live in a poorly insulated house but cannot independently ameliorate this. This is either because they are renting and thus dependent on the owner, or because they are homeowner but lack a sufficient income to make the required investments (Mulder et al. 2021b). Without proper aid, these households could thus fall behind in the energy transition.

The Dutch government aims to achieve a just and inclusive energy transition (Rijksoverheid 2019). The just transition is the process of moving towards a low-carbon economy in a way that prevents and reduces inequality in society using principles from energy, environmental and climate justice (Heffron and McCauley 2018). However, sustainable initiatives tend to be socio-economically exclusive, and might even worsen socio-economic inequalities and vulnerability (Walker and Cass 2007; Radtke 2014; Bouzarovski and Simcock 2017). In fact, it is the group of households which already face payment risks that have the fewest opportunities to take part in the energy transition in the Netherlands (Nationale Ombudsman 2022b). This large group of vulnerable households at risk of being excluded from the energy transition highlights the importance of energy transition designs and measures that focus on the inclusion and wellbeing of all households. Despite these issues and just transition intentions, the Dutch government has no comprehensive policy or monitoring on energy poverty, despite the obligation by the European Commission to do so (Mulder et al. 2023).

The deployment of new low-carbon energy systems therefore raises the question of how the benefits and burdens are distributed, and what inequalities might arise as a result. A framework used to investigate this is energy justice, which applies justice principles to energy issues such as policy, security, production and consumption (Jenkins et al. 2016). To ensure a just energy transition, the effect of new energy systems on energy poverty and inequalities should be examined. Currently a knowledge gap exists on the effect of the switch to a heat network on distributive energy justice and energy poverty. Informing local residents and the public about the potential effects of geothermal heat networks on their wellbeing and on society as a whole is a minimum requirement for social acceptance (Meller et al. 2018).

1.3 Problem statement

Vulnerable households are not sufficiently protected in the heat transition, and energy justice is needed as a framework to assess the available options (Lavrijssen and Vitéz 2021). The switch from natural gas to a new heat network might lead to an unequal distribution of costs and benefits between households. For this new heating system, effects on differences in access to clean and affordable energy and the ability to participate in the energy transition are unknown. A knowledge gap also exists on examining energy poverty in the heating transition, at the neighbourhood level, and between household groups. In this thesis, agent-based modelling will be used to explore the effects from the transition to a geothermal heat network on energy poverty in Delft. Through modeling and simulation, these potential effects can be explored *ex ante* which can help in designing just sustainable energy systems and policies. Understanding these distributive justice aspects of a new sustainable energy technology is essential for ensuring a fair and inclusive energy transition and obtaining social acceptance.

1.4 Outline

The thesis is further structured as follows. First, the objective and scope of this thesis, research questions and methodology are illustrated in Chapter 2. Next, the contextual background of this thesis and the theoretical and background underlying the model's design are presented in Chapter 3. Chapter 4 covers the model description, modelling objectives, and the conceptualization, formalization, and implementation steps of model development. The results of model evaluation and validation are described in Chapter 5. In Chapter 6, the experimental design and modelling results are presented. The key results, model usage, research approach and its limitations, scientific contributions and relevance of this thesis are discussed in Chapter 7. Finally, the conclusions and respective recommendations are presented in Chapter 8. Supplementary materials such as model input data, the data preparation process, interview materials, model implementation details, evaludation results and additional figures can be found in Appendices.

Chapter 2.
Research approach

Synopsis

Research objectives

Three steps of tackling energy justice are identifying the distribution of effects of an energy system, identifying who is affected, and identifying remediation strategies (Jenkins et al. 2016). Based on this framework, this thesis has the following research objectives:

1. Build an agent-based model that can represent socio-economic qualities of households in a specific neighbourhood in the context of heating
2. Explore inequalities in energy poverty and inclusivity that might arise from the switch to a heat network and in which scenarios and for what types of households these inequalities
3. Determine policy interventions that contribute to a just and inclusive heat network.

Research questions

The main research question is:

"What inequalities might arise for households from the switch to a geothermal heat network in the Voorhof and Buitenhof districts in Delft and how can these be reduced?"

This question will be answered following these sub questions:

1. What are the characteristics of the households and the current and planned heating system, and what policy options and socio-economic factors are relevant in the case in Delft?
2. In an agent-based model of a specific neighbourhood in Delft, how can the switch to a novel heat network be represented and the effect on energy poverty and inclusivity be explored?
3. What inequalities in energy poverty and accessibility to sustainable energy might arise as a result of the heat network?
4. What policy interventions lead to reduced inequalities and an accessible heat network?

Research approach

A research approach using agent-based modelling is used to answer these questions. The approach consists of the following steps:

1. Data collection, literature study and consultations with experts. The outcome of this step is data on relevant household and heat network characteristics, socio-economic factors, and policy options.
2. Agent-based model development. This iterative process consists of system analysis, model conceptualisation, formalisation and specification, software implementation, and evaluation. Model design and evaluation was done based on relevant literature and expert consultation. The 'evaludation' approach by Augusiak et al. (2014) was used to evaluate the conceptual and implemented model.
3. Agent-based model exploration, analysis, and interpretation of results. Various scenarios for heat network implementation and policy interventions are explored to determine the effects on the extent and distribution of energy poverty and inequalities in access to the heat network.

2.1 Research objectives and scope

This thesis research project aims to contribute to a just and inclusive implementation of geothermal heating systems. Jenkins et al. (2016) pose that tackling energy injustice requires three steps: identifying the concern (the distribution of effects); identifying who is affected (recognition); and identifying remediation strategies (procedure). Following this approach, this thesis aims to:

1. Build an agent-based model that can represent socio-economic qualities of households in a specific neighbourhood in the context of heating systems.
2. Explore inequalities in energy poverty and inclusivity that might arise from the switch to a heat network and in which scenarios and for what types of households these inequalities occur.
3. Determine policy interventions that contribute to a just and inclusive heat network.

Ultimately, by applying a justice perspective to examine the effects of a novel technology and corresponding socio-technical system, potential sources of injustice can be identified at an early stage (Correljé 2021). The whole systems energy justice conceptual framework defines three spatial scales for the analysis of energy justice: the macro scale (transnational and beyond any single country); meso scale (at the national and supra-local level) and micro scale (within communities and close to infrastructure), as well as three temporal scales: energy production; consumption; and waste disposal (Sovacool et al. 2019). This study will concern the micro scale at the consumption level.

2.2 Research questions

To achieve a just implementation of a new heating system, the potential inequalities that might arise and the possible interventions that might prevent these need to be examined. Therefore, the main research question of this thesis is:

What inequalities might arise for households from the switch to a heat network in the Voorhof and Buitenhof districts in Delft and how can these be reduced?

To answer the main question, an Agent-Based Modelling approach is used to answer the following sub questions:

1. What are the characteristics of the households and the current and planned heating system, and what policy options and socio-economic factors are relevant in the case in Delft?
2. In an agent-based model of a specific neighbourhood in Delft, how can the switch to a novel heat network be represented and the effect on energy poverty and inclusivity be explored?
3. What inequalities in energy poverty and accessibility to sustainable energy might arise as a result of the heat network?
4. What policy interventions lead to reduced inequalities and an accessible heat network?

2.3 Research methods

To answer the research question, a research approach using agent-based modelling (ABM) was employed. A flow diagram of the research approach is shown in Figure 1. The remainder of this chapter describes the steps taken in the writing of this thesis: Data collection & literature study; Model development; and Exploration, analysis & interpretation.

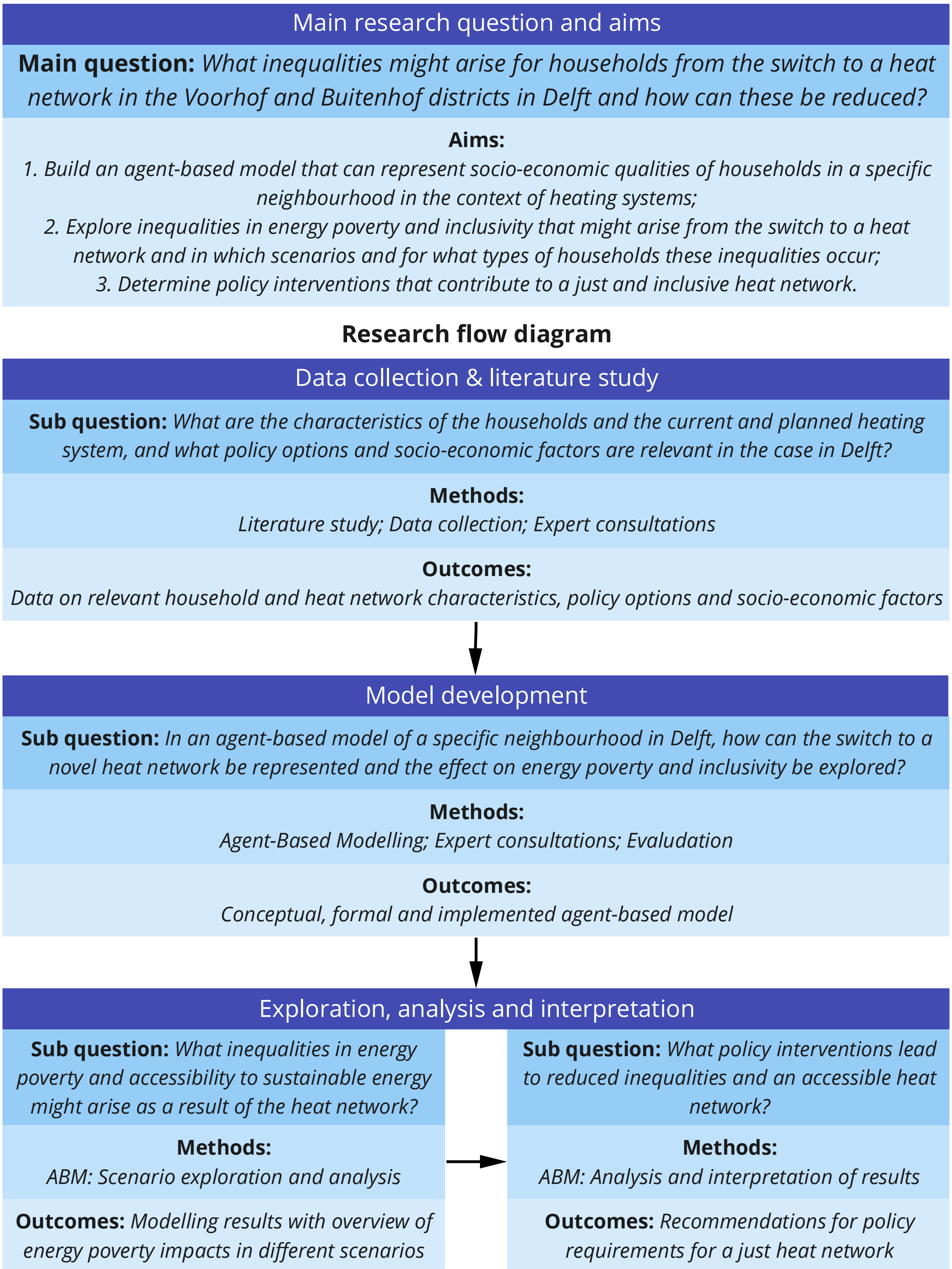


Figure 1. Research flow diagram showing the research phases, sub-questions, techniques, and outcomes per phase.

2.3.1 Data collection & literature study

The data collection and literature review phase forms the theoretical foundation of this study. The first sub-question is "What are the characteristics of the households and the current and planned heating system, and what policy options and socio-economic factors are relevant in the case in Delft?" To determine the socio-economic factors and characteristics of the two chosen districts, data on households and housing were collected at the neighbourhood and household level. The relevant characteristics of the planned heat network and related policy interventions were acquired through interviews with relevant stakeholders such as project consortium members, academic experts, and Gemeente Delft advisors, as well as studying policy documents. In addition, all necessary data needed to build the agent-based model was acquired. This included reviewing decision-making theories and household behaviour models used in other studies and ABMs of energy systems to determine a suitable approach for the agent-based model developed in this thesis.

2.3.2 Model development

Model development was done using the method described by (Nikolic and Ghorbani 2011), which consists of five iterative steps (Figure 2): system analysis, model design, detailed model design, software implementation and model evaluation. These steps were performed in an iterative process. Chapter 4 describes the results of the first four steps. Chapter 5 focuses on model verification and validation. Then, in Chapter 6 scenarios, experiments and results are discussed.

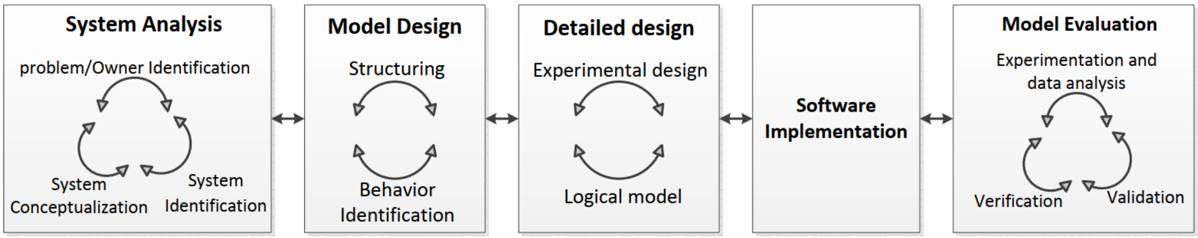


Figure 2. The methodological framework for agent-based modeling by Nikolic and Ghorbani (2011).

During the system analysis phase, brainstorms were held with domain experts (an academic expert on geothermal energy, an academic researcher on ABM and ethics & philosophy of technology, and a member of the Geothermie Delft consortium). The results of the system analysis step are not shown since these are incorporated into the (description of the) conceptual and implemented model itself. In addition, the modelling objectives and model requirements were determined during this first phase. These, too, are described in Chapter 4. Relevant literature and expert knowledge were used to aid model conceptualization and evaluation. After a conceptual and formalized model and a first working version of the implemented model were made, interviews with academic and industry experts were held to verify the model design and assumptions. Based on this feedback, the model was improved.

2.3.3 Model evaluation

The *evaludation* method developed by Augusiak et al. (2014) was used to evaluate, test and verify the model. The model is a spatial model representing the selected Delft neighbourhoods, where combinations of model input parameters represent the various specifications of heating systems and related policy interventions. Various conceptualisations and parametrisations of this model are evaluated in this phase. The method consists of six steps (see Table 1 for a summary of each step): (i) data evaluation; (ii) conceptual model evaluation; (iii) implementation verification; (iv) model output verification; (v) model analysis; and (vi) model output corroboration. The results of these steps are described in Chapter 5.

Table 1. ABM evaluation steps of the Evaludation method (Augusiak et al. 2014).

Term	Definition
Evaludation	The entire process of assessing model quality and establishing model credibility throughout all stages of model development, analysis, and application.
Data evaluation	The assessment of the quality of numerical and qualitative data used to parameterise the model, both directly and inversely via calibration, and of the observed patterns that were used to design overall model structure, whereby not

	only the measurement protocols need to be evaluated but conclusions drawn from the data should be challenged as well.
Conceptual model evaluation	The assessment of the simplifying assumptions underlying a model's design and forming its building blocks, including an assessment of whether the structure, essential theories, concepts, assumptions, and causal relationships are reasonable to form a logically consistent model.
Implementation verification	The assessment of (1) whether the computerised implementation the model is correct and free of programming errors and (2) whether the implemented model performs as indicated by the model description. The aim is to ensure that the modelling formalism is accurate.
Model output verification	The assessment of (1) how well model output matches observations and (2) to what degree calibration and effects of environmental drivers were involved in obtaining good fits of model output and data. The aim is to ensure that the individuals and populations represented in the model respond to habitat features and environmental conditions in a sufficiently similar way as their real counterparts
Model analysis	The assessment of (1) how sensitive model output is to changes in model parameters (sensitivity analysis), and (2) how well the emergence of model output has been understood. The aim is to understand the model and be able why which output is being produced to avoid drawing the wrong conclusions from model output.
Model output corroboration	The comparison of model predictions with independent data and patterns that were not used, and preferably not even known, while the model was developed, parameterised, and verified. This step strengthens a model's credibility by proving that the model can predict or reproduce patterns and data that could not have influenced the model development.

2.3.4 Exploration, analysis, and interpretation

The final research phase focused on answering the questions "*What inequalities in energy poverty and accessibility to sustainable energy might arise as a result of the heat network?*" and "What policy interventions lead to reduced inequalities and an accessible heat network?". Various scenarios were explored to examine the effect of the scenario conditions (e.g., specific combinations of policy interventions and heat network specifications) on energy poverty. The model results were analysed focussing on the extent and distribution of energy poverty and heat network access between different groups of households, to determine in which conditions energy poverty occurs and what interventions might reduce inequalities. We define inequality as a situation in which certain social groups are differently affected – i.e. more severely or disadvantageously – by the effects of a system, or when these groups have unequal access to a system, compared to other social groups. We speak of an inequality when the prevalence or severity of energy poverty is greater for specific household groups because of heat network implementation, or when a particular group has less opportunity to switch to the heat network. Various interventions were explored to determine what policy requirements are needed to avoid or reduce these inequalities. The result of this phase is an overview of energy poverty and heat network access in various scenarios and the effect of policy interventions on these aspects (Chapter 6). The model use and limitations of the research approach are discussed in Chapter 7. Based on the results, key findings and recommendations for policy interventions for a just heat transition are presented in Chapter 8.

Chapter 3.

Theoretical and contextual background

Synopsis

Examining energy justice and inequality

The capability approach, energy justice and energy poverty are three frameworks that can be used to examine inequalities between households caused by heating systems. In this thesis, we combine elements of each framework to capture the different dimensions of inequality in the distribution of effects of the energy transition. The goal of this chapter is to introduce these frameworks, describe the transition to a low-carbon heat network in Delft and the relevant characteristics of the two neighbourhoods, discuss theories used in agent-based modelling to represent household energy behaviour and decision-making, and identify relevant socio-economic factors and policy interventions. In doing so, we aim to answer the first research question:

What are the characteristics of the households and the current and planned heating system, and what policy options and socio-economic factors are relevant in the case in Delft?

The **capability approach** is a framework that focuses on individuals' ability to achieve the things they value. It emphasises the importance of expanding people's capabilities, such as their ability to live a healthy life, to improve their wellbeing. There is a knowledge gap in energy poverty research that looks at capabilities, i.e. quantifying energy poverty by measuring opportunities. In this thesis, we use this framework to examine the opportunities households have to fulfil their energy services requirements, to participate in the heating transition, and what interventions affect these opportunities.

Energy justice focuses on the distribution of benefits and burdens in relation to energy systems. Little research has been done on distributive justice of new energy systems in the heating transition. In this thesis, we use this framework to identify and address the unequal distribution of energy benefits and burdens between different groups of households as a result of a new heat network.

Energy poverty concerns households' inability to access or afford adequate energy services and emphasises the negative impacts of this on one's quality of life. A research gap in energy poverty is its distribution on a local scale, the distinction between household characteristics and the effects of the energy transition on energy poverty. We use this framework to measure the prevalence and severity of energy poverty before and after the implementation of the heat network and to examine policies that aim to reduce energy poverty.

Agent-based modelling of energy systems

In this thesis, we apply these frameworks in an **agent-based model** (ABM) to explore the inequalities in energy poverty caused by the implementation of a heat network in the city districts Voorhof and Buitenhof in Delft. Agent-based modelling is well suited to study complex socio-technical systems due to its ability to represent heterogeneous agents and the interactions between these actors and their environment. Few studies have focused on modelling energy justice or energy poverty aspects of the energy transition or heat networks. To model the decision-making of households in the context of energy systems, the Consumat framework of Jager (2000) is used, in which agents employ different decision-making strategies depending on their level of satisfaction and certainty. Research indicates also that investment costs and energy prices are the key factors that households consider when determining to switch to a heat network.

The transition to a low-carbon energy system in Delft

In the case project **Open Warmtenet Delft**, geothermal energy will be used to heat multi-family corporation dwellings in a new heat network. After these dwellings are connected, other multi-family complexes and individual homeowners are planned to be able to connect to the heat network. Voorhof and Buitenhof are districts with a low income built in the 1960s. Many buildings have a mediocre energy label (D or E), and many households are vulnerable to energy poverty. It is thus important to investigate the effect of the planned energy transition on energy poverty in these neighbourhoods.

Policy options to alleviate energy poverty in the energy transition

To tackle this, we consider three kinds of **policy interventions**, that each tackle a different aspect of energy poverty. Firstly, interventions that increase the affordability of energy commodities directly increase the access to affordable energy. Secondly, interventions that increase dwelling energy efficiency decrease the amount of energy households need to fulfil their required level of energy services and contribute to the energy transition. The third type of intervention focuses on increasing households' ability to achieve thermal comfort in other ways, such as expanding their opportunities to achieve adequate energy services through behaviour change. In the model scenario design, interventions of each type will be selected.

3.1 Examining justice and inequality: the capability approach, energy justice and energy poverty

We describe and compare three frameworks that are used to examine justice and inequality in the effects of policies and technologies such as energy systems on households. These frameworks are the capability approach (CA), energy justice and energy poverty. Overall, these frameworks offer different perspectives on the inequalities caused by heating systems and can be used together to understand and address these inequalities in a comprehensive way. For each framework, we explain which elements we use in this study and how we use these elements to examine inequalities and justice aspects of the heating transition. We also describe the knowledge gap in the literature that we aim to address in this thesis.

3.1.1 The capability approach

The capability approach is a framework for the assessment of wellbeing and justice developed by Amartya Sen and later expanded by Martha Nussbaum (Nussbaum 2003). It conceptualizes wellbeing in terms of people's capabilities to function: *capabilities* are the set of opportunities for what people are able to do and be, i.e. their doings and beings. The doings and beings that people actually achieve are called *functionings*. The distinction between capabilities and functionings is thus the difference between what is possible and what is actually realized (Robeyns 2005).

The capability approach can be used to evaluate the impact of policies on people's capabilities (Robeyns 2005). The capability set is the 'freedom to achieve', i.e. the possible beings and doings that a person can undertake. A person uses goods and services to enable these capabilities – such as using electricity to cook a warm meal – which are acquired using means such as income, non-market production and transfers in kind. In this view, energy consumption can be seen as a material requirement to achieve one's capabilities. A person's capability set is also influenced by their social context – such as social institutions, norms, environmental factors, and other people's behaviour – which determine how the goods and services available to the person can be converted into beings and doings.

The effect of a good or service on someone's capability set differs from person to person, since every individual has unique characteristics that determine the utility, benefits, or drawbacks of a good or service. This is conceptualized using *individual conversion factors* that determine the relation between a good and the capability to achieve a being or doing. For example, a person's health might cause them to require more energy to achieve the same level of thermal comfort. The energy efficiency of a building determines the amount of energy needed to keep a comfortable temperature. Similarly, one's awareness of efficient heating system use might affect their energy needs. These conversion factors are specific to a person and their social and environmental context. Figure 3 shows a non-dynamic representation of a person's capability set and the context influencing this set.

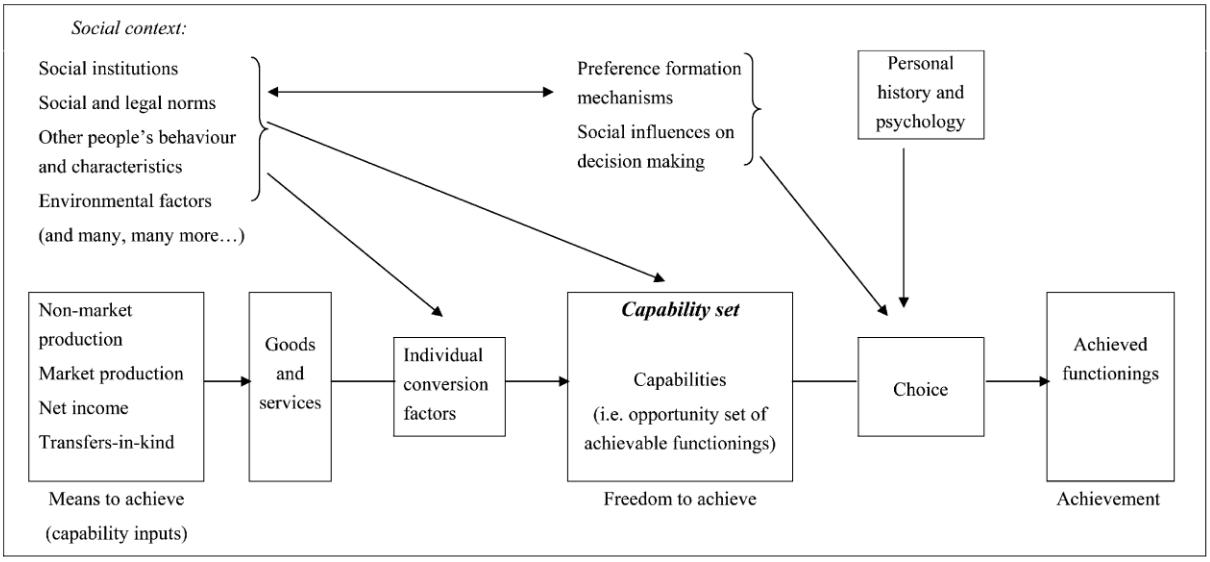


Figure 3. Non-dynamic representation of the influences of the social and personal context on a person's capability set. Image source: Robeyns (2005).

The focus of the capability approach is not on a person's available commodities (such as energy or food), means, or achievement. Rather, it focuses on one's freedom to achieve well-being and the distribution of one's opportunities, and how these are affected by a person's characteristics and environment. This distinguishes the approach from other approaches for evaluating well-being and justice (Alkire 2007). By taking this focus, the capability approach advocates for justice to be about increasing the opportunities that vulnerable people have to attain well-being.

Scientific interest in using the capability approach to evaluate energy justice has grown recently among social scientists and philosophers (Melin et al. 2021). To assess injustices in the context of energy systems, the capability approach is suitable since it serves as a 'metric of justice' (Hillerbrand et al. 2021) and has been adapted to energy contexts through the conceptualization of energy capabilities (Hillerbrand and Goldammer 2018). Most research using the capability approach in the energy domain has been done on the effects of energy systems in the Global South (Melin et al. 2021). In the context of Western regions, technological developments in the energy sector have been evaluated using the energy capability approach, such as the effect of smart grids (Hillerbrand et al. 2021) and the effects of decentralised energy systems and sustainable heating systems (de Wildt et al. 2020, 2021). However, a knowledge gap exists on applying the capability approach to real, local cases in the energy transition.

The capability approach could be used to assess the extent to which households in the neighbourhood are able to use the heat network to enhance their well-being. This could include factors such as households' ability to control the temperature in their homes, to afford the cost of heating, and to access information and support to manage their energy use. In this thesis, we use this framework to examine the opportunities households in a specific neighbourhood have to participate in the heating transition and what interventions affect these opportunities. In addition, we use the central idea in the capability approach that every household has distinct characteristics, conversion factors and decision-making to investigate the differences in energy poverty effects between household types. We also investigate interactions between one's social context and conversion factors and decision-making.

3.1.2 Energy justice

Energy justice is a framework used to evaluate where injustices emerge, which societal groups are affected and ignored, and which processes exist to remediate, i.e. reveal and/or reduce, these injustices in the context of energy (Jenkins et al. 2016). The aim of energy justice is to "provide all individuals, across all areas, with safe, affordable and sustainable energy" (McCauley et al. 2013). Energy justice is often conceptualised using three core tenets of energy justice (Walker and Day 2012; McCauley et al. 2013): distributional justice, procedural justice, and recognition justice.

The first tenet, distributional justice, aims to assess where in society injustices emerge. On the consumption side, this means evaluating if affordable access to energy services such as heating is distributed evenly throughout society. Injustices result from three types of inequalities: in income, in energy prices and in energy efficiency of housing and energy systems. Together, these inequalities result in unequal access to energy services (Walker and Day 2012).

Procedural justice, the second tenet, is concerned with fair and non-discriminatory procedures that engage all stakeholders in local communities in energy decision-making. This also includes ensuring that information, for example on energy prices and efficient usage of the energy system, is available to the entire population.

The third tenet, recognition justice, states that no individual or group should be ignored, mispresented, or disrespected. On the consumption side, this means recognising and respecting more vulnerable energy users, such as persons with a medical condition or the elderly, who may have higher energy needs.

The energy justice framework can be used to identify and evaluate the distribution of benefits, such as the availability of clean and affordable energy, and burdens, such as the cost of heating, associated with the heat network among different households in the city districts. In this thesis, we focus on distributive energy justice and use this framework to identify and address unequal distribution of energy benefits and burdens between different groups of households as a result of a new heat network.

3.1.3 Energy poverty

Energy poverty, also referred to as energy vulnerability or fuel poverty, can be defined as having inadequate access to clean and affordable energy. It can be seen as a form of inequality where the access to energy services is compromised (Walker and Day 2012). Besides this view, where energy poverty is a form of distributive injustice, one can also see energy poverty as the result of unjust procedures and the failure to recognise the diversities and needs of all social groups (Walker and Day 2012). Due to these different perspectives, no single metric, but multiple indicators are needed to capture energy poverty, and many different indicators are used (Thomson et al. 2017). Mulder et al. (2021b) distinguish three dimensions of energy poverty:

1. The affordability of energy;
2. The energetic quality of the dwelling;
3. The choice and possibility to participate in the energy transition.

For the first two dimensions, they reserve the term energy poverty for households that have a low income. In their view, high-income homeowners with a high energy bill or house with poor energetic quality do not experience energy poverty, since they have no issues paying the bill and have the possibility to invest in the energetic quality of their home. The third dimension is based on the idea that a household that faces no issues with accessing energy today, may have problems in the future due to being left behind in the switch to renewable energy systems. With these three dimensions, the authors go beyond the common definitions of energy poverty in Dutch studies. They also view the lack of the opportunity to live in a home with good energetic quality as a form of energy poverty or ‘choice poverty’ (Mulder et al. 2021b).

Energy poverty may lead to the deprivation of multiple capabilities of the affected individual (Bartiaux et al. 2018). For example, living in a poorly insulated home may lead to a lack of comfort and health problems. Energy poverty is largely by infrastructural characteristics, income, and energy prices, which are often spatially unequal (Bouzarovski and Simcock 2017). There may be large differences in the prevalence and extent of energy poverty between regions and even between close neighbourhoods within a city (Marí-Dell’Olmo et al. 2022), as is the case in Delft (CBS 2021a). There is high spatial inequality: recent research in the Netherlands found that energy poverty is concentrated in a small number of neighbourhoods with high occurrence of energy poverty (Mulder et al. 2023).

Despite these issues, the Dutch government had no policy or targets aimed at reducing energy poverty until October 2021, when the energy tax was lowered and funds were made available as a response to rapidly rising energy prices (Rijksoverheid 2021b). The municipality of Delft, however, decided that in the heat transition, affordability is a key criterium, and sees the transition as an opportunity to combat energy poverty. The ‘*warmte-uitvoeringsplannen’* per neighbourhood should include sufficient financial arrangements and guarantees that everyone should be able to participate in the energy transition. Therefore, the municipality will investigate which groups will experience a rise or fall in their energy expenses as a result of the transition to a gas-free heating system (Gemeente Delft 2021b).

Measuring energy poverty

As we saw in the previous section, energy poverty is a complex multidimensional problem, for which an accepted does not exist and which cannot be captured with a single indicator (Straver et al. 2020b). Following considerations such as the aim for an inclusive and just energy transition, the insight that affordability is only one of multiple dimensions of energy poverty, the finding that poor energetic quality of the home is a main cause of energy poverty, and the degree to which households can participate in the energy transition is distributed unequally, Mulder et al. (2021b; 2023) have defined the following indicators for energy poverty:

1. **High Energy Quote (HEQ)**
   A household is energy poor if a high fraction of the income is spent on energy expenses.
2. **Low Income & High energy Costs (LIHC)**
   A household is energy poor if it has a low income and high energy costs.
3. **Low Income & house with Low Energetic Quality (LILEQ)**
   A household is energy poor if it has a low income and lives in a home with a low energy quality.
   a. **Low Income & house with Low Energetic Quality & underconsumption energy (LILEQ-)**
      A variant of LILEQ that measures hidden energy poverty: households who under-consume, presumably due to financial problems.
   b. **Low Income & house with Low Energetic Quality & overconsumption energy (LILEQ+)**

A variant of LILEQ that measures the number of households with unusually high energy consumption.

4. **House with Low Energetic Quality & inability to invest in renovation (LEQ)**
   A household is energy poor if it lives in a home with low energetic quality which they cannot improve independently.
   a. **LEQ for owners (oLEQ)**
      The group of homeowners with low energetic quality and insufficient funds or limited lending capacity to improve the sustainability of their home independently.
   b. **LEQ for renters (rLEQ)**
      The group of renters of a home with low energetic quality who cannot decide to improve the sustainability of their home.

A summary of advantages and disadvantages for each indicator is given in Table 3. For a full discussion on the applicability and shortcomings of these indicators, please refer to the original paper. HEQ is the most widely used indicator for energy poverty, and LIHC has also been used in the UK (Turai et al. 2021). To our best knowledge, the other indicators have barely been used outside of the Netherlands.

The Dutch Statistics Bureau (CBS) has used these indicators to measure energy poverty in the Dutch province of South Holland (which includes the municipality of Delft) at neighbourhood level (CBS 2021a). See Table 2 for the definitions used for these indicators. This study uses the same indicators for energy poverty, with slightly adapted definitions for indicators HEQ and HC (see Model Formalization). However, examining hidden energy poverty and modelling its potential causes and related household behaviours is outside the scope of this study, so the LILEQ- and LILEQ+ indicators will not be used.

Table 2. List of energy poverty indicators and their definitions used by CBS and TNO.

Indicator component	Definition
High Energy Quote (HEQ)	Energy bill is higher than 8% of income including savings[1].
Low Income (LI)	Income is lower than 130% of the social minimum[2].
High energy Costs (HC)	Energy bill is among the highest 50% of Dutch households.
Low Energetic Quality (LEQ)	Energy label is D, E, F or G.
Owners unable to renovate	LEQ homeowners with less than €40000 equity or a home equity (*woningoverwaarde*) of less than €80000. Includes LILEQ by definition.
Renters unable to renovate	Any renter of a house with LEQ.

Table 3. Advantages and disadvantages of various energy poverty indicators based on Mulder et al. (2021b).

Indicator	Advantages	Disadvantages

[1] Savings are converted to an annual revenue (annuity) by dividing financial belongings by the expected remaining lifespan, taking revenue from interest into account (Mulder et al. 2021b).

[2] The social minimum is the minimum income needed to fulfil basic needs. The Dutch government sets the amount twice a year based on the social assistance benefit. The amount depends on the living situation of the receiver (UWV 2022). See Appendix A.5 Economic and technical parameters, Table 29 for the amounts used in this thesis.

HEQ	Indicator is easy to understand and communicate.	It is a very rough indicator that can both underestimate and overestimate the poverty issue. Underestimation occurs because it does not consider households that under-consume due to financial issues. Overestimation is due to counting households with a high income that deliberately consume a high amount of energy. The energy demand is hard to determine for the 13% of households with e.g. shared gas or electricity connections.
LIHC	More accurate than HEQ due to not counting high-income households.	A generic increase in energy prices does not influence LIHC, since it is a relative indicator, while this will increase the issues for households with energy poverty. LIHC also underestimates energy poverty due to not considering under-consuming households and households for which energy consumption is unknown.
LILEQ	Considers the actual cause of energy poverty: inefficiency and low spending ability. It is also not hindered by practical issues with determining energy use.	The indicator does not respond to changes in energy consumption or energy prices. Energy labels data can be unreliable and energy labels are not known for every household, making this indicator less reliable. It is also difficult to determine and compare energetic quality of dwellings.
oLEQ/rLEQ	Indicator gives insight in the unequal opportunities to participate in the energy transition. It considers two groups who might not have payment issues now, but risk being left behind in the energy transition which can cause future payment issues and problems with comfort and health.	Energy labels data can be unreliable and energy labels are not known for every household, making this indicator less reliable. It is also difficult to determine and compare energetic quality of dwellings.

By focusing on the opportunities and choices that households have, rather than only financial affordability, these indicators conceptually align with the capability approach (Mulder et al. 2021b), but they only cover a limited set of capabilities (being able to afford energy, being able to improve energy efficiency). When using the definition by Day et al. (2016) that energy poverty is the "inability to realise essential capabilities" due to a lack of access to energy services, one can assess a broader set of capabilities. However, one should then first define what capabilities are considered 'essential' in the context of energy services. This can be done based on a list of pre-defined core capabilities, such as the list by Nussbaum (2003), which is then specified with respect to secondary capabilities enabled by energy use. Such an attempt has been made by Hillerbrand and Goldammer (2018), who described 'energy capabilities'. While their work describes the link between energy services and individual wellbeing, it is still no concrete list of essential capabilities in the context of energy. Alternatively, deciding which capabilities are essential can be done with an inclusive and deliberative process as recommended by Sen. Since this is an expensive and time-consuming process that is specific for each context, and no work on this has been found in relation to energy poverty in the Netherlands, using such a deliberatively made list is outside of the scope of this thesis. Instead, we will assess energy poverty as a result of the following inequalities (Figure 4): inequalities in income, energy prices, and energy efficiency (Walker and Day 2012) and in personal characteristics and homeownership, using the set of indicators by Mulder et al. (2021b). Inclusion of these factors in the assessment of energy poverty enables us to assess policy options that target each of these factors specifically (see Section 3.4) and their effect on the distribution of energy poverty (distributional justice), and allows us to explore which social groups are affected (procedural justice).

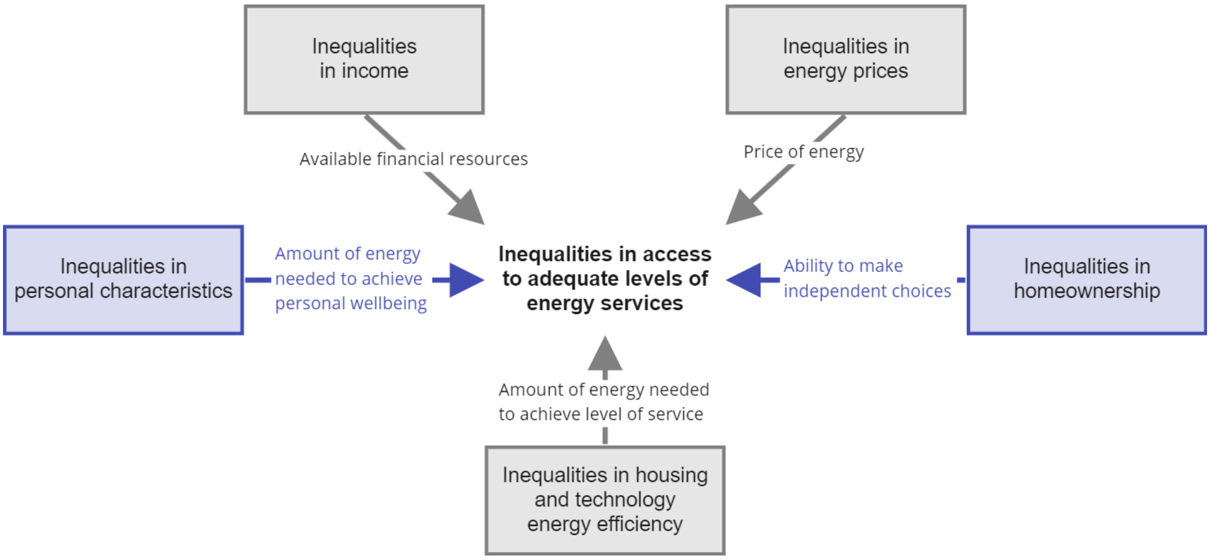


Figure 4. Interacting inequalities in energy poverty. Adapted from Walker and Day (2012), blue items added by author.

The Dutch government does not see energy poverty as a distinct issue but takes a broader social welfare approach, which fails to recognise the broader dimensions of energy poverty such as energetic quality and opportunities to improve one's energy situation (Feenstra et al. 2021). The development of just energy transitions policy provide a window of opportunity to integrate measures to alleviate energy poverty and follow a holistic approach to energy poverty (Straver et al. 2020a). During the current energy transition, addressing energy poverty involves seeking justice in each of the three tenets of energy justice (Walker and Day 2012): reducing unfair distribution of affordable access to sustainable energy systems; recognising which groups are vulnerable to energy poverty and what their needs are; and creating fair procedures that involve all citizens in the transition. In remainder of this thesis, we focus on distributive justice using the energy poverty framework and indicators to examine the distribution of energy poverty in an agent-based model with various scenarios for the switch to a heat network.

3.1.4 Comparing and applying frameworks on energy poverty and inequality

Energy justice, energy poverty and capability approach are closely related (see Table 4 for a comparison and an overview of elements used from each framework in this study). Both the capability approach and energy justice recognise that individuals differ in social contexts, personal characteristics, and opportunities. Energy poverty, however, is usually conceptualised in a more narrow sense by measuring it using one's income, energy quote or ability to pay energy bills, as is often done (Thomson et al. 2017; Straver et al. 2020a). This overlooks important dimensions of energy poverty such as the ability to improve one's situation, the potential impact of the energy transition and the lived experience of people with energy poverty (Feenstra et al. 2021). Recently developed indicators such as LILEQ+/- and oLEQ/rLEQ do consider these broader dimensions but have not been employed at the neighbourhood level.

The view by Mulder et al. (2021b) that the lack of choices and opportunities in the context of the energy transition is a form of energy poverty aligns with the capability approach's emphasis on the opportunities for wellbeing. Similarly, Day et al. (2016) define energy poverty as "An inability to realise essential capabilities as a direct or indirect result of insufficient access to affordable, reliable and safe energy services, and taking into account available reasonable alternative means of realising these capabilities". This view acknowledges that energy is an important requirement in fulfilling a range of basic capabilities. Energy poverty can also be seen as a form of injustice (Walker and Day 2012), where interactions between procedural injustices, distributional injustices and recognition injustices produce inequalities in access to energy services (see Figure 5). The three frameworks discussed in this chapter are thus closely related and intertwined.

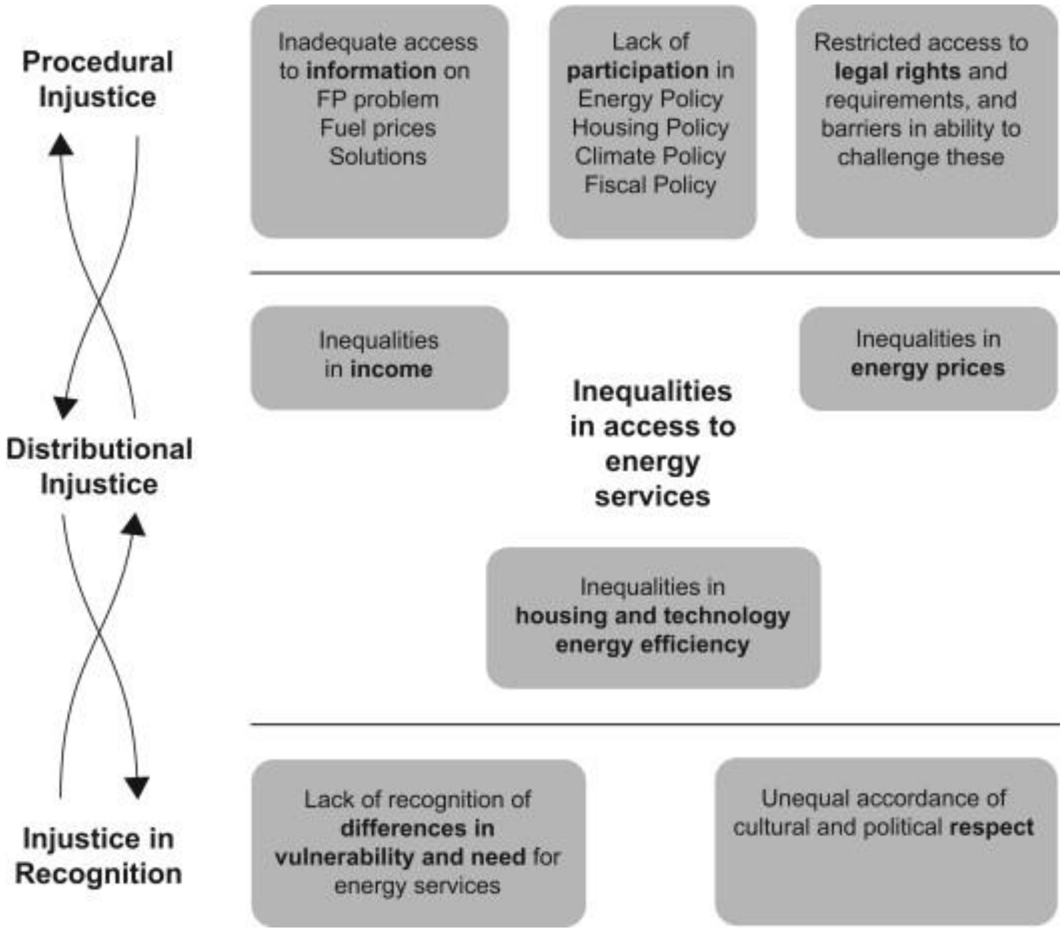


Figure 5. Three forms of injustice and interacting distributional inequalities that produce energy poverty. Image source: Walker and Day (2012).

The use of these frameworks calls for a modelling approach that can integrate the elements relevant to examine inequalities in heat network implementation: recognising differences between household characteristics and their influence on one's ability to convert capability inputs into opportunities to achieve; distinguishing opportunity from achievement; and investigating inequalities between groups of individuals and the effects of policies on these inequalities in multiple conditions.

Table 4. Comparison of frameworks on justice and inequality used in the context of energy systems, and elements used in this thesis, and research gaps we address.

	Capability approach	Energy justice	Energy poverty
Aim	To increase (vulnerable) individuals' freedom to achieve wellbeing	To provide all individuals with safe, affordable, and sustainable energy	To provide all individuals access to adequate energy services.
Measures of inequalities	Capabilities (opportunities); Freedom to achieve wellbeing	Distribution of effects;	Affordability of energy; Energetic quality of the dwelling;

		Fairness of procedures; Recognition of affected groups	Possibility to participate in the energy transition
Elements used in this study	Means – goods – conversion factors – capability chain; Heterogeneity in personal characteristics. conversion factors and decision-making; Effect of social context on individual conversion factors and decision-making; Focus on opportunities to achieve rather than achievement itself to broaden energy poverty measurement.	Distributive justice; Assessing the distribution of benefits and burdens of an energy technology; Recognizing which groups are affected.	Measuring the prevalence and severity of energy poverty; Use of a set of indicators.
Research gap addressed in this study	Lack of energy poverty research looking at *opportunities*, e.g. to increase energy efficiency or to choose sustainable energy supply.	Knowledge gap on justice of new energy systems and heating transition.	Lack of research on local scale, on effects of energy transition on energy poverty, and on distinction between household characteristics.

3.1.5 Recent work and addressing the research gap

Quantitative data on energy poverty is important to inform policy making and increase knowledge and awareness of the issue, but this research has been very limited in the Netherlands until recently (Mulder et al. 2023). Much of the work being done on energy poverty in the Netherlands has been carried out by TNO (Straver et al. 2020b; Mulder et al. 2021b; Faaij et al. 2022; Mulder et al. 2023) and Netherlands Environmental Assessment Agency PBL (van Middelkoop et al. 2018; Luteijn et al. 2021). This work has mostly been limited to the affordability of energy, determined using the energy quote. A very recent study is the first to estimate a set of three energy poverty indicators – the affordability of energy, the energetic quality of houses, and households' ability to participate in the energy transition – for the Netherlands using georeferenced data at the household level (Mulder et al. 2023). Only a few other scholars have studied spatial aspects of energy poverty, such as spatially heterogeneous determinants of energy poverty (Mashhoodi et al. 2018) and the relation between land surface temperature and energy expenditure (Mashhoodi 2020). Other recent studies have explored drivers of energy poverty using machine learning (Dalla Longa et al. 2021). Most studies have focused on the occurrence of energy poverty; only a few studies have examined possible impacts increasing energy prices on energy poverty (van Middelkoop et al. 2018; Mulder et al. 2023). Most studies emphasised the need to look at energy poverty as a multi-dimensional phenomenon.

This thesis addresses the following research gaps. While interdisciplinary research can lead to novel methodologies, frameworks and insights, most energy research is monodisciplinary (Sovacool 2014). Dutch national policy fails in recognising the experience of vulnerable households – energy poverty is mostly addressed at the municipal level – and no national strategy on energy poverty exists (Feenstra et al. 2021). There is a lack of disaggregated data on energy poverty; better distinction between various household characteristics that influence energy vulnerability is needed (Straver et al. 2020a; Feenstra et al. 2021). Moreover, very few studies have focused on geographical inequalities in energy poverty on a neighbourhood scale, let alone at the level of single buildings or household. In addition, there is a lack of research on the impact of energy systems on energy poverty and on different social groups. Especially in the context of heating systems, little research has been done on energy justice of these systems. While local and regional studies have investigated costs for various low-carbon energy technologies for households or society, these have not focused on affordability, energy poverty or distributional justice (Brouwer 2019). This thesis can provide insights in how new heating systems can be designed to be more inclusive for vulnerable households. The use of an agent-based modelling approach in energy justice and energy poverty research is also relatively new. We employ this bottom-up approach to examine how energy poverty may emerge from the interactions between socio-economic conditions, technology and household characteristics in the local energy transition, in line with research directions proposed by Shahzad et al. (2022).

3.2 Agent-based modelling of energy systems

3.2.1 Using ABM to study socio-technical systems and complex adaptive systems

The energy transition, and specifically the implementation of thermal energy systems in the built environment, can be analysed through the lens socio-technical systems (STS) and complex adaptive systems (CAS) (Nava Guerrero et al. 2019a). STS focuses on the interactions between the social and technical elements of a system, such as the interface of policy, household behaviour and technology. It poses that the social and technical aspects of a system should be considered together rather than treating them as separate domains. A complex adaptive system is a dynamic network of many interconnected parts that can adapt and change over time in response to their environment. Through the lens of STS and CAS, neighbourhoods can be regarded as "networks of individual actors who own technology, interact with each other, and are able to make their own decisions" (Nava Guerrero et al. 2019a) and the implementation of a heat network and related policies can be seen as conditions in the environment that interact with these households.

Agent-based modelling is a method used to study complex socio-technical systems (van Dam et al. 2013) that analyses how individual behaviour and decisions lead to broader behaviour of the system as a whole (Nikolic and Ghorbani 2011). Central in ABM are heterogeneous actors that have unique states, which interact with other agents and the environment (Figure 6). Specific rules govern the agents' behaviour and interactions with other agents and the environment. This way, the effect of certain mechanisms and conditions on the behaviour of a system and the actors in it can be studied.

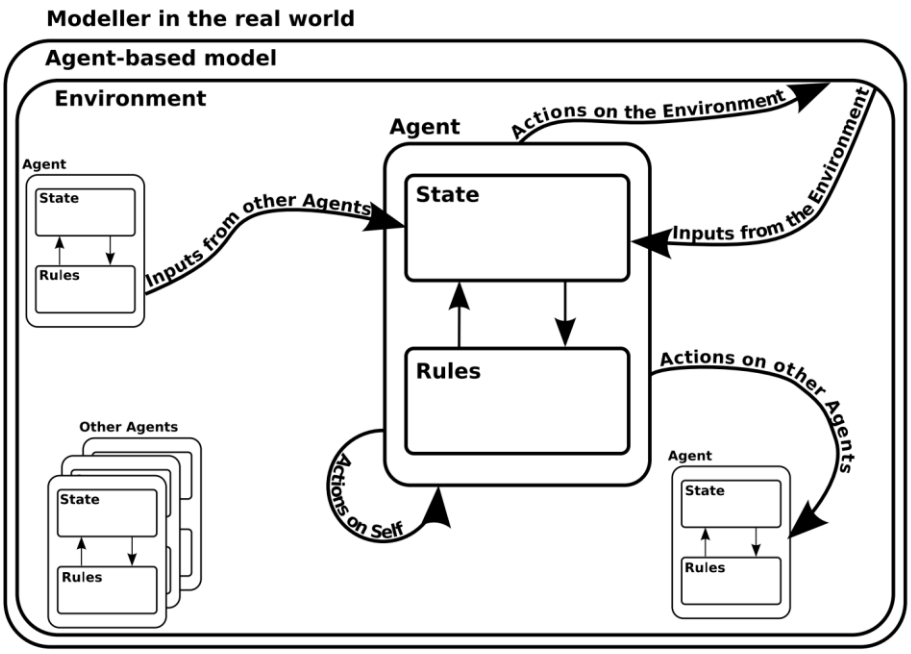


Figure 6. Structure of an agent-based model. Image source: van Dam et al. (2013).

3.2.2 Potential of ABM to model heat transitions

ABM is used to study various aspects of the energy transition. But what makes ABM a suitable tool to explore inequalities between households in access to clean and affordable energy because of the implementation of a heating system?

Agent-based models, as opposed to equation-based accounting models, can account for heterogeneity of household characteristics, behaviour such as decision-making, and the interactions between households. This makes it a suitable method for representing the inequalities between households that underly energy poverty and exploring the effects of policies that target these inequalities. It also allows researchers to easily incorporate different assumptions and scenarios in the models (Rai and Douglas Henry 2016a), such as changes in energy prices, the implementation of energy-saving interventions or different models for household decision-making. ABM allows for the study of the emergence of phenomena such as energy poverty inequality resulting from the interactions between households, the energy technology, and the policy environment. An additional advantage is that ABM is able to represent a dynamic and heterogeneous spatial environment (Filatova et al. 2013). Due to these features of ABM, the approach is more suitable to reflect the complex socio-technical features of local energy infrastructures than standard techno-economic modelling approaches (van Dam et al. 2013). The flexibility of ABM makes it possible to explore a wide range of outcomes and identify potential interventions that can reduce inequalities and energy poverty.

3.2.3 Knowledge gaps in ABMs of energy justice and heating systems

Few ABM studies focus on energy justice or accessibility aspects of heat networks. A review of ABM studies on the adoption of energy efficiency by households by Hesselink and Chappin (2019) did not find any studies on this topic that included heat districts as the energy technology under study. Assa and Lengfelder (2020) partly fill this gap by using ABM to address distributional concerns of energy justice. However, this model was highly abstract and with a simplified economy and household characteristics, and did not represent a real neighbourhood. The authors suggest that including details of costs and benefits of installing alternative energy systems, introducing more demographic details, and having heterogeneous household sizes as directions for further research with potential for additional insights in energy justice. A recent study by Nava-Guerrero et al. (2021) looked at the effect of household decision-making on energy system uptake, but this study did not investigate energy poverty.

To our best knowledge, few studies have focused explicitly or exclusively on energy poverty in the heating transition. De Wildt et al. (2020; 2021) explore the relation between social acceptance of heating systems and the fulfilment of capabilities by applying the capability approach in an agent-based model. A shortcoming of the studies by De Wildt et al. is that the affordability of energy is conceptualised as the function of costs and willingness to pay, making the results difficult to compare with empirical data on energy poverty and covering only a single dimension of energy poverty. In addition, the model has only been applied to one specific case. By applying a combination of elements from the capability approach, energy justice and energy poverty frameworks, energy poverty inequalities can be explored more explicitly.

3.3 Behaviour and decision-making in an energy context

In the model, we simulate two aspects of household energy choices: the usage of energy, and the choice in energy system. The way we take decisions depend on how familiar the situation is Figure 7. In familiar situations, limited or no thinking is involved in making choices, but habits and intuitive responses are at the basis of decisions. For unfamiliar decisions, however, we make decisions through intensive thinking (Wendel 2020). We assume that using energy is a familiar context, while deciding which energy system to adopt is an unfamiliar context. We will therefore use different decision-making rules for these choices. The next two sub-sections will discuss models for energy use decision-making and heating system choice, respectively.

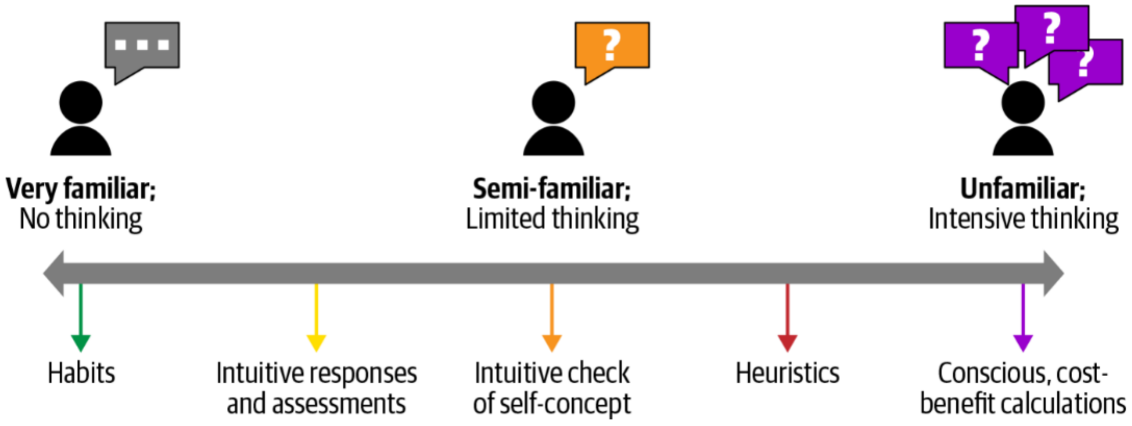


Figure 7. In familiar situations, we make choices with little to no thinking by using habits and intuitive responses, while in unfamiliar situations we make conscious decisions through intensive thinking. Image source: Wendel (2020).

3.3.1 Energy use decision-making

Predicted energy consumption and actual energy use might differ per household, even differing a factor two on average for dwellings with low energy efficiency (Majcen 2016). Actual energy savings after renovation are often much lower than theoretical savings – the reduction in primary energy consumption assumed when improving a dwelling from energy label G to label A is much lower than expected (Majcen 2016). So, we choose to use average measured energy demand data per dwelling type, size, energy label and year of construction instead of theoretical values. Since these values are averages, we include factors in the model that determine individual energy consumption of households. We assume that using energy is a familiar setting, so limited to no thinking is done and energy use is driven by habits, intuitive responses, and intuitive checks of self-concept (Wendel 2020). Thus, rather than making concrete decisions on how much energy households use, we define just two factors that modulate the expected energy demand of households. These are environmental attitude, and awareness campaigns. Having an environmental attitude and values can drive pro-environmental behaviour (Fietkau and Kessel 1981) such as energy saving. Households that have pro-environmental attitudes and behaviours spend on average up to 9% less in electricity and 6% less in gas (Longhi 2015). Finally, we will consider awareness campaigns and initiatives such as energy coaches that may increase knowledge and willingness to save energy. Since the influence of income on energy use and energy choices is debated and differs from study to study based on our literature review, we exclude this factor from our analysis.

3.3.2 Heating system decision-making

To determine which factors households consider when deciding whether to switch to a heat network, we looked at recent empirical research on Dutch households (Schalkwijk 2020; Van Aalderen et al. 2021). To determine what decision-making method to use in the model, we consulted reviews on decision-making models and psychology theories used in ABM simulation of technological innovations and energy transition research (Kiesling et al. 2011; Hesselink and Chappin 2019; de Vries et al. 2021) and examined the decision-making methods used in similar ABM studies (Sopha et al. 2011, 2013; Robinson and Rai 2015; Snape et al. 2015; Rai and Douglas Henry 2016b; Busch et al. 2017; de Jong

2018; Nava Guerrero et al. 2019b; Sachs et al. 2019; Assa and Lengfelder 2020; de Wildt et al. 2020, 2021; Nava-Guerrero et al. 2022; Krumm et al. 2022).

Empirical data on heating system choice

When asked about the switch to a heat network, 38% of respondents in (Schalkwijk 2020) have a positive attitude to connecting their neighbourhood to a heat network, while 15% has a negative attitude; the others are neutral or don't know. 59% of households think the switch will take (a lot of) effort, and 46% think the costs will be higher. In deciding whether to switch to a heat network, households cite the costs for applying changes to the home, costs of the heat, the performance in heating the home and the adjustments that the inhabitant should perform themselves as most important factors (Figure 8). Regarding participation, 51% of interviewees preferred to be well-informed, but did not have the desire to be actively involved in the plans for a heat network in their neighbourhood. Whether neighbours participate was only considered important by 3% of respondents.

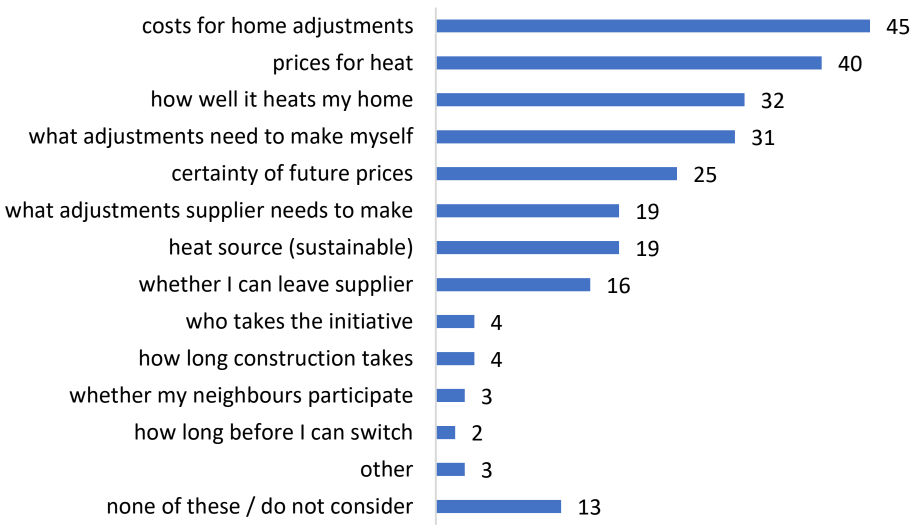


Figure 8. Most important factors in the choice of whether to switch to a heat network (%). Translated from Schalkwijk (2020).

Edelenbosch et al. (2022) also found that increasing income levels lead to increased investments in energy-saving measures. In their study, income was the most important factor that affected energy demand, dwelling efficiency, and investments in energy-saving measures, followed by dwelling improvement potential. They also found that there are additional factors and drivers that influence the decision-making processes and chosen strategies, which are complex and heterogeneous. Characteristics such as household composition, specific sociodemographic groups, environmental preferences, and energy-saving habits caused variation in the patterns found. The authors highlight the difficulty of linking energy use patterns sociodemographic groups, and the presence of group-specific barriers and enabling factors in adopting energy technologies (Edelenbosch et al. 2022). This emphasizes the importance of representing heterogeneity in the model – in terms of sociodemographic characteristics and employed decision-making strategies – and further investigating the differences between these groups.

Theories for heating system decision-making

Many types of decision rules can be used to simulate consumer adoption behaviour – for a review see Kiesling et al. (2011). We present a brief overview based on this review in Table 5. We will focus on social psychology approaches since these represent behavioural richness rather than simplifications such as homo economicus. Perhaps the most widely used such approach is the theory of planned behaviour, which poses that behaviour is based on one's attitude, intention and perceived control (Ajzen 1991). A related conceptual model, the theory of consumer behaviour or Consumat framework, assumes that agents employ different decision-making strategies, related to the level of social comparison needed to make a choice, depending on their level of confidence and satisfaction (Jager 2000; Jager and Janssen 2012). Another social psychology approach is the theory of environmental behaviour, which conceptualises pro-environmental behaviour as a consequence of opportunities, incentives, perceived consequences and environmental attitude (Fietkau and Kessel 1981; Kollmuss and Agyeman 2002).

Table 5. Overview of decision rule types used for simulating consumer adoption behaviour. Adapted from Kiesling et al. (2011).

Type of decision rule	Examples
Simple decision rules	Adopt new technology once a certain percentage of friends does
Utilitarian approach	Adopt based on greatest (expected) utility
State transition approach	Adopt based on probability to go from one state (e.g. potential adopter) to another (e.g. adopter)
Opinion dynamics approach	Adopt based on opinion, opinion is based on (non-)adoption of others
Econometric approach	Estimate adoption probabilities based on empirical data
Social psychology approaches	Model of consumer behaviour or Consumat framework (Jager 2000; Jager and Janssen 2012); Theory of planned behaviour (Ajzen 1991); Theory of pro-environmental behaviour (Fietkau and Kessel 1981; Kollmuss and Agyeman 2002)

Jager's meta-model of behaviour

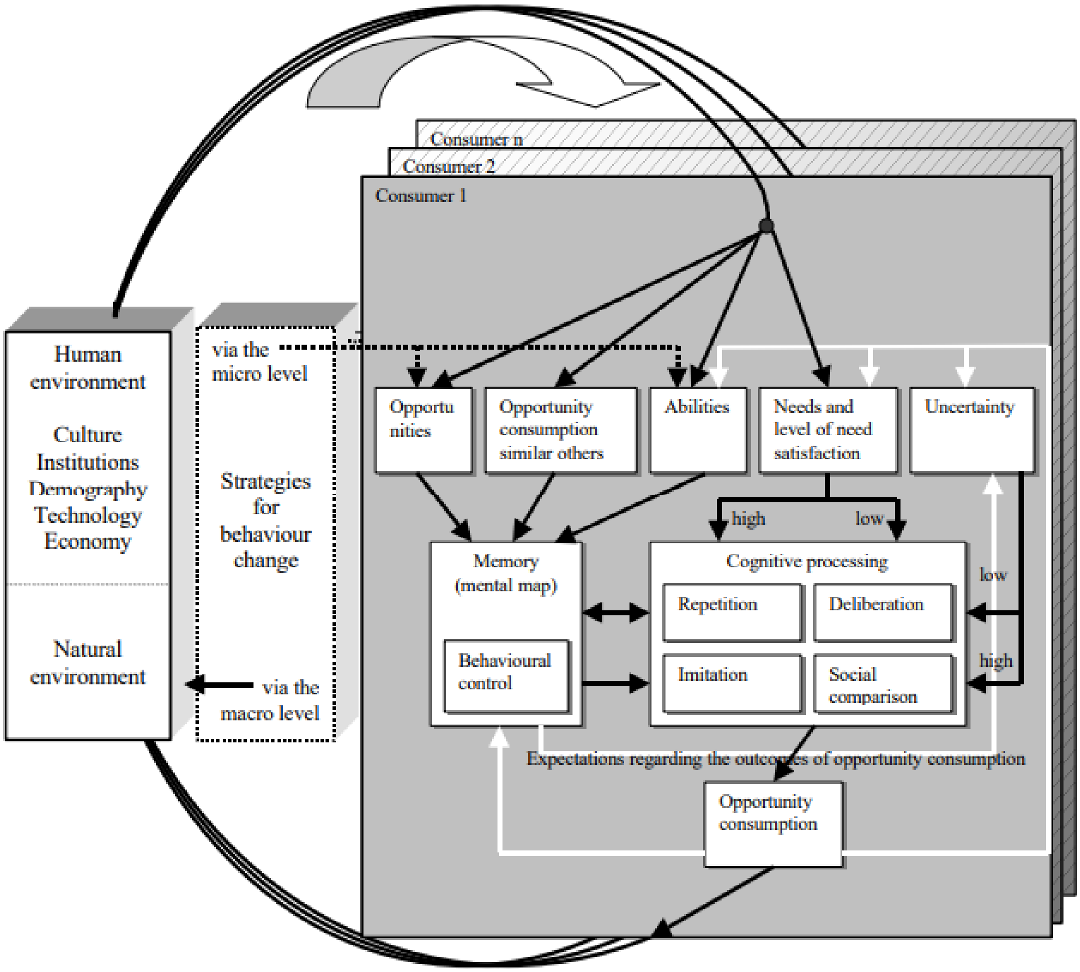


Figure 9. Schematic representation of Jager's conceptual meta-model of behaviour. Image source: Jager (2000).

In Jager's modelling of consumer behaviour, 'consumats' may choose different strategies for decision-making: repetition, deliberation, imitation, social comparison (Jager 2000). The choice of strategy depends on the agent's level of need satisfaction and certainty (Figure 9). Jager considers the nine types of universal needs postulated by Max-Neef (1992): subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. Satisfiers such as food, shelter, and work can satisfy the need subsistence. In Jager's model, uncertainty 'relates to the difference between the expectations of the consumat and the actual outcomes of behaviour' (Jager 2000).

- Repetition: if the consumat is satisfied and certain, it will consume the same product as in the previous period.
- Deliberation: if the consumat is unsatisfied and certain, it will check which of the consumption opportunities yields the best outcomes.
- Imitation: if the consumat is satisfied and uncertain, consumats adopts the behaviour that most of its neighbourhood performed in the previous time step.
- Social comparison: when the consumat is unsatisfied and uncertain, it will engage in social comparison. First, it reasons which neighbouring consumats are comparable by observing the abilities of eight neighbours (such as housing or household type). It will then consume the product which has been consumed the most by comparable neighbours.

Selection of heating system decision-making strategy

We choose to use elements of Jager's model of consumer behaviour as a basis for household decision-making in our model, to allow varying decision-making strategies depending on the household's situation and avoid the 'homo economicus' simplification (Jager 2000). This model is also less generic than Ajzen's theory of planned behaviour, since it was specifically designed for simulating consumer choice (Jager 2000). In addition, the model of consumer behaviour includes a social element of decision-making – comparison and deliberation with others – as well as habitual behaviour, which are lacking in Ajzen's theory. While Fietkau and Kessel's model of pro-environmental behaviour is even more specific to decision-making in the context of environmental sustainability options, it is less suited in the context of heat networks, since environmental sustainability is not considered often in the choice to switch to a heat network (Schalkwijk 2020). Interviews with domain experts also indicated that costs are the key factor in deciding whether to join a heat network, and that environmental attitude plays only a very minor role. Jager's Consumat framework has been used in ABM studies focusing on topics such as diffusion of electric vehicles (Kangur et al. 2017) and green consumption (Bravo et al. 2013).

3.4 The transition to a low-carbon energy system in Delft

3.4.1 Open Warmtenet Delft: A heat network based on geothermal energy and residual heat

For the local heating transition in Delft, the districts Voorhof and Buitenhof have been assigned as priority districts where implementation of measures to become natural gas-free will start first. In these districts, a heat network has been determined to be the low-carbon heating alternative with the lowest costs (Gemeente Delft 2021b). The city of Delft considers geothermal energy as a promising source of sustainable heat in these neighbourhoods (Gemeente Delft 2021b).

Geothermie Delft (GTD) aims to develop a deep geothermal plant on the Delft University of Technology (TU) campus. GTD is a collaboration between TU Delft, Aardyn (formerly Hydreco Geomec), Energie Beheer Nederland (EBN) and Shell and aims to study geothermal energy and its application and to use geothermal energy to heat buildings (Geothermie Delft 2021). In the planned deep geothermal plant, heat is obtained using a geothermal doublet by extracting water from a depth of 2.2 km. This water has a temperature of approximately 75 °C. After using this water for heating in the local heat network, the cooled water is pumped back into the earth via another well to a distance of 1.5 km from the first well (Geothermie Delft, n.d.). In the current plans, the heat network of the TU Delft campus will be connected first, after which the Open Warmtenet Delft will be connected.

Open Warmtenet Delft (OWD) is a collaboration of the municipality of Delft and the housing corporations DUWO, Vestia, Vidomes and Woonbron (Gemeente Delft 2021c). Network operator NetVerder and energy supplier Equans (formerly Engie) engage in developing the heat network in the Voorhof and Buitenhof districts. Three variants of the project were planned: one where only the buildings owned by housing corporations are connected to the heat network ('basis' scenario); one where buildings in the Poptahof and Martinus Nijhofflaan areas are also connected ('basis+' scenario); and a 'futureproof' scenario in which an expected 10000 additional dwellings (both ground-level and stacked housing) in the area can be connected. Figure 10 shows the trace of the 'basis' scenario and Figure 11 shows the neighbourhoods to be connected in the 'basis+' scenario. In all scenarios, 70 corporation-owned buildings with collective gas boilers are connected first, representing 5300 dwellings, 10% of dwellings in Delft (Peter and Frenken 2019). Other buildings can be connected to the heat network after this first phase has been completed. In December 2021, the city council of Delft approved the investment of €3.8 million as subsidy for the realisation of OWD, signalling the green light for the 'futureproof' variant of the project. This subsidy will be repaid through the net income generated from the extra connections (Gemeente Delft 2021d).

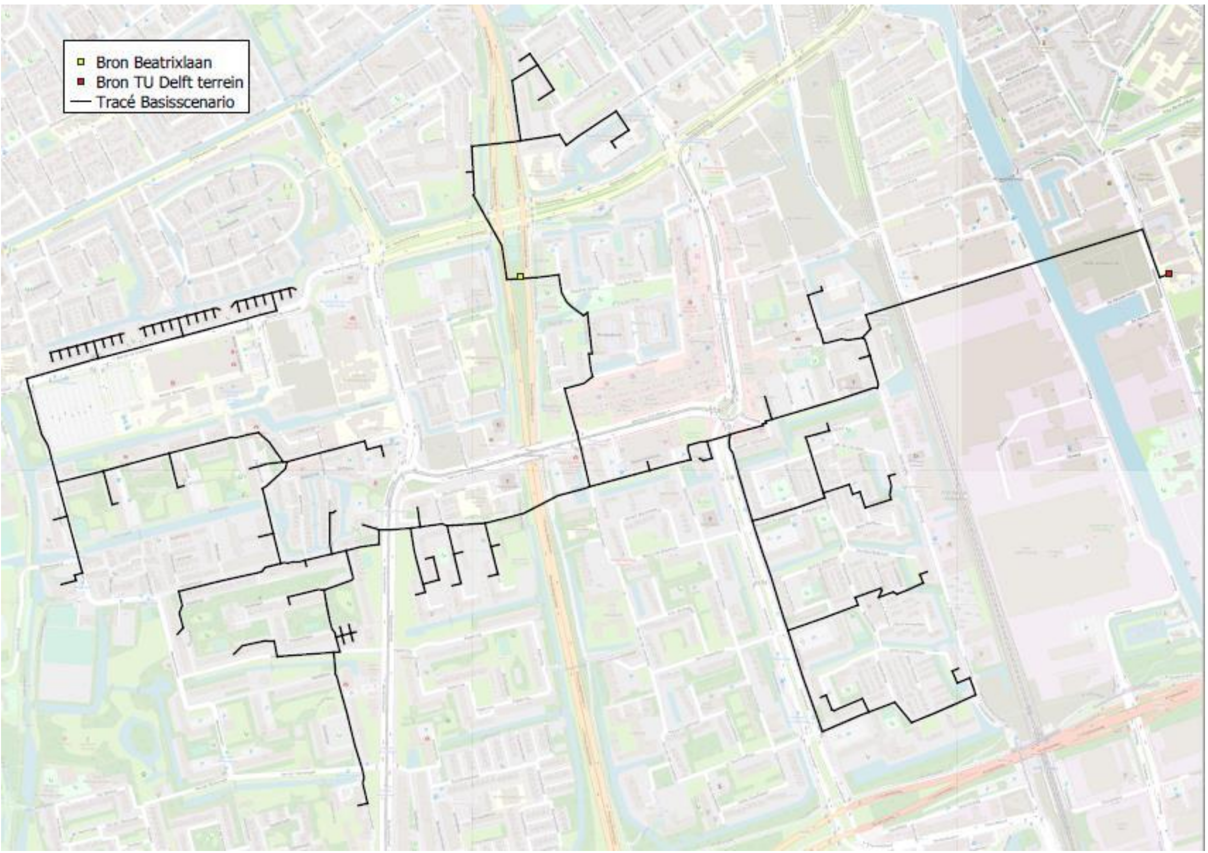


*Figure 10. The Open Heat Network in the 'basis' scenario of OWD. '*Bron TU Delft terrein*' indicates the location of the future geothermal well at the TU Delft campus. Image source: Peter and Frenken (2019).*

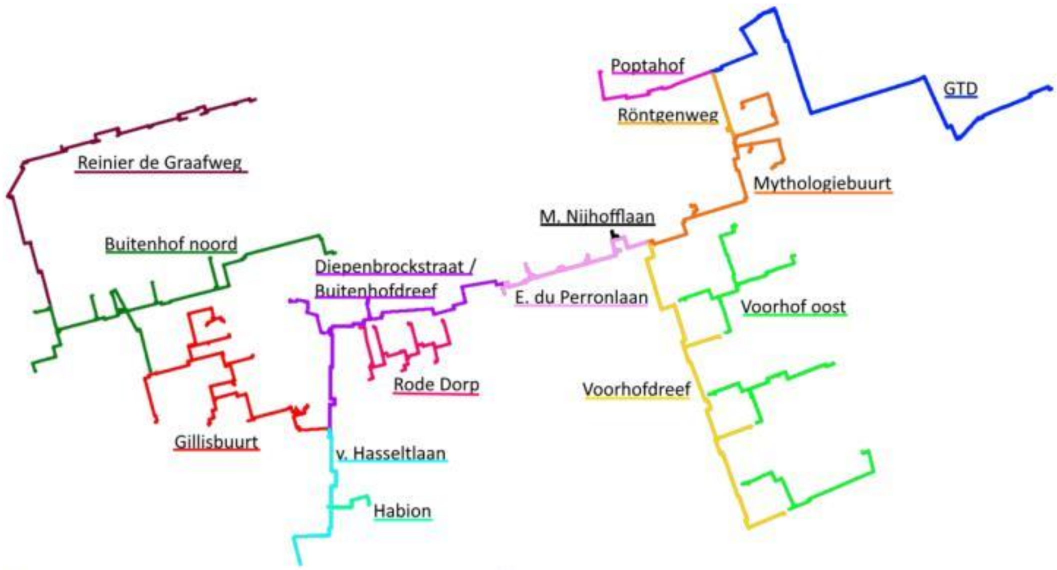


Figure 11. Areas connected to the heat network in the Basis+ *variant of Open Warmtenet Delft. Image source: van Dijk et al. (2021).*

3.4.2 Building requirements and changes

In buildings with an extant collective boiler, no significant changes to dwellings need to be made (Gemeente Delft 2020). Renovations are still needed, though. To compensate for the extra heat demand of badly performing buildings, the corporations owning these buildings must pay a substantial fee to supplier NetVerder. This pressures these corporations into actually renovating their building stock up to the design requirements (Peter and Frenken 2019). More technical and governance details of OWD are shown in Table 6.

Table 6. Technical and governance details of Open Warmtenet Delft (Gemeente Delft 2021c).

Heat network aspect	Specification
Order of connections	70 multi-family buildings with collective boilers of the housing corporations are connected to the heat network first. When this work is finished, buildings with individual boilers and dwellings with ground level entrances could be connected later. This includes individual homeowners and buildings with a homeowner's association.
Type of heating	The 70 buildings in Voorhof and Buitenhof have collective gas boilers.
Costs for households	Heating costs for housing corporation renters should not rise when connecting to the new heating system*, neither should the rent. This is unless the dwelling is renovated; then the costs can change. Then, the aim is that total housing costs (rent + heating costs) do not increase. Costs for individual homeowners are not known yet. New connections to the heat network (except the 70 initial corporation buildings) will need to pay a connection fee (*bijdrage aansluitkosten*, or BAK). *For average use in a year with average weather conditions.
Changes to buildings	This depends on the building. In buildings with a central gas boiler, only this boiler needs to be exchanged for a collective connection with the new heat network. Residents will barely notice this. Part of the buildings in Voorhof and Buitenhof will be connected to the heat network in parallel with a planned renovation. During this renovation, changes will be made to the dwellings. Changes too cooking equipment and warm water will be made at a later point for most buildings, to achieve a completely gas-free building (outside the scope of this thesis).
Residents' approval	In buildings with a central gas boiler, no approval is required. In buildings with individual boilers, 70% of renters need to approve the change. Homeowners can always decide for themselves to connect or not.
Heat suppliers and contracts	In the open heat network, multiple suppliers will be able to share heat with consumers. However, contracts are long-term (15 years), and at the start of the network, only the geothermal well of GTD will be the heat source. Consumers will thus be stuck with the same heat supplier for 15 years, even if there is a choice in heat supplier.

3.4.3 Costs

Currently no alternative low-carbon techniques exist that can compete with heat networks at the planned scale of OWD (Peter and Frenken 2019). In addition, the developers of OWD claim that the reduced variations in energy price compared to gas are a main advantage of the heat network (Peter and Frenken 2019). While this is an often-mentioned advantage of heat networks powered by renewable energy, heat network prices are not independent of gas prices in the Netherlands. This is because of three reasons. Firstly, the maximum price of heat from a heat network supplier is regulated by the 'Warmtewet' (Heating Law), according to the principle 'no more expensive than usual' (Rijksoverheid 2013). Therefore, if gas prices rise, suppliers may also increase the price of heat from a heat network (ACM 2022a). Secondly, renewable energy projects may be subsidized with the subsidy for stimulation of renewable energy production and climate transition (SDE++). The SDE++ compensates the difference between the cost price of the sustainable energy production and the conventional energy price (RVO 2022). If conventional energy prices rise, the received subsidy for sustainable heat thus decreases, meaning that suppliers must raise their prices to compensate. Lastly, some heat networks still (partly) depend on gas powered heating systems, for example to provide extra heat during cold weather or as back-up source when the primary source is not able to supply heat. This dependence means that suppliers are still partly reliant on gas prices. So, while heat network costs are 'not higher than conventional', prices are not independent from prices of gas or other fossil fuels and can still vary considerably. For example, the unusually high energy prices of 2021 and 2022 allowed heat network suppliers to greatly increase their prices (ACM 2022b). With an average heat demand, the yearly heating costs in 2022 went up by 27% to 54% (depending on the supplier), and the price per gigajoule (GJ) of heat sometimes even increased by 89% (Woonbond 2022a). This was even before the Russian invasion of Ukraine, which resulted in gas prices increasing even further.

3.4.4 Financial incentives and aids

The Dutch Climate Accord states the intention to keep the heating transition 'housing cost neutral', e.g. investments in sustainability or higher rents should be compensated by lower heating costs (Rijksoverheid 2019). However, a report by the Netherlands Environmental Assessment Agency (PBL) concluded that housing cost neutrality is almost impossible to achieve, and long-term subsidization is needed as long as sustainable renovation costs do not greatly decrease (Schilder and Van Der Staak 2020). The report showed that especially single-person households and couples – as opposed to households with children – and households with low energy labels, will probably not achieve housing cost neutrality without subsidies when making their homes gas free and energy neutral. Financial measures are thus needed to keep the heat transition affordable for all.

Currently, two financial arrangements are available for homeowners that want to connect to a heat network (Gemeente Delft 2020; Nationaal Warmtefonds 2022):

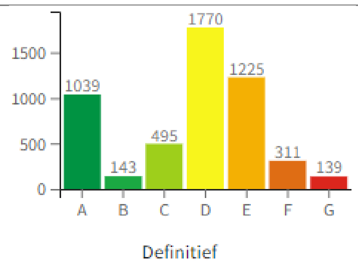
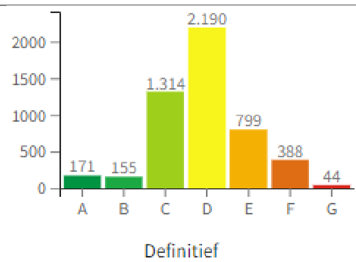
- ISDE subsidy to connect to heat network, with the criterium that the dwelling is completely gas-free. Subsidy: €3325.
- *Warmtefonds* loan (*Energiebespaarlening*) for heat network connection of individuals: €2500-25000, 1.5% interest per year.

Currently, the *Energiebespaarlening* has an interest, and no zero-interest loans are currently available. Following the Russian invasion of Ukraine and the consequent rise in energy prices, the Dutch government announced the National Insulation Programme (*Nationaal Isolatieprogramma)*, which contains the plan to offer a zero-interest loan for homeowners without the ability to take on other loans or with low income (Rijksoverheid 2022a).

3.5 Household and housing characteristics of Voorhof and Buitenhof

The city districts in which the planned heat network will be constructed are Voorhof and Buitenhof. Table 7 shows the 'district passports' with quantitative data of the Voorhof and Buitenhof districts that are relevant for the heating transition. This data is retrieved from the *Datavoorziening Wijkpaspoort Warmtetransitie* by the Association of Dutch Municipalities (VNG) and The Netherlands' Cadastre, Land Registry and Mapping Agency (Kadaster), which bundles data from the Statistics Netherlands (CBS), the Registry of Addresses and Buildings (BAG) and energy label database of the Netherlands Enterprise Agency (RVO). Most buildings in these districts were built in the 1960, with some additional neighbourhoods and buildings built in later periods. The districts are characterised by a high share of apartment buildings, a large portion of which are owned by social housing corporations. Average annual income is quite low compared to that of the Netherlands, and most households (65% and 63% in Voorhof and Buitenhof, resp.) are among the 40% lowest incomes in the Netherlands. Electricity and energy use are lower than average: the average Dutch household uses 1095 m^3 (38.5 GJ) natural gas and 2764 kWh (10 GJ) electricity annually as of 2021 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2022), while Voorhof households use 640 m^3 and 2300 kWh and Buitenhof households use 920 m^3 and 2490 kWh.

Table 7. District passport showing quantitative data of the Voorhof and Buitenhof districts in Delft. Data retrieved via Datavoorziening Wijkpaspoort Warmtetransitie (VNG and Kadaster 2022).

	Voorhof	Buitenhof	Source
Number of dwellings	7397	6657	CBS Statline, 2019
Ownership			Dataset Woningvoorraad Kadaster, October 2020
Corporation	47%	68%	
Private	53%	32%	
Building type	*corporation/private*	*corporation/private*	Dataset Woningvoorraad Kadaster, October 2020
Apartment	3200/3600	4327/707	
Terraced house	180/240	133/1121	
Corner house	82/84	44/280	
2-under-1-roof	0/0	0/1	
Freestanding	0/16	0/42	
Other	0/0	0/2	
Electricity use	2300 kWh	2490 kWh	Energieverbruik particuliere woningen; woontype en regio's, CBS Statline, 2019
Natural gas use	640 m^3	920 m^3	
District heating	16.8%	0%	
Average income	€20200	€20300	Kerncijfers wijken en buurten, CBS statline, 2018 (CBS 2021b)
Distribution			
40% lowest	64.8%	63.2%	
Average	30%	27%	
20% highest	5.5%	10.2%	
Household types			
Single person	5180	4000	
Without children	1635	1505	
With children	1415	1850	
Distribution of energy labels			RVO energy labels, 2020

3.5.1 Energy poverty in Voorhof and Buitenhof

Voorhof and Buitenhof have a high occurrence of energy poverty compared to the whole municipality of Delft (Table 8), despite their low energy use. Especially the energy quality of dwellings in these districts is lacking, with 18% and 20% of households having a low income and low energy quality in Voorhof and Buitenhof, respectively. The share of households with a high energy quote (6% and 9% respectively) is comparable to that in the Netherlands (8%). There are major differences between neighbourhoods within these districts, with the share of households with HEQ, LIHC, and LILEQ ranging from 1%, 0%, and 0% respectively in Buitenhof-Zuid, to 20%, 15% and 42% in Gillisbuurt. One should note that for a significant share of households, the required data was not available. The data was available for 30% of dwellings in Voorhof and 66% of dwellings in Buitenhof (CBS 2021a).

Table 8. Three indicators for energy poverty in Delft, 2018 (CBS 2021a).

Area	Municipality	HEQ (%)	LIHC (%)	LILEQ (%)	HEQ, LIHC or LILEQ (%)

Netherlands	-	8	4	6	11
South Holland	-	6	3	8	12
Delft	Delft	6	3	12	14
Buitenhof	Delft	9	5	20	24
Voorhof	Delft	6	4	18	19

3.6 Policy options to alleviate energy poverty in the heat transition

3.6.1 Policy intervention positioning

Based on the elements of the capability approach, energy justice and energy poverty frameworks we use in this study, a selection of policy interventions is made to examine their effect on reducing inequality and energy poverty. Policy interventions to tackle energy poverty can target different points in the chain from energy production to capability fulfilment (Figure 12; see Day et al. (2016)). Examples are improving affordability of fuels at the stage of the energy source (i.e. commodities); improving efficiency of buildings at the domestic energy services stage (i.e. conversion factors); or providing alternative energy services to fulfil secondary capabilities. Research on energy justice using ABM by Assa and Lengfelder (2020) suggests that, while targeting *commodities* with policy interventions may improve (the distribution of) one capability, it may worsen that of another. On the other hand, targeting *conversion factors* resulted in better capabilities overall, and targeting *capabilities* directly lead to the best outcomes in both average and distribution of capabilities (Assa and Lengfelder 2020). To choose policy interventions that might reduce energy poverty in the context of switching to a novel heat network, we first look at potential targets based on the commodity-capability chain (Figure 12) and the different inequalities at the foundation of energy poverty (Figure 5). Since energy poverty policy is mostly made at the local or regional level in the Netherlands, we focus mostly on interventions that can be implemented by the municipality or provincial government.

We choose the following intervention targets. Firstly, based on inequalities in housing and technology efficiency that underlie energy poverty, we will consider interventions that target the conversion factor dwelling energy efficiency. Secondly, since inequalities in energy prices contribute to energy poverty, interventions that target the affordability of energy commodities (i.e. electricity, gas, heat). And lastly, we focus on the capability of thermal comfort directly, with interventions that reduce the level of energy services needed. In the following section, we discuss the available policy options.

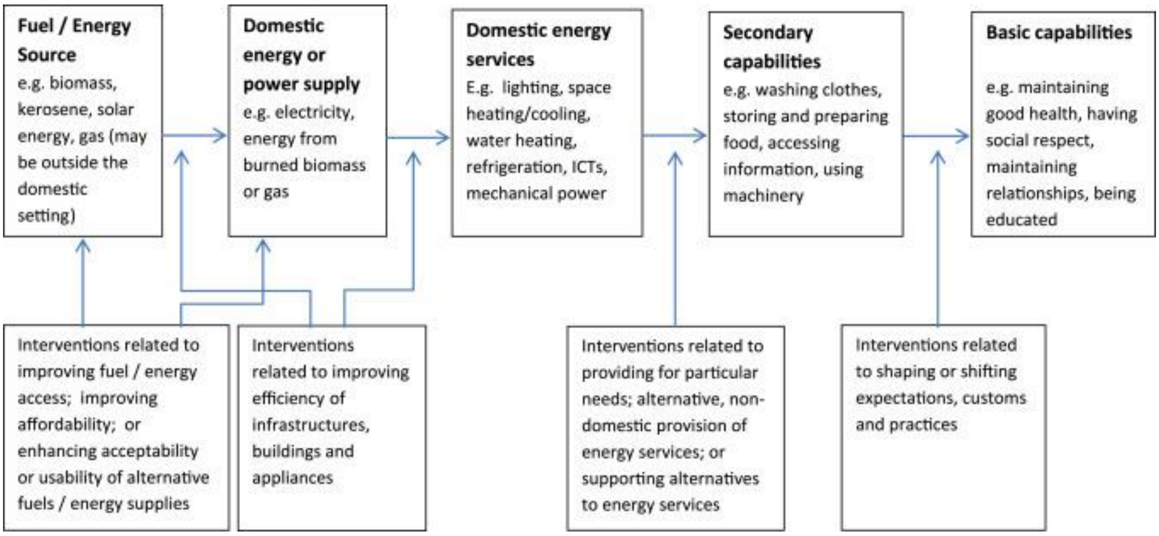


Figure 12. Positioning of interventions related to energy poverty alleviation in the commodity-capability chain. Image source: Day et al. (2016).

3.6.2 Policy intervention options

Interventions that target the affordability of energy commodities

We first consider interventions that target the commodities that are available and their price. High upfront investments costs and a lack of sufficient capital are main barriers in adopting energy efficient technologies (Pelenur and Cruickshank 2012; Schalkwijk 2020). Subsidies are the most often used intervention to target this barrier in ABM studies on the adoption of energy efficient technologies (Hesselink and Chappin 2019). Regulation and subsidies are interventions often used to target fuel prices in ABM studies on the adoption of energy efficient technologies (Hesselink and Chappin 2019). Van Berkel et al. (2021) list the following incentives through energy prices: 1) lowering energy tax for gas use up to 1000 m^3 and increased energy tax for gas use above 1000 m^3; 2) abolishing fixed fees (such as a standing charge per gas or heat network connection) and making these fees dependent on energy use. In an ABM exploring heating transition scenarios by Nava-Guerrero et al. (2022), full transitions occurred when natural gas tax was increased and there was a cap on the price of heat from networks. Another intervention that can be considered is offering alternative energy commodities, such as the implementation of a heat network to provide an alternative energy source to natural gas for space heating and warm tap water.

Interventions that target dwelling energy efficiency

The second type of interventions target individual conversion factors through the dwelling energy efficiency. A study by CE Delft on energy poverty in the heat transition lists the following *financial* policy options in this category (van Berkel et al. 2021): 1) a one-off subsidy for energy measures (pre-payment required); 2) a voucher system for insulation measures (assigned before taking these measures); 3) a building-bound renovation service provider that takes care of financing and executing efficiency measures striving for neutrality in living expenses (i.e. the monthly fee for this service is equal to the savings in energy costs); 4) a 'social loan system' where households repay loan according to financial capacity; 5) an energy saving mortgage, with repayment according to financial capacity; 6) subsidy for prioritising neighbourhoods with low energetic quality; 7) abolishing the landlord's tax for housing corporations, to allow them to invest in energy measures with neutrality in living expenses; and 8) public investments in heat network infrastructure to reduce investment costs for homeowners. Furthermore, van Berkel et al. (2021) list the following *regulatory* options: 9) mandatory standard for insulation, with costs partially covered by the government; 10) norms for banks that makes loans more attractive for more efficient buildings, incentivising homeowners to invest in energy saving measures; 11) mandatory energy efficiency for new heating installations; 12) making energy costs part of rents, to give an incentive for landlords to invest in energy saving measures.

In 2022 the Dutch government announced the National Insulation Programme (*Nationaal Isolatieprogramma*) with the goal to insulate 2.5 million dwellings by 2030 (Rijksoverheid 2022a). Proposed policy interventions include offering 0%-interest loans to support homeowners with a low income with making sustainability improvements and an 'energy saving mortgage' for homeowners with no loan capacity. First, the dwellings with poor energy efficiency should be improved to label B, which can save households €2000 to €4000 yearly in energy costs without increasing total housing costs and repay itself within 10 years (Faaij et al. 2022).

Interventions that target the ability to achieve thermal comfort

Lastly, we consider an intervention that targets the capability of achieving thermal comfort directly. The aim of these interventions is to increase households' ability to achieve thermal comfort. This does not necessarily need to take place by increasing energy consumption. For instance, increased thermal comfort can also be reached by educating people on efficient energy use or by different means than turning on a heater. Awareness campaigns – such as encouraging people to wear warm clothes, switching off appliances when not at home, and heating only the rooms that are being used – are a policy intervention aimed to reduce energy demand, and thus reduce the amount of energy services required to achieve the same level of thermal comfort (Assa and Lengfelder 2020). Energy coaches and displays for energy use management can also be used for this (van Berkel et al. 2021).

3.7 Conclusion

A knowledge gap exists in the energy justice and energy poverty research in the context of the heat transition. Few studies have focused on the local impacts of the switch to a new heating system, heat networks in particular, and on the differences in the effects on the access to affordable energy between household groups. We combine the capability approach, energy justice and energy poverty frameworks in an agent-based model of energy consuming households in a particular neighbourhood. The relevant frameworks, theories and policy interventions chosen to incorporate in the model are summarized in Table 9. The final description of model elements is given in the next chapter and the selection of policy interventions is done in Chapter 6.

Table 9. Summary of selected frameworks, theories and policy interventions used in this study.

Selected frameworks, theories, and policy interventions	Contribution to answering the research question
Frameworks	
Capability approach	We use this framework to examine the opportunities households have to fulfil their energy services requirements, to participate in the heating transition, and what interventions affect these opportunities. This broadens the scope of energy poverty and allows us to identify more concrete inequalities.
Energy justice	We use this framework to identify and address the unequal distribution of energy benefits and burdens between different groups of households as a result of a new heat network.
Energy poverty	We use this framework to measure the prevalence and severity of energy poverty before and after the implementation of the heat network and to examine policies that aim to reduce energy poverty.
Energy decision-making	
Energy consumption factors	Individual differences in energy consumption depend on individual characteristics such as pro-environmental attitude, energy use awareness and building energy efficiency, which may produce or influence inequalities.
Consumat framework (theory of consumer behaviour)	We use elements from this framework to represent the different methods households use to make energy system decisions, depending on their circumstances. The differences in decision-making strategies that households use may influence inequalities.
Heating system choice factors	Households mainly consider costs in their decision to switch to a heat network. Increasing income levels lead to increased investments.
Interventions to reduce energy poverty and inequalities	
Increasing affordability of energy commodities	Increasing the affordability of energy commodities targets the energy quote of households and increases access to affordable energy.
Increasing dwelling energy efficiency	By increasing dwelling energy efficiency, households need less energy to fulfil their demands and thus are less at risk of energy poverty. This also increases sustainability of the energy system.
Increasing the ability to achieve thermal comfort	By targeting households' ability to achieve thermal comfort directly, the intervention focuses on expanding their opportunities to achieve adequate energy services.

Chapter 4.
Model development

Synopsis
The goal of this chapter is to describe outcomes of the modelling process, the conceptual model and formalized agent-based model. The chapter explores the second research question:

> In an agent-based model of a specific neighbourhood in Delft, how can the switch to a novel heat network be represented and the effect on energy poverty and inclusivity be explored?

Modelling objectives

The **purpose** of the ABM is to explore inequalities in energy poverty and accessibility to clean and affordable energy of households as a result of the switch to a heat network in specific neighbourhoods in Delft.

Model conceptualisation and formalisation

The model consists of two types of **agents**:

- Buildings have properties such as number of households, year of construction, building ownership and type of energy system.
- Households have properties such as dwelling category, floorspace, energy label, household type, income, energy use environmental attitude, and susceptibility.

The agents follow these **rules**:

- Households consume energy based on the energy label, dwelling category, floorspace, household type, environmental attitude, and awareness.
- Heat network is implemented for corporation multi-family buildings first. Later, homeowners can connect.
- Homeowners adopt one of four decision-making strategies to decide whether to switch to the heat network, depending on their certainty and satisfaction: repetition, deliberation, imitation, or social comparison

The model **environment** represents:

- A specific geo-spatially explicit neighbourhood
- The available energy systems
- The prices of energy
- The implementation of policy interventions
- The available financial options

The model uses the following inputs: GIS building and address data; data on energy demand, renovation costs, and rent increase per energy label; figures on household ownership, composition, and income; and economic parameters. This data is used to set up buildings and households and assign state variables. During the model run, various scenarios for heat network implementation and policy interventions are implemented. The model output is a spatially explicit representation of GIS and socio-economic data, the distribution and extent of energy poverty among various groups, and the distribution of heat network connections.

4.1 Modelling objectives & requirements

Based on the aims of this thesis to reduce inequalities in energy poverty and energy system access caused by the implementation of a heat network, we define the following purpose and design requirements for the model. The purpose of the ABM is to explore inequalities in energy poverty and accessibility to clean and affordable energy of households as a result of the switch to a heat network in specific neighbourhoods in Delft. Policy makers and industry professionals can use the results to design more just energy systems and energy policy. Based on the aims of this thesis, the following model requirements can be stated (Table 10).

Table 10. Model design requirements.

Research aim	Corresponding design requirement
Build an agent-based model that can represent socio-economic qualities of households in a specific neighbourhood in the context of heating .	Inclusion of household characteristics such as income, homeownership, household type, dwelling type, dwelling energy efficiency; Inclusion of heterogeneity in household characteristics; Representation of specific neighbourhoods; Representation of current heating systems, a heat network, and their characteristics.
Explore inequalities in energy poverty and inclusivity that might arise from the switch to a heat network and in which scenarios and for what types of households these inequalities .	Inclusion of indicators that measure occurrence and severity of energy poverty and heat network access. Ability to represent inequalities between households as an emergent property; Inclusion of different scenarios of heat network implementation.
Determine policy interventions that contribute to a just and inclusive heat network.	Ability to represent the implementation of policy interventions that target affordability of energy, dwelling energy efficiency, and factors that influence thermal comfort; Ability to alter these parameters; Inclusion of different scenarios of heat network implementation and policy interventions.

To direct modelling efforts, the following modelling questions were posed:

- Energy poverty
  - What is the effect of the novel heat network on the extent and distribution of energy poverty?
  - What policy and design measures decrease inequality in energy poverty?
- Inclusivity
  - Do certain types of households have unequal access to a heat network connection compared to others?
  - What policy and design measures decrease inequality in heat network access?

4.2 Model conceptualisation

The agent-based model is based on the assumption that the micro-level behavioural choices of households influence the implementation of the heating system and the distribution inequalities at macro-level. Emergent patterns, such as the diffusion of the heat network and the occurrence of inequalities in energy poverty and heat network access, are assumed to be a result of decision rules followed by the different households. The model consists of agents, rules governing the agents' decision-making, and an environment represented by parameters for neighbourhood characteristics, energy system properties, energy prices, financial instruments policy interventions (Figure 13). In the next section, we describe the conceptualisation of agents, followed by the model rules, and the model environment. The detailed formal model specification is described using the ODD+D protocol in the Appendix.

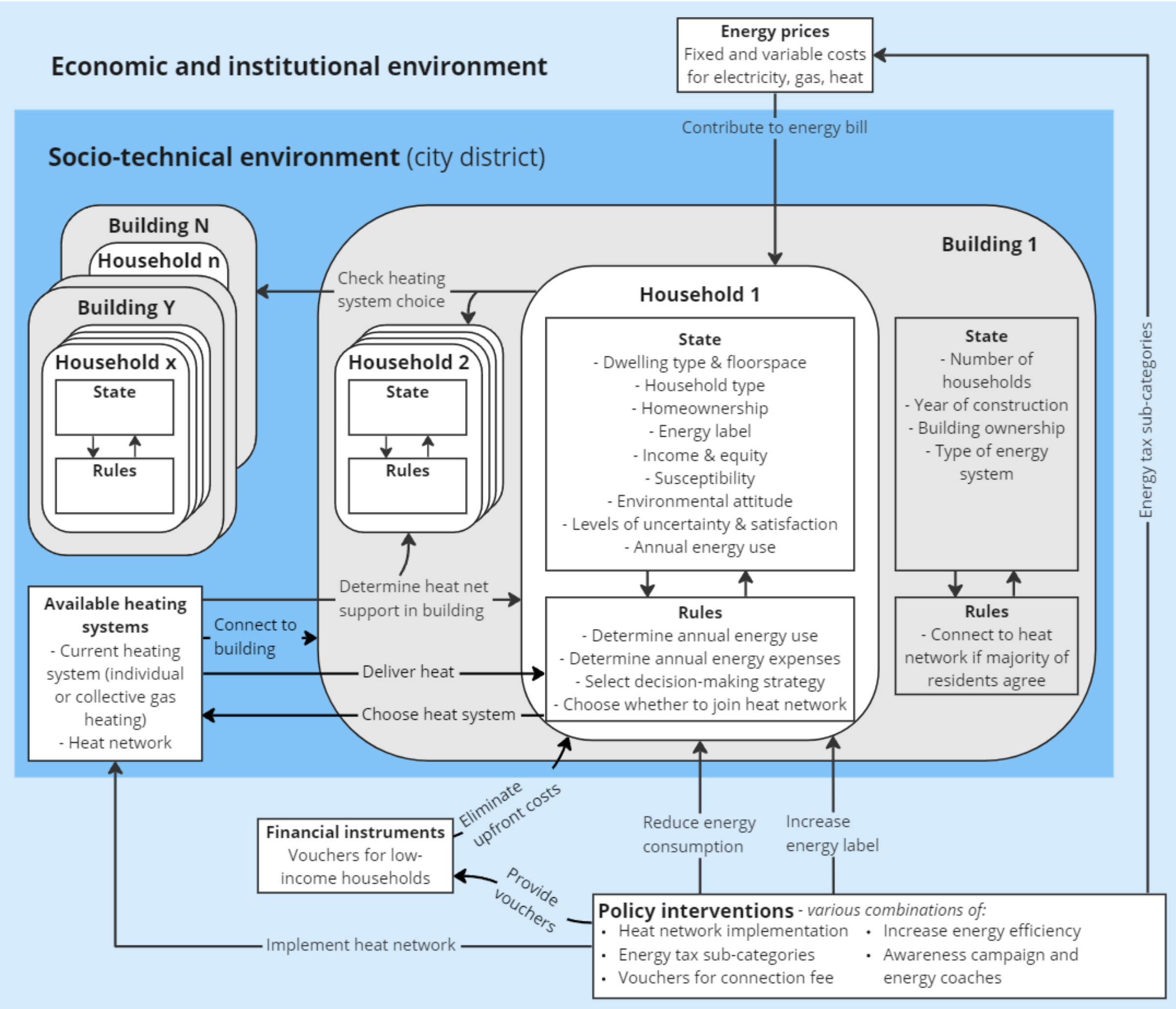


Figure 13. Schematic representation of the agent-based model design.

4.2.1 Agents

The model's agents represent households occupying a single dwelling. The dwelling can be a single-family building or part of a building with multiple dwellings. The buildings are separate agent types and have properties such as number of households, year of construction, building ownership, heating system type, and total floor area. Households are characterized by factors such as household type, dwelling type, floorspace, homeownership, income, environmental attitude, susceptibility to awareness campaigns, functional energy demand, energy consumption, levels of uncertainty and satisfaction, and energy poverty indicators.

4.2.2 Rules

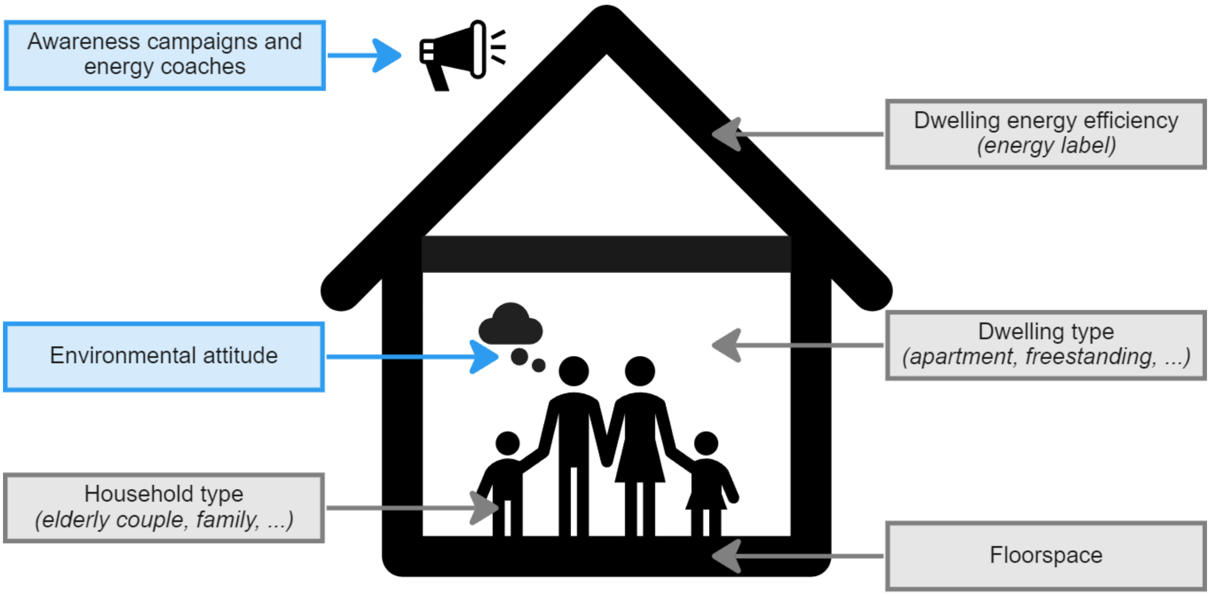


Figure 14. Factors determining a household's expected functional energy demand (grey) and actual energy use (blue and grey) in the model. The factors in blue represent factors that influence the behaviour of the household in an energy context and thereby determine the actual energy use.

The model takes a bottom-up approach to explore the emergence of energy poverty. Households consume energy for heating and electricity. The expected annual functional energy demand for a household's situation is determined based on their dwelling type, energy label, floorspace and household type, and their actual annual meter energy consumption is determined based on environmental attitudes and awareness and the efficiency of the heating system (Figure 14). For example, an elderly couple will have a higher energy demand than a young couple; a family reached by an energy awareness campaign might reduce their energy consumption; and a household with no concern for the environment will consume more than average. Based on the household's energy consumption, their annual energy expenses are determined according to the energy system of their home and corresponding energy costs. Based on these expenses and household characteristics such as income, energy label and homeownership, energy poverty indicators are determined.

In scenarios in which a heat network is implemented, eligible households that are homeowners can decide on whether they would like to switch from their current heating system to the heat network. A simplified version of the Consumat framework (Jager 2000; Jager and Janssen 2012) is used to represent household decision-making. Households employ different decision-making strategies depending on their level of needs satisfaction and uncertainty: repetition, imitation, deliberation, or social comparison. In the context of household energy use, we conceptualise need satisfaction as follows. The need we consider in our model is the ability to heat one's home sufficiently as part of Nussbaum's (2003) central capability *Bodily Health & Integrity*. This need would be part of the need *subsistence* in the list of fundamental needs of Max-Neef (1992). We consider that this need is not satisfied if the household is experiencing energy poverty unwillingly, i.e. LIHC, LILEQ, or oLEQ (a high energy quote might be caused by a deliberately high energy consumption). This way, we integrate the framework of Jager based on Max-Neef with the concepts of energy poverty and the capability approach.

Table 11. Decision-making strategy options for the choice to switch to the heat network, based on the Consumat framework (Jager 2000).

	Satisfied	**Not satisfied**
Certain	*Repetition*: keep the current heating system	*Deliberation*: when the household can afford it, switch to the heat network (assuming that this is advantageous in total energy costs)
Uncertain	*Imitation*: choose the heating system that most neighbours have	*Social comparison*: choose the heating system that most comparable households have

We conceptualise uncertainty differently from Jager, who formalises uncertainty as the difference between a consumer's expected outcomes and actual outcomes of behaviour. Certainty concerns the availability and need-satisfying capacity of opportunities. For opportunities that involve a large number of needs, it is more difficult to obtain information on the capacity to fulfil each need. Also, the lower the cognitive ability of a consumer, the lower their level of certainty (Jager 2000). Since heat networks are a novel technology that is not well-known (Schalkwijk 2020), we assume that a consumer's certainty about the option is influenced by their level of knowledge and attitude towards sustainability. Here, we assume that if one's knowledge about sustainability is high, they also are more certain about the option to switch to a heat network. Furthermore, we assume that the policy option of awareness campaigns and energy coaches increases the level of certainty. Methodological reasons, i.e. keeping the model simple, are the main reason for this simplification, since the purpose of the model is not to investigate the effects of household decision-making, but to investigate the effects of heat network implementation on inequality.

Renters do not have the influence to take this decision: multi-family corporation buildings are connected first in each scenario, as has been decided by the housing corporations. After this group is connected, private owners in multi-family buildings will have the choice to connect to the heat network. If more than 50% of households in the building agree, the building will be connected to the heat network. After this, single-family buildings of corporations and individuals who choose to connect will be connected.

4.2.3 Environment

The model environment in which the agents act represents the implementation of the heat network, the implementation of policy interventions, the energy prices, and the available financial options for households. The agents are distributed in a geo-spatially explicit way corresponding to the characteristics of a specific neighbourhood that is represented in the model.

Heat network implementation

In the heat network implementation scenarios, the heat network is implemented in the following dwelling order: 1) corporation multi-family buildings with collective heating systems; 2) privately-owned multi-family buildings with collective heating systems; 3) single-family buildings. Multi-family buildings with individual heating systems are not connected to the heat network in the model. A variation of this scenario, where only corporation multi-family buildings with collective heating systems are connected, is also examined. When a building is connected to the heat network, its state variables representing the energy system are modified. The variables representing the heating system of the households in this dwelling, also those in multi-family buildings with collective heating systems that did not choose to connect to the heat network, are updated accordingly.

Policy intervention implementation

Policy interventions are represented as specific parametrizations of environment variables such as energy costs, heat network connection costs, and energy consumption modifiers. In addition, the implementation of policy interventions may cause modifications of agent states, such as dwelling energy labels. The chosen policy interventions are described in Chapter 6.

4.3 Model formalisation and implementation

Table 34 in Appendix C. shows the description of the formalisation and implementation of the agent-based model using the Overview, Design Concepts, Details + Decisions (ODD+D) protocol developed by Müller et al. (2013). ODD+D is an expansion of the ODD protocol, which aimed to establish a complete, transparent and easy to understand standard for describing ABMs (Grimm et al. 2006). In this section, we will elaborate on the most important model details. For a full model description following the ODD+D elements, see Appendix C.

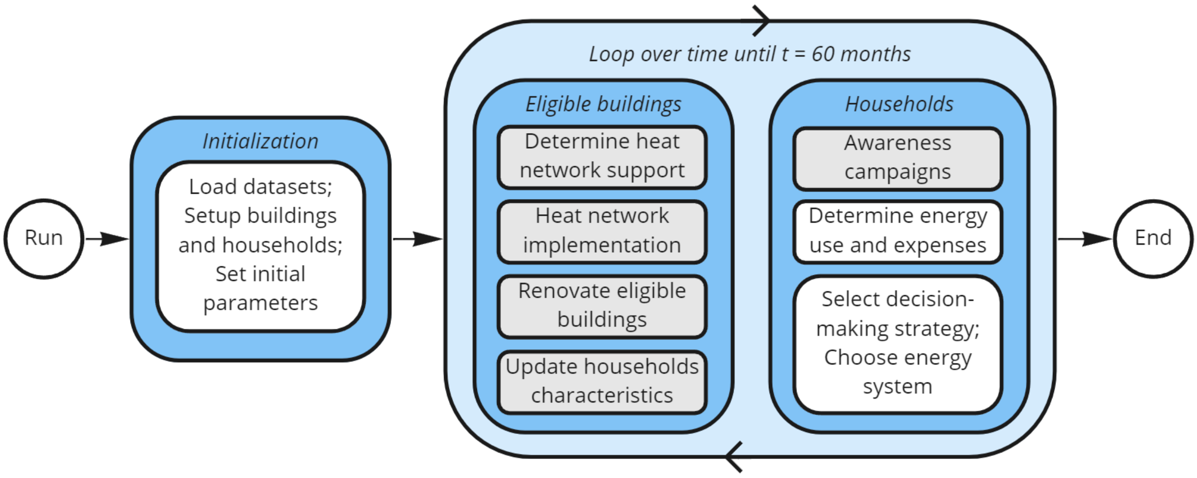


Figure 15. Flowchart of model processes. Processes in white occur for in all scenarios, processes in grey only occur in specific scenarios following the scenario rules and timings.

An overview of the model processes is shown in the flowchart of Figure 15. During model initialisation, input datasets are loaded. The data input used in the model, the model processing and model output are shown in Figure 16. At the end of the model run, the distribution and extent of energy poverty is assessed using key performance indicators. Energy poverty indicators are measured using the definitions shown in Table 12.

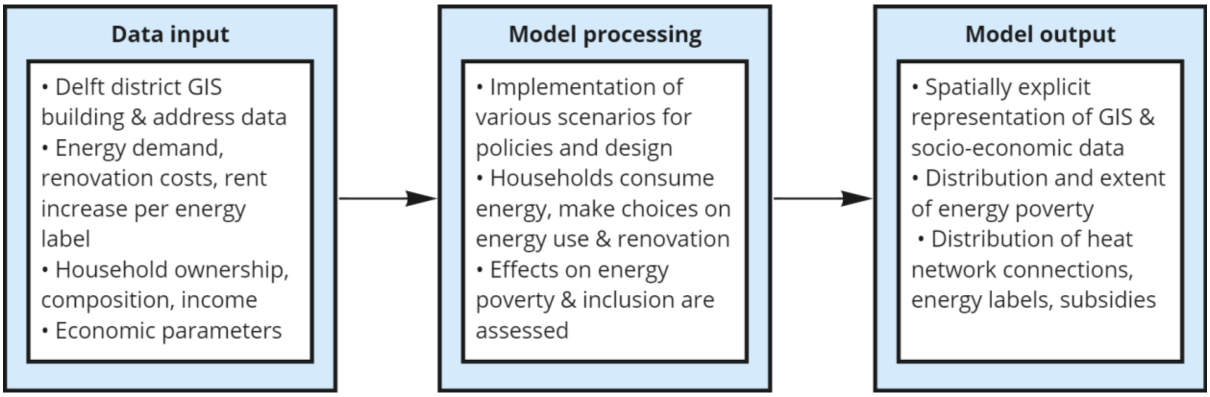


Figure 16. Model inputs, processing, and outputs.

Table 12. Energy poverty indicators and definitions used in this study.

Indicator component	Definition
High Energy Quote (HEQ)	Energy expenses are higher than 10% of spendable household income.
Low Income (LI)	Income is lower than 130% of the social minimum.
High energy Costs (HC)	Energy expenses are higher than the average at the start of the model.
Low Energetic Quality (LEQ)	Energy label is D, E, F or G.
Owners unable to renovate (oLEQ)	LEQ homeowners with less than €40000 equity or LI.
Renters unable to renovate (rLEQ)	Any renter of a house with LEQ.

Chapter 5.
Model evaluation and validation

Synopsis

In this chapter the process and results of evaluating the agent-based model are described. The chapter structure follows the steps of the Evaludation method for model evaluation by Augusiak et al. (2014): data evaluation, conceptual model evaluation, implementation verification, model output verification, model analysis and model output corroboration.

Data evaluation involved assessing the quality of data used for developing and testing the model. This was done by compiling a list and description of all data sources used in the model and assessing the quality of this data.

Conceptual model evaluation was done to assess the logical consistency of the structure, theories, concepts, assumptions, and causal relationships underlying the model design. This was done through consulting and comparing similar ABM studies, doing interviews with domain experts, and testing alternative conceptual designs.

Implementation verification involved assessing whether the implemented model performed as intended. This was done by performing code walkthroughs, single-agent testing, interaction testing and multi-agent testing.

Model output verification was done by comparing model output to observation data. This was done to evaluate model performance and realism.

Model analysis involved exploring the model's sensitivity to changes in parameters and process formulations. The effects of price levels, varying energy tax levels, heterogeneity in household decision-making and implementing the model with different neighbourhoods and scales were examined. In addition, variations of conceptualisations for the household energy use were evaluated.

Model output corroboration was done by comparing model output to new data and patterns that were not used for model development.

5.1 Data evaluation

The quality of data used for developing and assessing the model was assessed by compiling a list and description of all data sources used for the model parameters and assessing the quality of the data. See Table 39 in Appendix E.1 Data evaluation for the description and full evaluation of the data sources used. Based on this evaluation, we deem the quality of the available data sufficient to be used for the purpose of the model.

5.2 Conceptual model evaluation

The conceptual model evaluation step involves assessing "the simplifying assumptions underlying a model's design and forming it's building blocks" and checking the logical consistency of "the structure, essential theories, concepts, assumptions and causal relationships" that form the model (Augusiak et al. 2014). There are no specific testing strategies available for this. Augusiak et al. recommend evaluating multiple alternative conceptual models for key processes or behaviours in de model and consulting domain experts. The model's conceptual design was evaluated during the iterative steps of the modelling process and several conceptualisations for decision-making and energy use were assessed.

Three methods were used to ensure a logically consistent model. Firstly, during the conceptual model development, similar ABM studies were compared and an overview of key model features and decision-making processes used was made (see also section 3.2.1). Models focusing on heating systems and household energy decision-making were selected for this. From these, key features and decision-making models deemed relevant for the context of heat networks and energy poverty were selected (see also section 3.3). Secondly, the conceptual model and key model assumptions were discussed with experts. And lastly, alternative conceptual designs were implemented and evaluated.

A late version of the conceptual model and key model assumptions were evaluated using semi-structured interviews with relevant experts. The interviews were done with experts from the academic, public and industry sectors. A list of respondents and the interview questions are shown in Appendix D. Mock interviews were done with peers before the actual interviews to improve the questions and explanation of elements of the study. The purpose of the interviews was to evaluate model assumptions on heat network implementation, household energy decision-making and policy intervention options. Furthermore, the energy poverty indicators used and the usefulness of the expected model outcomes for the respondent's work were discussed. A print-out with explanations of key model elements was used during the interviews as an aid during the discussion of these elements. The one-on-one interviews were performed online or in-person and lasted one hour.

A description of key model features and assumptions underlying the model's design that were discussed during the expert interviews and the feedback given by the experts is given in Table 38 in Appendix D. Based on the feedback, some of the discussed assumptions were changed in the final model:

- A scenario was added where only housing corporation buildings are connected, not private homeowners;
- Campaigns do not reach every person: there is a 50% chance of failing to reach the person, and variable effect;
- Heat network connection fee for apartments was reduced from 8000 to 6000 euro;
- Income was removed as a factor that affected energy use.

Finally, to evaluate the conceptual model, alternative conceptualisations of the capability approach, heat network implementation, and household choices available were implemented and tested in various phases of model development by inspection of model results, agent states and behaviour, and discussions with members of the supervision team (intermediate results not shown). In addition, variations of conceptualisations for the household energy use determination and for the choice to switch to the heat network were assessed. This was done in the model analysis phase (see section 5.5 Model analysis).

5.3 Implementation verification

Implementation verification involves assessing whether the implemented model is free of programming errors and whether the model performs as intended (Augusiak et al. 2014). To verify the model implementation, single-agent testing, interaction testing and multi-agent testing (Nikolic and Ghorbani 2011) were performed, along with walkthroughs of the code to check for errors, ensure unit consistency and correct conversion between units, and assess whether the code and model descriptions matched. Furthermore, consistent use of comments in the code made sure that the code was more understandable and that units, functions and variable meanings were clear.

With single-agent testing, the behaviour of a single household is verified using normal operating inputs and extreme value inputs. NetLogo allows for the inspection of each agent, and testing various inputs using the BehaviorSpace tool. If the agent behaves as expected under these conditions, the test is passed. In this step, the proper assignment of household variables, such as (proxy) energy labels, income, dwelling characteristics, household type, and ownership were checked, as well as calculation of energy consumption and expenses over time and the behaviour of household decision-making. See Appendix E. for single-agent testing results. Some households had extremely high energy use due to having a remarkably high floorspace. This was due to floorspace being calculated using BAG floorspace data, but in cases where buildings had other uses, e.g. shops or offices, this value was too high. Consequently, a correction is put in place for households with a floorspace of over 300 m^2, which are set to 300 m^2.

In the interaction testing step, interactions between buildings and households (e.g. proper assignment of building characteristics and updating the household's variables when the building is connected to the heat network) and among households (e.g. social comparison when determining whether to switch to the heat network) were tested in a minimal model. This step confirmed that these interactions happen correctly.

With multi-agent testing emergent behaviour of multiple agents is studied and outcomes are inspected. In Nikolic and Ghorbani (2011), exploring the variability of model outcomes is also part of multi-agent testing. Following the Evaludation method, we do this in Evaludation step 5 (Model analysis). Within the NetLogo interface, plots and monitors were used to inspect (intermediate) agent states, aggregated agent variables and emergent outcomes. Inspected variables include household and dwelling characteristics, income distribution, energy demand and energy use levels for each end-use (i.e. space heating, warm tap water, electric appliances, and cooling) and split for multiple types of groups (e.g. energy use for each energy label), energy expenses, decision-making strategies adopted, heat network connections, and energy poverty levels. The model was tested at two spatial scales: a selection of neighbourhoods ('*buurten*': Multatulibuurt, Roland Holstbuurt, Gillisbuurt, Buitenhof Noord, Het Rode Dorp) and districts ('*wijken*': Voorhof, Buitenhof). A selection of results from the implementation verification phase are given in Appendix E.

5.4 Model output verification

The next step to validate the model is to compare model output of experiments to observation data (Augusiak et al. 2014). The model can be considered valid of the model outcomes correspond with observed reality (Nikolic and Ghorbani 2011). The following modelling outcomes were compared with empirical data:

- Average income
- Homeownership
- Heat and electricity consumption
- Heat and electricity expenses

The implementation of interventions was not verified with empirical data, since such data does not exist and one cannot make the same changes in the real world to test the effects on the future state of the world (Nikolic and Ghorbani 2011). See Appendix E. Evaludation results for the results of this step.

5.5 Model analysis

During model analysis, the model's sensitivity to variations in parameters and changes in process formulations are explored (Augusiak et al. 2014). We explored the effect of changes in the following parameters individually, while keeping the rest of the model unchanged:

- Energy price levels;
- Energy tax levels;
- Different neighbourhoods and scales.

In addition, variations of conceptualisations for determining the energy use and modelling energy system decision-making were tested. Three methods of determining energy use were compared:

- Environmental attitude and awareness campaigns moderate expected functional demand (according to conceptual model);
- Income, environmental attitude, and awareness campaigns moderate expected functional demand;
- Energy use is equal to functional energy demand.

Three conceptualisations for the heat network decision-making method by households were tested:

- Adapted Consumat framework: households employ different decision-making strategies depending on satisfaction and certainty (according to conceptual model);
- All households connect if they can afford it;
- Households choose randomly whether to connect or not (coin flip).

The results of these analyses can be found in Appendix E.4 Model analysis.

5.6 Model output corroboration

In model output corroboration, model results are compared to new data that was not used for the development or parametrisation of the model (Augusiak et al. 2014). For this, we compared the extent and distribution of energy poverty produced by the model to real-world data on energy poverty (See Appendix E.5 Model output corroboration). The model overestimates the share of LIHC households, likely due to the different definitions used in the model versus the definition used by CBS. Since the purpose of the model is to compare energy poverty levels before and after the implementation of a heat network, the focus will be on the relative difference rather than the absolute difference. So, this high estimation of LIHC will not lead to different conclusions. The share of HEQ and LILEQ households are comparable to observed levels. We also compared the distribution of income groups, household types and renters-homeowners among HEQ households. The model produces realistic distributions of these socio-economic groups among households with energy poverty.

Chapter 6.

Experimental design and results

Synopsis

In this chapter, the experimental design of the agent-based model is described, followed by the results of the model experiments.

Experimental design

To explore the effect of policy and design conditions of the heat network on energy poverty, combinations of the following interventions are examined across multiple scenarios:

- Implementation of the heat network;
- Lower energy tax for gas use up to 1000 m^3 and increased energy tax above 1000 m^3;
- Vouchers to cover costs of heat network connection for low-income homeowners;
- Renovation of dwellings with labels G, F, E, D to label B;
- Awareness campaigns and energy coaches that reduce energy use of affected households.

Results

We present the results for the chosen scenarios, and compare outcomes for different energy price levels. Results include: the spatial distribution of HEQ households; the extent of energy poverty measured using the HEQ, LIHC and LILEQ indicators, both in general and per income group; the energy expense per energy label group and ownership group over time during a scenario run; the energy quote per income group over time during a scenario run; Gini coefficients of energy expenses; and distribution of household groups connected to the heat network. These are the key findings:

Inequalities in energy poverty and accessibility as a result of heat network implementation:

- Within districts, high inequality occurs in the distribution of energy poverty.
- When gas prices are low, switching to a heat network increases energy poverty.
- Renters and low-income groups are affected most in changes in energy expenses.
- The distribution of income groups or household types among energy-poor groups is unaffected.
- Low-income households are affected most by high heat network prices.
- High heat network prices increase inequality in energy expenses.

The effect of policy interventions on energy poverty and inequality:

- Building renovations are most effective in decreasing energy use and energy poverty.
- Vouchers increase accessibility of the heat network.
- Awareness and energy efficiency interventions reduce the fraction of HEQ households in all income groups except the lowest, when energy prices are high.
- Tested interventions did not reduce energy poverty inequalities between household composition groups.
- Building renovation decreases inequality in energy expenses, other measures do not.
- Low-income renters have good heat network access; vouchers increase access for homeowners.

6.1 Experimental design

This section described the dependent variables that the model is measuring, the independent parameters that are varied, the scenarios that are assessed and the setup of model runs and parameter sweeps.

6.1.1 Dependent and independent variables

To explore governance and design conditions of the heat network on energy poverty, the independent variables shown in Table 13 are varied in multiple scenarios. The table also shows the dependent variables that are compared between different socio-economic groups, and household types across scenarios. The various metrics for energy poverty discussed in section 3.1.3 are adopted to assess the effect of taking a different energy poverty definition on the result. By assessing varying conceptualisations of energy poverty across different socio-economic groups, a better view on energy poverty can be obtained compared to using a single indicator (Mulder et al. 2021b).

Table 13. Description of independent and dependent variables.

Variable	Description
Independent variables	
Heating system	Next to the baseline scenario (keep the natural gas heating system), two variants of heat network implementation are assessed.
Energy costs	Fixed and variable energy costs depend on the heating system. In addition, a scenario with an adapted energy tax policy is explored.
Building energy efficiency	A scenario is considered where the energy efficiency of buildings with poor energy labels are improved, to be financed with a monthly fee.
Financing of energy measures	A scenario is considered where vouchers are available for low-income households to cover upfront connection costs of the heat network.
Awareness of energy use	A scenario is considered where a campaign for energy consumption awareness and energy coaches variably reduces the energy consumption of households.
Dependent variables	
Mean energy use	Average meter energy consumption of households.
Mean energy quote	Average share of household income spent on energy expenses.
Energy poverty HEQ LIHC LILEQ oLEQ, rLEQ	See section 3.1.3 for the definition of each energy poverty indicator. Measuring energy poverty in different ways allows us to examine different dimensions of energy poverty.
Fraction connected to heat network	Fraction of households of the specified group connected to the heat network.
Characteristics of groups with energy poverty Household type Mean income Homeownership	For each group of energy-poor households, the household type, income, and ownership fraction are determined.

6.1.2 Runs over time

The model is run for five years (60 time steps). Each scenario is repeated ten times.

6.1.3 Scenario design

Selection of policy interventions

We selected policy interventions (Table 14) from the options described in Chapter 3. The selection is based on the positioning of the intervention in the chain from energy production to capability fulfilment, making sure that different positionings are examined. We consider three interventions that directly target either the availability or the costs of energy *commodities*: 1) implementation of a heat network as alternative energy source; 2) creating an extra energy tax sub-category, to lower energy tax for gas use of to 1000 m^3 and increase energy tax for gas use above 1000 m^3; and 3) vouchers for low-income homeowners (up to 130% of social minimum) to cover the upfront costs of the heat network connection. The chosen intervention to target the *conversion factor* energy efficiency is to improve energy labels of households with poor energy efficiency (with labels G, F, E, D) to label B. To directly target the *capability* of thermal comfort, we examine an awareness campaign as an intervention. In the next paragraph we will describe each intervention and its implementation in the model.

Table 14. Selected policy interventions.

Aim and positioning	Intervention	Target group	Number of households in target group
Providing affordable and sustainable energy commodities	Implementation of heat network.	1) Corporation multi-family buildings, or 2) All buildings[3] in specified order	Buitenhof: 7367 Voorhof: 8568
	Lower energy tax for gas use of to 1000 m^3 and increased energy tax for gas use above 1000 m^3.	All households	Buitenhof: 7367 Voorhof: 8568
	Vouchers to cover upfront costs of heat network connection.	Low-income homeowners	Buitenhof: 2028 Voorhof: 2152
Increasing energy efficiency conversion factor	Renovation to label B, service provider, monthly fee equal to renovation costs paid over 10 years.	Homeowners with labels G, F, E, D	Buitenhof: 623 Voorhof: 2567
	Renovation to label B, abolishing landlord's tax, allowed rent increase from energy label improvement.	Corporation dwellings with label G, F, E, D	Buitenhof: 3033 Voorhof: 2300
Fulfilling thermal comfort capability with alternative means or less energy	Awareness campaigns, energy coaches and displays reduce energy use by up to 15%, depending on a household's susceptibility.	All households	Buitenhof: 7367 Voorhof: 8568

Intervention 1: Implementation of heat network (Corp/All)

Two options for the heat network implementation are tested:

1. Only corporation-owned multi-family buildings (*Corp*);
2. First multi-family corporation buildings with collective heating systems, then private multi-family buildings with collective heating systems, then single-family buildings with individual heating systems (*All*).

Multi-family buildings with individual heating systems are not connected to the heat network in our scenarios. Connecting such a building to the heat network would require changing every dwelling's heating system, which involves a decision-making process where a certain majority of residents must agree. This process involves decision-making at various levels: the household level and the housing corporation or homeowner association level. Simulating such a multi-level decision-making process is outside the scope of this study.

[3] Not all buildings will be connected, see scenario description.

The target group of this intervention is renters of corporation multi-family buildings and optionally all other buildings.

*Intervention 2: Energy tax sub-categories (*Tax*)*

Lower energy tax for gas use of to 1000 m^3 and increased energy tax for gas use above 1000 m^3. All gas consumed until 1000 m^3 has a reduction in energy tax of €0.05 per m^3, gas consumed above this threshold has an increase in energy tax by €0.10 per m^3. The target group of this intervention is all households.

*Intervention 3: Vouchers for low-income households to cover connection fee (*Vou*)*

Homeowners need to pay a fee to connect to the heat network. In this scenario, vouchers are given to low-income homeowners to cover the upfront costs of the heat network connection. These homeowners thus do not need to pay a connection fee. The target group of this intervention is low-income homeowners.

*Intervention 4: Increasing energy efficiency of dwellings with energy labels G-D (*Eff*)*

In this scenario, dwellings are renovated to improve their energy label to label B. This is done starting the worst energy labels, G in the first year, F in the second, E in the third and D in the fourth year of the model run. For homeowners, the renovation is financed via a building-bound renovation service provider with a monthly fee equal to the renovation costs divided over a period of 10 years for homeowners. For corporation buildings, renovations are financed by abolishing the landlord's tax for housing corporations so they invest in renovations, where they can increase rents according to the government's rules for rent (*Uitvoeringsregeling huurprijzen woonruimte*) (Rijksoverheid 2021a). The target group of this intervention is homeowners and renters with label G, F, E or D.

*Intervention 5: Awareness campaign and energy coaches (*Awa*)*

In this scenario, we assume that a combination of interventions such as awareness campaigns, energy coaches and displays reduce each household's energy use by up to 15%, depending on the individual conversion factors of households. These interventions enable households to reach the same level of thermal comfort using other means than turning up the heating, such as wearing a warm sweater, placing draft strips and heating occupied rooms only. The intervention is implemented starting after 12 months. The effect of the awareness campaign on households is determined by the household's susceptibility. The target group of this intervention is all households.

Scenarios

Table 15. Scenarios representing combinations of policy interventions.

Scenario	*Baseline*	*Corp/All*	*Awa-Tax*	*Awa-Vou*	*Awa-Tax-Vou*	*Eff-Tax*	*Eff-Vou*	*Eff-Tax-Vou*
Heating system	Natural gas	Heat network, for selected buildings according to a specific sequence (*Corp*/*All*) and homeowner choice						
Interventions - financial	None	None	Energy tax sub-categories (*Tax*)	Vouchers for low-income homeowners for heat connection fee (*Vou*)	Energy tax sub-categories (*Tax*); Vouchers for low-income homeowners for heat connection fee (*Vou*)	Energy tax sub-categories (*Tax*)	Vouchers for low-income homeowners for heat connection fee (*Vou*)	Energy tax sub-categories (*Tax*); Vouchers for low-income homeowners for heat connection fee (*Vou*)
Interventions - other	None	None	Awareness campaigns targeting thermal comfort (*Awa*)			Energy efficiency improvement for dwellings with label G-D (*Eff*)		

Table 16. Baseline scenario specifications.

Scenario name	**Baseline**
Neighbourhood	Voorhof
Heat network implementation	None
Interventions - financial	None
Interventions - other	None
Decision-making model	Simplified model of consumer behaviour
Factors influencing energy consumption	Baseline (environmental awareness and campaign modify typical energy demand)
Energy prices	2023 prices
Heat network costs relative to maximum	92% (note no heat network implemented in this scenario)
Gas tax reduction – low consumption	0
Gas tax increase – high consumption	0
Maximum savings due to awareness campaign	*15% (note no awareness campaign implemented in this scenario)*
Include extra costs of rent increase	*False. Currently, these costs are determined by the model, but the total housing costs were not assessed in this thesis report.*

6.2 Results

In this section, the model results will be presented to answer the following research questions:

3. *What inequalities in energy poverty and accessibility to sustainable energy might arise as a result of the heat network?*
4. *What policy interventions lead to reduced inequalities and an accessible heat network?*

First, results of the baseline model, with no heat network implementation, will be shown. Then, model results of heat network implementation scenarios, with no additional financial or other interventions, are shown. Lastly, the results of various scenarios for financial and other interventions are described.

6.2.1 Baseline results, no heat network

Within districts, high inequality occurs in the distribution of energy poverty

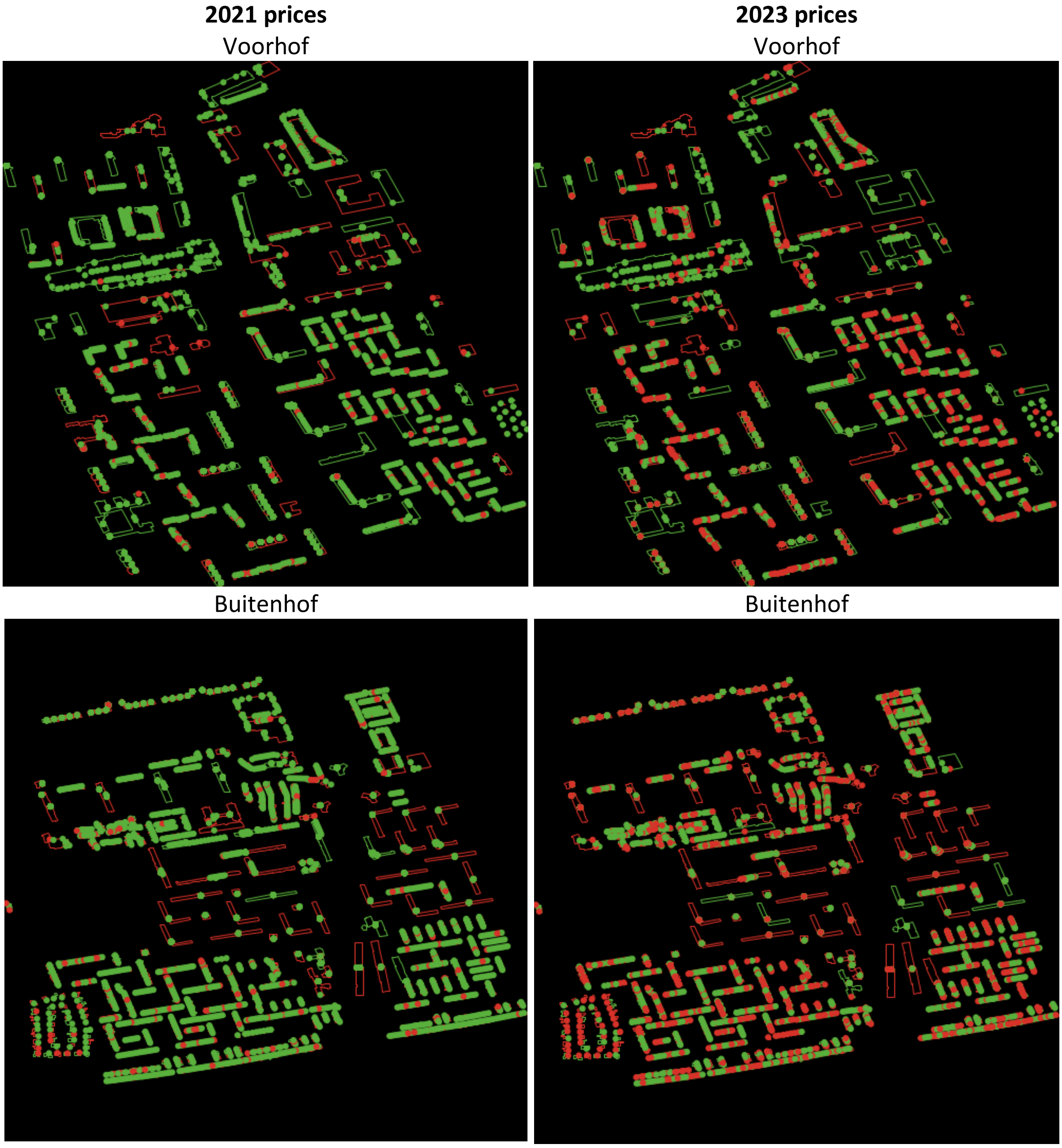


Figure 17. Households with high energy quote (HEQ) at the end of model run, Voorhof and Buitenhof, 2021 and 2023 energy prices. Building colour: green, private ownership; red, corporation ownership. Dwelling colour: green, no HEQ; red, HEQ.

First, we present the results of the baseline model runs: no heat network implementation and no interventions. The results of the scenarios will be compared against the baseline results in the next section. Figure 17 shows the model view at the end of two baseline model runs for Voorhof with energy price levels of 2021 and 2023[4], respectively. Additional results for Voorhof and Buitenhof are shown in Table 44 in Appendix F. With 2023 prices, a much greater number of households have a HEQ

[4] Note that since this thesis was completed in January 2023, the 2023 prices are not based actual prices, but on the regulated energy price ceilings in January 2023, which we refer to as ‘2023 prices’.

than with 2021 prices, while the amount of households with LILEQ and oLEQ or rLEQ stay constant across the years (not shown). Energy prices thus greatly influence the level of energy poverty when measured in terms of the energy quote, but do not affect the other indicators.

The previous results in Figure 17 show that the distribution of households with HEQ is spatially unequal: some buildings have low levels of HEQ households – mostly buildings with homeowners – while other buildings have high shares of HEQ households in the 2023 scenario. We tested this for a two model runs with 2021 and 2023 prices: in the 2021 run, 33 buildings with more than ten households (28%) had a share of HEQ inhabitants that was 12.5% or higher, while the share of households with HEQ in Voorhof was 6.8%. At the same time, 68 of these buildings (57%) had HEQ levels below the scenario average, and 16 buildings had no HEQ households at all. In the 2023 run, 30 ten-plus-family buildings (25%) had HEQ shares of 50% and higher, up to 88%, while 16 buildings had HEQ shares below 20%, and the average was 34%. This shows that energy poverty levels can vary greatly from building to building, with about a quarter of buildings having more than double the district average share of HEQ households. The high energy prices exacerbate this inequality.

6.2.2 Scenario results, heat network, no interventions

What inequalities in energy poverty and accessibility to sustainable energy might arise as a result of the heat network?

To determine the effect of a novel heat network on the extent and distribution of energy poverty, scenarios where a heat network is implemented were modelled. Two scenarios for heat network implementation are considered: only multi-family corporation buildings are connected (*Corp*) and corporation buildings are connected and other buildings may connect too (*All*).We first show the results of these scenarios with no other interventions implemented. Scenarios are assessed for multiple energy price reference years. First, we show results of overall energy poverty levels, then we examine which household groups are affected and how income groups and household types are distributed among energy-poor groups, and finally we asses overall inequality in energy expenses.

When gas prices are low, switching to a heat network increases energy poverty

The impact of the switch to a heat network on energy expenses depends on energy prices. In Figure 18 we compare overall levels of energy poverty in the different scenarios for heat network implementation and energy prices. The figure shows that in the years with low energy prices (2019-2021), switching to the heat network increases the share of households with HEQ by two percentage points and LIHC by three to six percentage points. With the 2023 price ceiling, however, heat network prices are more favourable and cause a decrease in HEQ households of one percentage point, but no difference in LIHC prevalence. The results show that heat network prices must be significantly lower than the maximum allowed prices as determined by ACM to increase the affordability of energy.

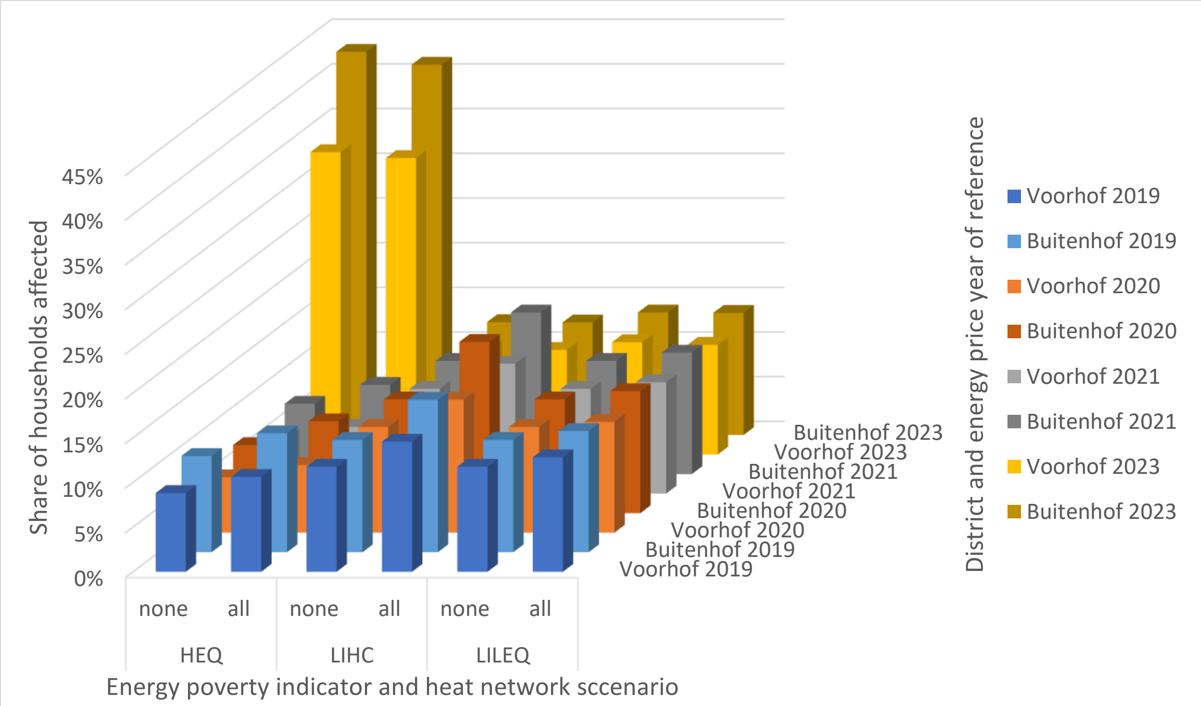


*Figure 18. Fraction of households with energy poverty in two scenarios for heat network implementation (*none *and* all*) measured using indicators HEQ, LIHC, and LILEQ, Voorhof and Buitenhof, for multiple years of reference for energy prices.*

Renters and low-income groups are affected most in changes in energy expenses

Let us now look at energy expenses of specific household groups. Figure 19 shows that renters and low-income households are most affected by the implementation of a heat network in the scenario where all households may connect. Whether the effect is favourable for the household depends on the relative price of the heat network compared to that of natural gas: in the 2021 scenario, energy prices are low, and switching causes an increase in energy expenses. Renters and low-income households thus face increased inequality in energy expenses and energy quotes. In the 2023 scenario, however, energy prices are high, and heat network prices are thus relatively favourable. This results in decreased inequality in energy expenses and energy quotes when renters and low-income households connect to the heat network.

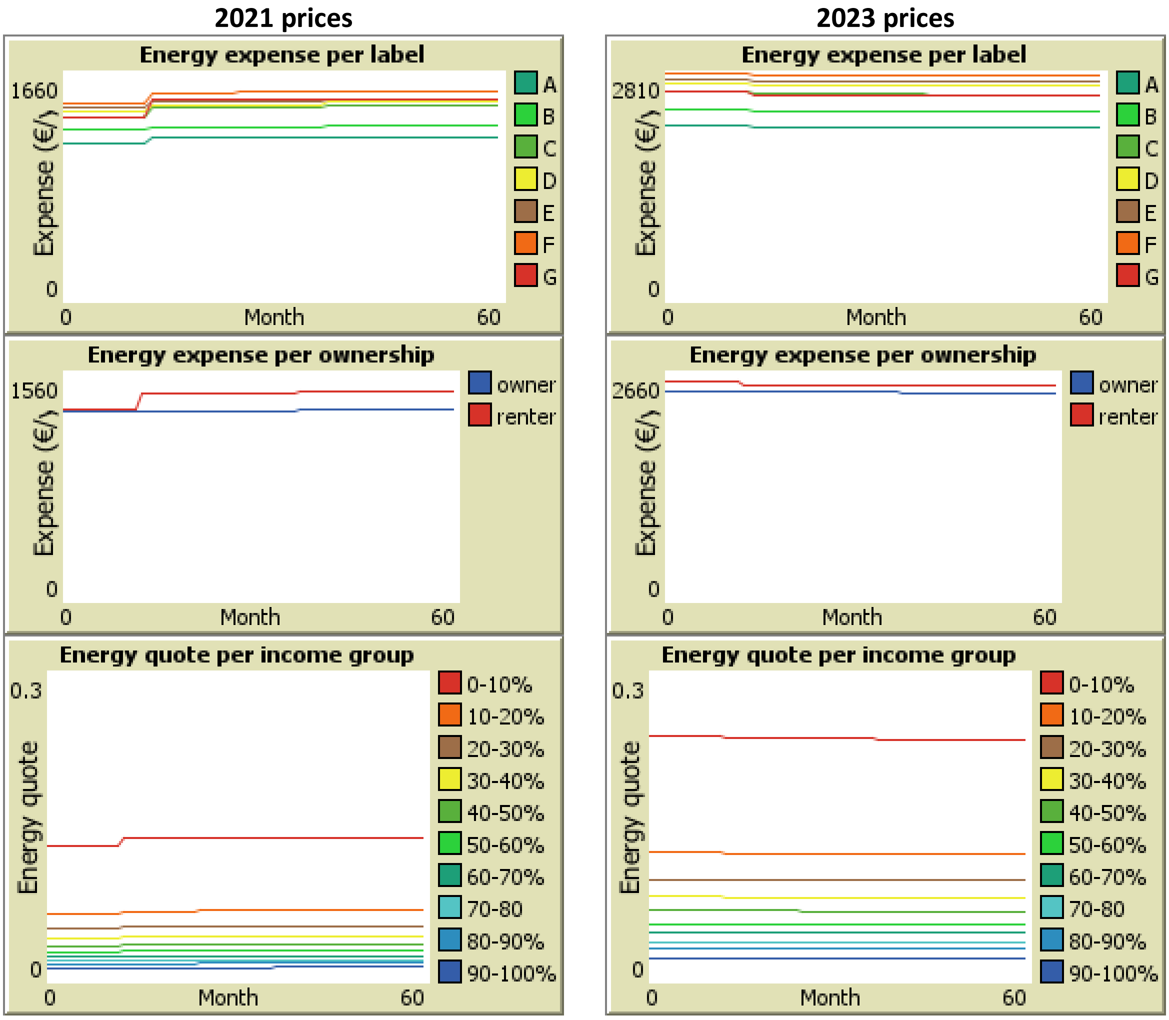


Figure 19. Average energy expense per energy label, energy expense per ownership, and energy quote per income group in the scenario when switching to a heat network. Results are from two model runs using 2023 and 2021 energy prices, respectively. The jumps at t=12 months, t=24 months and t=36 months represent the moments when multi-family corporation buildings, other multi-family buildings and other buildings can connect, respectively.

The distribution of income groups or household types among energy-poor groups is unaffected

To determine if the implementation of a heat network affects the distribution household types among households with energy poverty, we examined the distribution of income groups and household types for HEQ and LIHC households (see Figure 38 and Figure 39 in the Appendix). With 2021 energy prices, 97% of HEQ households is in the 0-10% income group, while with 2023 prices, this group represents 38% of HEQ households. The only change in distribution that the heat network causes is the share of 10-20% households among households with HEQ, which rises from 2% to 5%. In the other scenarios and years, the distribution of income groups among households with HEQ or LIHC is not affected. The distribution of household types among households with HEQ or LIHC is also not altered when the heat network is implemented for corporation buildings). Single-person households are highly represented in these energy poverty groups.

Low-income households are affected most by high heat network prices

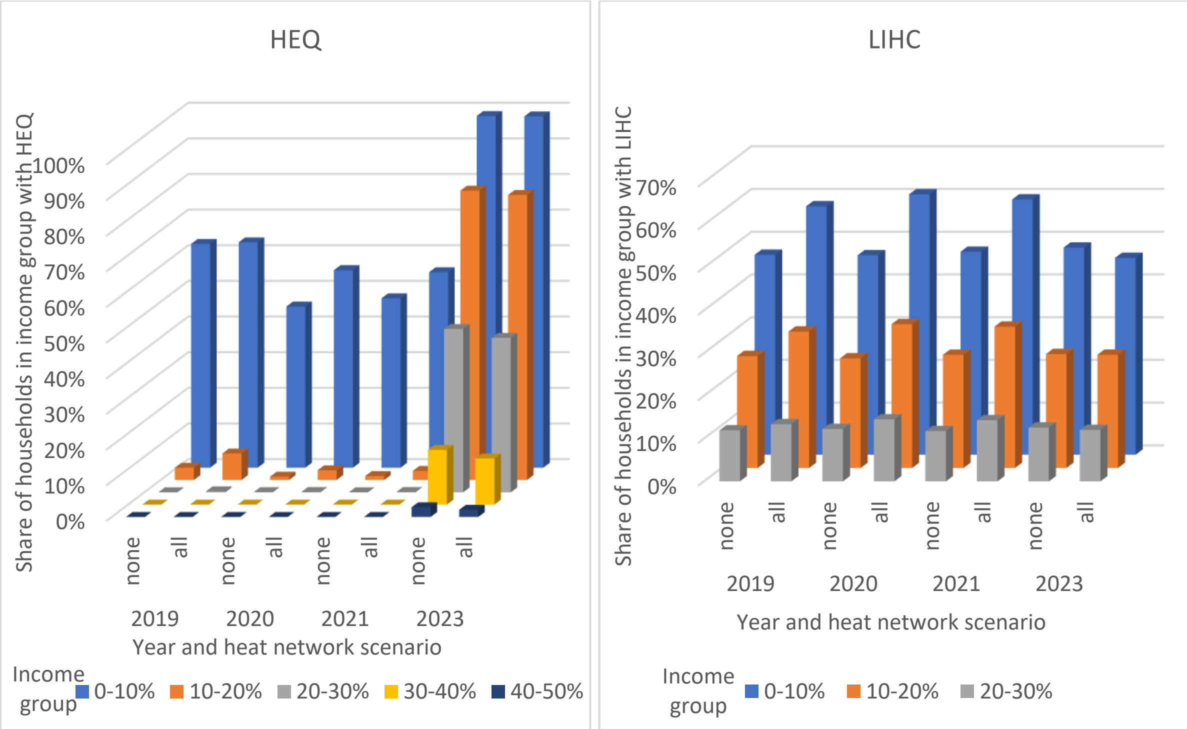


Figure 20. Share of households with HEQ per income group and share of households with LIHC per income group, Voorhof.

To assess which income groups are most affected by energy poverty in the switch to a heat network, we show the share of HEQ and LIHC households for each income group in Figure 20. With the high energy price level of 2023, almost 100% of households in the 0-10% income group and 80% of households in the 10-20% income group have a HEQ, whether they are connected to a heat network or not. The switch to a heat network decreases the share of HEQ households in the 10-20%, 20-30% and 30-40% income groups by a few percent with the 2023 prices. When energy prices are lower, however, we see a different picture. The switch to a heat network increases the share of HEQ households among the two lowest income groups in the 2019, 2020 and 2021 energy price scenarios. The effect of the heat network on LIHC levels is larger; the switch results in the share of HEQ households rising by 13% in the 0-10% income group and by 7% in the 10-20% income group. These results indicate that switching to a relatively expensive heat network affects low-income households the most and increases inequality in energy poverty levels.

High heat network prices increase inequality in energy expenses

Let us assess the level of inequality in energy expenses for the heat network scenarios in the four reference years for energy prices (Table 17). We use the Gini coefficient for energy expenses to express inequality, where a value of 0 means perfect equality and 1 means maximum inequality. In years with low energy prices (2019-2021), part of a neighbourhood switching to a heat network increases inequality in energy expenses if the heat network prices are close to the maximum allowed price. Only in 2023, with high energy prices and a price cap, does the heat network not increase inequality.

Table 17. Gini coefficient of energy expenses for baseline and heat network scenarios and various energy prices, Voorhof.

	Heat price as percentage of maximum	**Energy price reference year**			
		2019	2020	2021	2023

No heat network (*none*)	–	0.088	0.103	0.104	0.117
Heat network open to all (*all*)	92% 100%	0.096 0.102	0.108 0.120	0.109 0.117	0.114 0.116

6.2.3 Scenario results, heat network, interventions

What policy interventions lead to reduced inequalities and an accessible heat network?

To determine what policy interventions lead to reduced inequalities and an accessible heat network, we present the results for the scenarios where the heat network, the financial interventions and other interventions are implemented. An overview table with all key indicator results is given in Table 18. We will discuss these results in detail in the upcoming sub-sections. First, we look at the effect of the selected policy interventions on the extent and distribution of energy poverty. Then, we examine the effect of the policy interventions on inequality in energy poverty and accessibility of the heat network.

Table 18. Overview of scenario results: key indicators. HN*, share of households connected to the heat network;* HN unaffordable*, fraction of households that wanted to connect to the heat network as homeowner but could not afford it and could not get a voucher;* Voucher*, fraction of households that used a voucher to connect.*

Heat network	Financial inter-vention	Other inter-vention	Mean energy use [GJ]	Mean EQ	Gini of energy expenses	HEQ	LIHC	LILEQ	oLEQ	rLEQ	HN	HN unaffordable	Voucher
none	*none*	*none*	*38.5*	*10%*	*0.117*	*35%*	*12%*	*13%*	*18%*	*26%*			
none	*none*	*awa*	*35.6*	*9%*	*0.122*	*29%*	*12%*	*13%*	*20%*	*25%*			
none	*none*	*eff*	*34.6*	*9%*	*0.107*	*29%*	*12%*	*0%*	*0%*	*0%*			
corp	none	none	38.0	10%	0.116	33%	12%	12%	21%	23%	35%	18%	
corp	none	awa	35.2	9%	0.119	28%	12%	13%	20%	25%	34%	17%	
corp	none	eff	34.0	9%	0.105	28%	12%	0%	0%	0%	36%	18%	
all	none	none	38.0	10%	0.114	32%	12%	12%	22%	21%	39%	20%	
all	none	awa	35.0	9%	0.118	28%	12%	13%	20%	24%	42%	18%	
all	none	eff	33.9	9%	0.104	27%	12%	0%	0%	0%	40%	19%	
none	*tax*	*none*	*38.5*	*10%*	*0.118*	*33%*	*12%*	*12%*	*20%*	*24%*			
none	*tax*	*awa*	*35.7*	*9%*	*0.122*	*27%*	*12%*	*13%*	*21%*	*23%*			
none	*tax*	*eff*	*34.5*	*9%*	*0.107*	*28%*	*12%*	*0%*	*0%*	*0%*			
corp	tax	none	37.9	10%	0.116	33%	12%	13%	20%	24%	38%	17%	
corp	tax	awa	35.2	9%	0.119	27%	11%	12%	22%	22%	36%	18%	
corp	tax	eff	33.9	9%	0.105	28%	12%	0%	0%	0%	37%	17%	
all	tax	none	37.9	10%	0.114	33%	12%	12%	22%	22%	43%	18%	
all	tax	awa	35.0	9%	0.118	27%	12%	13%	21%	23%	43%	18%	
all	tax	eff	33.9	9%	0.104	27%	12%	0%	0%	0%	40%	19%	
all	vou	none	37.7	10%	0.112	33%	12%	12%	22%	22%	56%	12%	7%
all	vou	awa	34.8	9%	0.116	28%	12%	13%	20%	24%	58%	11%	6%
all	vou	eff	33.6	9%	0.103	27%	12%	0%	0%	0%	57%	12%	7%
all	tax-vou	none	37.6	10%	0.113	32%	12%	12%	22%	22%	62%	12%	6%
all	tax-vou	awa	34.8	9%	0.117	27%	12%	12%	21%	23%	57%	11%	6%
all	tax-vou	eff	33.6	9%	0.103	27%	12%	0%	0%	0%	60%	11%	6%

Building renovations are most effective in decreasing energy use and energy poverty

Both the awareness campaign (*awa*) and the energy efficiency improvement (*eff*) interventions decrease the fraction of households with a HEQ (see Appendix Figure 41 for a detailed comparison of HEQ fractions in all scenarios). This is the case regardless of the scenario for heat network implementation. In Table 18 we see that the average household energy use is reduced by 3 GJ (7%) in the *awa* scenarios and by 4 GJ (10%) in the *eff* scenarios, thereby also reducing the average energy quote of households. The fraction of households with LIHC is not affected by these interventions. The interventions of energy taxes or vouchers for heat network connections do not influence the fraction of households with HEQ, LIHC or LILEQ. No more households experience LILEQ, oLEQ and rLEQ in the energy efficiency scenario's due to all buildings being renovated to label B.

Vouchers increase accessibility of the heat network

We will now focus on the accessibility of the heat network. In the corporation-only scenarios, about 35% of all households are connected to the heat network, which increases to 42% of all households in the scenarios where all households may connect, but no further financial incentives are given (Table 18). We can see that on average, 18% of households are homeowners that want to connect to the heat network, but lack the funds to do this. Vouchers enable one third of these homeowners who lack the funds to connect to the heat network. 6-7% of all households used a voucher to connect to the heat network. As a result, the highest heat network rollouts can be seen in the *vou* scenarios: up to 60% of all households connect. Vouchers therefore increase the accessibility of the heat network for low-income homeowners.

Awareness and energy efficiency interventions reduce the fraction of HEQ households in all income groups except the lowest, when energy prices are high

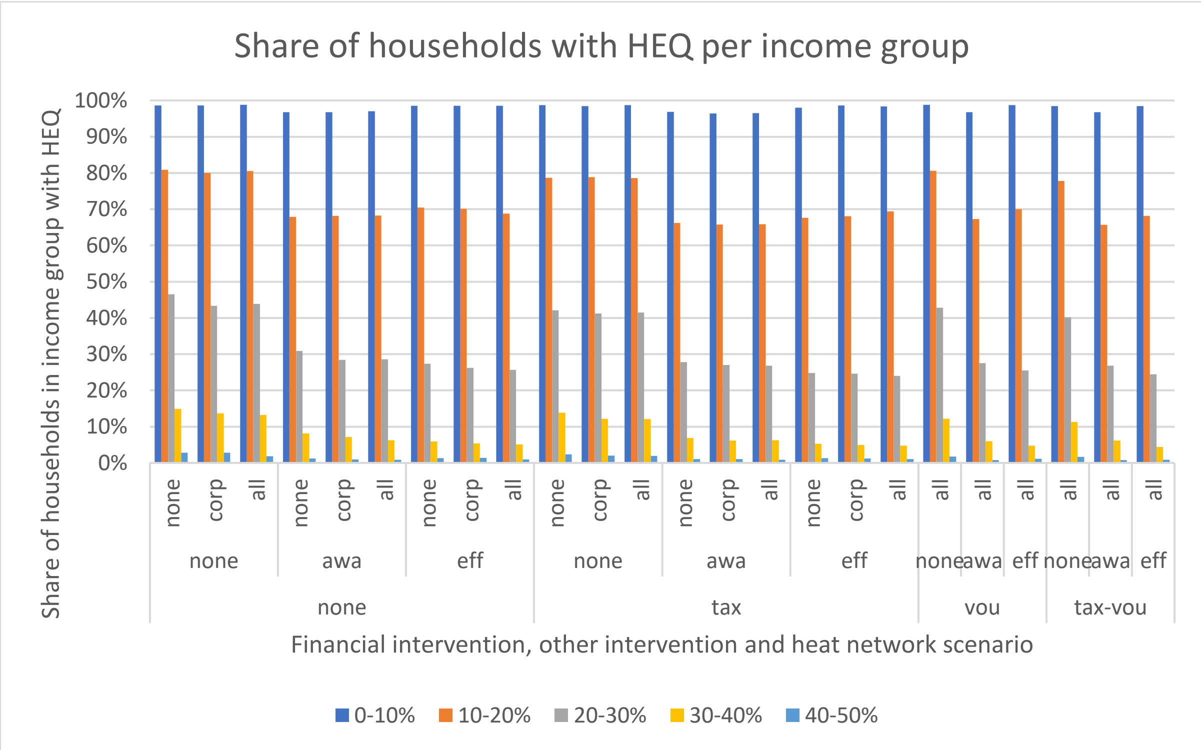


Figure 21. Share of households with HEQ per income group for the lowest five income groups, Voorhof, 2023 energy prices.

Figure 21 shows the share of households with HEQ for each income group. We can see that with the high energy price level of 2023, almost 100% of all households in the 0-10% income group have a high energy quote, and the interventions fail to reduce this fraction. This means that while the energy quote of these households is reduced, it is still above 10% of the household's income. The share of households with HEQ decreases from approximately 80% to 68% for the 10-20% income group and from 45% to 28% for the 20-30% income groups in the *awa* and *eff* scenarios. No significant effect is observed on the fractions of LIHC per income group (see Appendix Figure 42). The energy tax and voucher scenarios do not influence the share of households with HEQ per income group.

Tested interventions did not reduce energy poverty inequalities between household composition groups.
We saw in Appendix Figure 39 that energy poverty levels differ between household groups. The levels of HEQ and LIHC were determined per household type in each scenario (see Appendix Figure 43 and Figure 44). Single-person households experience HEQ up to five times as often as couples. Of the household groups, elderly singles have the highest occurrence of HEQ and LIHC. Elderly pairs are twice as likely to experience LIHC than other pairs. For LIHC, elderly pairs, who often have higher energy needs, experience the second-highest occurrence of energy poverty, after elderly singles. All tested policy interventions fail to reduce the energy poverty differences between household groups. The awareness campaign and energy efficiency improvement merely reduce overall energy poverty levels.

Building renovation decreases inequality in energy expenses, other measures do not
Now let us assess the inequality in the modelled scenarios. First, we examine the level of inequality in energy expenses across all scenarios using the Gini coefficient (Table 19). We see that implementation of a heat network does not influence the level of inequality in energy expenses, likewise with the altered energy tax and vouchers for heat network connections. In scenarios where the awareness campaign is implemented, higher inequality occurs in energy expenses. Improving the energy efficiency of buildings leads to lower inequality in energy expenses, decreasing from 11.5% to 10.5% . The inequality effects of the interventions on energy expenses were not affected by the implementation of a heat network.

Table 19. Gini coefficient of households' energy expenses for all scenarios, Voorhof, 2023 energy prices. Cells are coloured based on the value of the Gini coefficient, where green indicates the lowest values and yellow the highest.

Financial intervention	**Other intervention**	**Heat network implementation**		
		none	corp	all
none	none	0.117	0.116	0.114
	awa	0.122	0.119	0.118
	eff	0.107	0.105	0.104
tax	none	0.118	0.116	0.114
	awa	0.122	0.119	0.118
	eff	0.107	0.105	0.104
vou	none			0.112
	awa			0.116
	eff			0.103
tax-vou	none			0.113
	awa			0.117
	eff			0.103

Low-income renters have good heat network access; vouchers increase access for homeowners
Finally, we move from the affordability of energy to the distribution of access to clean energy. What types of households are connected to the heat network? Figure 22 shows the distribution of income groups among households connected to the heat network. Lower income groups are represented more in the group of households connected to the heat network compared to the distribution of income groups for all households. This effect is slightly diminished in the scenario where all households can connect. We also see that the awareness campaign and energy efficiency improvement scenarios have no significant effect on the distribution of income groups connected to the heat network.

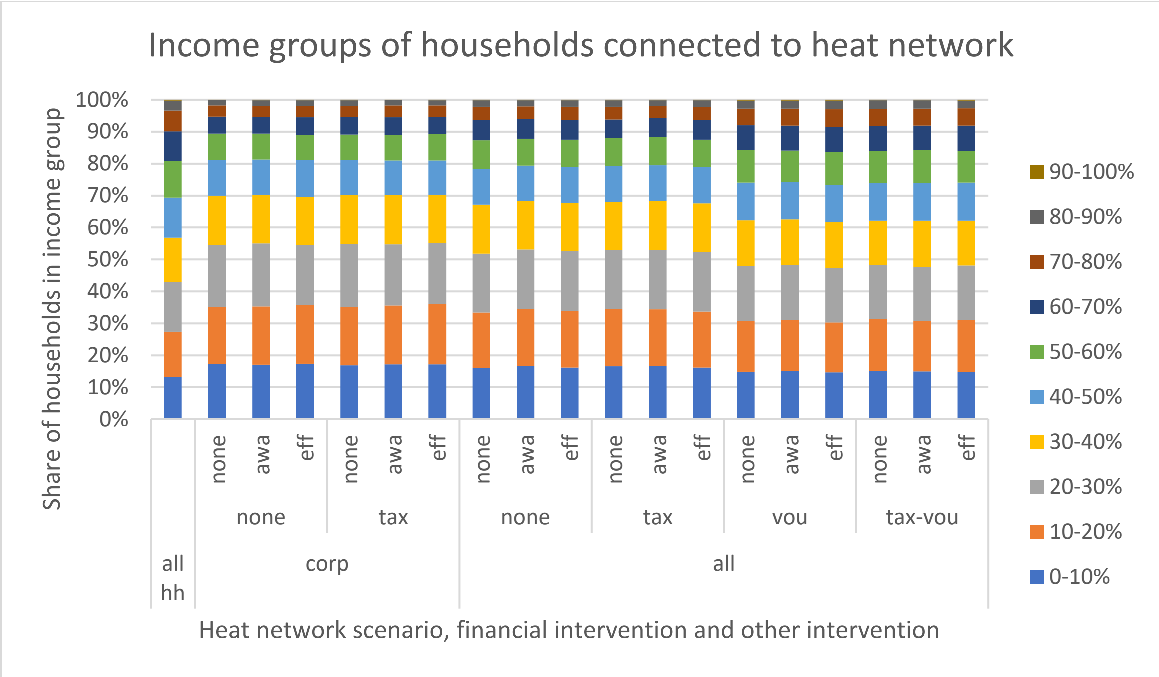


Figure 22. Income groups of households connected to the heat network for scenarios for heat network implementation (none, corp, all)*, financial interventions* (none, tax, vou)*, and other interventions* (none, awa, eff)*, Voorhof, 2023 energy prices. The first bar shows the distribution of income groups for all households* (hh)*; colours represent each income group.*

The figure also shows that the voucher financial intervention leads to an increase in the share of mid-income households in the group of connected households. Without this voucher, only renters – which have a lower average income than homeowners – and homeowners with sufficient financial means (in the *all* scenario) can connect to the heat network. The voucher ensures more equal opportunities for homeowners to join the heat network. Homeowners have a higher average income than tenants, so mid-income households benefit most from the vouchers. We further discuss the key results and their implications in the next chapter.

Chapter 7.
Discussion

Synopsis
The discussion focuses on the key findings, current and future uses of the model, limitations of the research approach, implications of the results, indicators used for energy poverty, and the scientific contributions of this thesis.

Model usage
In this study, a spatially explicit agent-based model was used to explore the emergence of energy poverty in the context of the switch to a heat network in a specific neighbourhood. Besides studying the potential impact of policy interventions on energy poverty, the model could further be used to support discussions between stakeholders in the just energy transition and explore other interactions between energy technologies and household characteristics in Delft and other cities.

Limitations of the research approach
The research approach comes with limitations, including the simplification of human psychology, interaction and decision-making in the model. While the model offers insights on energy poverty at the household level and has a detailed representation of household characteristics, the approach is computationally and data-intensive and can be time-consuming to run. A shortcoming that should be addressed in future studies is the lack of participation of citizens in the model development. Participation could help in validating the model and better incorporating lived experiences of energy poverty and factors that influence decision-making in the energy context. The results of this model are not a prediction of how energy prices or energy poverty will develop, how households will react to the implementation of a heat network, or what choices they will make. It is an exploration of the effects that could occur, to help design policy that prevents injustices.

Implications
The results suggest that it is possible to address energy poverty and inequality holistically in the transition to a low-carbon energy system. However, district heating pricing should be adjusted to account for differences in energy consumption and ensure that no household pays more after switching to a heat network. Low-income households and renters are vulnerable groups that are affected most in the transition. Policy is therefore needed to protect these groups.

Discussion on energy poverty indicators
Current energy poverty indicators fall short in measuring households' opportunities to participate in the transition to a clean energy supply, while a lack of such opportunities means the household is at risk of increasing energy costs. Hidden energy poverty is also not adequately measured using current indicators. It is important to further examine the capability effects that (hidden) energy poverty, and quantify the reduction in capabilities, or 'uncapability', that is caused by energy poverty.

Scientific contributions
The scientific contributions of this research include the use of an ABM to study energy poverty at a local scale, the use of a spatially explicit model using detailed household and housing data of an actual neighbourhood, and the integration of the capability approach and energy poverty frameworks which takes a broader look at energy poverty. This approach could serve as a starting point for better evaluation of distributive justice of novel energy technologies and contribute to a more just energy transition.

Relevance to Industrial Ecology
This study contributes to the field of Industrial Ecology by examining the interactions between technology and its social and institutional environment in the context of the energy transition. By applying the energy justice perspective, this thesis adopts a critical attitude towards sustainability.

7.1 Key findings

7.1.1 Inequalities in energy poverty and accessibility as a result of heat network implementation

To answer the third research question, “What inequalities in energy poverty and accessibility to sustainable energy might arise as a result of the heat network?”, an agent-based model was made in which households consume energy and a heat network is implemented. Various model scenarios were evaluated for the Voorhof and Buitenhof districts, which yielded the following key findings.

Key finding 1: Within neighbourhoods, high inequality can occur in the distribution of energy poverty.
The share of households with a high energy quote or low energetic quality varies greatly from building to building. Some buildings display very high levels of energy poverty, while others have none. The high energy prices worsen these differences.

The distribution of households with a high energy quote or a dwelling with low energetic quality is spatially unequal. Other studies have revealed geographical inequalities in energy poverty between neighbourhoods (Marí-Dell’Olmo et al. 2022; Mulder et al. 2023). This thesis shows that high inequalities can also occur within neighbourhoods from one building to the next. Since national averages on income and household characteristics were used to assign these characteristics to households in our model, the inequalities found in our model do not reflect actual differences in the particular households in Voorhof and Buitenhof. However, the model results still offer useful insights into how energy poverty can be distributed in a neighbourhood and on the influence of dwelling characteristics such as age, floorspace and energy label on the distribution of energy poverty. These results demonstrate the importance of using data on the household level to study energy poverty at the local scale.

Key finding 2: When gas prices are low, switching to a heat network increases energy poverty.
Despite the ‘no-more-than-usual’ principle, households with low energy demand switching to a heat network may have an increased energy bill. The switch may also increase the share of households with a low income and high energy costs. This increase in energy poverty does not occur when overall energy prices are high. Lower district heating prices can prevent the increase in energy poverty.

Despite the ‘no-more-than-usual’ principle, households with low energy demand switching to a heat network may have an increased energy bill. The higher cost is because ACM uses a standard household, with a heat demand of 35 GJ, as reference and due to the high fixed costs of heat networks. When a household’s heat demand is lower than average, the low variable heat costs do not sufficiently compensate for the high fixed costs, leading to a higher overall energy bill compared to their previous gas boiler. While the variable costs for heat network heat are lower than the variable costs for gas, the combination of high fixed heat network costs and the lower-than-average heat consumption of households in Voorhof and Buitenhof mean that their total energy costs are higher when switching to the heat network. This contrasts with the not-more-than-usual principle and goes against the goal of Open Warmtenet Delft to have housing cost neutrality. We should note that we assume that heat network prices are at 92% of the maximum allowed price. In reality, district heat providers often have lower prices. This shows that the current price cap principle should be reviewed, but that actual situations can be more favourable than depicted in this study.

The share of LIHC households also increases after implementing the heat network under 2019-2021 energy prices. This is because more low-income households are connected through the corporation-owned buildings. Since their heating bills increase, they are more likely to fall under the LIHC category.

This shows the importance of assessing the effect of heat network prices on the bill of households for varying energy consumption levels.

> ***Key finding 3: Renters and low-income groups are affected most in changes in energy expenses.***
> *Since mostly social housing buildings connect to the heat network, renters and low-income groups are most affected by the implementation of the heat network.*

Whether this effect is favourable depends on the relative price of the heat network compared to that of natural gas. In scenarios with low gas prices, it is especially renters that experience increased energy expenses when switching to the heat network. Therefore increased inequality between renters connected to the heat network and homeowners not connected occurs. The same is the case for low-income households, who constitute the majority of connected households.

> ***Key finding 4: The distribution of income groups or household types among energy-poor groups is unaffected.***
> *The heat network does not influence which types of households or income groups face energy poverty.*

No change in inequality between specific households types has been found in the switch to a heat network.

> ***Key finding 5: Low-income households are affected most by high heat network prices.***
> *With low energy prices, the switch to a heat network increases the share of households with energy poverty. With high energy prices, the heat network price is more favourable, and the share of HEQ households slightly decreases in the 10-50% income groups, but not in the 0-10% income group.*

This result shows the influence of the high fixed district heating costs compared to natural gas boilers. When the energy prices are higher, the variable prices become more important, and the effect of the unfavourable pricing for low-consumer households decreases.

> ***Key finding 6: High heat network prices increase inequality in heat expenses.***
> *In scenarios with 2019-2021 energy prices, inequality in energy expenses increased when part of the neighbourhood switches to the heat network. Inequality stayed constant with the 2023 regulated prices.*

The increase in energy expense inequality after implementation of a heat network is due to the high fixed heat network prices compared to natural gas and the lower than average energy demand in Voorhof and Buitenhof. The households that switch to the network face higher energy bills while the ones that keep their current heating system do not, increasing inequality between these households. This was not the case with the 2023 regulated prices, since the variable heating costs were higher, reducing the inequality effects of the high fixed heat network costs.

7.1.2 Policy and design measures that may decrease inequality in energy poverty and heat network access

To answer the second research question, “What policy interventions lead to reduced inequalities and an accessible heat network?”, various scenarios for policy interventions were assessed.

> ***Key finding 7: Building renovations are most effective in decreasing energy use and energy poverty.***
> *Increasing building efficiency reduces energy use, energy poverty and inequality.*

Compared to all other interventions, the intervention to improve the energy efficiency of buildings with a low energy label (D or worse) to B was the most effective. Not only did it decrease energy poverty, it also decreases energy use and thereby contributes to our climate goals. There was also less inequality in energy expenses. This suggests that this intervention is an effective method that can tackle multiple aims at once in the just energy transition. However, we did not include the renovation costs for this intervention in our analysis. We can therefore not draw conclusions on total housing costs. A more detailed analysis is needed to see if these overall costs affect inequality and affordability.

Key finding 8: Vouchers increase accessibility of the heat network.
Vouchers to cover the heat network fee increases the number of households connecting to the heat network.

Especially homeowners, which are often mid-income households, benefit from vouchers. These households would normally not be able to afford the upfront costs of a heat network connection.

Key finding 9: Awareness and energy efficiency interventions reduce the fraction of HEQ households in all income groups except the lowest, when energy prices are high.
With the high energy prices, awareness campaigns and energy efficiency improvement fail to lift the lowest income groups out of energy poverty, but do reduce energy costs.

With the current high energy prices, almost 100% of households in the 0-10% income group has a high energy quote. While energy awareness campaigns reduce overall energy poverty levels and energy expenses of the target households, this is not sufficient to reduce the fraction of very low-income households with HEQ. The energy poverty gap – the reduction in energy costs needed for a household to no longer be classified as energy-poor (Mulder et al. 2023) – is so high for many households with current energy prices that interventions such as awareness campaigns and energy efficiency improvement are not sufficient to lift low-income households out of energy poverty. More effective measures are needed to increase the affordability of energy for these households and close the energy poverty gap.

Key finding 10: Tested interventions did not reduce energy poverty inequalities between household composition groups.
While the awareness campaign and energy efficiency interventions reduced overall levels of energy poverty, none managed to decrease differences in HEQ and LIHC levels between groups of different household compositions.

We examined the distribution of household types among energy-poor households in all scenarios. No scenario had a significant effect on the distribution of household types. Especially single-person and elderly households faced higher levels of energy poverty, but the tested policy interventions did not improve this. The latter group, however, may make less use of financial aids such as vouchers (Nationale Ombudsman 2022a), which could even lead to increased inequality between household groups (not modelled). Our policies did not target specific household groups such as single-person households or the elderly. The findings suggest that policy should be targeted at specific household groups to reduce inequalities between these groups and specifically decrease energy poverty in single-person and elderly households.

Key finding 11: Building renovation decreases inequality in energy expenses, other measures do not.
The level of inequality in energy expenses was lowest in the scenarios with building renovations. The other measures had limited to no impact on this type of inequality.

This finding is in line with the previous findings that suggest that building renovation is an effective way to tackle energy poverty and inequality.

Key finding 12: Low-income renters have good heat network access; vouchers increase access for homeowners.
When housing corporations decide to switch to a heat network, especially low-income households have better access to clean energy. Vouchers targeted at homeowners with insufficient means to pay for the heat network connection fee cause increased accessibility of the heat network for homeowner groups.

In Open Warmtenet Delft, housing corporations are leading actors in the development of the new heat network. This causes households from lower income groups to constitute most potential heat network users. These households usually have very few opportunities to participate in the energy transition due to them being renters with little influence and having fewer financial means to invest in energy measures. The implementation of the heat network for corporation buildings therefore results in increased opportunities for low-income households to take part in the energy transition. Since social housing corporations are leading actors in the switch to a heat network in Voorhof and Buitenhof, especially low-income renters have increased access to low-carbon energy. Homeowners with insufficient financial means to pay for the costs of joining a heat network may be left behind in the heating transition. These low to mid-income groups may be overlooked. Vouchers can lead to a more accessible energy system for these homeowners.

7.1.3 Other findings

Key finding 13: Energy prices have the largest effect on the level of energy poverty
The current high energy prices cause high levels of energy poverty, especially among the lowest income groups. All policy interventions had a smaller effect on energy expenses than the increase in energy prices in 2022-2023 compared to earlier years.

This finding suggests that altering energy prices can be an effective tool in addressing energy poverty.

Key finding 14: The current way of determining maximum district heating prices is flawed.
Due to the high fixed costs of heat networks, households with a low energy demand often face an increased energy bill when switching to the heat network, despite the no-more-than-usual principle. The determination of heat prices should better reflect the varying situations of households and protect low-income households.

ACM determines maximum heat prices based on the average heat demand of Dutch households. When a household's heat demand is lower than average, the relatively low variable heat costs do not sufficiently compensate for the high fixed costs of heat networks, leading to a higher overall energy bill compared to their previous gas boiler. The 'no-more-than-usual' principle thus does not seem to apply to households that consume less heat than average. This creates inequality for low-income households and does not encourage saving energy. The way of determining maximum district heating prices should therefore be revised to reflect the varying energy consumption levels of households and to protect low-income households. We provide recommendations for this in Chapter 8.

7.2 Model usage

An agent-based model was developed that explores inequalities in energy poverty and access to energy because of the implementation of a heat network in specific neighbourhoods in Delft. By taking a bottom-up approach to examine the emergence of energy poverty, this model can be used to gain insights in the factors that may cause energy poverty, and how these are affected by policy interventions and energy systems. The model can be applied in a number of ways to support decision-making and policymaking related to energy poverty and accessibility to clean and affordable energy. In this study, the model used to:

- Explore the potential impacts of different scenarios for the implementation of a heat network in Delft, such as different price levels and target buildings, on the distribution and extent of energy poverty of households;
- Examine the spatial distribution of energy poverty and its distribution among household groups;
- Identify social groups that are at risk of energy poverty because of the switch to the heat network, and develop interventions to mitigate these risks;
- Evaluate the effectiveness of policy interventions aimed at addressing energy poverty and promoting accessibility to clean and affordable energy.

Space is explicitly included in the model using georeferenced (GIS) data of specific neighbourhoods. This allows for spatially explicit processes such as comparison with neighbours to be modelled. The model represents actual neighbourhoods and its spatial nature allows for easier visualization and communication of results. This is important, since the purpose of the model is to inform decision-makers and industry professionals, who might not be familiar with (agent-based) modelling. Results visualised for a particular neighbourhood could also help informing the neighbourhood heat execution plans. In addition, a spatially explicit model allows to investigate the spatial dimension of justice and inequalities, by looking at the geographical spread of e.g. energy poverty. The spatial dimension of energy justice is often overlooked, but necessary to understand policies and factors producing inequalities (Bouzarovski and Simcock 2017).

As with all models, this model comes with certain limitations (described in the next section), so we provide guidelines for the use of this model (Table 20). The main use of this model is to serve as an exploration of potential energy poverty effects and as a basis for supporting discussion and informing policy on energy poverty. It is not, however, a prediction nor a reflection of the actual households in the Voorhof and Buitenhof districts. The results do offer useful insights into how heat network implementation and policy could affect certain household groups and can be used to point towards households at potential risk of falling behind in the energy transition.

Table 20. Guidelines on what this model can and cannot be used for.

What this model can be used for	What this model cannot be used for
Pointing out household types potentially at risk of energy poverty	Predicting which specific dwellings currently experience energy poverty
Exploring potential distributions of energy poverty in various scenarios for heat network implementation and policy interventions	Predicting the response of households to the implementation of a heat network or policy interventions
Informing policymakers which social groups to particularly pay attention to when making policy	Predicting the effect of policy interventions on specific household groups
Supporting discussions between stakeholders in the energy transition on justice aspects of heat networks	Providing true facts on the justness of heat networks and how they should be implemented in the energy transition
Provide a basis for a further model to explore the effects of alternative energy technologies on energy poverty	Determine which heating technology is the best, cheapest, most environmentally friendly, easiest, or preferred

The model has more potential and can be further explored, which unfortunately could not be done due to the time limitations of a master's thesis. Further uses of this model include:

- Examining total housing costs (e.g. renovation costs and energy costs) to assess whether housing cost neutrality can be achieved. Renovation costs are already implemented in the model, but were not assessed in this thesis report.
- Assess different policy interventions or the effect of more targeted interventions, such as tailoring an awareness campaign to low-income households;
- Exploring hidden energy poverty by incorporating factors such as feedback interactions between spendable income for heating and energy use;
- Explore the effect of the broader heating transition on energy poverty by including other heating system technology alternatives, such as heat pumps;
- Simulate the impacts of the heat network on a wider range of stakeholders in the area by extending the model to include additional agents such as businesses;
- Explore the effect of the implementation of a heat network in different locations by using the input data for another neighbourhood;
- Supporting and promoting discussions between the different stakeholders involved in energy poverty, such as the policy makers, housing corporations and heat network developers, to raise awareness for energy poverty and inequality and support creation of more just policies;
- Facilitating social learning amongst stakeholders in a participatory modelling process (see e.g. Cuppen et al. (2020).

7.3 Discussion on the research approach

7.3.1 Limitations of research approach

The use of agent-based modelling comes with certain limitations. First, we describe general limitations of agent-based modelling approaches and of the approach taken in this thesis. In section 7.3.2 we discuss specific limitations for the agent-based model developed in this study. Besides these limitations, the model still provides a detailed representation of actual neighbourhoods and produces realistic outcomes. It is a useful and flexible tool to explore energy poverty effects in a wide range of scenarios, and the insights gained in this study can be applied to inform policy on energy poverty in the heat transition in Delft.

Common shortcomings of agent-based energy models are the simplification of human psychology and decision-making processes and the challenges of modelling complex social interactions (Pavlović et al. 2022). While the inclusion of psychology in energy transition research is important in understanding the processes underlying the required behaviour change, energy transition research often lacks in the inclusion of psychological factors and theories (de Vries et al. 2021). While we discussed elements of the agent-based model with an environmental psychologist, the psychological and behavioural aspects of the model are still simplified and limited. No conclusions can thus be drawn about the behaviour that households show in the transition to a heat network.

Another limitation is that agent-based modelling is a computational and data-intensive approach that can be time-consuming to implement and run. This limits the scale of the model and its ability to capture the full range of household characteristics, behaviour, and model parametrizations. It also limits the application of this approach to regions where data is available on dwelling and household characteristics at the household level.

As for the choice of policy interventions: an economist might say that policy making should not focus on a specific part of a person's life or issue, but on more general measures for alleviating poverty such as lowering income tax. While this might alleviate energy poverty for those who suffer from it due to their having limited financial means, this approach overlooks other causes of energy poverty and inequality such as poor dwelling energy quality, the inability to change one's energy situation and differences in energy prices. Policy interventions that incentivise households to participate in the transition to clean energy should be included to also pursue goals of a just transition.

While trying to operationalise the capability approach in an agent-based model, we ran into an apparent paradox. On the one hand one tries to keep a model as simple as possible, as not to complicate interpretation of the results, have too many variables to check, or be unable to explain the effect of each factor. On the other hand, the capability approach emphasises human diversity and the broad range of factors that can influence one's wellbeing and the many interconnections between those factors and wellbeing. As with all models, the model represents an incomplete and simplified version of reality to gain a better understanding of the factors that might cause inequality and energy poverty. It is therefore not desirable for the ABM to capture all elements of the capability approach; one should choose the key elements of the approach relevant to the research aim.

A last limitation of the research approach is that, while experts from various disciplines such as ethics of technology, modelling, and environmental psychology were consulted in various stages of model development, households were not involved. A participatory modelling approach (Barnaud et al. 2013; Uebelherr et al. 2017; Cuppen et al. 2020; McGookin et al. 2021) could help in understanding the barriers that households might face when considering the switch to a heat network, and the factors relevant in their decision-making and energy behaviour.

7.3.2 Limitations of model conceptualisation and modeling decisions

The agent-based model developed in this study comes with limitations particular to how this model is conceptualised and the decisions made in its development. Firstly, it should be noted that the results of this model are not a prediction of how energy prices or energy poverty will develop, how households will react to the implementation of a heat network, or what choices they will make. It is an exploration of the possible effects that could occur in specified scenarios. Empirical model evaluation by model output corroboration was only possible to a limited extent due to the lack of data on this novel technology. Moreover, the results are an incomplete assessment of possible socio-economic effects, let alone other wellbeing effects of the novel heat network. While the phenomenon of hidden energy poverty could be studied as well using this model, for example by incorporating interactions and feedback loops between a household's economic status and its energy use, this was not done in the current study. Further research is thus still needed to assess the broader effects of the heat network on household energy poverty and wellbeing.

Another limitation is that the model does not include other options for low-carbon heating systems, such as heat pumps or solar heat panels. This was done for methodological reasons – it is easier to implement an ABM with only the switch to a heat network as an option – and because adding heat pumps as an option does not contribute to answering the research questions. The aim of the study is to study the effect of heat network implementation on energy poverty. The omission of alternative technologies might influence household decision-making: households might prefer other heating systems to the switch to a heat network. Future research is needed to investigate the effect of heat pumps and a mix of energy systems that are needed in the switch to a carbon-free neighbourhood. Still, the scenarios with just a district heat network offer useful insights for the situation in which this technology is implemented.

Furthermore, one should note that the households in the model do not represent real households and their characteristics, as variables such as income, homeownership and household composition are assigned semi-randomly. The actual distribution of energy poverty can thus be different in the real Voorhof and Buitenhof neighbourhoods. However, the general patterns and relative results in energy poverty can likely be translated to the real case.

The model simplifies factors, such as the prices for energy, which stay constant throughout the model and are the same for all households. Not only do these market prices fluctuate, but households can also have higher or lower costs depending on their energy supplier and type of contract (e.g. when they have a variable contract). However, no data on fixed and variable contract prices was available and the inclusion of these might not contribute to our research aim, so fixed and average prices were used. The implementation of policies and their effects is also simplified. Policies such as vouchers and energy cost allowances are not always used by households, who may not be aware of the existence or that they have the right to these aids (NOS 2022b). Especially vulnerable households such as elderly may face difficulties in making use of these policies (Nationale Ombudsman 2022a).

Another limitation is that the model may not capture the complexity and diversity of household decision-making and behaviour. Various factors influencing energy decision-making and energy use have not been included, such as habits, perceived hassle (de Vries et al. 2020), plans of households, age of the current heating system, and other psychological and practical barriers (Kollmuss and Agyeman 2002; Pelenur and Cruickshank 2012; Snape et al. 2015; Hesselink and Chappin 2019). Other omitted decision-making factors include the moment and method with which households are included in the decision-making process when a heat network is developed, solidarity and connection with others, trust in the local government, mistrust towards large or monopolistic heat companies and lack of trust in commercial parties, and knowledge levels (Kort et al. 2020). Another limitation is that decision-making in the model occurs only at a single level – that of the individual household. In reality, one in six homeowners live in a building where they need permission from their homeowners' association for renovations such as insulation or placement of HR+ windows (NOS 2022a). Group decision-making models could be added to agent-based models to study complex socio-technical heat transitions (Nava-Guerrero et al. 2021, 2022). All these considerations might have influence on the roll-out of the heat network, but studying this effect is outside the scope of this study. For studies on the diffusion of heating systems, see for example (Sopha et al. 2011, 2013; Robinson and Rai 2015; Busch et al. 2017).

Detailed and high-quality data was used in the model, which resulted in a model that is able to examine energy poverty on a local, household scale and flexibly assess indicators for specific household groups. Still, a few shortcomings arise from the data used. An example is using the energy label to determine energy use. The energy label does not have one-to-one relationship with energy use, you need to look at what households actually consume. The determination of energy labels is not fully accurate, and having solar panels can result in a better energy label but not lower energy use per se. We do not expect overall model results to be significantly affected due to the uncertainty caused by this shortcoming. Another limitation here is that the costs for increasing energy efficiency of buildings and of connecting to a heat network are not specified for each building type (only the distinction between single-family and multi-family buildings is made. These costs might vary in specific cases for different dwelling types. Lastly, one should realise that not all micro-level data was specified on the household level, so characteristics such as income do not reflect the income levels of the actual households, but are based on averages of that household type.

The indicators for energy used in this study also cause limitations. Measuring energy poverty or wellbeing effects using concrete indicators is preferred over modelling a conceptualisation of capabilities and measuring these capabilities, because of the availability of data (e.g. on energy consumption and income from CBS). Capabilities are hard to measure in real life and would require surveys to be measurable which depend on a person’s own understanding of the described questions and capabilities. However, while the indicator approach, such as using the indicators of Mulder (2021b), is easier, the actual effects of energy poverty on one’s wellbeing remain unknown and personal differences remain out of sight.

The model is not suited to investigate or draw conclusions on hidden energy poverty caused by affordability issues. This is due to the driving factors for the energy consumption of households considered in this model: other than dwelling characteristics, only ‘environmental attitude’, and ‘energy use awareness’ caused by awareness campaigns play a role. There are not driving factors related to income, energy expenditure, or purchasing power that modify energy use and could cause model households to reduce their energy use due to affordability issues. However, while some studies do find a relationship between income and space heating energy consumption (Cayla et al. 2011) or overall energy consumption (Guo et al. 2018), other studies that control for other factors such as household type or dwelling size do not find such a relationship (Wiesmann et al. 2011), or find that the effect is small compared with the effect of household size and dwelling type (Longhi 2015). For Dutch homes, gas consumption is determined mostly by the building’s age, type and dwelling characteristics, and electricity consumption is determined by household composition (Brounen et al. 2012). Individual differences such as extra energy demand due to medical situation are also not included in the model. These situations might constitute a hidden group experiencing energy poverty. Research on the factors causing hidden energy poverty is therefore needed.

Another limitation of the model is that it does not account for the potential feedback effects that could arise from the interactions between households and the heat network. For example, if the switch to the heat network leads to an increase in energy poverty among some households, this could lead to resistance against the heat network and other households not choosing to connect.

The model’s variability is quite large. A large part of this uncertainty comes from the large variation in the fraction of renters in model, due to assignment of whole buildings to corporation or private ownership. This variability could be reduced if empirical data is used assign corporation or private ownership to specific buildings, but this information was not directly available and would have to be assigned to buildings individually and manually. Through repetition of scenario runs, variability in results was reduced, and insightful patterns did emerge from which we could draw reliable conclusions.

Overall, the agent-based model provides a useful starting point for exploring the potential impacts of a heat network on the extent and distribution of energy poverty in Delft. Incorporating all dimensions and contributing factors of energy poverty and human psychology in a model is impossible and undesirable. This was also not needed to assess the key factors of heat network implementations that contribute to energy poverty and inequality. However, further development of the model may be necessary to account for important psychological and social factors and other potential feedback effects between households’ socio-economic status and their energy consumption and decision-making. Inclusion of these factors might reveal relevant factors that contribute to energy poverty and inequality.

7.4 Implications for energy transition and translation to other cases and scales

The key findings discussed before call for a redesign of the district heating pricing structure and the implementation of policy measures that decrease energy poverty and inequality. We provide recommendations on these topics in the final chapter of this thesis. We showed that the switch to a heat network can increase access of vulnerable households to clean energy, if done correctly. However, the same households might face increased issues in energy affordability. Especially vulnerable households – low-income groups and renters – were most effected by the heat network, and current regulations and pricing structures do not seem to consider these groups. The heating transition is thus both an opportunity and a threat for vulnerable households. The results show that energy poverty alleviation and the just energy transition can be tackled together, such as through the renovation of buildings with poor energy efficiency. We therefore call for a more holistic approach to these issues that pays special attention to the situation of vulnerable households.

While two specific neighbourhoods in Delft were used in this study, many of the results apply to other neighbourhoods with similar characteristics in the Netherlands. This can be evaluated by using data from other neighbourhoods as model input and comparing the results. Since the ABM can be used flexibly, variables and input data can be tweaked to fit the circumstances and characteristics of other neighbourhoods and their institutional context to investigate the issues of energy poverty and inequality there.

7.5 Discussion on indicators for energy poverty

Current energy poverty indicators do not reflect which households have fewer opportunities to participate in the transition to a clean energy supply.

The energy transition can play a key part in addressing energy poverty if it is implemented in a just way, and households who stay behind in the transition may face energy affordability issues. While the oLEQ and rLEQ indicators represent the lack of opportunity to improve the energy efficiency of one's home, they do not consider the energy system itself. Opportunities to improve the home's energy system are not reflected in this indicator, even though the sustainability of the energy supply is also an important aspect of the energy transition and in energy justice. Renovating one's home might be easier than switching to an alternative energy supply. Households may be much more dependent on plans for their neighbourhoods (or the lack thereof), such as whether a heat network is being planned and for which dwellings. These opportunities are currently not assessed. The development of a new method to assess these might contribute to improving opportunities for households in the energy transition.

In addition, if a person lives in a dwelling with a good energy label, the oLEQ and rLEQ indicators indicate no energy poverty vulnerability, while they may still be at risk of increasing energy prices of a fossil fuel-based energy supply. Having an indicator that reflects the opportunities to improve the sustainability of one's energy system is important, considering that the costs of fossil fuel-based energy systems are expected to rise – caused by there being increasingly fewer users having to pay for the upkeep of current infrastructure and increasing carbon taxes on fossil fuels. Households with fewer opportunity to switch to a sustainable heating system thus face an increased risk of energy poverty.

Hidden energy poverty is not adequately measured using current energy poverty indicators.

LILEQ- is the currently the only used indicator that can give an indication into hidden energy poverty. However, this indicator only looks at LEQ households. Especially in scenarios where buildings with poor energetic quality have been renovated to a better energy label, the LILEQ- indicator loses its use.

Another problem with the LILEQ- indicator is that it is defined as 'underconsumption'. In the context of the energy transition and reducing our footprint, this definition seems contradictory to the need to reduce energy consumption. Of course, this 'underconsumption' is in the context of consumption that is insufficient to meet one's needs, such as thermal comfort or preparing a warm meal. It is therefore important to further examine the capability effects that (hidden) energy poverty causes, and instead quantify the reduction in capabilities or 'uncapability' (Bartiaux et al. 2018) that is caused by energy poverty.

7.6 Scientific contributions

This research contributes to the flourishing field of energy justice by combining the capability approach, energy justice and energy poverty in an agent-based model to improve the assessment of distributive justice for a particular case. The current work makes the following methodological contributions to the literature on energy poverty and energy justice. Firstly, the use of an ABM to study energy poverty allows for studying the interactions between household characteristics, technologies and policy interventions and their impact on energy poverty. Secondly, the use of a spatially explicit model of an actual neighbourhood, using detailed building and address data, allows for a more realistic representation of the emergence and distribution of energy poverty. By using data from a specific neighbourhood, the model can consider local characteristics such as the type and ownership of housing. This use of data allows for better calibration and verification of model results. Lastly, by integrating the capability approach and energy poverty frameworks, this study takes a broader look at energy poverty compared to most of the previous work. The multiple dimensions of energy poverty, such as the ability to switch to a clean energy system and to increase the sustainability of one's home, are especially relevant in the energy transition. Taking these dimensions into account can lead to a better understanding and representation of the experiences of those with energy poverty and to informing just energy policy. The approach used in this work could serve as a starting point for better ex ante evaluation of distributive justice of novel energy technologies and development of improved indicators for energy justice, which are needed to ensure a just energy system (Sovacool and Dworkin 2015).

To our best knowledge, examining distributive justice aspects of heat network implementation has not been done, and doing this for a specific case in Delft before the technology is implemented could serve to inform policy making and prevent injustices from occurring. Furthermore, by applying these concepts in a spatially explicit model rather than a simplified representation of a neighbourhood is useful in examining spatial inequalities in energy poverty and contributes to the emerging field on spatial aspects of energy justice (Bouzarovski and Simcock 2017).

As a further remark on the scientific relevance of this study, modelling justice, human behaviour and psychology are upcoming fields. Modellers, psychologists, and ethicists often speak different languages and are only recently beginning to collaborate. This thesis contributes to this emerging field by combining these disciplines and by consulting experts from the domains of climate psychology, ethics, energy system modelling and professionals from the industry.

Besides the contribution to energy justice, the recommendations in this thesis may contribute to speeding up the energy transition. Distributive justice – a fair distribution of societal costs – are an important factor for the public acceptance for the energy transition (Van Aalderen et al. 2021). Public acceptance is necessary for the implementation of sustainable energy systems. The energy transition may generate geographically-uneven inequality and may increase the vulnerability of certain social groups or places, so finding these inequalities and groups are essential for a just transition (Bouzarovski and Simcock 2017). Also, (Pellegrini-Masini et al. 2020) suggest that citizens experiencing higher levels of equality hold higher levels of pro-environmental attitudes or a higher sense of responsibility towards the environment, based on the work by (Wilkinson and Pickett 2010; Rothstein and Uslaner 2005). Designing an energy transition that promotes equality could thus increase citizens' acceptance and support, and thereby increase the pace of the transition. Drews and van den Bergh (2015) support this claim, observing that climate policies based on the principle of equality (progressive distribution of policy posts) are more likely to be supported. In sum, this work is an opportunity to mobilise policy-makers, researchers and energy professionals to ensure a just energy transition.

7.7 Relevance to Industrial Ecology

This thesis was written as part of a master's programme in Industrial Ecology (IE). IE is a concept that views industrial systems not in isolation from its surrounding environment, but as part of it and interacting with it (Jelinski et al. 1992). In this thesis, we apply this concept by examining the interactions between a technological system – a heat network – and its social and institutional environment, and viewing this as one complex sociotechnical system. Throughout the work, multiple methods, theories, and concepts relevant to the field of IE are combined, such as the study of complex socio-technical systems and agent-based modelling.

This work touches upon multiple challenges related to IE and the energy transition. In line with the holistic systems view of IE, scholars have emphasized the need to view social and environmental goals as intertwined issues. For example, Doughnut Economics describes the 'safe and just space for humanity', in which we provide everyone's needs while not transgressing the planetary boundaries (Raworth 2017). This study contributes to this view by exploring the governance and socio-economic effects of a sustainable energy technology. Using the lens of energy justice, this work adopts a critical attitude towards sustainability. This critical attitude involves taking multiple perspectives when examining the topic using three frameworks related to inequalities and justice. By examining inequalities that can be caused by a heating technology, design requirements for a just energy system can be adapted to prevent injustices. As such, this study contributes to a just energy transition by examining the distribution of energy system effects and identifying groups affected by injustices as to prevent these (McCauley et al. 2013; Jenkins et al. 2016; Heffron and McCauley 2018).

Chapter 8.
Conclusions and recommendations

Synopsis
In this chapter, we present a summary of the key findings of this thesis, discuss the recommendations that follow our main findings and provide suggestions for further research.

Recommendations
1. Shift the balance from fixed heat network costs to variable costs.
2. Determine maximum district heating prices in a more fair way that accounts for differences in energy consumption.
3. Develop policy for energy poverty and the energy transition in tandem.
4. Consider household differences when creating policy.
5. Tailor policy interventions and target them at specific socio-economic groups vulnerable to energy poverty.
6. Collaborate with housing corporations to lead the just energy transition.
7. Support households that cannot achieve housing cost neutrality.
8. Develop a national framework for energy poverty and a just transition that recognises regional and local differences.
9. Measure and monitor energy poverty using multiple indicators.
10. Develop an energy policy indicator on the ability to increase the sustainability of one's energy supply.
11. Use household-level microdata to capture local spatial inequalities in energy poverty.
12. Collaborate with social scientists and psychologists for better representation of human characteristics in models and policy.

Further research
Further research could focus on the following topics:
- Further examining what groups are vulnerable to (hidden) energy poverty in the energy transition.
- Addressing procedural justice of the energy transition in models.
- Examining spatial energy justice aspects of low-carbon energy technologies.
- Improving representation of psychology, decision-making and motivations, barriers and enabling factors in the decision to switch heating systems.
- Further investigating the effect of heat networks on capabilities within and between households.

Conclusion
The transition to a heat network constitutes both an opportunity and a threat for vulnerable households. Heat pricing and policy should be adjusted to account for the situation of these groups. If this is done, the switch to a heat network could address energy poverty, reduce inequality, and speed up the transition to a low-carbon energy supply.

8.1 Summary of key findings

Inequalities in energy poverty and accessibility as a result of heat network implementation

13. Within districts, high inequality occurs in the distribution of energy poverty.
14. When gas prices are low, switching to a heat network increases energy poverty.
15. Renters and low-income groups are affected most in changes in energy expenses.
16. The distribution of income groups or household types among energy-poor groups is unaffected.
17. Low-income households are affected most by high heat network prices.
18. High heat network prices increase inequality in energy expenses.

The effect of policy interventions on energy poverty and inequality

19. Building renovations are most effective in decreasing energy use and energy poverty.
20. Vouchers increase accessibility of the heat network.
21. Awareness and energy efficiency interventions reduce the fraction of HEQ households in all income groups except the lowest, when energy prices are high.
22. Tested interventions did not reduce energy poverty inequalities between household composition groups.
23. Building renovation decreases inequality in energy expenses, other measures do not.
24. Low-income renters have good heat network access; vouchers increase access for homeowners.

8.2 Recommendations

8.2.1 Remove counterproductive incentives in heat prices

Recommendation 1: Shift the balance from fixed heat network costs to variable heat costs.
Main actors: District heating energy providers, Dutch government

The high fixed heat costs of district heating are a source of inequality. Due to the high fixed costs of heat networks compared to natural gas-based systems, households with a low heat demand face relatively high costs and may even pay more than before the switch to a heat network. This violates the no-more-than-usual principle and produces inequality. By shifting the focus from fixed costs to variable costs, the no-more-than-usual principle may also apply to low-consumption households.

The increased energy prices of 2023 were effectively a shift from the fixed heat network costs to variable costs. This resulted in the heat network decreasing inequality slightly, but overall much more households faced energy poverty. The results show that shifting the balance from fixed heat network costs to variable costs reduce inequality in energy expenses. However, this shift should be accomplished by decreasing the fixed costs, not by increasing the variable costs, to reduce energy poverty. The high investment and upfront costs of the switch to a heat network should also be part of this shift to variable costs. This can be done by incorporating costs of the delivery set for individual heat network connections into the heat price. This would be similar to the situation for renters where boiler installation costs are in included in the rent.

Besides reducing inequality, this shift comes with other advantages. First of all, it makes sure that households with a low heat demand also profit from the no-more-than-usual principle. Importantly for the energy transition, it encourages household to switch to the heat network since they have the prospect of reducing their energy bill and decreases the barrier to switch to the heat network. It also encourages households to reduce energy consumption, since this will lead to more savings on the energy bill.

Recommendation 2: Determine maximum district heating prices in a more fair way that accounts for differences in energy consumption.
Main actors: Dutch government, district heating energy providers, ACM

ACM determines maximum heat prices based on the no-more-than-usual principle, based on the price of natural gas, as determined by the Dutch Heat Law. Due to the high fixed costs of heat networks, households with a low energy demand often face an increased energy bill when switching to the heat network, despite the no-more-than-usual principle. The determination of heat prices should better reflect the varying energy demand of households, protect low-income households and encourage lower energy consumption. This can be done by having multiple levels of district heating prices, based on consumption. This should ensure that households with low energy consumption do not pay more than usual when switching to a heat network.

In addition, heat network prices are coupled to gas prices. As a result, district heating prices may rise when the gas price increases, even if the heat network is not using gas as an energy source, as has been the case in the current energy crisis. This is also the case when gas is taxed more: this would also raise the maximum allowed price for heat. This creates a wrong incentive since the goal is to switch away from natural gas. Heat prices should therefore be based on actual costs of operation. Still, regulations on district heating prices are needed to protect consumers, since often only a single heat provider is present. The proposed change in the district heating price structure could tackle both the inequality caused by the current scheme and get rid of the connection with gas prices.

8.2.2 Create policy interventions that reduce inequalities in the energy transition

Recommendation 3: Develop policy for energy poverty and the energy transition in tandem.
Main actors: National and local policy makers

Energy-poor household experience difficulties in affording energy or a lack of opportunities to invest in renovations or low-carbon energy systems. The energy transition may alleviate these difficulties and provide an opportunity to increase the sustainability of their home and energy system, but only if combined with effective policy that ensures that all household are included. Since energy poverty can be a highly local issue with large differences between neighbourhoods and buildings, the creation of the neighbourhood execution plans (*warmte-uitvoeringsplannen*) is a great opportunity to incorporate local energy needs. Policy for energy poverty should thus not be seen as a separate issue but intertwined with energy transition policy.

Recommendation 4: Consider household differences when creating policy.
Main actors: National and local policy makers

Policymakers can also benefit from investigating household differences to create policies that are targeted more specifically and effectively. The example of how determining heat prices based on the average household produces inequality shows the importance of considering household heterogeneity. Furthermore, the socio-economic situation of households may mean that they respond differently to policies than expected, and interventions might not even reach these households. For example, households might not understand complicated subsidy schemes and procedures, might not have the time or energy to apply for these, or might not even consider changing their energy system. These differences should be considered when creating policy, and tailored policies that target socio-economic groups specifically are needed. Collaborate with citizens and community representatives to ensure that the needs of vulnerable households are recognised. Since these households are often hard to reach and underrepresented in participative processes, special attention should be given in involving these households in the process.

Recommendation 5: Tailor policy interventions and target them at specific socio-economic groups vulnerable to energy poverty.
Main actors: National and local policy makers

Specific groups in society, such as low-income groups, single-person households and renters, experience higher levels of energy poverty and are affected more by the implementation of a heat network. Generic policy interventions may be less effective for these groups and fail to reduce inequalities between groups. To reduce inequalities between socio-economic groups, interventions adapted to the situations of these groups and the barriers they face are therefore needed. For example, instead of targeting all households in an awareness campaign, efforts could be focused on informing elderly households on how to apply for energy vouchers. Energy improvement efforts should be focused on the homes of renters that have little influence on the energy quality of their homes, particularly of renters with additional energy needs such as elderly and those with poor health.

Recommendation 6: Collaborate with housing corporations to lead the just energy transition.
Main actors: Housing corporations, national and local governments

Low-income renters are at risk in the energy transition due to having limited opportunities to invest in renovations and energy systems. Housing corporations therefore have a large responsibility in reducing energy poverty of their tenants. Our results show that when housing corporations lead the energy transition by investing in a new heat network of energy efficiency improvement, this increases opportunities for their tenants to participate in the energy transition. Especially low-income households have better access to clean energy this way. This reduces inequalities with other households. In addition, the large scale of most housing corporations allows for a project-based approach with lower costs. Governments should work to enable housing corporations, for example using taxation policy and providing a solid business case as has been done in Delft.

Recommendation 7: Support households that cannot achieve housing cost neutrality.
Main actors: National and local policy makers

Switching to a low-carbon energy system and investing in renovations to improve energy efficiency requires large upfront costs. However, despite a decrease in energy costs this might lead to an overall increase in housing costs for some households. These include households with a low energy consumption such as single-person households. To incentivise these households to still participate in the energy transition and prevent them from having increased costs, these households should be supported. Vouchers help in increasing opportunities for these households to participate in the energy transition by removing the barrier that upfront investment costs pose and by decreasing the housing costs after the intervention.

8.2.3 Develop a framework of energy poverty indicators and just transition aims

Recommendation 8: Develop a national framework for energy poverty and a just transition that recognises regional and local differences.
Main actors: National, regional, and local policy makers, citizens

A national framework and indicators for energy poverty and a just transition is currently lacking. Fundamental criteria that the energy transition should follow should be determined on a national level to ensure that all citizens have the same opportunities and protection. This framework should outline principles that policy for energy poverty and the energy transition should follow, such as the recognition of vulnerable groups and that energy transition plans should reduce inequality. These principles can be based on the principles of energy justice. At the same time, regional and local circumstances differ greatly and energy poverty has high regional and local inequality. To take local circumstances into account, more specific criteria should be defined in a participative process.

Table 21. Energy justice principles of the energy justice decision-making tool (Sovacool and Dworkin 2015).

Principle	**Explanation**
Availability	People deserve sufficient energy resources of high quality
Affordability	All people, including the poor, should pay no more than 10 percent of their income for energy services
Due process	Countries should respect due process and human rights in their production and use of energy
Good governance	All people should have access to high quality information about energy and the environment and fair, transparent, and accountable forms of energy decision-making
Sustainability	Energy resources should not be depleted too quickly
Intragenerational equity	All people have a right to fairly access energy services
Intergenerational equity	Future generations have a right to enjoy a good life undisturbed by the damage our energy systems inflict on the world today
Responsibility	All nations have a responsibility to protect the natural environment and minimize energy-related environmental threats

Having clear criteria helps in designing better energy systems and policies, to obtain public acceptance and support, to protect vulnerable groups and to reduce uncertainty about the energy transition. These criteria should be defined together with a diverse group of citizens to ensure recognition of all socio-economic groups. Well-defined indicators are important to compare energy poverty and inequality between regions and determine the progress made. These criteria could be based on the energy justice decision-making tool (Sovacool and Dworkin 2015), which includes principles for energy justice (Table 21). Including citizens in this process contributes to recognising the lived experience of people experiencing energy poverty and informing the creation of more just energy policy (Straver et al. 2020a).

Recommendation 9. Measure and monitor energy poverty using multiple indicators.
Main actors: National government and agencies, municipalities, scientists

There is no single indicator for energy poverty that captures the full picture of the problem. Due to the multi-dimensionality of energy poverty, multiple indicators are needed to capture all dimensions, including affordability of energy, underconsumption, and opportunity to participate in the energy transition. Each indicator comes with its own advantages and shortcomings. Relying on a single indicator results in policies that fail to meet the needs of households (Middlemiss et al. 2018). Only when data is available on each of the aspects and the underlying causes of energy poverty can effective policy be made. Moreover, the energy poverty levels should be monitored continuously, especially in the context of a new energy technology and policy to assess the effects.

Use a framework of indicators that reflects the diverse dimensions of energy poverty (see e.g. Mulder et al. 2023).

- Choose energy poverty metrics carefully. Using ‘fraction of income spent on energy’ as metric results in ‘hidden energy poverty’, where households that turn down their heating to uncomfortable levels to save money stay out of sight.
- The availability of recent and accurate data on energy use and energy labels is crucial for models such as the one in this study. This data is not always available on a household level. For example, energy (gas) use data is often only given on a neighbourhood level, or only a theoretical estimate is given on household level, while actual usage is often much lower (Majcen 2016).

Other academics have also recommended the implementation of a national measurement and monitoring system for energy poverty based on multiple indicators (Straver et al. 2020a; Feenstra et al. 2021). By including diverse indicators – e.g. on household indebtedness to energy providers, social services dependency to pay energy bills, difficulties to improve the energy efficiency of one’s home, or the inability to switch to low-carbon heating systems – the experiences of energy poverty can be accounted for (Straver et al. 2020a).

Recommendation 10. Develop an energy poverty indicator on the ability to increase the sustainability of one’s energy supply.
Main actors: Policy makers, research institutes, citizens

Currently, no indicator exists that examines to what extent households can obtain a sustainable energy supply. The oLEQ and rLEQ indicators are used to determine a household’s opportunities to participate in the energy transition to reduce the risk of future energy affordability. While this indicator reflects one’s ability to improve the energy efficiency of one’s home, it does not indicate the opportunities one has to improve the sustainability of one’s energy supply (see section 7.4 for further discussion). An indicator, like the oLEQ and rLEQ indicators, is needed to ensure that all people have access to clean and affordable energy and that no households are left behind in the energy transition. It should be able to assess to what extent households are able to obtain a sustainable energy supply, reflecting the dimension of energy poverty concerning environmental sustainability of energy and to ensure the aim of energy justice that all people have access to clean and affordable energy. This indicator would be useful to determine which households and what socio-economic groups are at risk to be left behind in the energy transition.

Recommendation 11. Use household-level microdata to capture local spatial inequalities in energy poverty.
Main actors: Policy makers, researchers

Microdata of household characteristics can be used to determine which households are at risk of energy poverty, which can occur highly concentrated locally. By using household-level data instead of aggregated data on e.g. a neighbourhood level, researchers and policy makers can determine if energy poverty is a highly concentrated phenomenon, what characteristics determine energy poverty in a specific area and which households have the highest occurrence and severity of energy poverty. This can be used to inform more targeted and effective policy for energy poverty.

Recommendation 12: Collaborate with social scientists and psychologists for better representation of human characteristics in models and policy.
Main actors: Modellers, policy makers, researchers

Most models still assume that the individuals in the model are rational actors, lack in heterogeneity of actors and fall short in representing human decision-making and psychology. Collaborating with social scientists and psychologists when developing models could ensure better representation of these factors. Investigate individual differences in decision-making, psychology, socio-economic factors, and other causes for energy poverty and how these factors interact to produce inequality. This will lead to better examination of the diverse effects of policies on heterogeneous individuals with different socio-economic contexts.

8.3 Further research

Based on the time and methodological limitations of this thesis and its outcomes, we provide directions for further research. First, while this work examines low-income and homeowner-renter socio-economic groups potentially affected by energy poverty, this is only a selection of possible social groups. To protect vulnerable groups, it is necessary to further investigate what groups are vulnerable (McCauley et al. 2013; Jenkins et al. 2016), such as those with medical conditions, a different cultural background or language. Furthermore, the hidden effects of energy poverty are still relatively unexplored, which could be done in future research using a model such as the one developed in this thesis.

The distributional aspect of energy justice was addressed in this thesis. However, the procedures used in the development of new energy systems and the way that affected groups are involved may also lead to injustices (Walker and Day 2012; McCauley et al. 2013; Lavrijssen and Vitéz 2021). Further research could focus on incorporating procedural justice aspects in models to examine procedural injustices in the energy transition. The inclusion of various social groups is important to understand the circumstances and differences in these groups and the way that policy and technology affects them. For instance, by involving vulnerable groups, one can see what barriers they face in the energy transition or in using already available tools and financial aids. In addition, the needs of vulnerable groups should be recognised, which can be achieved using more participatory research.

Another interesting aspect to further explore is the spatial aspect of energy justice (Bouzarovski and Simcock 2017). Questions that could be addressed are for example whether the implementation of a heat network or other low-carbon energy technology in one neighbourhood leads to inequalities between this neighbourhood and other nearby neighbourhoods, and whether heat networks cause other spatial injustices. Since heat networks are more financially viable and more efficient in dense urban areas, households outside these areas may face higher costs or fewer opportunities to participate in the energy transition.

Models such as the one developed in this study could be further improved in their representation of psychology and decision-making (de Vries et al. 2021). By involving psychologists and behavioural scientists in the model design and by including empirical data from households of interest could improve the quality of models. Further research is also needed on the factors that households consider when in their energy transition decision-making, at what moments households may consider changing their heating system, and what moments are the best to switch. It might be beneficial to clarify household motivations, barriers and enabling factors through questionnaires and interviews to further understand their decision-making strategies and energy poverty, and using this empirical data as a basis for ABM. A methodological approach to link empirical data to an ABM in the context of energy has been developed by Edelenbosch et al. (2022), who showed the potential for this approach. However, one should note that efforts and data requirements are high for this approach. A final improvement in the modelling of household decisions is to consider the multiple levels that decision takes place in, such as the homeowner association or group decisions (Nava-Guerrero et al. 2021, 2022).

This study only looks at the effect of heat networks on inequality in energy poverty. Energy systems might also produce inequalities in other capabilities of households and conflicts in capabilities within and between households (de Wildt et al. 2020, 2021). Expanding the model to include other capabilities could yield new insights on diverse types of inequalities within and between households in the switch to a new heat network.

8.4 Conclusion

In this thesis, an agent-based model was built to explore inequalities that could occur in energy poverty and heat network access because of the implementation of a heat network. The main research question was "What inequalities might arise for households from the switch to a geothermal heat network in the Voorhof and Buitenhof districts in Delft and how can these be reduced?". Various scenarios for the implementation of a heat network and policy interventions were explored. The interventions that were considered were an energy awareness campaign, energy efficiency improvement of dwellings with poor energy labels, reduced energy tax for low energy use and increased energy tax for high energy use, and vouchers to cover heat network connection costs.

The implementation of a heat network in Voorhof and Buitenhof may lead to a more inclusive energy transition. The leading role of the housing corporations in this project provides increased opportunity for low-income renters to participate in the energy transition. By combining this project with the increase of dwelling efficiency and raising awareness of energy use, energy poverty can be reduced. However, the high fixed costs of district heating is a main driver of inequality. Due to this, households with a lower energy use than average may experience an increase in their energy expenses after switching to a heat network. Displacing the heat costs from the fixed costs to the variable costs could therefore contribute to reducing inequality and a more just heat network. The results of this thesis highlight the importance of considering the vulnerable households' needs and of applying justice principles in designing the energy transition.

Appendices

The NetLogo model and data input files can be found on the 4TU.ResearchData repository using the DOI 10.4121/21930939.

Overview of appendices

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F.3 Additional scenario results, heat network, interventions

Appendix A. Model input data

A.1 Functional energy demand of households

Source: Functioneel ontwerp Vesta MAIS 5.0 (PBL 2021), Table B.4. This data is based on CBS data of actual energy consumption for the year 2018 (CBS, 2019) broken down per dwelling type, year of construction, floorspace classification, and certified energy label (RVO, 1-1-2020). The PBL input data distinguishes between low-rise apartments and high-rise apartments, however, BAG does not include this distinction. Since the neighbourhoods of interest consist mostly of high-rise buildings, the figures for high-rise apartments were used for the dwelling category 'apartments'.

*Table 22. Functional energy demand for space heating (*V RV*); warm tap water (*warmwatervraag*); electric appliances (*elektrische apparatuur*); and cooling (*koudevraag*), per dwelling type*[1] *(*Type woning*), energy label (*schillabel*) and year of construction (*Bouwjaar*), fixed demand per connection (*aansl*) and variable demand per floor area in* m^2 *(PBL 2021).*

		V RV schillabel G		V RV schillabel F		V RV schillabel E		V RV schillabel D		V RV schillabel C	
Type woning[1]	Bouwjaar	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2
vrijstaand	voor 1930	31.76778	0.179139	29.23456	0.204506	29.09763	0.19694	26.29055	0.18602	26.15362	0.163974
vrijstaand	1930 - 1945	34.36946	0.178797	31.39122	0.195058	26.25632	0.221383	28.72107	0.178797	33.95867	0.127003
vrijstaand	1946 - 1964	30.26154	0.177565	33.37671	0.182152	28.51568	0.211318	25.67437	0.189957	24.98971	0.172053
vrijstaand	1965 - 1974	16.64661	0.269308	33.4206	0.18044	35.71419	0.176264	26.95063	0.204951	21.40494	0.199405
vrijstaand	1975 - 1991	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	24.17979	0.18133
vrijstaand	1992 - 1995	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	19.78109	0.153054
vrijstaand	1996 - 1999	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	15.63894	0.165891
vrijstaand	2000 - 2005	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	15.63894	0.165891
vrijstaand	2006 - 2010	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	15.63894	0.165891
vrijstaand	2011 - 2014	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	15.63894	0.165891
vrijstaand	2015 - 2020	16.64661	0.269308	35.95582	0.155177	20.37997	0.232611	27.84269	0.184582	15.63894	0.165891
2 onder 1 kap	voor 1930	19.78109	0.181193	21.69812	0.166439	18.24062	0.164454	15.53624	0.173183	15.98127	0.151206
2 onder 1 kap	1930 - 1945	22.82779	0.173868	23.23859	0.164488	20.39728	0.167911	20.36304	0.153568	15.98127	0.176812
2 onder 1 kap	1946 - 1964	21.39002	0.157949	26.07989	0.118445	24.81329	0.117829	20.19188	0.112831	16.22089	0.132891
2 onder 1 kap	1965 - 1974	25.77305	0.172156	17.11219	0.220869	21.6309	0.186534	25.0884	0.142784	19.71387	0.155074
2 onder 1 kap	1975 - 1991	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	22.55518	0.131008
2 onder 1 kap	1992 - 1995	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	11.17202	0.174107
2 onder 1 kap	1996 - 1999	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	17.29966	0.123238
2 onder 1 kap	2000 - 2005	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	17.29966	0.123238
2 onder 1 kap	2006 - 2010	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	17.29966	0.123238
2 onder 1 kap	2011 - 2014	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	17.29966	0.123238
2 onder 1 kap	2015 - 2020	25.77305	0.172156	32.75651	0.045632	9.82064	0.258217	23.27407	0.144256	17.29966	0.123238
rijwoning hoek	voor 1930	22.68283	0.164248	22.51167	0.159079	14.94626	0.215323	14.09044	0.179858	9.332105	0.223642
rijwoning hoek	1930 - 1945	29.32397	0.142374	27.8862	0.153225	13.23463	0.2449	14.53547	0.203616	9.058244	0.227236
rijwoning hoek	1946 - 1964	23.64135	0.155005	22.61437	0.16572	22.9567	0.149734	17.30831	0.155382	16.21287	0.148159
rijwoning hoek	1965 - 1974	21.72432	0.167192	20.90274	0.162126	19.84153	0.160346	23.70981	0.120602	18.74608	0.141586
rijwoning hoek	1975 - 1991	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	19.08841	0.090374
rijwoning hoek	1992 - 1995	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	8.162174	0.178797
rijwoning hoek	1996 - 1999	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	7.340591	0.182563
rijwoning hoek	2000 - 2005	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	7.340591	0.182563
rijwoning hoek	2006 - 2010	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	7.340591	0.182563
rijwoning hoek	2011 - 2014	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	7.340591	0.182563
rijwoning hoek	2015 - 2020	25.42145	0.146071	25.18182	0.109544	14.43277	0.207176	24.83949	0.078975	7.340591	0.182563
rijwoning tussen	voor 1930	15.05058	0.179242	15.32445	0.171985	13.68128	0.177599	9.470664	0.192627	11.59309	0.15949
rijwoning tussen	1930 - 1945	16.72798	0.176606	18.74771	0.159285	14.3317	0.192901	10.73727	0.201117	9.231035	0.18828
rijwoning tussen	1946 - 1964	15.76947	0.173457	15.8037	0.179893	23.77991	0.08031	16.1118	0.139669	12.8597	0.142545
rijwoning tussen	1965 - 1974	15.13435	0.190299	13.73081	0.19071	17.01714	0.153602	24.06907	0.07473	20.91966	0.072881
rijwoning tussen	1975 - 1991	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	20.81697	0.061995	15.37398	0.086814
rijwoning tussen	1992 - 1995	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	6.028466	0.149186	6.405025	0.144873
rijwoning tussen	1996 - 1999	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	6.028466	0.149186	6.199629	0.144667
rijwoning tussen	2000 - 2005	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	6.028466	0.149186	16.50365	0.036526
rijwoning tussen	2006 - 2010	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	6.028466	0.149186	22.5286	0.004553
rijwoning tussen	2011 - 2014	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	6.028466	0.149186	22.5286	0.004553
rijwoning tussen	2015 - 2020	15.13435	0.190299	15.819	0.146071	9.725591	0.190505	6.028466	0.149186	22.5286	0.004553
meergezins	voor 1930	8.116657	0.220527	8.116657	0.21214	6.47349	0.219294	4.65916	0.212927	3.974507	0.203855
meergezins	1930 - 1945	8.493216	0.220287	10.71834	0.189409	7.192376	0.248324	8.219355	0.199645	3.837577	0.227784
meergezins	1946 - 1964	10.41024	0.169897	10.7868	0.164146	9.554428	0.166816	10.06792	0.142716	8.561681	0.131864
meergezins	1965 - 1974	17.07457	0.167363	18.61504	0.11913	15.94489	0.137102	13.92517	0.138745	13.17205	0.113173
meergezins	1975 - 1991	15.04256	0.183898	9.359938	0.236787	11.99585	0.191326	11.65353	0.146173	17.06228	0.062851
meergezins	1992 - 1995	15.04256	0.183898	9.359938	0.236787	11.99585	0.191326	4.739535	0.15456	8.642056	0.110161
meergezins	1996 - 1999	15.04256	0.183898	9.359938	0.236787	10.45639	0.113926	4.739535	0.15456	8.607824	0.101568
meergezins	2000 - 2005	15.04256	0.183898	9.359938	0.236787	10.45639	0.113926	20.14422	0.083185	15.11203	0.064323
meergezins	2006 - 2010	15.04256	0.183898	9.359938	0.236787	10.45639	0.113926	11.45578	0.151343	12.38006	0.08589
meergezins	2011 - 2014	15.04256	0.183898	9.359938	0.236787	10.45639	0.113926	11.45578	0.151343	8.340608	0.150076
meergezins	2015 - 2020	15.04256	0.183898	9.359938	0.236787	10.45639	0.113926	11.45578	0.151343	8.340608	0.150076

[1]Dwelling types: vrijstaand, free-standing; 2 onder 1 kap, two under one roof; rijwoning hoek, corner house; rijwoning tussen, terraced house; meergezins, apartment.

Table 22 (continued)

		V RV schillabel B		V RV schillabel A+		Warmwatervraag		Elektrische apparatuur		Koudevraag	
Type woning	Bouwjaar	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2	GJ / aansl	GJ / m2
vrijstaand	voor 1930	25.73367	0.137922	27.45446	0.12981	8.5	0	9.7	0	0	0.01296
vrijstaand	1930 - 1945	31.06112	0.108013	29.74805	0.131214	8.5	0	9.7	0	0	0.01296
vrijstaand	1946 - 1964	16.6365	0.188424	31.69931	0.116049	8.5	0	9.7	0	0	0.01296
vrijstaand	1965 - 1974	16.58298	0.177613	18.49517	0.183282	9.2	0	9.56	0	0	0.01296
vrijstaand	1975 - 1991	11.88045	0.177333	19.90071	0.155382	9.7	0	9.46	0	0	0.01296
vrijstaand	1992 - 1995	13.54739	0.164279	19.1649	0.135287	10.6	0	9.28	0	0	0.01296
vrijstaand	1996 - 1999	11.21079	0.153593	18.10369	0.131385	10.6	0	9.28	0	0	0.01296
vrijstaand	2000 - 2005	12.33236	0.149511	18.03522	0.130187	10.6	0	9.28	0	0	0.01296
vrijstaand	2006 - 2010	12.33236	0.149511	17.65866	0.121971	10.6	0	9.28	0	0	0.01296
vrijstaand	2011 - 2014	12.33236	0.149511	10.70944	0.135698	10.6	0	9.28	0	0	0.01296
vrijstaand	2015 - 2020	12.33236	0.149511	1.329695	0.126318	10.6	0	9.28	0	0	0.01296
2 onder 1 kap	voor 1930	3.000267	0.232672	9.682459	0.161544	7.5	0	9.9	0	0	0.01296
2 onder 1 kap	1930 - 1945	3.000267	0.232672	9.682459	0.161544	7.5	0	9.9	0	0	0.01296
2 onder 1 kap	1946 - 1964	9.721895	0.159606	12.14721	0.146071	7.5	0	9.9	0	0	0.01296
2 onder 1 kap	1965 - 1974	13.24547	0.167104	9.033289	0.194955	8.2	0	9.77	0	0	0.01296
2 onder 1 kap	1975 - 1991	17.8989	0.120085	14.98977	0.161715	8.2	0	9.77	0	0	0.01296
2 onder 1 kap	1992 - 1995	12.12981	0.152045	11.92513	0.155177	8.6	0	9.68	0	0	0.01296
2 onder 1 kap	1996 - 1999	12.5176	0.134174	21.51027	0.086711	8.6	0	9.68	0	0	0.01296
2 onder 1 kap	2000 - 2005	14.3919	0.108806	11.34318	0.12334	8.6	0	9.68	0	0	0.01296
2 onder 1 kap	2006 - 2010	14.16569	0.081855	13.671	0.099343	8.6	0	9.68	0	0	0.01296
2 onder 1 kap	2011 - 2014	14.16569	0.081855	13.60253	0.080173	8.6	0	9.68	0	0	0.01296
2 onder 1 kap	2015 - 2020	14.16569	0.081855	4.325487	0.127209	8.6	0	9.68	0	0	0.01296
rijwoning hoek	voor 1930	15.60914	0.134203	9.879827	0.183042	7.1	0	9.98	0	0	0.01296
rijwoning hoek	1930 - 1945	15.23062	0.146832	14.91203	0.109544	7.1	0	9.98	0	0	0.01296
rijwoning hoek	1946 - 1964	13.54448	0.145077	16.11017	0.108826	6.4	0	10.13	0	0	0.01296
rijwoning hoek	1965 - 1974	12.9939	0.154402	13.57695	0.145249	7.3	0	9.94	0	0	0.01296
rijwoning hoek	1975 - 1991	6.731089	0.186129	9.160942	0.162913	7.3	0	9.94	0	0	0.01296
rijwoning hoek	1992 - 1995	7.826191	0.182344	6.861334	0.17866	7.7	0	9.86	0	0	0.01296
rijwoning hoek	1996 - 1999	7.275614	0.167375	7.956778	0.153225	7.7	0	9.86	0	0	0.01296
rijwoning hoek	2000 - 2005	7.722957	0.152716	13.6394	0.089998	7.7	0	9.86	0	0	0.01296
rijwoning hoek	2006 - 2010	14.56773	0.090467	16.64886	0.077777	7.7	0	9.86	0	0	0.01296
rijwoning hoek	2011 - 2014	14.56773	0.090467	10.82931	0.101021	7.7	0	9.86	0	0	0.01296
rijwoning hoek	2015 - 2020	14.56773	0.090467	6.721393	0.11687	7.7	0	9.86	0	0	0.01296
rijwoning tussen	voor 1930	9.554432	0.169337	6.526657	0.190915	7.1	0	9.98	0	0	0.01296
rijwoning tussen	1930 - 1945	9.623254	0.160115	10.42918	0.132617	7.1	0	9.98	0	0	0.01296
rijwoning tussen	1946 - 1964	11.72233	0.130452	16.93338	0.077845	6.4	0	10.13	0	0	0.01296
rijwoning tussen	1965 - 1974	11.56565	0.145972	7.705865	0.155587	7.3	0	9.94	0	0	0.01296
rijwoning tussen	1975 - 1991	12.63239	0.096867	3.974507	0.177017	7.3	0	9.94	0	0	0.01296
rijwoning tussen	1992 - 1995	3.719933	0.172159	1.886316	0.178592	7.7	0	9.86	0	0	0.01296
rijwoning tussen	1996 - 1999	3.066123	0.159598	6.199629	0.127209	7.7	0	9.86	0	0	0.01296
rijwoning tussen	2000 - 2005	5.337252	0.139847	7.808563	0.093661	7.7	0	9.86	0	0	0.01296
rijwoning tussen	2006 - 2010	9.845099	0.081589	11.40299	0.079317	7.7	0	9.86	0	0	0.01296
rijwoning tussen	2011 - 2014	7.746025	0.082587	8.219355	0.081371	7.7	0	9.86	0	0	0.01296
rijwoning tussen	2015 - 2020	7.746025	0.082587	1.680921	0.117076	7.7	0	9.86	0	0	0.01296
meergezins	voor 1930	1.9906	0.190287	1.509757	0.188451	5.6	0	8.28	0	0	0.01296
meergezins	1930 - 1945	4.368782	0.182469	4.65916	0.164864	5.6	0	8.28	0	0	0.01296
meergezins	1946 - 1964	6.421186	0.120115	6.850049	0.092668	5.6	0	8.28	0	0	0.01296
meergezins	1965 - 1974	12.30727	0.068316	7.181337	0.144838	6.1	0	8.18	0	0	0.01296
meergezins	1975 - 1991	13.30549	0.066068	6.518629	0.136383	5.4	0	8.32	0	0	0.01296
meergezins	1992 - 1995	5.161984	0.135752	4.876466	0.149939	6	0	8.21	0	0	0.01296
meergezins	1996 - 1999	3.858871	0.142137	2.411716	0.149939	6	0	8.21	0	0	0.01296
meergezins	2000 - 2005	5.585496	0.104998	5.047629	0.123511	6	0	8.21	0	0	0.01296
meergezins	2006 - 2010	8.979917	0.068902	7.553258	0.082158	6	0	8.21	0	0	0.01296
meergezins	2011 - 2014	12.43317	0.019742	5.77316	0.100028	6	0	8.21	0	0	0.01296
meergezins	2015 - 2020	12.43317	0.019742	5.77316	0.100028	6	0	8.21	0	0	0.01296

A.2 Costs for thermal insulation per energy label

Table 23. Costs for thermal insulation per energy label, single-family dwellings in €/m². Source: CE Delft, Table 23 (Naber et al. 2016).

Label	A+	A	B	C	D	E	F
Currently G	441	141	116	102	80	57	30
Currently F	337	138	107	89	61	30	-
Currently E	337	132	96	75	43	-	-
Currently D	253	160	80	34	-	-	-
Currently C	267	157	72	-	-	-	-
Currently B	119	84	-	-	-	-	-
Currently A	64	-	-	-	-	-	-

Table 24. Costs for thermal insulation per energy label, apartments in €/m². Source: CE Delft, Table 24 (Naber et al. 2016).

Label	A+	A	B	C	D	E	F
Currently G	303	170	140	123	96	66	33
Currently F	277	166	128	106	72	35	-
Currently E	232	147	107	85	49	-	-
Currently D	198	122	76	49	-	-	-
Currently C	218	185	69	-	-	-	-
Currently B	82	70	-	-	-	-	-
Currently A	31	-	-	-	-	-	-

A.3 Distribution of household compositions and net monthly spendable income, renters and homeowners

Table 25. Distribution of household compositions and net monthly spendable income, renters and homeowners. Source: WoOn 2021, Figure 2.2 (renters), Figure 2.5 (income) and Figure 3.3 (homeowners), (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2022).

	Alleenstaand < 35 jr (%)	Alleenstaand 35-64 jr (%)	Alleenstaand 65+ jr (%)	Paar < 35 jr (%)	Paar 35-64 jr (%)	Paar 65+ jr (%)	Paar met kinderen (%)	Eenoudergezin (%)
Renters	16	21	21	6	5	9	10	11
Homeowners	3	10	9	4	15	17	36	5
Net spendable monthly income (€)	1973	1932	1707	3934	3460	2626	3989	2537

A.4 Reasonable rent increase after energy label improvement

Table 26. Additional rent after energy label improvement, dwellings < 70 m², in €/month (Woonbond 2022b).

Label	A+	A	B	C	D	E	F
Currently G	27	23	19	15	10	7	2
Currently F	25	21	17	13	8	5	-
Currently E	20	16	12	8	3	-	-
Currently D	17	13	9	5	-	-	-
Currently C	12	8	4	-	-	-	-
Currently B	8	4	-	-	-	-	-
Currently A	4	-	-	-	-	-	-

Table 27. Additional rent after energy label improvement, dwellings 70-90 m², in €/month (Woonbond 2022b).

Label	A+	A	B	C	D	E	F
Currently G	39	37	28	19	9	6	1
Currently F	38	36	27	18	8	5	-
Currently E	33	31	22	13	3	-	-
Currently D	20	28	18	9	-	-	-
Currently C	20	18	9	-	-	-	-
Currently B	11	9	-	-	-	-	-
Currently A	6	-	-	-	-	-	-

Table 28. Additional rent after energy label improvement, dwellings > 90 m², in €/month (Woonbond 2022b).

Label	A+	A	B	C	D	E	F
Currently G	37	33	24	16	8	2	1
Currently F	36	32	23	15	7	1	-
Currently E	35	31	22	14	6	-	-
Currently D	29	25	16	8	-	-	-
Currently C	21	17	8	-	-	-	-
Currently B	13	9	-	-	-	-	-
Currently A	4	-	-	-	-	-	-

A.5 Economic and technical parameters

Table 29. Economic and technical parameters used in the model.

Parameter	Value	Source
Gross Calorific Value natural gas	35.17 MJ/m³	(ACM 2020)
Gas central heating efficiency	104% (space heating) 72% (warm tap water)	(PBL 2021)
Cost of heat network connection	€5000 (apartment) €10000 (other dwellings)	Interviews, CE Delft (Hers et al. 2018)
Social minimum	1756 €/month (couple) 1266 €/month (single)[5]	(UWV 2022)
Average equity	€33800 (homeowner) €2300 (renter)	(CBS 2022a)
Average annual spendable household income	€48400	(CBS 2022a)

A.6 Energy prices

Table 30. Fixed and variable electricity prices for 2019-2021 and 2023, excluding VAT. Source: PBL (Luteijn et al. 2021) for 2019-2021, Dutch energy price cap (Rijksoverheid 2022b) for variable prices in 2023, own estimation for fixed prices in 2023.

Type and unit	Costs	2019	2020	2021	2023[6]
Fixed [€/y]	Network management costs	198	200	209	220
Fixed [€/y]	Delivery costs	55	57	58	61
Fixed [€/y]	Tax reduction	258	436	453	682[7]
Variable [€/kWh]	Delivery costs	0.07	0.06	0.07	0.40 in total
Variable [€/kWh]	Energy tax	0.10	0.10	0.09	
Variable [€/kWh]	Surcharge for Sustainable Energy (ODE)	0.02	0.03	0.03	

[5] We assume all single-person household are aged 21 or above.
[6] Own estimation for 2023, variable costs is based on energy price cap by the Dutch government.
[7] Amount for 2022 (Belastingdienst 2023).

Table 31. Fixed and variable gas prices for 2019-2021, excluding VAT. Source: PBL (Luteijn et al. 2021) for 2019-2021, Dutch energy price cap (Rijksoverheid 2022b) for variable prices in 2023, own estimation for fixed prices in 2023.

Type and unit	Costs	2019	2020	2021	2023[1]
Fixed [€/y]	Network management costs	147	153	152	152[1]
Fixed [€/y]	Delivery costs	55	56	57	59[1]
Variable [€/m³]	Delivery costs	0.29	0.23	0.25	1.45 in total[2]
Variable [€/m³]	Energy tax	0.29	0.34	0.34	
Variable [€/m³]	Surcharge for Sustainable Energy (ODE)	0.05	0.08	0.08	

[1]Own estimation for 2023

[2]2023 variable costs based on energy price cap by the Dutch government.

Table 32. Fixed and variable heat network prices, including VAT. Based on maximum allowed prices by Autoriteit Consument & Markt (ACM 2022a).

Type and unit	Costs	2019	2020	2021	2023[1]
Fixed (maximum) [€/y]	Supply space heating & warm tap water	318.95	469.17	478.60	478.60
Fixed (market)[4] [€/y] (difference with maximum)	Supply space heating & warm tap water	293.43 (-8%)	431.64 (-8%)	440.31 (-8%)	440.31 (-8%)
Variable (maximum) [€/GJ]	Supply space heating and warm tap water	28.47	26.06	25.51	47.39
Variable (market)[4] [€/GJ] (difference with maximum)	Supply space heating and warm tap water	26.19 (-8%)	23.98 (-8%)	23.47 (-8%)	43.60 (-8%)

[1]2023 fixed prices are yet unknown, so 2021 prices were used. Variable costs for 2023 is based on the energy price cap by the Dutch government.

[2]These are the costs for an individual delivery set. Separate costs for collective delivery sets are regulated, but for simplicity we assume each household connected to the heat network pays the costs for the individual set.

[3]Maximum costs for delivery sets were determined since 2020, so an estimation is used.

[4]The market price for total costs including fixed costs for a heat consumption of 30 GJ was on average 4-12% lower than the maximum price in 2021.

A.7 Corporation building ownership

Table 33. Corporation building ownership per neighbourhood and building category, % of dwellings (CBS 2021b).

	Apartment	Terraced house	Corner house	Two-under-one roof	Freestanding	Other
Voorhof	47	43	49	0	0	0
Buitenhof	86	11	14	0	0	0

Appendix B. Input data preparation process

B.1 Data inputs

- CBS Wijken en buurten 2021
- BAG 2.0 File Geodatabase by Esri Nederland, version November 2022
- Energy labels File Geodatabase by Esri Nederland, version November 2022

B.2 Software

QGIS Desktop version 3.24.0

B.3 Operations

Creating buildings shapefile per neighbourhood

- Select “Delft” in CBS layer gemeente_2021_v1. Create new layer consisting of only 'Delft' from gemeente_2021_v1 using *Save Selected Features As…*
  - gemeente_2021_v1_Delft
- Clip 'wijk_2021_v1' using *Clip…* with 'gemeente_2021_v1_Delft' as overlay layer
  - Temporary layer wijk_2021_v1_Delft
- Clip 'buurt_2021_v1' using *Clip…* with 'gemeente_2021_v1_Delft' as overlay layer
  - Temporary layer buurt_2021_v1_Delft
- Clip 'Pand' from BAG using *Clip…* with 'gemeente_2021_v1_Delft' as overlay layer. Use *Invalid feature filtering* “Skip (Ignore) Features with Invalid Geometries”
  - Temporary layer Pand_Delft
- Select Features in Pand_Delft with “gebr_woonfunctie” > 0 using *Select by Expression*.
- Reproject 'Pand_Delft' to WGS 84 using *Reproject Layer…* with *Selected features only*.
  - Temporary layer Pand_Delft_woon
- For each of the following neighbourhoods / districts, select the neighbourhood / district in ‘buurt_2021_v1_Delft’ / ‘wijk_2021_v1_Delft’ and clip Pand_Delft_woon using *Clip…* with the respective selected neighbourhood as overlay:
  - Roland Holstbuurt
  - Multatulibuurt
  - Buitenhof Noord
  - Gillisbuurt
  - Het Rode Dorp
  - Wijk 24 Voorhof
  - Wijk 25 Buitenhof
- Use *Multipart to singleparts* tool and save each clipped layer to shapefiles (.shp) using the following names:
  - roland_holstbuurt.shp
  - multatulibuurt.shp
  - buitenhof_noord.shp
  - gillisbuurt.shp
  - het_rode_dorp.shp
  - wijk_24_voorhof.shp
  - wijk_25_buitenhof.shp

Create address and energy label shapefile per neighbourhood

- Clip 'Adres' using 'gemeente_2021_v1_Delft' as overlay layer.
  - Temporary layer Adres_Delft
- Add energy label data using *Join attributes by field value* tool from the *Processing algorithm Toolbox*. Use Adres_Delft as *Input layer* and Energielabels_Adres as *Input layer 2*, using ‘identificatie’ as *Table field*. Copy the following layers in Layer 2 fields to copy: “Energielabel” “Energielabels_gebouwsubtype” “Energielabels_Woning_type” “Energielabels_gebruiksopprvl”
- *Clip* the resulting layer using ‘Pand_Delft_woon’ as overlay layer
- *Reproject* layer to WGS 84
  - Temporary layer Adres_Delft_energy_labels

- For each of the following neighbourhoods / districts, select the neighbourhood / district in 'buurt_2021_v1_Delft' / 'wijk_2021_v1_Delft' and clip Adres_Delft_energy_labels using *Clip…* with respective selected neighbourhood as overlay:
    - Roland Holstbuurt
    - Multatulibuurt
    - Buitenhof Noord
    - Gillisbuurt
    - Het Rode Dorp
    - Wijk 24 Voorhof
    - Wijk 25 Buitenhof
- Use *Multipart to singleparts* tool and save each clipped layer to shapefiles (.shp) using the following names:
    - address_roland_holstbuurt.shp
    - address_multatulibuurt.shp
    - address_buitenhof_noord.shp
    - address_gillisbuurt.shp
    - address_het_rode_dorp.shp
    - address_wijk_24_voorhof.shp
    - address_wijk_25_buitenhof.shp

Appendix C. Model formalisation and implementation

In this appendix, we describe the model in detail. First, we present the ODD+D table. Then, we describe the model according to each ODD+D element.

C.1 Overview, Design, Details + Decision-making Table

Table 34. ODD+D description of the agent-based model.

Overview	**Purpose**	To explore inequalities in energy poverty and access to energy of households as a result of the switch to a heat network in specific neighbourhoods in Delft.
	Entities, state variables and scales	*Entities and variables:* The model includes two types of entities: *buildings* and *households*. Buildings have variables representing the year of construction, total floorspace, heating system, heat network connection and owner. Households have variables representing socio-economic characteristics (household type, income, equity, homeownership,), dwelling properties (energy label, floorspace, category, heating system), environmental attitude. These factors are used to determine functional energy demand and actual energy use, energy poverty indicators, satisfaction, uncertainty, and decision-making strategy. External variables include energy prices, policy interventions such as energy efficiency improvements and awareness campaigns, and energy costs. *Inclusion of space:* Space is explicitly included in the model using georeferenced (GIS) data of specific neighbourhoods. The data includes the shapes, positions and characteristics of buildings. *Temporal and spatial resolutions:* One time step represents one month, and the simulation is run for five years. The spatial extent of the model landscape is the size of a neighbourhood.
	Process overview and scheduling	*Initialization:* • Load datasets • Create and set-up buildings and households • Set initial parameters *Go:* Each year: • Implement heat network for eligible buildings (specific scenarios and timings) • Renovate eligible buildings (specific scenarios and timings) • Awareness campaign (specific scenarios and timings)

		• Households determine energy consumption and expenses • Homeowners select decision-making strategy and make heating system choice • Calculate reporters The model runs for five years (60 timesteps).
Design	**Theoretical and empirical background**	*General concepts and theories* Capability approach, energy justice, energy poverty. *Assumptions and theories underlying agents' decision models* Agent decision-making is based on a combination of theory (Consumat framework) and empirical data on factors influencing the choice to connect to heat network. We assume that households take different decision-making strategies depending on their level of satisfaction and uncertainty. Assume cost is the most important factor when making the decision to connect to the heat network.
	Individual decision making	Each month, the household determines its energy use based on the predicted energy demand for their household's situation, their environmental attitude and optional awareness campaigns. Each year, the household will evaluate which heating system it prefers with a specific strategy. The strategy used is determined based on the level of satisfaction and uncertainty: • Repetition: if the household is satisfied and certain, it will use the same heating system as in the previous period. • Deliberation: if the household is unsatisfied and certain, it will choose to connect to the heat network if it can afford it. • Imitation: if the household is satisfied and uncertain, household will choose the heating system that the majority of its ten closest neighbours have if it can afford it. • Social comparison: when the household is unsatisfied and uncertain, it will engage in social comparison. First, it reasons which neighbouring households are comparable by observing the household type of neighbours. It will then use the heating system which is the most used by neighbours with the same household type if it can afford it.
	Learning	None.
	Individual sensing	Households sense their endogenous variables such as income, homeownership, energy label, heating system, energy expenses, level of satisfaction and uncertainty, and environmental attitude. They also know the heating system choice of closest neighbours or other households with the same household type, as well as the heating system and ownership of their building. In addition, agents sense exogenous variables such as energy costs, the availability of financial arrangements such as vouchers, and the availability of the heat network. Households are not completely aware or affected by policy interventions such as awareness campaigns. Their internal variable susceptibility determines how much they are affected by the awareness campaign.
	Individual prediction	Households that take the deliberation strategy assume that switching to the heat network will be favourable, or at least neutral, in their total energy expenses.
	Interaction	See also Figure 13. *Agent-agent interactions* Agents interact with other agents when checking the heating system choice of neighbours or similar households. *Agent-environment interactions* For the implementation of the heat network, agent support within buildings is compared to determine if over 50% of inhabitants agree with heat network connection. Households choose available heating systems, and the energy system supplies the required energy to households at the respective costs. Implemented policies interact with the available heating systems and their costs, energy prices, and financial instruments, as well as agent states such as awareness and dwelling efficiency.
	Collectives	Households belong to a certain building and share the same heating system and homeownership of that building.

	Heterogeneity	Households can differ in the variables such as household characteristics, dwelling characteristics, environmental attitude and susceptibility to campaigns.
	Stochasticity	Semi-random assignment of these variables: • Building ownership (corporation or private) and heating system type (collective or individual) • Household type • Income and equity (according to household type and ownership) • Environmental attitude • Susceptibility
	Observation	The model provides the following outputs: • Average energy quote per household type • Average and inequality in energy poverty indicators per household type • Fraction of households connected to heat network per household type • Socio-economic characteristics of households with energy poverty and heat network access
Details	**Implementation details**	The model has been implemented in NetLogo 6.3.0 using the GIS, CSV and Table Extensions.
	Initialization	*Initial state at the start of a simulation run:* • No implementation of heat network *Variation of initialisation among simulations:* • Heat prices
	Input data	*Input data from external sources:* • GIS building & address dataset • Heat demand data per building type, age, energy label • Renovation costs per energy label • Corporation and private ownership per dwelling type • Income and equity data • Household categories • Heat network connection fees
	Sub models	*Sub models listed in 'Process overview and scheduling':* • Household decision-making • Heat network implementation • Capability evaluation See main text for details.

C.2 Entities, variables and scales

Entities

The model includes two types of entities: *buildings* and *households*. Agents representing *buildings* and their characteristics are present in the model environment. In addition, building outlines are represented as drawings based on a geospatially explicit dataset of specific neighbourhoods. The colour of the drawing can represent a building characteristic of choice, such as the number of households within that building or whether the building is connected to the heat network. At the same time, buildings represent a group of agents, namely the households inhabiting that building. *Households* are agents representing inhabitants of a single dwelling within a building and the characteristics of that dwelling (e.g. energy label). The colour of the household can represent a household characteristic of choice, such as the income or energy label.

Variables

Global

Energy poverty indicators

Four indicators for energy poverty are measured in the model: High Energy Quote (HEQ); Low Income High energy Costs (LIHC); Low Income Low Energetic Quality (LILEQ); and owner or renter Low

Energetic Quality unable to renovate (oLEQ/rLEQ). For each indicator, we measure the fraction of households that fulfil the indicator definition.

We use indicators definitions given in Table 12, adapted from (Mulder et al. 2021b). Three definitions have been altered. Firstly, the HEQ has been defined in terms of spendable household income, without savings, since no data on savings per household type have been found. The threshold of 10% is a commonly used rule of thumb. Secondly, the HC has been defined in terms of modelled households, instead of Dutch households, since energy costs are only modelled for households of a certain neighbourhood. Lastly, for the definitions of underconsumption and overconsumption, energy use is taken instead of energy expenses, to make sure that households with a cheaper energy source (such as a subsidised heat network compared to carbon-taxed natural gas) are not regarded as under-consumers.

Accessibility indicators

We measure the fraction of households connected to the heat network, the fraction of households that want to connect but do not have the funds to do this, and the fraction of households who used a voucher to connect.

Inequality indicators

The model keeps track of the averages and distribution of energy expenses using a Lorenz curve and Gini coefficient. In the model, this is implemented based on the calculation of the Lorenz curve and Gini index in the Wealth Distribution model from the NetLogo model library (Wilensky 1998).

Buildings:

Buildings have the following variables:

- Geographical location
- **Nr_households:** Number of households in the building, based on the BAG. *Integer*
- **Buildingid**: Unique building ID, based on the BAG. *Integer*
- **Heating_system:** Heating system present in the building. For multi-family buildings, we assume that 80% have collective heating systems and 20% have individual heating systems based on the stakeholder interviews. *String*
- **Building_connected?**: Whether the building is connected to the heat network. *Boolean*
- **Owner:** Whether the building is privately or corporation-owned. Randomly assigned based on distributions per building type (see Appendix Table 33) *String*
- **Bouwjaar:** Year of construction, based on the BAG. *Integer*
- **Total_floorspace:** Total floor area of the building, based on the BAG. *Float*

Households:

Household and dwelling characteristics

Geographical location and corresponding building.

Household composition

The household type – single, couple, with or without children – and age group is determined based on the distribution of households for renters and homeowners (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2022), see Appendix Table 25.

Dwelling type

The dwelling type is one of the following categories, based on the building type specified in BAG: apartment, corner house, terraced house, freestanding, two-under-one-roof.

Floorspace

A dwelling's floorspace is based on the floorspace specified in BAG. If multiple dwellings occupy one building, the building's total floor area is divided equally among the dwellings in the building.

Income

A household's income is assigned using a normal distribution with mean $I_{avg_{C,T,O}}$ and a standard deviation of 1/3 of the mean. Here, $I_{avg_{C,T,O}}$ is the average income for household composition C, with dwelling type T depending on house ownership O (whether the household is a renter or a homeowner). The income averages are given in Appendix Table 25.

A household is also assigned its income group (0-10% of incomes, 10-20%, etc.). Income groups are based on CBS data on spendable household income for 2021 (CBS 2022b).

Equity

A household's equity is assigned using a normal distribution with the average equity of Dutch homeowners as the mean and a standard deviation of 1/3 of the mean. The used values of average equity are different for homeowners and renters (see Appendix Table 29).

Heating system

All households are assumed to have a gas boiler at the start of the scenario. For single-family buildings, all buildings have individual heating systems. For multi-family buildings, we assume that 80% have collective heating systems and 20% have individual heating systems based on the stakeholder interviews.

Energy label

Each household is assigned an energy label based on the energy label database by Rijksdienst voor Ondernemend Nederland (RVO). If the energy label is unknown, the energy label of the closest neighbour with a known energy label is used. All labels A and higher are clustered to one category (A+) since energy demand data used was also clustered for labels A and above. Since only <1% of dwellings have this energy label, results are not affected significantly.

Energy demand

The functional energy demand of a household is the expected energy need for a household of that dwelling type, composition, year of construction and energy label. The model distinguishes the following categories (end-uses) of energy demand: demand for space heating, warm tap water, electricity demand for appliances and cooling. All types of energy demand are given in GJ per year and are calculated using characteristic values depending on the dwelling type, construction year or energy label, and floorspace. These characteristic values can be found in Appendix Table 22. Note that the functional demand is not equal to the meter demand. The meter demand depends on the efficiency of the heating system used to deliver the functional energy demand (PBL 2021).

Space heating

A household's functional energy demand for space heating D_{SH} is the energy used to heat rooms in the dwelling and is calculated as follows:

$$D_{SH} = climate\_effect \cdot \left(D_{SH_{Xarea}} \cdot area + D_{SH_{Xcon}}\right)$$

Where:

$Climate\_effect$ is given as a factor representing climate scenarios such as cold or mild winters. For example, a mild winter would result in a climate effect factor of 0.9, where an average winter is represented by a climate effect of 1. In this study, we set this factor to 1, but the model allows for variation in this parameter. $D_{SH_{Xarea}}$ is a factor representing the variable space heating demand per unit area which is specified per energy label X, and $D_{SH_{Xcon}}$ is the fixed energy demand for space heating per network connection con for a given energy label X. The floorspace of the dwelling is represented by $area$.

Warm tap water

The functional energy demand for warm tap water D_{TW} is determined depending on the dwelling's construction year, dwelling type and floorspace:

$$D_{TW} = D_{TW_{Xarea}} \cdot area + D_{TW_{Xcon}}$$

Where:

$D_{TW_{Xarea}}$ is the variable energy demand for warm tap water per unit area for a given energy label X, and $D_{TW_{Xcon}}$ is the fixed energy demand for warm tap water per network connection con for a given energy label X.

Appliances

The electricity demand for appliances D_{app} (e.g. lighting, domestic appliances) is determined based on the dwelling type, year of construction and floorspace:

$$D_{app} = D_{app_{Xarea}} \cdot area + D_{app_{Xcon}}$$

Where:

$D_{app_{Xarea}}$ is the variable electricity demand for appliances per unit area for a given energy label X, and $D_{app_{Xcon}}$ is the fixed electricity demand for appliances per network connection con for a given energy label X.

Cooling

The electricity demand for cooling D_c (e.g. lighting, domestic appliances) is determined based on the dwelling type, year of construction and floorspace:

$$D_c = D_{c_{Xarea}} \cdot area + D_{c_{Xcon}}$$

Where:

$D_{c_{Xarea}}$ is the variable electricity demand for cooling per unit area for a given energy label X, and $D_{c_{Xcon}}$ is the fixed electricity demand for cooling per network connection con for a given energy label X.

Energy use

Due to personal preferences, individual circumstances and choices, the actual energy used by a household can differ from the expected energy demand for that household type. These differences can come from a household's environmental attitude, ability to afford energy expenses, and awareness on energy use due to campaigns. For each type of energy end-use T, the actual energy use U is determined as follows:

$$U_T = D_T \cdot c_{env} \cdot c_{inc} \cdot (1 - CampaignEffect)$$

Where:

c_{env} is a conversion factor representing a person's environmental awareness. The higher this awareness, the more energy a household will save. Someone with no environmental awareness will use 20% more energy than expected; someone with the highest environmental awareness will save 20%. This conversion factor is calculated as follows:

$$c_{env} = 1.2 - 0.4 \cdot environmental\_awareness$$

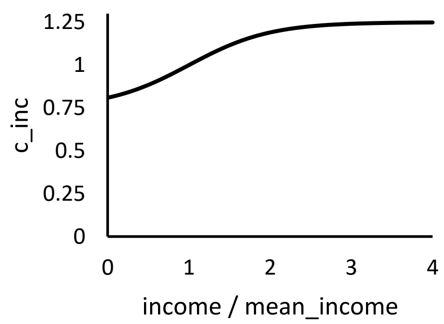
Where:

$environmental\_awareness$ is a factor between 0 and 1 representing someone's awareness of environmental issues such as climate change. A value of 0 means the household has no awareness or interest in these issues, while a value of 1 means the household has high awareness.

c_{inc} is the income-based conversion factor. In this study, this factor is set to 1 after evaluation with experts, since the effect of income on energy use is under debate. Incorporation of this factor in the model does allow experimentation with using income as a factor, which we did during model development and testing in the following way: A low-income household will use up to 20% less energy, a high-income household up to 25% more. c_{inc} equals 1 when the household has an income equal to the mean income of the Netherlands. The c_{inc} is a logistic S-curve with the function:

$$c_{inc} = 0.75 + \frac{0.5}{1 + e^{-2(\frac{income}{mean\ income} - 1)}}$$

This function looks like:



Energy expenses

Annual energy expenses consist of electricity expenses and heat expenses, which are calculated in the following way.

Electricity expenses

A household's annual expenses for electricity $E_{electricity}$ are calculated as follows:

$$E_{electricity} = (costs_{electricity,fixed} + (U_{app} + U_c) * costs_{electricity,variable} - tax\ reduction) * (1 + VAT_{\%})$$

Where:

U_{app} is the electricity use for appliances, U_c is the electricity use for cooling, and $cost_{electricity}$ are the fixed costs and variable costs per unit electricity. $tax\ reduction$ is the annual energy tax refund and VAT is the value added tax expressed as a fraction (i.e. 0.21). These costs are given in Appendix Table 30. The efficiency of household appliances is out of the scope of this study, so we assume the functional electricity demand is equal to the meter demand.

Heat expenses

A household's annual expenses for heat $E_{heat,gas}$ are calculated as follows, depending on their heating system:

$$E_{heat,gas} = \left(costs_{gas,fixed} + \left(\frac{U_{SH}}{\eta_{gas,SH}} + \frac{U_{TW}}{\eta_{gas,TW}}\right) * costs_{gas,variable}\right) * (1 + VAT_{\%})$$

The VAT and the gas central heating efficiency for space heating $\eta_{gas,SH}$ and warm tap water $\eta_{gas,TW}$ are given in Appendix Table 29. The fixed and variable gas costs are given in Appendix Table 31.

For a household that is connected to the heat network (HN), its annual expenses for heat $E_{heat,HN}$ are calculated as follows:

$$E_{heat,HN} = \left(costs_{HN,fixed} + (U_{SH} + U_{TW}) * costs_{HN,variable}\right)$$

Where:

U_{SH} is the energy use for space heating, U_{TW} is the energy use for warm tap water, and $cost_{HN}$ are the fixed costs per year and variable costs per unit energy for the heat). These costs are given in Appendix Table 32. The heat costs are given including VAT, hence the exclusion of VAT in the equation. The efficiency is not included in this equation since the functional demand and meter demand are equal for heat networks.

For both heating systems, running costs – capital costs, operational costs and metering costs – of the system are excluded. This means that the costs for a central heating boiler and the (rental) costs for a delivery set for a heat network connection are excluded.

Total energy expenses

The total annual energy expenses of a household, which include energy taxes and VAT, are calculated as such:

$$E_{energy} = E_{heat} + E_{electricity}$$

Personal conversion factors

Environmental attitude

This float variable has a value between 0 and 1, where 0 represents a household that has a low attitude towards the environment and does not act in an environmentally sustainable way, and 1 represents a household with a high environmental attitude and displays environmentally-friendly behaviour.

Campaign effect

$$CampaignEffect = savings * susceptibility$$

Where $savings$ is the maximum energy reduction caused by the campaign (set in the scenario, 15% in our case) and $susceptibility$ is factor unique to each household being a random floating number between 0 and 1 representing to what extent a campaign influences the household's behaviour.

Ownership

This string variable represents whether the household is a homeowner or renter. At the model start, all buildings are assigned randomly whether they are privately owned or owned by a housing corporation, following the distribution of ownership per building category based on Voorhof and Buitenhof data (see Appendix Table 33). Each household in a building is labeled 'owner' or 'renter' depending on their building ownership.

Exogenous factors and model drivers

Spatial and temporal scale

Space is explicitly included in the model using georeferenced (GIS) data of specific neighbourhoods. The GIS data includes the shapes and positions of buildings. The neighbourhoods can be selected and the model is run for a single neighbourhood at a time. The spatial extent of the model landscape is the size of a neighbourhood. The model world does not wrap horizontally nor vertically. The temporal resolution of the model is months. One time step represents one month and the simulation is run for a duration of five years (60 timesteps).

C.3 Process overview and scheduling

First, the model is initialized by setting up the map (importing external datasets and drawing the map of the neighbourhood's buildings) and setting up the model agents and initial parameters. When running the model, the following process steps will take place.

At the start of each year, household energy use and expenses is determined. Then, homeowners select a decision-making strategy depending on their level of satisfaction and certainty, and use this strategy to decide whether to join the heat network or not.

If the heat network is implemented in the scenario, the following steps happen. In the first month, corporation-owned multi-family households with a collective heating system are connected to the heat network. Then, in the scenario where the heat network is open for all, every year (every 12 months), the level of heat network support among all households in privately-owned buildings is assessed. If more than half of the households agree, the building has enough support to be connected to the heat network. This will happen starting in month 13 for multi-family private buildings, and in month 25 for individual dwellings (private and corporation-owned).

In the renovation scenario, the following additional steps will take place. Starting in month 12, every year the dwellings with the worst energy labels will be renovated to label B, and the costs for renovation will be calculated for the renovated building based on the floorspace and energy label (see Appendix Table 23 and Table 24).

In the awareness campaign scenario,

Each year, the model reporters and KPIs are calculated and the map and graphs are updated. This process is repeated until 60 ticks (5 years) have passed.

C.4 Individual decision-making

We use a simplified version of Jager's model of consumer behaviour (Jager 2000; Jager and Janssen 2012). Individuals adopt a specific decision-making strategy depending on their level of needs satisfaction and uncertainty.

Satisfaction:

- Unsatisfied if any of LIHC, LILEQ, oLEQ are true, else satisfied.

Certainty:

- Certainty (C) is determined by one's environmental attitude and the effect an awareness campaign has on the household. If C is lower than 0.5, the household is considered uncertain.

$$C = EnvironmentalAwareness + \frac{CampaignEffect}{2})$$

Strategies:

- Repetition: if the household is satisfied and certain, it will use the same heating system as in the previous period.
- Deliberation: if the household is unsatisfied and certain, it will choose to connect to the heat network if it can afford it. We assume a household can afford it if their equity is more than €40000 (congruent with the definition of oLEQ), if it is a low-income household in the scenario with vouchers for heat network connections, or if it is not a low-income household and the equity is at least thrice the connection fee.
- Imitation: if the household is satisfied and uncertain, household will choose the heating system that the majority of its ten closest neighbours have.
- Social comparison: when the household is unsatisfied and uncertain, it will engage in social comparison. First, it will seek the ten closest neighbours with the same household type (e.g. family, elderly couple, single person below 35). It will then use the heating system which is the most used by these comparable neighbours.

C.5 Learning

There is no learning.

C.6 Individual sensing

Households sense the following variables (Table 35).

Table 35. Individual sensing.

Endogenous variables	Exogenous variables	Variables of other agents
Income Homeownership Energy label Heating system Heat network support	Awareness campaigns, to a certain extent Availability of vouchers for heat network connections Option of connecting to heat network	Of households: • Heat network choice Of their own building: • Building ID • Heating system • Heat net connection • Ownership

C.7 Individual prediction

Households that take the deliberation strategy assume that switching to the heat network will be favourable, or at least neutral, in their total energy expenses.

C.8 Interaction

See also Figure 13.

Agent-agent interactions

Agents interact with other agents when checking the heating system choice of neighbours or similar households (see C.4 Individual decision-making).

Agent-environment interactions

For the implementation of the heat network, agent support within buildings is compared to determine if over 50% of inhabitants agree with heat network connection. Households choose available heating systems and the energy system supplies the required energy to households at the respective costs. Implemented policies interact with the available heating systems and their costs, energy prices, and financial instruments, as well as agent states such as awareness and dwelling efficiency.

C.9 Collectives

A building represents the collective of households that are situated in that building. Households belong to a certain building and share the same heating system and homeownership of that building.

C.10 Heterogeneity

Buildings are heterogeneous in:

- Location
- Ownership
- Heating system (gas boiler or heat network) and type (individual or collective)
- Number of households in building
- Year of construction
- Total floorspace

Households are heterogeneous in:

- Dwelling characteristics (building, dwelling category, energy label, floorspace)
- Household characteristics (homeownership, household type, income, equity)
- Personal characteristics (environmental attitude, susceptibility to campaigns)
- Decision-making strategy (repetition, imitation, deliberation, social comparison)

C.11 Stochasticity

The following variables are set stochastically in a semi-random way:

- Building ownership (corporation or private) and heating system type (collective or individual). These factors are assigned randomly with weighting according to respective ownership and heating system type distributions of the corresponding neighbourhood.
- Household type is assigned randomly according to distributions of housing types per ownership in the Netherlands.
- Income and equity are assigned with a normal distribution with the means according to household type and ownership in the Netherlands.
- Environmental attitude is a random value between 0 and 1.
- Susceptibility is a random value between 0 and 1.

C.12 Observation

The NetLogo View is used to visualise agent states such as dwelling ownership, heating system or year of construction and household energy label, decision-making strategy or energy quote. Various indicators are tracked using plots and monitors in the NetLogo interface (Figure 23).

The model provides the following outputs:

- Average energy use, energy poverty levels for each indicator, Gini coefficient of energy expenses, fractions of households connected to heat network, unable to connect, and using vouchers to connect.
- Average energy quote per household type.
- Average and inequality in energy poverty indicators per household type.
- Fraction of households connected to heat network per household type.
- Socio-economic characteristics of households with energy poverty and heat network access.

C.13 Implementation details

NetLogo (version 6.3.0) was used to implement the agent-based model (Wilensky 1999). The GIS Extension for NetLogo (version 1.3.1) was used to load and use real-world geographic data in vector format in a spatially-explicit model (Walker and Johnson 2019). The NetLogo Csv Extension (version 1.1.1) was used to use .csv files in NetLogo and the Table Extension (version 1.3.1) was used to create tables. All used extensions come pre-installed with NetLogo. The NetLogo interface of the model can be seen in Figure 23.

Model interface

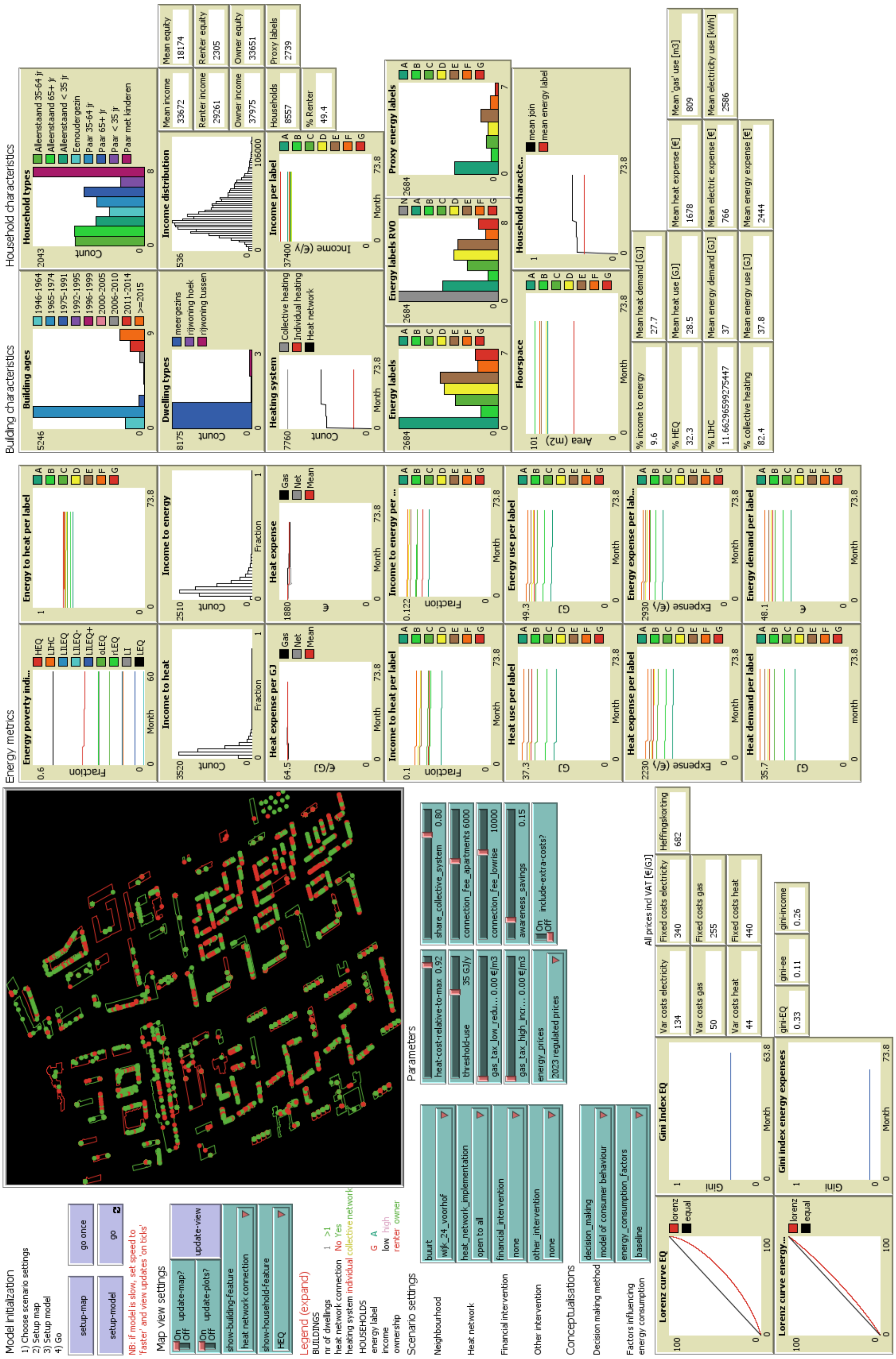


Figure 23. NetLogo model interface.

C.14 Initialization

At initialization, input data are loaded, the map is drawn and buildings and households are created. Initial variables are set based on input data and/or determined as described above.

Initial state at the start of a simulation run:

- No implementation of heat network

Variation of initialisation among simulations:

- Heat prices

C.15 Input data

Figure 16 gives an overview of model inputs and outputs. The ABM uses four main inputs: a geospatial housing dataset, a geospatial address dataset (including energy label data), a characteristic functional energy demand dataset, and socio-demographic data. The attributes, file types and sources of the input datasets are shown in Table 36.

Table 36. Used attributes, file types and sources of input data.

Input	Attributes used in model	File type	Source
Housing dataset	Geolocation, contour, ID, floorspace, number of dwellings	.shp	BAG 2022
Address and energy label dataset	Geolocation, dwelling type	.shp	BAG 2022
	Energy label, heat demand		RVO 2022
Functional energy demand	Fixed and variable functional energy demand for space heating, warm tap water, electricity for appliances and cooling, depending on dwelling type and energy label (Table 22).	.csv	PBL 2021
Socio-demographic data	Household type and income distribution (Table 25)	.csv	WoOn 2021
	Reasonable rent increase after renovation (Table 26, Table 27, Table 28)	.csv	Woonbond 2022b
	Social minimum, equity, average income (Table 29)	Entered manually	UWV, CBS 2022
	Ownership distribution (Table 33)		CBS 2021b
Energy system data	Renovation costs (Table 23, Table 24)	.csv	
	Gas central heating efficiency and calorific value (Table 29)	Entered manually	ACM 2020
	Heat network costs (Table 29)		CE Delft 2018
	Energy prices (Table 30, Table 31, Table 32)		See table.

Spatial data of buildings and addresses

Shapefiles of buildings and addresses are obtained from the *BAG 2.0 file geodatabase*, version November 2022, provided by Esri Nederland. Energy label data are from RVO, obtained from the *Energielabels file geodatabase*, version November 2022, provided by Esri Nederland. These datasets are combined and processed using QGIS version 3.24.0. See Input data preparation process for a description of the data management and processing steps taken. A file containing the residential building dataset and a file for the residential address dataset have been made for the following areas:

- Wijk 24 Voorhof (district)
- Wijk 25 Buitenhof (district)
- Buitenhof Noord (neighbourhood, for testing)
- Gillisbuurt (neighbourhood, for testing)Het Rode Dorp (testing)
- Het Rode Dorp (neighbourhood, for testing)

- Multatulibuurt (neighbourhood, for testing)Roland Holstbuurt (testing)
- Roland Holstbuurt (neighbourhood, for testing)

The specific neighbourhoods were chosen because they have both been selected as priority neighbourhood and a local heat network is considered the preferred heating system in these neighbourhoods (Gemeente Delft 2021b). In addition, these neighbourhoods are planned to be connected to the Open Warmtenet.

Heat demand input data concerns the functional demand: useful products that an end user needs, such as warm water or space heating. This is different from the net inputs to the meter (*metervraag*), such as the gas consumption of a building.

C.16 Submodels

There are no Submodels.

Appendix D. Interviews

D.1 List of interviewees

Table 37. List of interviewees.

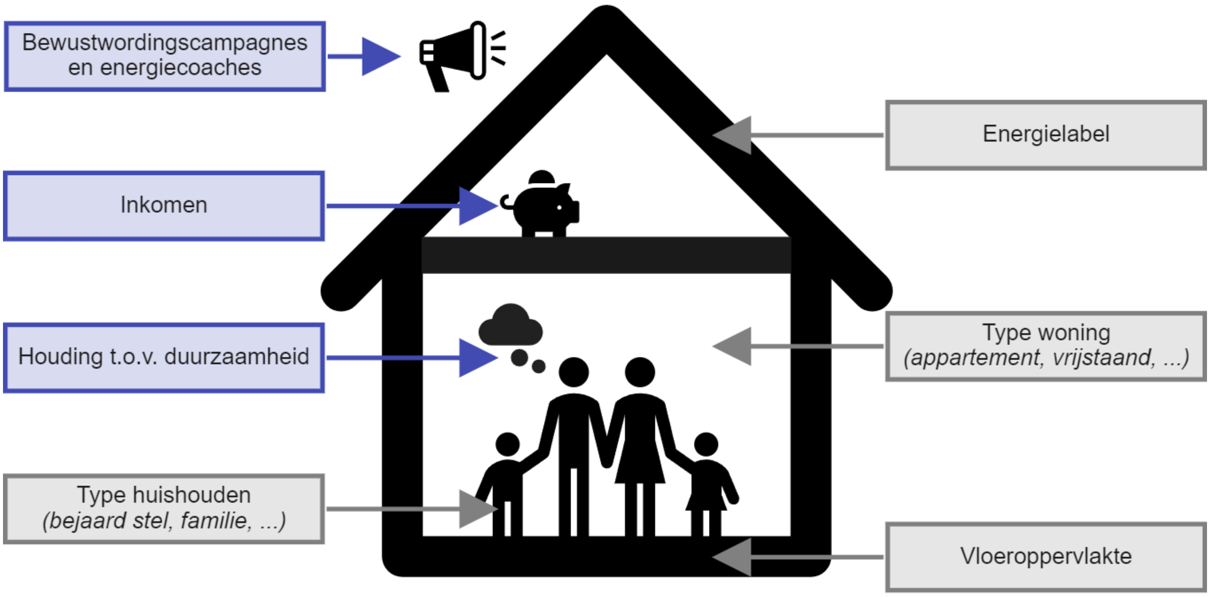
Function	Organisation
Energy Director (Energieregisseur) Open Warmtenet Delft	Infinitus Energy Solutions
Advisor Energy Transition	Gemeente Delft
Associate Professor Climate Psychology and Co-Director TPM Energy Transition Lab	Faculty of Technology, Policy and Management, Delft University of Technology
Associate Professor Energy & Industry Group and Co-Director TPM Energy Transition Lab	Faculty of Technology, Policy and Management, Delft University of Technology

D.2 Interview questions

1. Bij welke organisatie bent u werkzaam en wat is uw rol?
2. Wat is uw link met de warmtetransitie, warmtenetten of Open Warmtenet Delft?
3. Wat vindt u van de manier waarop het verbruiken van energie door huishoudens wordt gerepresenteerd in het model, met name de factoren die het gedrag bepalen? Zou u dingen aanpassen of toevoegen?
4. Wat vindt u van de manier waarop de keuze voor de overstap naar een warmtenet wordt gemaakt door huiseigenaren in het model? Komt dit overeen met hoe huishoudens deze keuze zouden maken?
5. Zijn er andere factoren of manieren om deze keuze te maken die zouden kunnen worden meegenomen in het model?
6. Bent u het eens met de gekozen beleidsopties? Reflecteren zij realistische beleidsopties?
7. Missen er relevante beleidsopties die u mee zou nemen in de modelscenario's?
8. Wat vindt u van de gekozen indicatoren voor energiearmoede en toegankelijkheid?
9. Helpen de te meten indicatoren en verwachte modeluitkomsten
    a. in het maken van beleid voor een eerlijke warmtetransitie?
    b. uw onderzoek naar een eerlijke warmtetransitie?
    c. uw werk in de warmtetransitie?
10. Representeert het model de implementatie van een warmtenet en de daaropvolgende effecten op de energie-uitgaven van huishoudens op een logische manier?
11. Zijn er volgens u nog relevante zaken waarmee het model rekening dient te houden?

D.3 Print-out used during interviews

Factoren met invloed op energieverbruik huishoudens



Keuzemodel overstap naar warmtenet huiseigenaren

	Tevreden	Niet tevreden
Zeker	*Herhaling*: blijft bij huidig warmtesysteem	*Overweging*: wanneer het huishouden het kan betalen, stapt het over naar warmtenet
Onzeker	*Imitatie*: kies het systeem dat de meeste buren hebben	*Sociale vergelijking*: kies het systeem dat vergelijkbare type huishoudens hebben

Een huishouden is **ontevreden** wanneer deze in energiearmoede leeft: een hoge energiequote, een laag inkomen en hoge kosten, of een laag energielabel heeft en dit niet kan veranderen.

Een huishouden is **onzeker** wanneer het een lage houding t.o.v. duurzaamheid heeft. De bewustwordingscampagne kan ook onzekerheid wegnemen.

Beleidsopties modelscenario's

Doel	Interventie
Betaalbare energie	Implementeren warmtenet
	Verlagen energiebelasting op gas voor gebruik onder 1000 m^3 en verhogen energiebelasting op gas voor gebruik boven 1000 m^3
	Vouchers voor aansluitkosten warmtenet voor lage inkomens
Verhogen energie-efficiëntie gebouwen	Huiseigenaren: Renovatie naar label B, via 'service provider', met maandelijkse betaling gelijk aan renovatiekosten verspreid over 10 jaar
	Huurders: Renovatie naar label B, afschaffing verhuurdersheffing, huurverhoging t.h.v. extra huurpunten door kwaliteitsverbetering woning
Verhogen warmtecomfort	Bewustzijnscampagnes, energiecoaches en displays verlagen verbruik met 10%

Indicatoren voor het meten van energiearmoede

Betaalbaarheid

1) **Hoge Energie Quote (HEQ)**
   Een huishouden is energiearm als een (te) hoog aandeel van het inkomen opgaat aan energiekosten.
2) **Laag Inkomen & Hoge Energiekosten (LIHK)**
   Een huishouden is energiearm als het een relatief laag inkomen heeft én relatief hoge energiekosten.

Huiskwaliteit

3) **Laag Inkomen & huis met Lage Energie Kwaliteit (LILEK)**
   Een huishouden is energiearm als het een relatief laag inkomen heeft én in een huis woont met een relatief lage energiekwaliteit.
   a. **Laag Inkomen & huis met Lage Energie Kwaliteit & onderconsumptie energie (LILEK–)**
      Een variant op LILEK die verborgen energiearmoede meet: mensen die, waarschijnlijk vanwege financiële problemen, energie onder-consumeren.
   b. **Laag Inkomen & huis met Lage Energie Kwaliteit & overconsumptie energie (LILEK+)**
      Een variant op LILEK die het aantal huishoudens meet met opvallend hoge energieconsumptie.

Kunnen deelnemen aan de energietransitie

4) **Huis met Lage Energie Kwaliteit & niet zelf kunnen verduurzamen**
   Een huishouden is energiearm als het in een huis woont met een relatief lage energiekwaliteit dat ze niet op eigen kracht kunnen verduurzamen.
   a. **Eigenaar van huis met Lage Energie Kwaliteit & niet zelf kunnen verduurzamen (eLEK)**
      De groep eigenaren van een huis met lage energiekwaliteit en onvoldoende eigen vermogen of te beperkte leencapaciteit om zelf hun huis te kunnen verduurzamen.
   b. **Huurder van huis met Lage Energie Kwaliteit & niet zelf kunnen verduurzamen (hLEK)**
      De groep huurders van een huis met lage energiekwaliteit die niet zelf kunnen besluiten tot verduurzaming.

Toegankelijkheid warmtenet

1) **Aandeel huishoudens in de wijk dat is aangesloten op het warmtenet**
   Wanneer dit aandeel aan het eind van de modelsimulatie laag is, is de toegankelijkheid lager dan wanneer dit aandeel hoog is. Dit aandeel wordt vergeleken tussen de verschillende modelscenario's.

D.4 Interview results

Table 38. Description and evaluation of model assumptions as discussed during expert interviews. Assumptions that are changed in the final model are underlined.

Model feature	Assumption	Evaluation
Household energy behaviour and decision-making		
Determining energy demand	The expected average energy demand is based on empirical data split into specific household types based on energy label, dwelling type, household composition and depends on floorspace.	The factors included are relevant and important for energy demand. One should take care when using energy labels to determine energy use, since this comes with uncertainty (see Discussion).
Determining actual energy use	<u>Income is related to actual energy use via an S-curve: lower income uses less energy than average, higher income uses more.</u> The higher one's attitude to sustainability, the more energy the household saves. Awareness campaigns reduce energy use (see below).	There are other factors that might determine energy use, such as how long people are at home, but this might already be partly covered by factors such as household composition. The relationship between income and energy use was challenged by all respondents. Sub-elements related to income may work in opposing ways. High income households may have more appliances or less financial reasons to reduce energy use, but they also have more opportunities to take energy-saving measures. The relationship between income and energy use might already be encompassed in the other model factors, such as floorspace, household category and dwelling type (higher incomes generally have larger houses, and families likely have a larger income than young singles). The translation between one's attitude towards sustainability and one's behaviour is not always the same for each choice: one might choose to travel sustainably but pay no attention to heating. The model assumes a linear relationship between sustainability knowledge/attitude and behaviour, but in reality, this relationship is not linear. Other factors play a role, such as the social norm – what do others do? – one's self-efficacy, habits, emotions, perceptions and hassle. Of course, in ABM you need to make choices.
Homeowner choice to connect to heat network and decision strategies	Homeowners adopt different strategies – repetition, imitation, deliberation, social comparison – depending on their level of certainty and satisfaction. Certainty is related to attitude towards sustainability and is increased through awareness campaigns.	Respondents agreed that households will follow different decision-making strategies and that the level of satisfaction and certainty play an important role, and that costs were the major factor when considering the choice. Other mentioned relevant factors that influence the decision to switch were the existing age of the heating system, the changes required in the building and street, and what other options are available. Furthermore, a large change in the environment, such as an energy crisis, can lead to different decision-making. Also, what the municipality and laws and regulations dictate regarding the energy transition plays an important role, especially regarding certainty about future options. Households often wait until there is certainty in this regard. Path dependency plays a role as well: if someone recently invested in a new gas

	A household is not satisfied if it has energy poverty (HEQ, LIHC, LILEK, oLEQ or rLEQ).	boiler, they will probably not change their heating system in the near future. Lastly, perceptions play a role, and whether people think they will succeed, as well as future plans of households. Many of these factors are already part of the current conceptualisation, key is to create a coherent narrative. Certainty is conceptualised as the attitude towards sustainability, but this might not be consistent. In this context, uncertainty comes from regulation and what the municipality will do, from uncertainty on what the future will bring, from the presence of other choices, from adaptations that need to be made in the house. Dissatisfaction is conceptualised as having energy poverty. Is a household not satisfied if its energy quote is high? This can also be a deliberate choice or not cause dissatisfaction. The concept of satisfaction might be broader. What does it mean to be satisfied? Satisfaction can also be a composite of factors such as perception if one can change, and some households might be easier satisfied than others. In the model, the only choice homeowners can make is to switch to the heat network or keep their current system. In reality there will be more alternatives, such as heat pumps. For buildings with homeowner associations (HOAs), another level of decision-making occurs. A level of agreement needs to be achieved within the HOA to make a decision for the whole building. A limitation of this choice model is that it is a consumer model, but the choice of energy system is much more difficult than buying consumer products such as a TV. Factors such as policies and governance play a larger role here.
Policy interventions and scenarios		
Implementation of heat network	See below.	See below.
Energy tax on natural gas	Lower energy tax for gas use of to 1000 m^3 and increased energy tax for gas use above 1000 m^3.	Relevant option. The effect of this measure will be less than that of a cap on the energy price since the tax comprises only part of the energy price.
Vouchers for heat network connection fee	Low-income homeowners receive vouchers to cover upfront costs of heat network connection.	Relevant option. The issue with subsidies for households is that many people do not use them because they find it a hassle. Even if people have a right to compensation, many do not apply for it.
Improving dwelling energy efficiency	For homeowners with labels D or worse: Renovation to label B, service provider, monthly fee equal to renovation costs paid over 10 years. For corporation dwellings with label D or worse: Renovation to label B, abolishing landlord's tax,	Relevant option, other municipalities have done this already. Delft is considering such a system with costs spread over a period of 30 years. The possible rent increase can be dangerous: it might lead to distrust and worsened image of the housing corporation. Cooperative actions such as renovating an entire street at once can also be considered. Implementation of this intervention can also be done in other ways, such as regulation to have renovations when households move out or when the lifetime of the current heating system expires.

	allowed rent increase from energy label improvement	
Awareness campaign, energy coaches and smart meters	The campaign reaches all households and has the same effect on each household: a 10% decrease in energy use.	Relevant option. The current campaign [to save energy as a response to the Russian invasion of Ukraine] will probably lead to a higher reduction in energy use than 10%. These campaigns do not reach every household or have the same effect on every household.
Other	-	The proposed policy options were deemed relevant and realistic. The municipality uses instruments to entice or nudge people to make sustainable choices, using awareness, unburdening, making people understand, financing, and other forms. These are represented in the proposed policy scenarios. Respondents missed other sustainable energy system options, such as heat pumps. Subsidies are also an often-used policy option. For example, a subsidy for heat network operators can lead to reduced connection fees.
Energy poverty conceptualisation		
Indicators for energy poverty	The following indicators are compared: HEQ, LIHC, LILEK, o/rLEQ.	The indicators are relevant and cover the different dimensions of energy poverty. The indicators correlate and overlap and there are many, so it might be good to choose. One might find underlying structures that explain energy poverty by comparing correlations of energy poverty indicators.
Indicator for heat network accessibility	The fraction of households connected to the heat network at the end of each scenario.	A low fraction of households connecting to a heat network might in reality also be caused by homeowners being satisfied or successful in finding alternative heating systems, so it is not a bad sign per se.
Heat network implementation		
Order of connections	First, connect corporation multi-family buildings with collective heating. Then, connect other multi-family buildings with collective heating. Lastly, other buildings can connect.	In reality, there is a threshold value for the number of households that will connect to the heat network. There needs to be a minimum level of heat demand, otherwise the network will not be developed. As a third step, it would make sense to first have single-family corporation buildings as a group, and lastly private single-family buildings.
Connection fee	€8000 for apartments, €10000 for single-family buildings	The cost of the heat network will depend on the amount of people that will connect: the less households that participate, the more expensive it will be. €8000 for apartments is high, OWD will be closer to €5000 excluding VAT.
Other	The heat network provides both warm tap water and space heating.	In most of the corporation buildings to be connected in Delft, tap water is a separate system from collective heating. Most multi-family buildings have collective heating systems; only a few have individual heating systems.

Appendix E. Evaluation results

E.1 Data evaluation

Table 39. Description and evaluation of data sources.

Description	Source	Evaluation
Building characteristics		
Building dataset: geolocation, contour, year of construction, building type, total floorspace, number of dwellings, object ID **Address dataset: geolocation, dwelling type**	BAG 2.0, version November 2022, File Geodatabase by Esri Nederland on maps.ArcGIS.com	The BAG is the Dutch building and address register managed by Kadaster, a government agency. Data are checked and updated regularly and the data is recent. Esri is the developer of ArcGIS, GIS software for professionals. Esri converts the BAG dataset into a geodatabase useable for GIS software on a monthly basis and is a leading actor in the industry. These BAG dataset is commonly used as building inventory and defined neighbourhoods in energy transition models of Dutch municipalities and neighbourhoods (Brouwer 2019). This dataset is thus deemed reliable for use in this study. Floorspace of individual dwellings was not available, so this was calculated based on the number of dwellings in a building and the building's total useable floorspace. However, this led to outliers for dwellings in buildings with other functions (such as offices) rather than dwellings. To deal with this, if a dwelling had a floorspace of more than 300 m^2, the floorspace was set to 300 m^2. This was the case for 8 households in Voorhof and 6 households in Buitenhof. Mixed-use buildings with mainly residential functions might still have an overestimation for the residential floorspace. In addition, variability of dwelling size within the building is lost.
Energy labels	RVO, version November 2022, File Geodatabase by Esri Nederland on maps.ArcGIS.com	The dataset is from RVO, the Netherlands Enterprise Agency. The data is updated monthly. Esri converts the dataset into a geodatabase useable for GIS software on a monthly basis and is a leading actor in the industry. This dataset is thus deemed reliable for use in this study. Energy labels were known for 5611 (65%) of 8568 dwellings in Voorhof and 5181 (70%) of 7367 dwellings in Buitenhof. Dwellings with an unknown energy label were assigned the energy label of their closest neighbour. This gives uncertainty in the model and might produce a bias towards higher energy labels, since newer buildings are more likely to have a known energy label and have a better label than older buildings. So, the model households with an unknown label probably have a better label assigned to them than would be the real case.
Socio-demographic data		
Distribution of household compositions, renters and homeowners	Report WoOn 2021 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2022), Figure 2.2 (renters), and Figure 3.3 (homeowners).	WoOn is a large, long-term country-wide research by the CBS and Dutch Ministry of Internal Affairs and Kingdom Relations on the living situation of households. Data is collected by the Dutch Central Statistics Bureau and from the year 2021. The data is recent, high-quality, and representative for the Netherlands and thus suitable for this study.
Net spendable monthly income per household composition	Report WoOn 2021 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2022), Figure 2.5	
Corporation building ownership	Dataset Woningvoorraad Kadaster, October 2020. Retrieved from Datavoorziening Wijkpaspoort Warmtetransitie (VNG and Kadaster 2022).	Kadaster is the Dutch register for buildings and addresses, the data is reliable and specific for each neighbourhood, and therefore suitable for this study.
Economic and financial data		
Possible rent increase after energy label	Vergoedingentabel voor faire huurverhoging bij	The table is based on an agreement between Aeges (representatives of the housing corporations) and Woonbond (representatives of renters) and valid from July 2022. It is based on the agreement that increasing

improvement, per energy label	verduurzamingsmaateregelen (Woonbond 2022b)	a buildings sustainability will not lead to higher total housing costs for renters. This is also the aim for the heat transition in Delft, so we consider this table suitable for use in this study.
Social minimum, couples and singles	Dutch Employee Insurance Agency (UWV 2022)	Official and recent data from a Dutch government agency.
Equity, homeowners and renters	Netherlands Statistics Bureau (CBS 2022a)	Official and recent data from a Dutch government agency.
Gas price	(Rijksoverheid 2022b)	Gas and electricity price based on the price ceiling set by the Dutch government starting January 2023. This represents the real-life gas prices and is thus suitable for this study.
Electricity price		
Energy and energy system data		
Functional energy demand for space heating per m^2 per dwelling type, year of construction and energy label	(PBL 2021), Table B.4. This data is based on CBS data of actual energy consumption for the year 2018 (CBS, 2019) broken down per dwelling type, year of construction, floorspace classification, and certified energy label (RVO, 1-1-2020). The data forms the basis of the Vesta MAIS model, a technical-economic model to determine transition paths for the heat supply in the Dutch built environment.	The CBS data is recent (2018) and was used by PBL to make estimates on the country-wide average energy demand per dwelling type, year of construction and energy label. The data is based on actual usage data of natural gas. A linear regression was performed to estimate a base and variable demand for 10 energy labels, 5 dwelling types and 11 construction year categories. The resulting estimate was corrected from 'meter demand' to functional demand by accounting for boiler efficiency, and reduced by 37 m^3 as correction for gas used for cooking. Corrections for weather effects and 'contaminated' energy labels were performed (PBL 2021). Because of this thorough description of data, the level of detail and fine granularity in categories, the bases of actual usage data and the corrections made, the data is deemed reliable. The data is recent and from the Netherlands, making it suitable for this study.
Functional energy demand for warm tap water per m^2 per dwelling type and year of construction		Functional demand for tap water is based on theoretical demand data from 2012 and corrected by PBL for the difference between theoretical and actual use. A correction was also made for the average floor area per combination of dwelling type and construction year. The resulting demand as calculated by the Vesta MAIS model was compared to actual use data from the Nationale Energie Verkenning 2015, and the figures were then fitted to the national use data (PBL 2021). The comparison and fit with actual Dutch use data means the estimated functional warm water energy demand is a reliable estimate and the split per dwelling type makes it suitable for this study.
Functional energy demand for electric appliances per m^2 per dwelling type and year of construction		Energy demand for electric appliances is based on theoretical demand data from 2012 and fit with actual use data from the Nationale Energie Verkenning 2015. The data was corrected for pump energy for HR boilers (PBL 2021). The fit with actual Dutch electricity use data means the energy demand data is an accurate estimate and the split per dwelling type makes it suitable for this study.
Functional energy demand for space cooling per m^2.		The estimate is based on electricity use data on cooling installations in the service and the percentage of total electricity use spent on cooling per building type (PBL 2021). Though no data from household cooling appliances was used, this data is not available. However, this data was split in process cooling and space cooling, and the space cooling data was used to make estimates per building type. All residential dwellings are assumed to have the same cooling demand per m^2. Though this brings uncertainty into the model, space cooling demand is only a small fraction of total energy demand, so this is not expected to influence model outcomes.
Costs of increasing energy efficiency per	CE Delft (Naber et al. 2016), Table 23 and Table 24.	CE Delft is an independent research bureau. Costs are based on 'example dwellings' (*voorbeeldwoningen 2011*) from RVO. These *voorbeeldwoningen* represent the Dutch dwelling stock.

m², per energy label, apartments and single-family dwellings	Only a distinction between apartments and single-family dwellings are made – so no further distinction between freestanding, terraced, corner houses etc – so the estimate is quite rough and non-specific. Still, it is the best data available for The Netherlands and the figure is per m², per energy label step and split between apartments and single-family dwellings, which are the most distinct dwelling types. We consider this dataset suitable for this study.

E.2 Implementation validation

Single-agent testing

For single-agent testing, we ran various parametrizations of the model and recorded the behaviour of agents using plots and monitors in the NetLogo interface. The following checks were done:

- Switch to heat network changes heat expenses, not electricity expenses;
- Efficiency improvement decreases heat use, not electricity use;
- Awareness campaign decreases both heat and electricity use;
- Different energy prices are used when switching to heat network;

We also ran the model using the All-Vou-Eff scenario with 2023 prices and exported the NetLogo world to .csv. The variables of five random households were investigated. These were household 2729, 2817, 4250, 6137 and 7685. The following checks were done:

- Variables had assigned values when they should, with correct type (e.g., string, Boolean, float), and realistic values;
- Variables representing income groups and low-income category matched with household income;
- Building characteristics matched with building type (e.g., no collective system for single-family buildings);
- Energy poverty variables matched with dwelling energy quality, income, energy expenses, ownership;
- Energy demand was calculated correctly for the respective dwelling size, age, type, energy label and household type;
- Energy consumption was calculated correctly considering the gas boiler efficiency and environmental attitude;
- Energy expenses were calculated correctly based on relevant energy price and demand;
- Energy quotes were calculated correctly based on energy consumption and income;
- An energy label was assigned, and proxy energy labels were assigned when buildings had no initial energy label;
- Renovation costs matched required label improvement and floorspace;
- Satisfaction and certainty levels matched agent state;
- Heat network choice was consistent with adopted strategy;
- Vouchers were correctly assigned to low-income homeowners, and not to other groups.

Multi-agent testing

Agent tracking and recording

During multi-agent testing, agents were tracked and recorded using the NetLogo view, plots, and monitors. The following checks were done:

- The timeline of the model run matches the conceptual design;
- Energy labels are improved in the right order and at the right time;
- Heat network is implemented in the right order and at the right time;

- Agent variables update responding to policy interventions accordingly;
- If a building is connected to the heat network, all households in that building follow;
- Patterns of energy use, expenses, energy poverty indicators, energy poverty distributions, etc. over time make sense and follow changes in heat network connections, energy efficiency improvements and awareness campaigns;

All model runs in this section use 2023 energy prices, unless stated otherwise. We present a selection of examples and results of the multi-agent testing phase (see Figure 24, Figure 25, Figure 26, Figure 27, Figure 28, Figure 29, Figure 30).

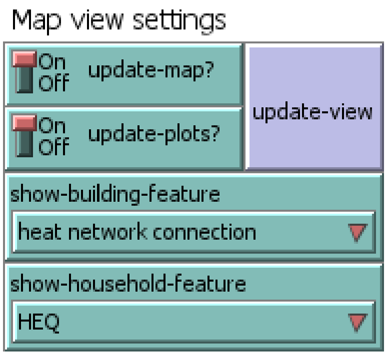


Figure 24. Settings for what building and household features the NetLogo view shows. Choices for "show-building-feature" are "heat network connection", "nr of dwellings", "heating system", "construction year", or "ownership". Choices for "show-household-feature" are "energy label", "initial energy label", "income", "ownership", "fraction income to energy", "HEQ", "LIHC", "LILEQ", "oLEQ and rLEQ", "decision strategy" and "choice".

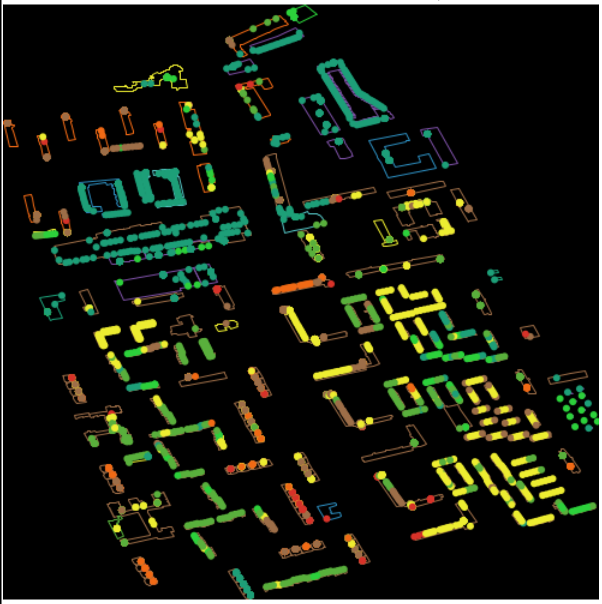
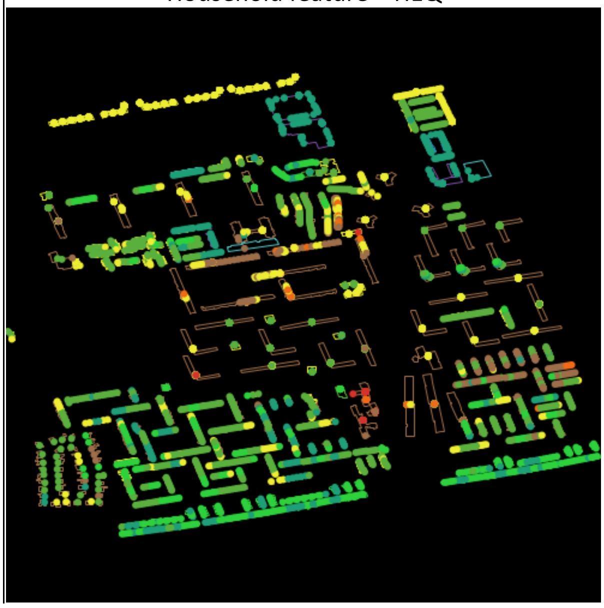
District = Voorhof Building feature = construction year Household feature = HEQ	District = Buitenhof Building feature = construction year Household feature = HEQ
	
Building colour: red, 1946-1964; orange, 1965-1974; brown, 1975-1991; yellow, 1992-1996; green, 1997-1999; lime, 2000-2005; turquoise, 2006-2010; cyan, 2011-2014; sky, ≥2015. Dwelling colour: green, no LILEQ; red, LILEQ.	

Figure 25. NetLogo view showing building year of construction (line drawings) and initial household energy labels (circles), Voorhof and Buitenhof.

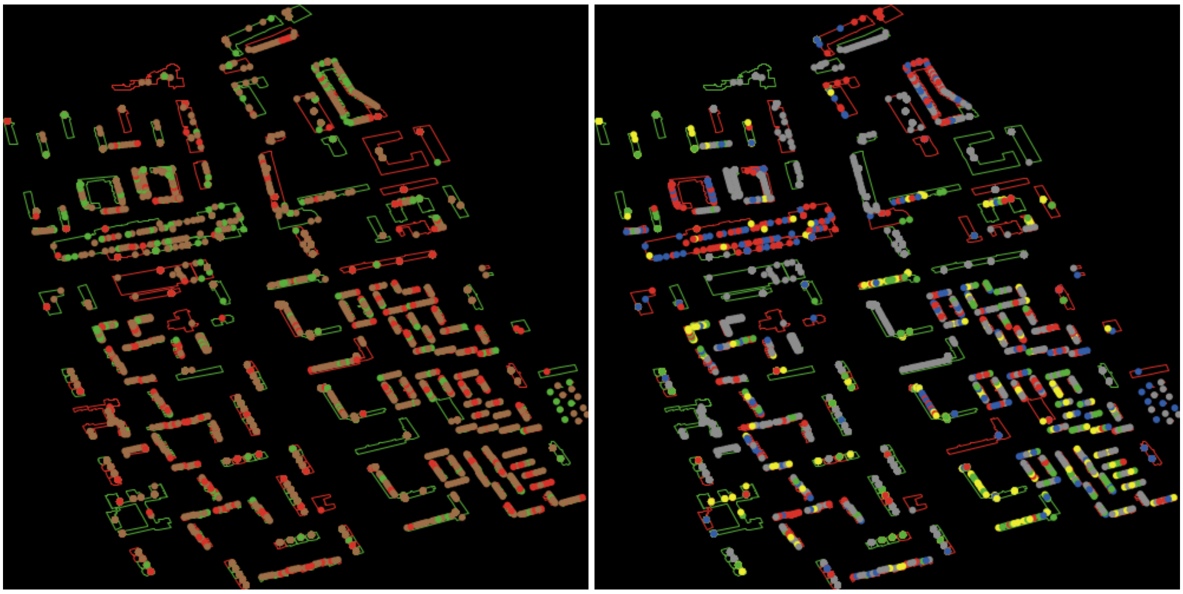


Figure 26. Left: NetLogo view showing building feature 'ownership' and household feature 'energy quote'. Right: NetLogo view showing building feature 'heat network connection' and household feature 'decision strategy'.

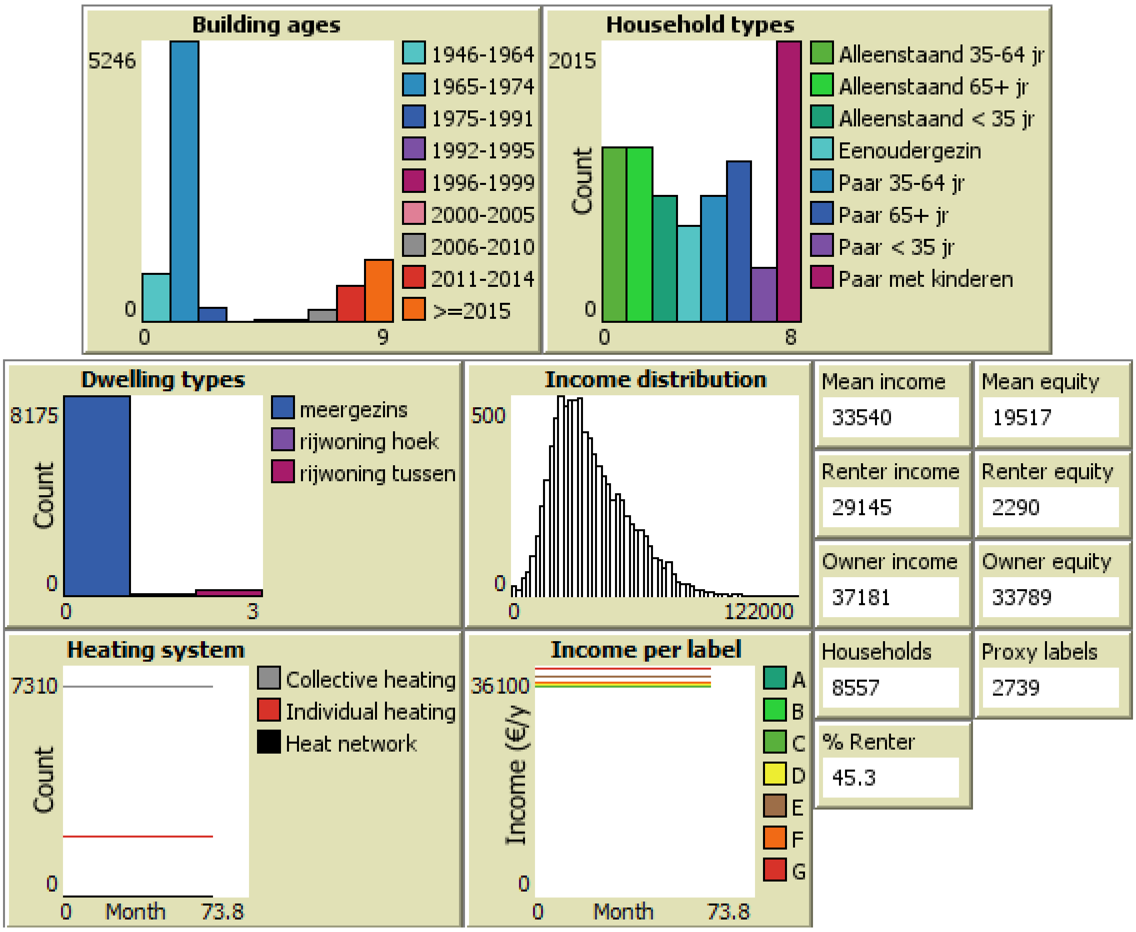


Figure 27. Examples of plots and monitors in the NetLogo model showing building and household characteristics.

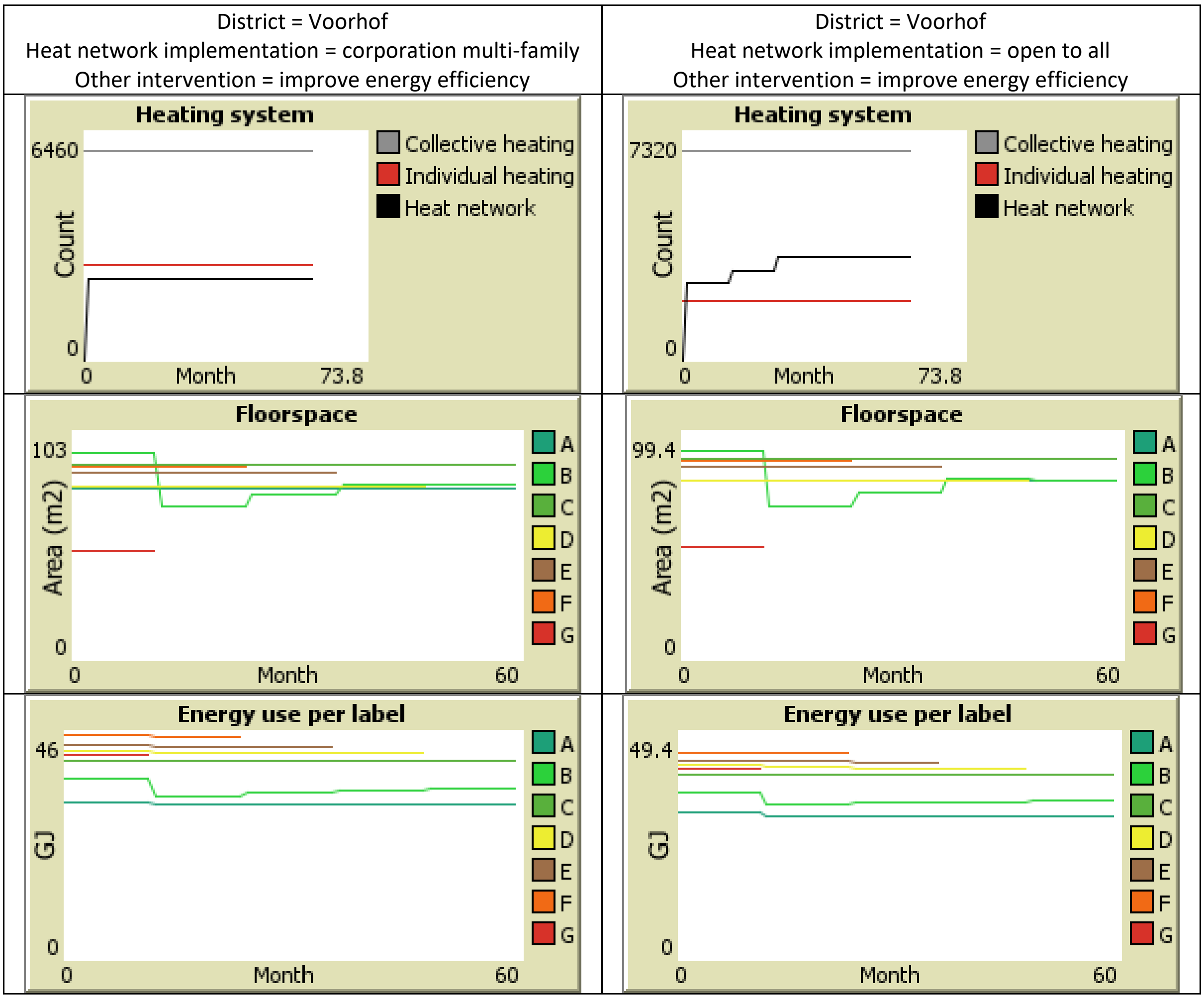
% income to energy: 9.9	Mean heat demand [GJ]: 27.7		
% HEQ: 34.1	Mean heat use [GJ]: 29.2	Mean heat expense [€]: 1713	Mean 'gas' use [m3]: 831
% LIHC: 11.8	Mean energy demand [GJ]: 37	Mean electric expense [€]: 765	Mean electricity use [kWh]: 2584
% collective heating: 77.7	Mean energy use [GJ]: 38.5	Mean energy expense [€]: 2478	

Figure 28. Monitors in the NetLogo model tracking variables related to energy consumption and energy poverty.

All prices incl VAT [€/GJ]

Var costs electricity: 134	Fixed costs electricity: 340	Heffingskorting: 682
Var costs gas: 50	Fixed costs gas: 255	
Var costs heat: 44	Fixed costs heat: 440	

Figure 29. Monitors in the NetLogo model showing energy prices used in the current scenario.



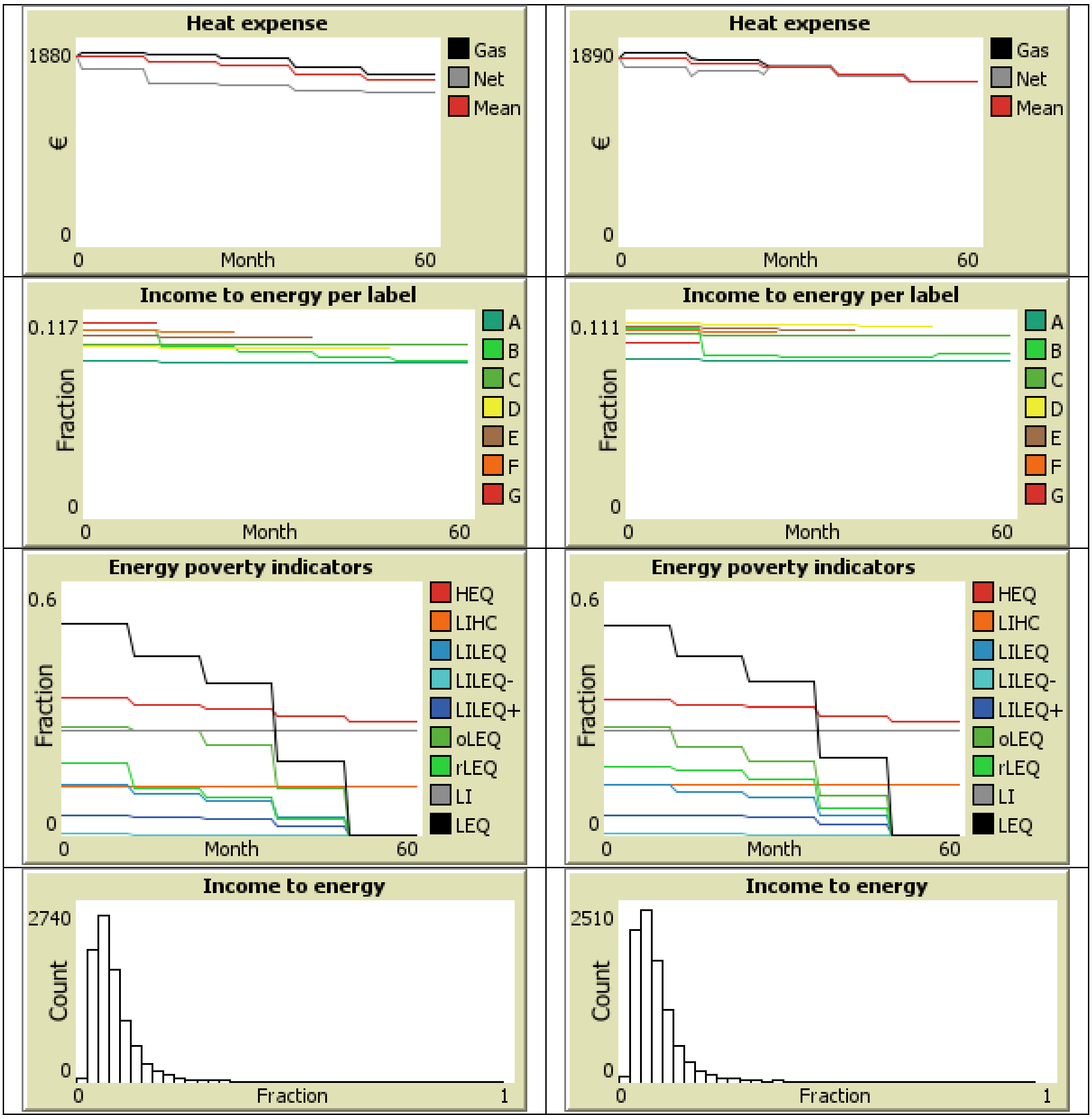


Figure 30. Monitors for various scenario variables of all model households for two heat network implementation scenarios.

Assignment of energy labels

Figure 31 shows the distribution of initial, proxy and all used energy labels in the model for households in the Voorhof district. Proxy labels were assigned based on the energy label of the closest neighbour with a known energy label. 2739 households (32%) had no known energy label. Most proxy labels were assigned to households built in the period 1965-1974 (55%) and 2015-2022 (28%) (see Table 40). The latter is mostly due to there being no known energy labels for buildings built in 2021 (475 dwellings) or 2022 (263 dwellings). Since these two age groups comprise most assigned proxy labels, we will further investigate the labels assigned to these dwellings.

A *B* *C*

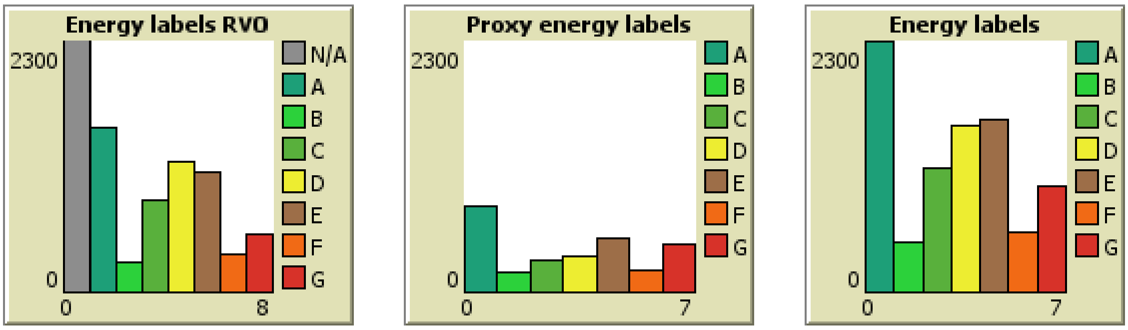


Figure 31. Energy labels of households in Voorhof. A. Initial energy labels; B. Assigned proxy labels; C. All used energy labels.

Table 40. Count and percentage of unknown energy labels per dwelling age group.

Construction year	Households (% of total)	Unknown labels (% of age group)	% of unknown labels	% of households
1946-1964	898 (10%)	84 (9%)	3%	1%
1965-1974	5246 (61%)	1510 (29%)	55%	18%
1975-1991	262 (3%)	145 (55%)	5%	2%
1992-1995	17 (0%)	1 (6%)	0%	0%
1996-1999	44 (1%)	26 (59%)	1%	0%
2000-2005	28 (0%)	18 (64%)	1%	0%
2006-2010	210 (2%)	148 (5%)	5%	2%
2011-2014	684 (8%)	48 (7%)	2%	1%
2015-2022	1168 (14%)	759 (65%)	28%	9%

Table 41 shows the distribution of initial and assigned energy labels for dwellings built in 1965-1974 and 2015-2022. The assigned labels for dwellings built in 1965-1974 follow the distribution of known energy labels. Energy labels E and F are assigned relatively often and G is assigned less often than in the distribution of known labels. A rule of thumb used to estimate energy labels is that unrenovated buildings from before 1975 have label G and on average buildings from 1965-1974 have label E when considering renovations done. The assigned proxy labels are thus reasonable. For buildings built after 2015, the assigned labels are mostly A and G. This is due to the proximity of poorly insulated buildings close to the new buildings with unknown labels. The assignment of proxy labels for this building group was improved by assigning label B to all buildings built after 2015-2019 (18 dwellings) and label A to buildings built in 2020 or later (741 dwellings).

Table 41. Distribution of initial and assigned energy labels for dwellings built in 1965-1974 and 2015-2022.

Construction year	label	A	B	C	D	E	F	G	no label
1965-1974	initial	384	179	683	1043	657	279	511	1510
	assigned	126	47	249	325	469	204	90	
	final	510	226	932	1368	1126	483	601	
2015-2022	initial	307	19						755
	assigned	375	0	17		14		349	
	final	682	19	17		14		349	

Assignment of household incomes

The distribution of assigned household incomes in the model is compared to the distribution of incomes in the Netherlands in Figure 32. The distribution of households is skewed toward the lower income groups. This is consistent with data from Voorhof and Buitenhof that average income is low compared to other Dutch households and that most households are among the 40% poorest households in the Netherlands (see Table 7).

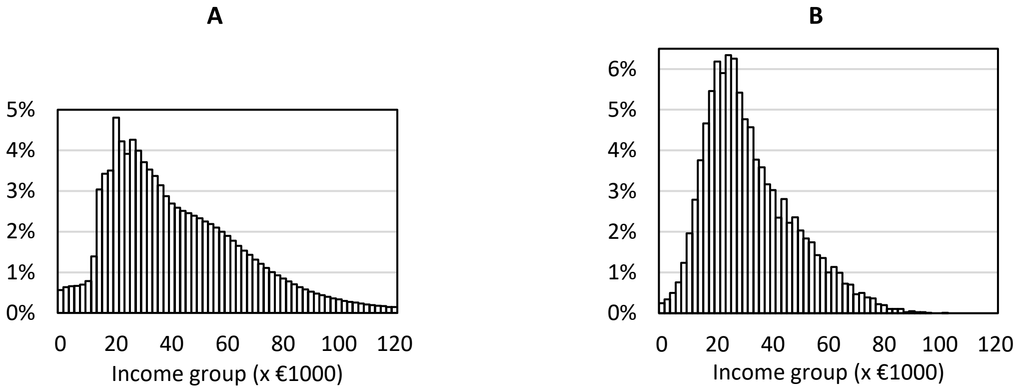


Figure 32. Income distribution of A. the Netherlands (CBS 2021c) *and B. model households, Voorhof.*

E.3 Model output verification

Table 42. Comparison of observation data and model output on household characteristics. Table based on Table 7 (VNG and Kadaster 2022).

	Voorhof		Buitenhof	
	Actual (2018)	**Model**	**Actual (2018)**	**Model**
Number of dwellings	7397	8557	6657	7367
Ownership				
Corporation	47%	46%	68%	79%
Private	53%	54%	32%	21%
Electricity use	2300 kWh	9.3 GJ = 2583 kWh	2490 kWh	9.4 GJ = 2611 kWh
Natural gas use	640 m^3	29.2 GJ = 830 m^3	920 m^3	30.8 GJ = 876 m^3

The data of VNG and Kadaster 2022 are from 2019. In the meantime, new buildings have been built in Voorhof and Buitenhof. On 1 January 2022, there were 8200 households in Voorhof and 7165 households in Buitenhof. The remaining difference could be caused by the fact that we assume that every address with housing function is occupied and by a further number of buildings being finished between January and November 2022.

The Gini coefficient for disposable income was 0.29 in the Netherlands in 2019 (CBS 2021c). In the model, this was 0.26 in both the Voorhof and the Buitenhof scenario.

E.4 Model analysis

In the model's interface, various parametrizations and options for conceptualisation can be chosen (Figure 33).

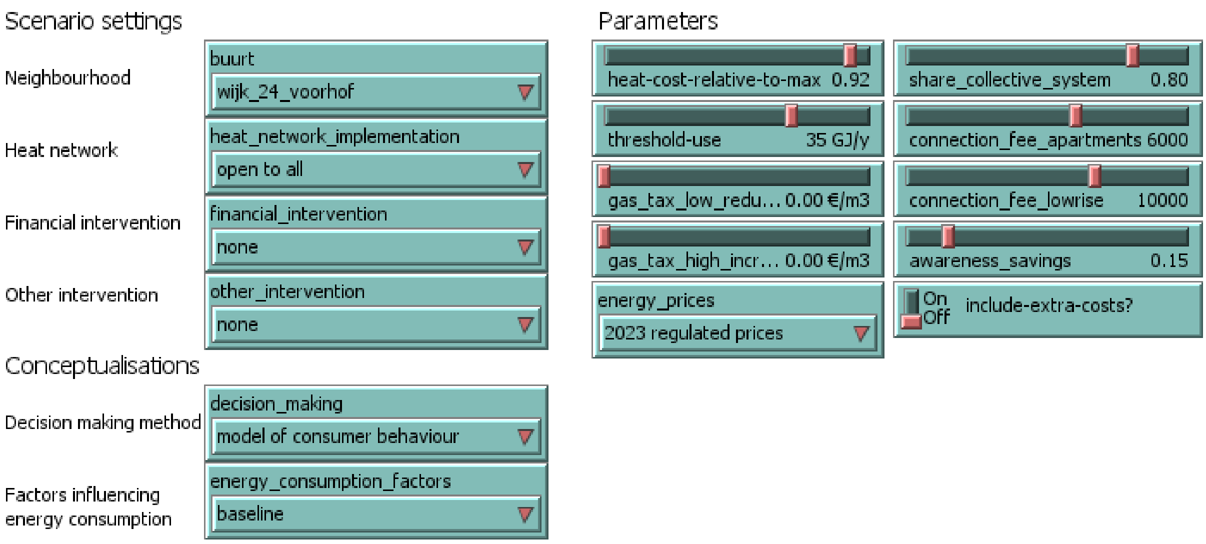


Figure 33. Available settings for scenarios, various conceptualisations, and model parameters in the NetLogo model.

E.5 Model output corroboration

We compare energy poverty levels of our model to real-world data on energy poverty (Table 43). The share of households with HEQ is matches well with observed values. The share of LIHC households is overestimated, likely due to the different definitions used in the model versus the definition used by CBS. In the model, the costs are compared to other households in the model rather than in Dutch households since this data is not available in the model. On the other hand, the share of LILEQ households is underestimated. This is due to the share of households with LEQ being decreased since 2018 after completion of new dwellings and renovation of existing ones. Since the purpose of the model is to compare energy poverty levels before and after the implementation of a heat network, the focus will be on the relative difference rather than the absolute difference. So, this high estimation of LIHC will not lead to different conclusions.

Table 43. Comparison of energy poverty levels in Delft, 2018 (CBS 2021a) *and model results, baseline scenario.*

Area	Prices	HEQ (%)	LIHC (%)	LILEQ (%)
Netherlands	2018	8	4	6
South Holland	2018	6	3	8
Delft	2018	6	3	12
Buitenhof	2018	9	5	20
Buitenhof (model)	2019	11	13	13
Buitenhof (model)	2020	8	13	13
Buitenhof (model)	2021	8	13	13
Buitenhof (model)	2023	43	13	14
Voorhof	2018	6	4	18
Voorhof (model)	2019	9	12	12
Voorhof (model)	2020	6	12	12
Voorhof (model)	2021	6	12	12
Voorhof (model)	2023	34	12	12

In Figure 34 the distribution of income groups, household types and ownership among households with HEQ is shown. When we compare this to a similar figure from van Berkel et al. (2021), we conclude that the model produces realistic distributions of these socio-economic groups among households with energy poverty. Households from lower income groups, and more financially vulnerable household types such as singles, are more likely to experience energy poverty than other groups.

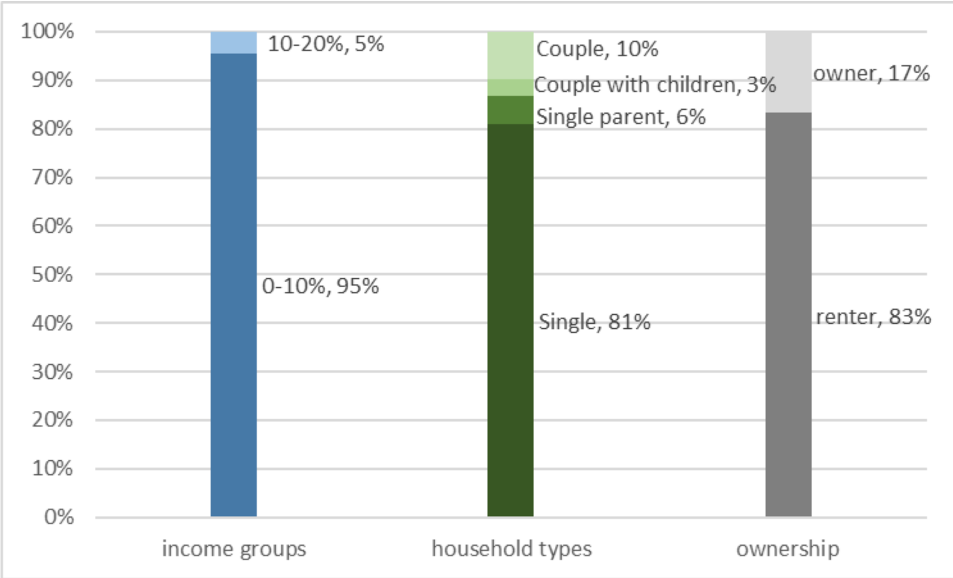


Figure 34. Distribution of income groups, household types, and homeownership for households with HEQ, Buitenhof, 2019 energy prices. Income groups above 20% had a 0% share of the households with HEQ.

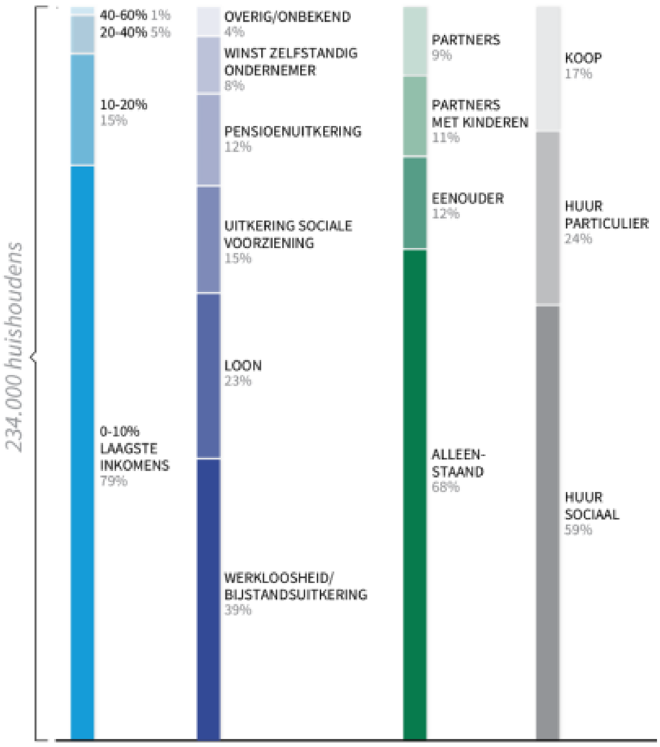
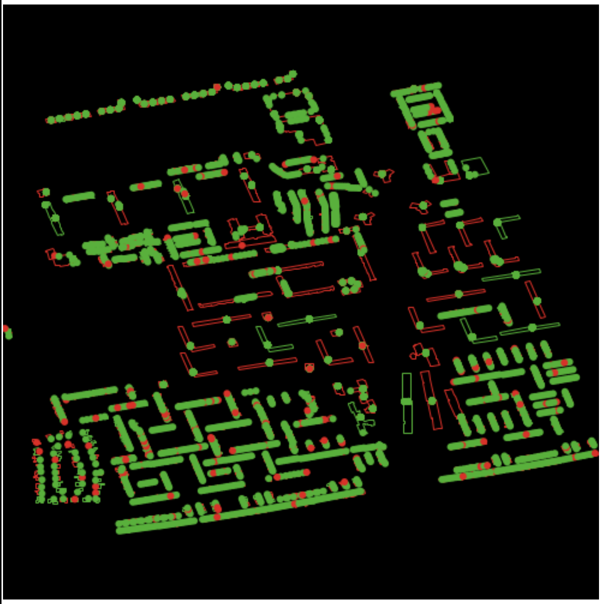
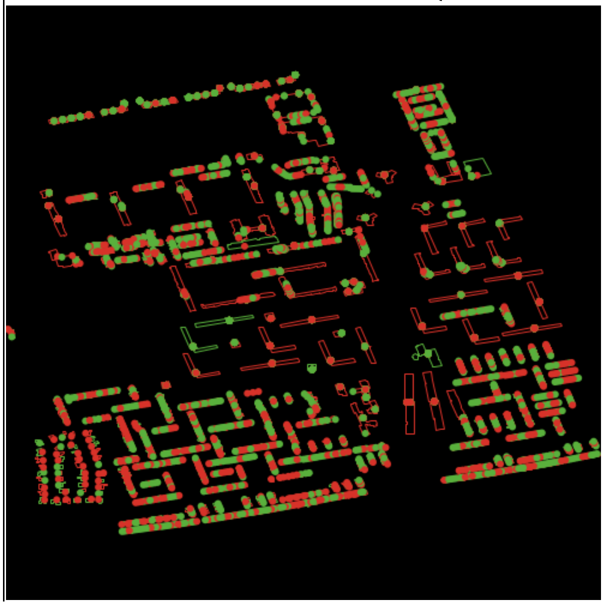
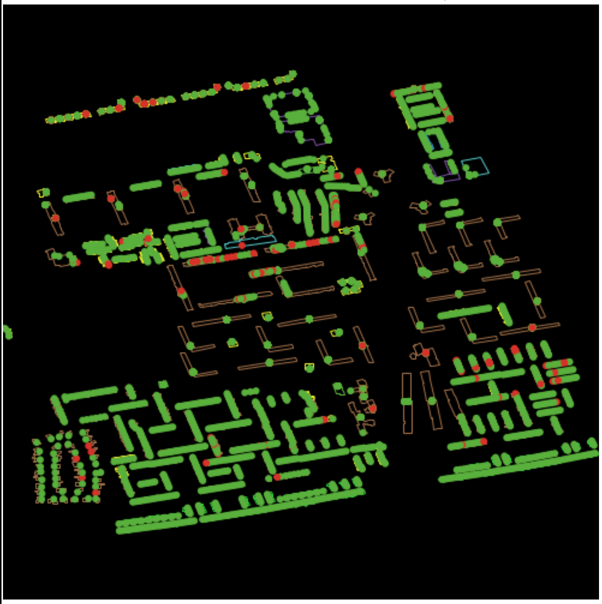
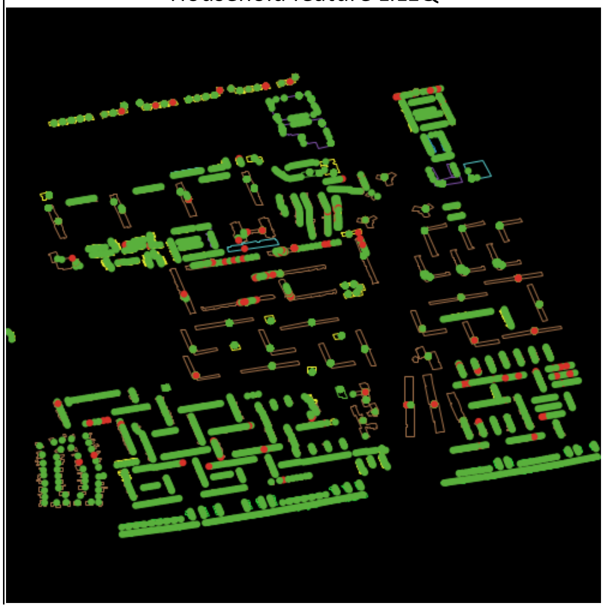


Figure 35. Energy poor households (HEQ and payment risk) per income group and household type. Image source: Figure 5 in van Berkel et al. (2021)

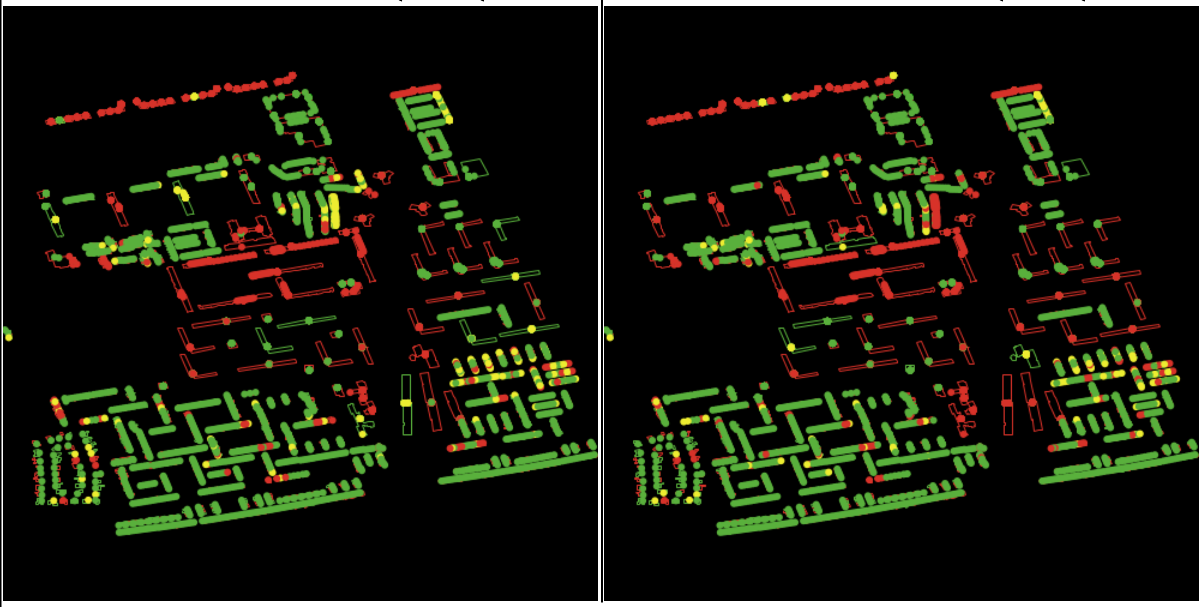
Appendix F. Additional results

F.1 Additional baseline results, no heat network implementation

Table 44. Households with high energy quote (HEQ), low income and home with low energetic quality (LILEQ), and owners or renters with home with low energetic quality (oLEQ and rLEQ), Buitenhof, 2021 and 2023 energy prices.

<table>
<tr><td>2021 prices, t=60
Building feature = ownership
Household feature = HEQ</td><td>2023 prices, t=60
Building feature = ownership
Household feature = HEQ</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Building colour: green, private ownership; red, corporation ownership.
Dwelling colour: green, no HEQ; red, HEQ.</td></tr>
<tr><td>2021 prices, t=60
Building feature = construction year
Household feature = LILEQ</td><td>2023 prices, t=60
Building feature = construction year
Household feature LILEQ</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Building colour: red, 1946-1964; orange, 1965-1974; brown, 1975-1991; yellow, 1992-1996; green, 1997-1999; lime, 2000-2005; turquoise, 2006-2010; cyan, 2011-2014; sky, ≥2015.
Dwelling colour: green, no LILEQ; red, LILEQ.</td></tr>
</table>

2021 prices, t=60 Building feature = ownership Household feature = oLEQ & rLEQ	2023 prices, t=60 Building feature = ownership Household feature = oLEQ & rLEQ



Building colour: green, private ownership; red, corporation ownership.
Dwelling colour: green, no oLEQ or rLEQ; yellow, oLEQ; red, rLEQ.

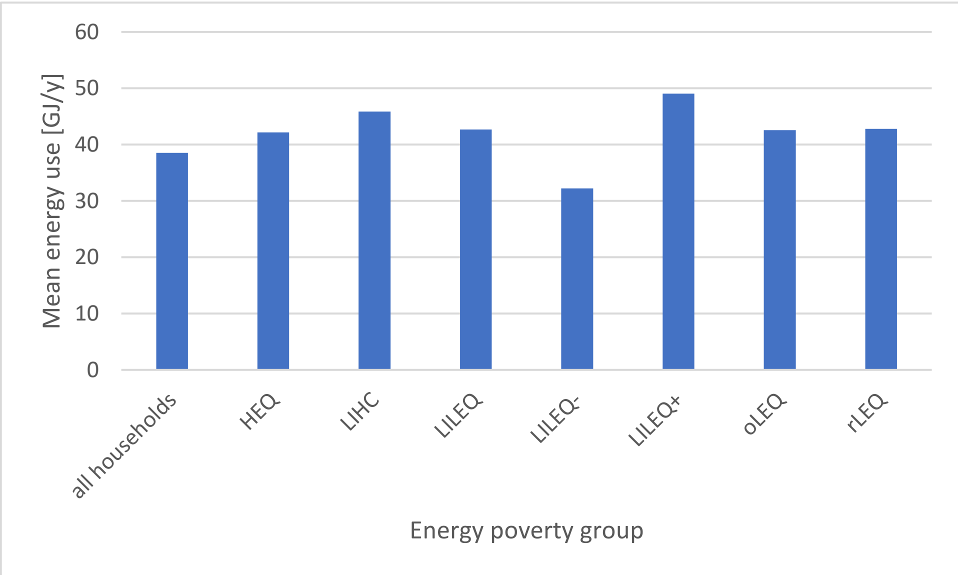


Figure 36. Mean energy use of households with energy poverty per energy poverty group, Voorhof, 2023 prices.

Households with HEQ, LIHC, LILEQ, LILEQ+ and oLEQ or rLEQ have a higher energy consumption than average in Voorhof, while LILEQ- households have a lower energy use (Figure 36).

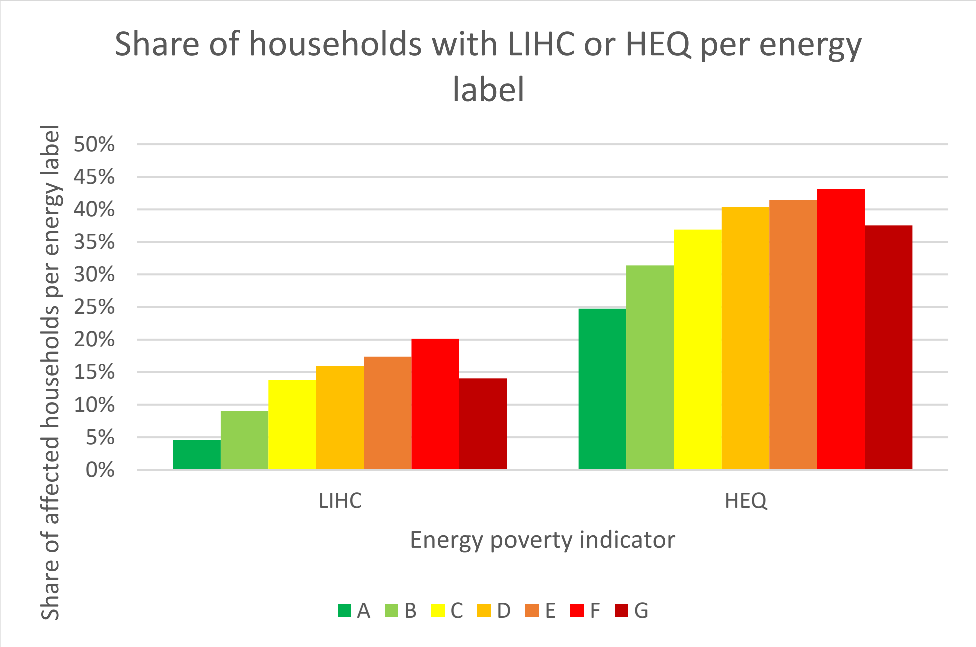


Figure 37. Share of households with LIHC or HEQ per energy label.

F.2 Additional scenario results, heat network, no interventions

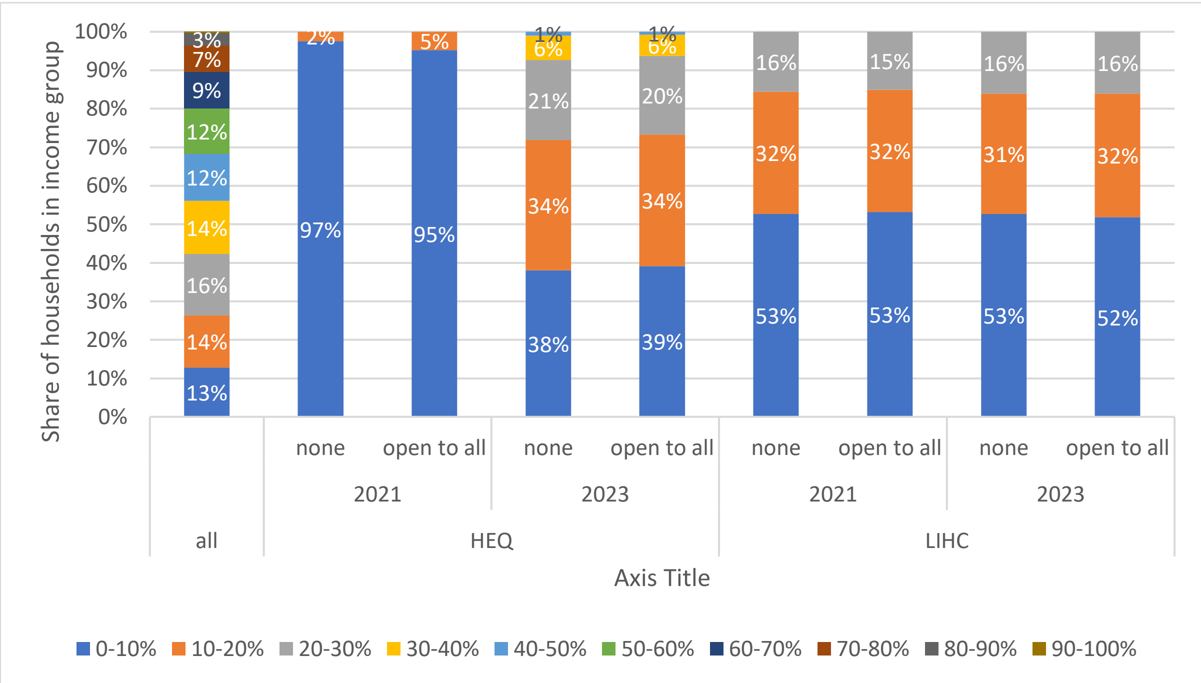


Figure 38. Distribution of income groups of all households, households with HEQ and households with LIHC for the baseline and two heat network scenarios, Voorhof, 2021 and 2023 energy prices.

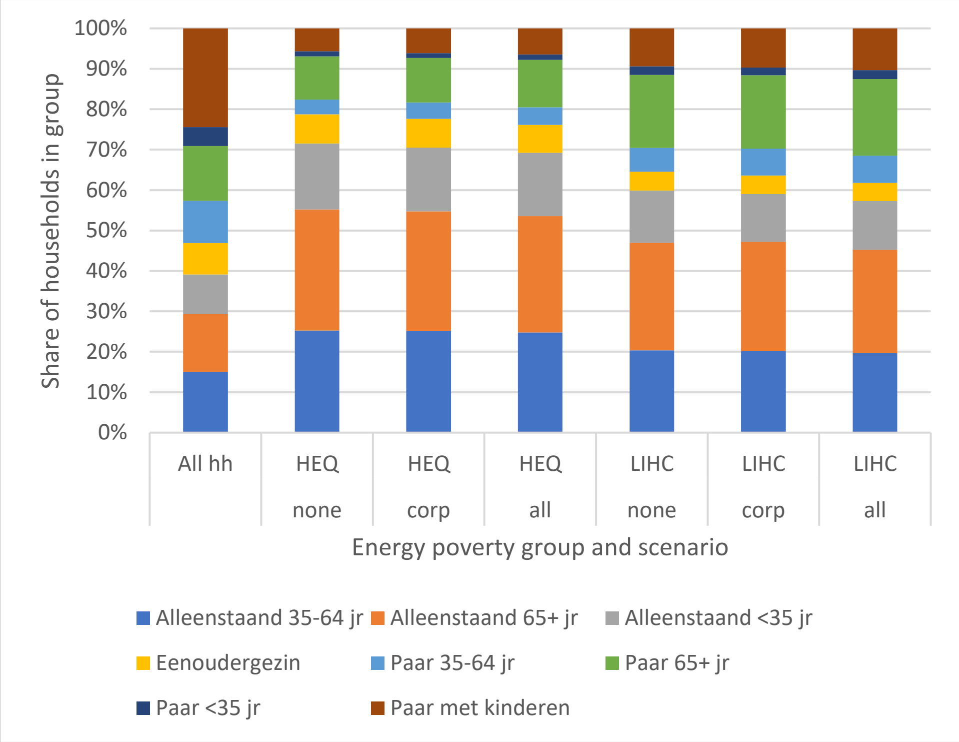


Figure 39. Distribution of household types of households (hh), households with HEQ and households with LIHC for baseline and two heat network scenarios, Voorhof, 2023 energy prices.

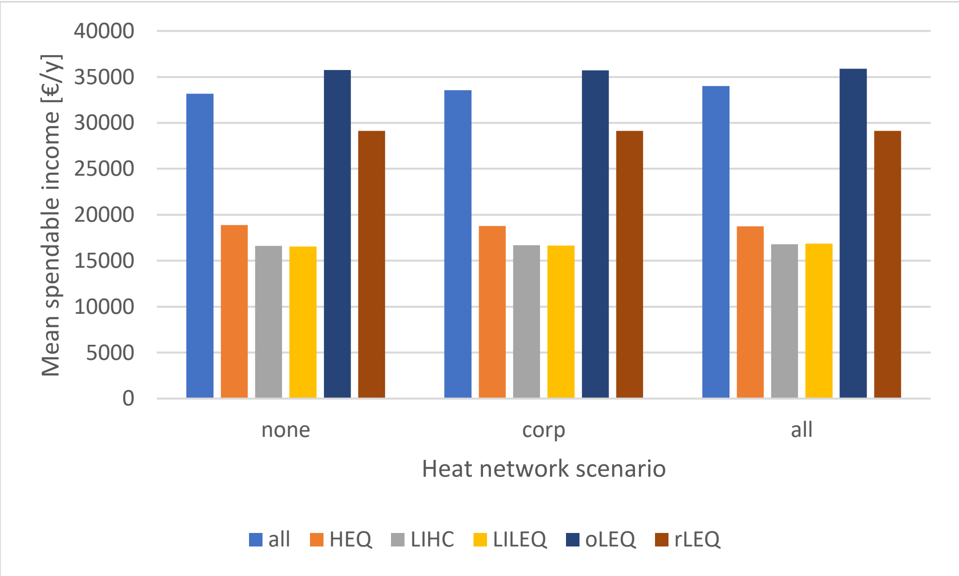


Figure 40. Mean annual spendable income per energy poverty group for the baseline and two heat network scenarios.

F.3 Additional scenario results, heat network, interventions

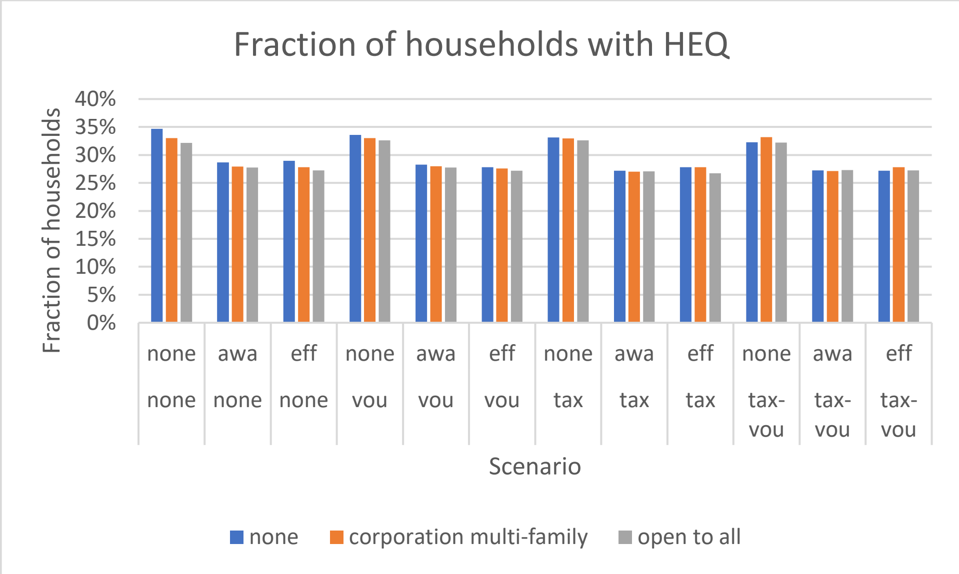


Figure 41. Fraction of households that have HEQ per scenario, Voorhof, 2023 energy prices.

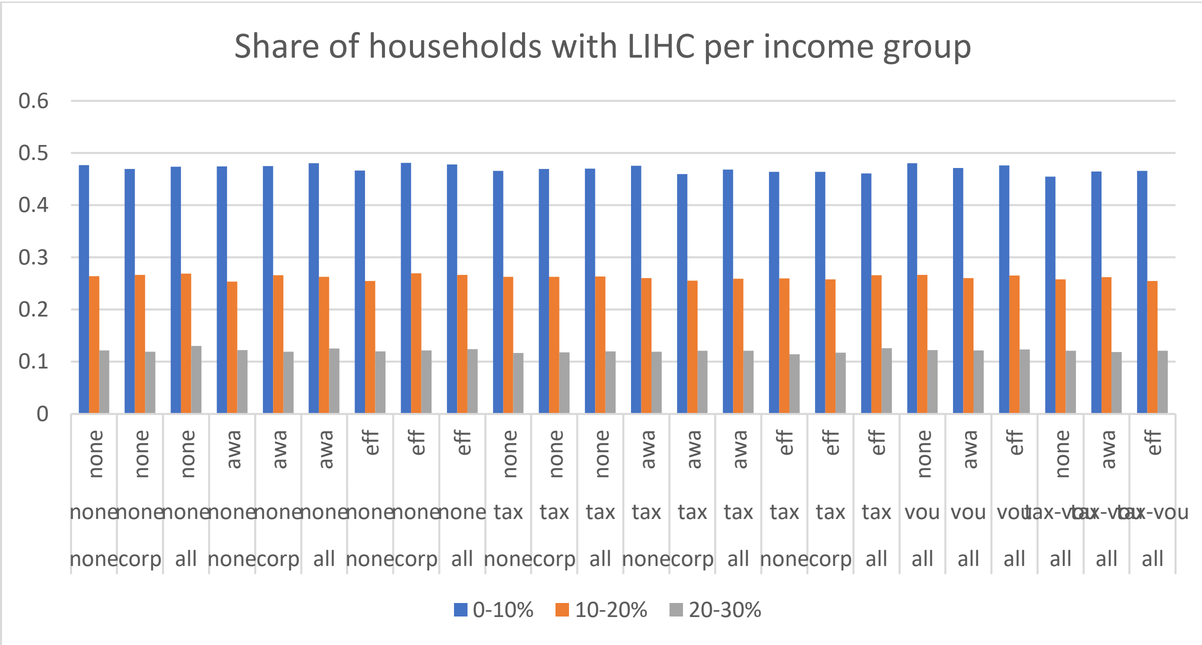


Figure 42. Share of households with LIHC per income group, Voorhof, 2023 energy prices.

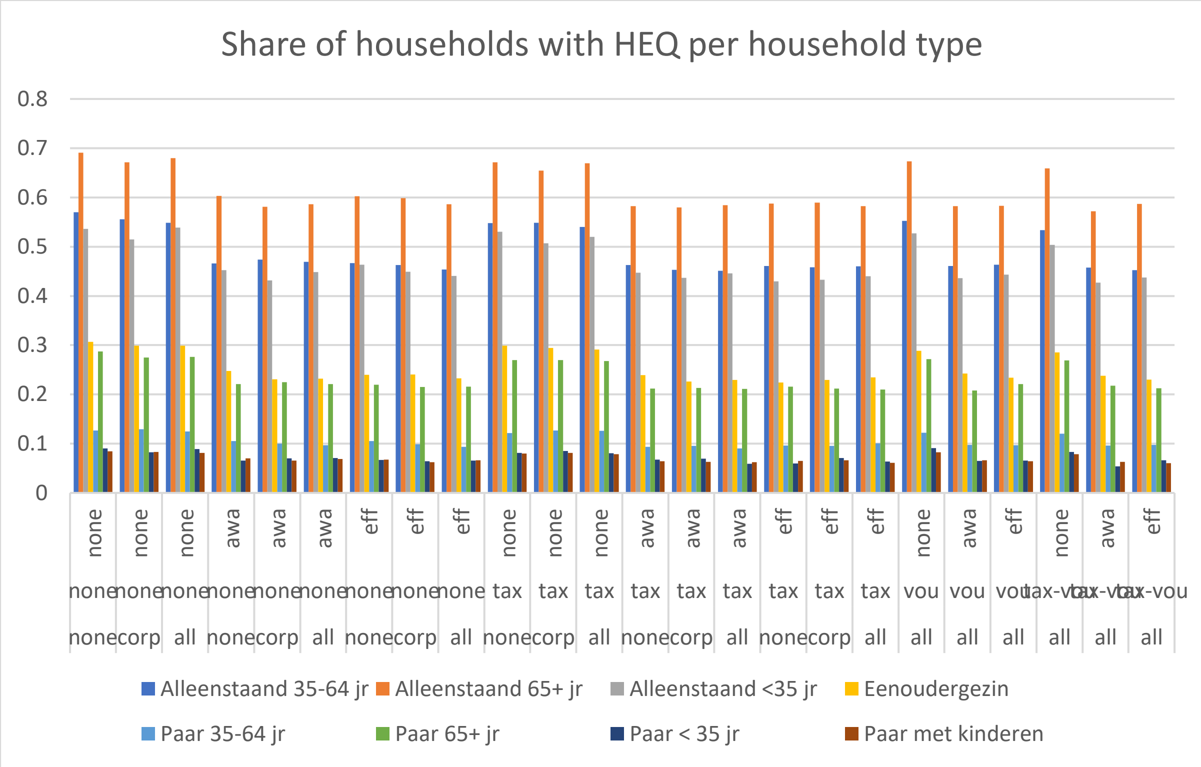


Figure 43. Share of households with HEQ per household type, Voorhof, 2023 energy prices.

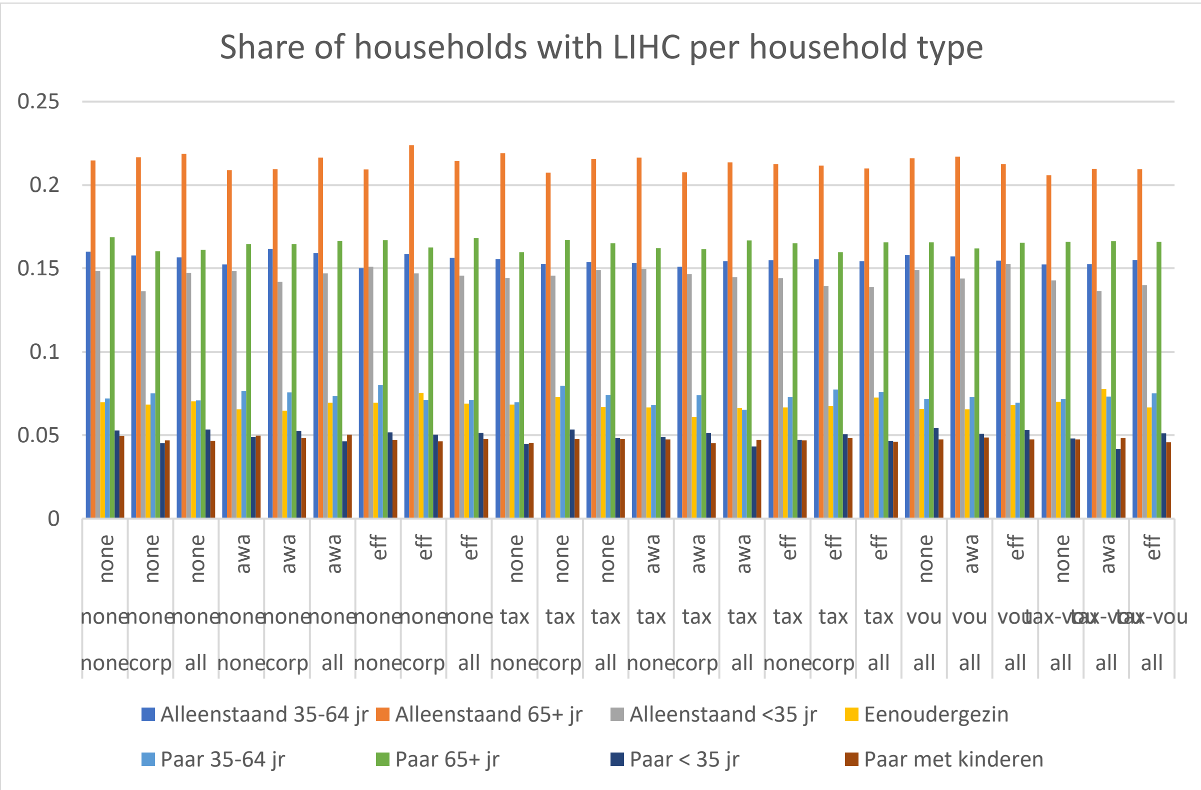


Figure 44. Share of households with LIHC per household type, Voorhof, 2023 energy prices.

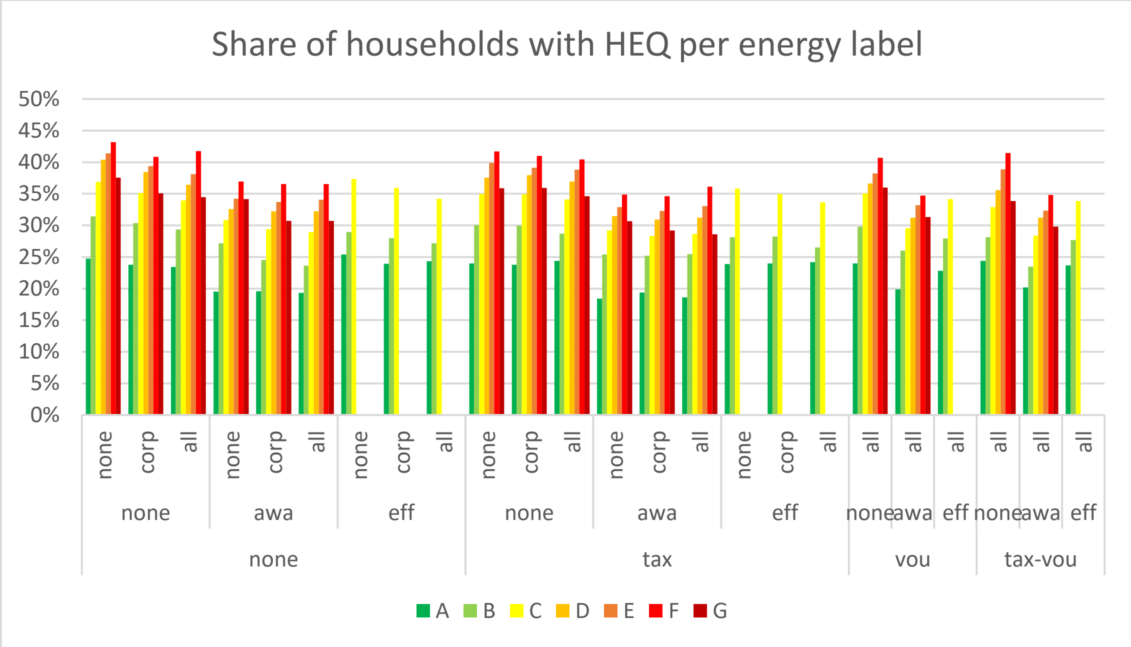


Figure 45. Share of households with HEQ per energy label, Voorhof, 2023 prices.

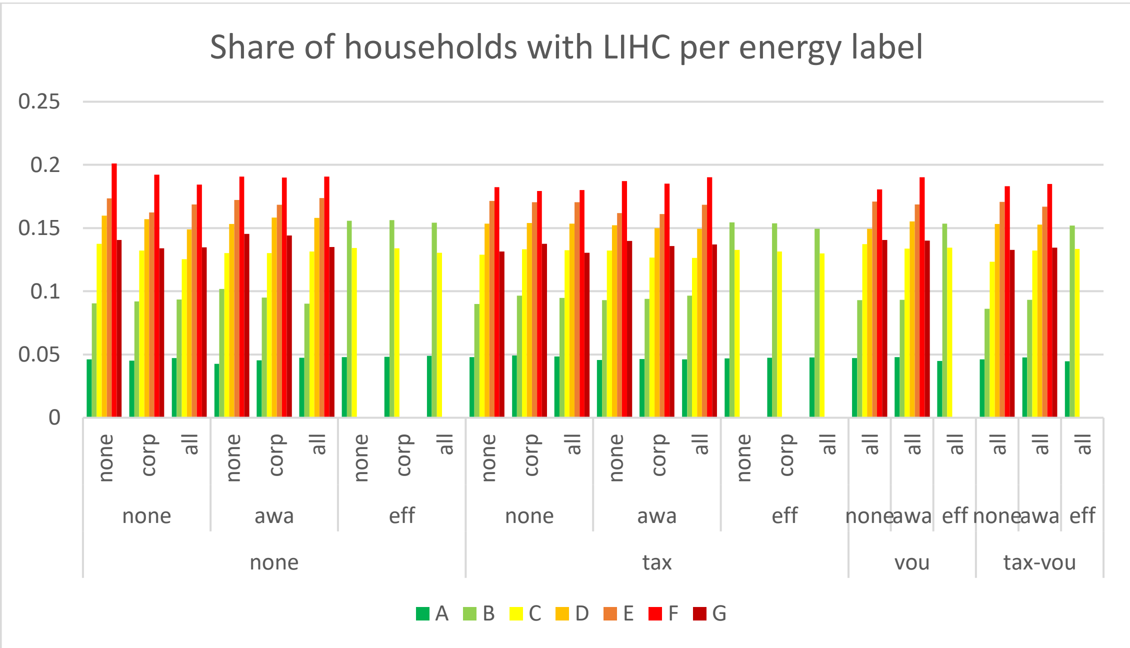


Figure 46. Share of households with LIHC per energy label, Voorhof, 2023 energy prices.

When comparing the energy poverty levels between dwelling energy label groups, we see that the better the energy label, the lower the fraction of households with HEQ (Figure 45) or LIHC (Figure 46). Compared to energy label A, each step towards a poorer energy label almost doubles the share of households with LIHC. For HEQ, this effect is less pronounced, but significant differences between energy labels still exist. In the *eff* scenarios, the energy label of dwellings with label D or worse is improved to label B. This leads to an increase in the share of households with LIHC for the group of households with this energy label. The share of households with HEQ in this group is not affected by the energy efficiency improvement.

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