Modeling Equitable Heating Transition Pathways for Dutch Urban Neighborhoods

Incorporating energy poverty aspects in the design of integrated energy systems

MSc Thesis

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To obtain the degree of Master of Science, at the Delft University of Technology, to be defended publicly on: January 21 2026

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Acknowledgements

I would like to express my gratitude to everyone who supported me throughout the process of completing this thesis. Their guidance, encouragement, and expertise have been invaluable, and this work would not have been possible without their contributions.

First and foremost, I would like to thank my thesis committee for their time, thoughtful feedback, and commitment to helping strengthen this research. I deeply appreciate the time and insights that each of you brought.

I am grateful to Dr. Stefan Pfenninger-Lee, for providing clear direction, intellectual insight, and encouragement throughout this project. Your ability to challenge my thinking while giving me the space to explore my own ideas has been valuable.

My heartfelt thanks go to Meijun Chen, my daily supervisor. Your patience, constant availability, and hands-on guidance kept me moving forward, even at the most complex moments of the project. Your detailed feedback and practical advice have helped me tremendously.

I would also like to thank Dr. Francesco Sanvito, who was also always willing to meet and help me. Your critical perspective, thoughtful questions, and constructive suggestions have helped me along the way.

Finally, I would like to thank Dr. Jenny Lieu for your time and willingness to be a part of this thesis committee.

SUMMARY

The Dutch heating transition aims to accelerate the shift away from heating with natural gas toward low-carbon alternatives. Although national climate policy provides long-term emission reduction targets, heating transition pathways are often assessed using aggregated data, which do not show distributional impacts across households. This thesis addresses this gap by examining how neighborhood-scale heating systems can be designed to achieve decarbonization goals while incorporating dimensions of energy poverty. A community-level energy system optimization model was developed using Calliope, allowing for detailed representation of household heterogeneity, technology choices, cost-sharing structures, and equity-based objective functions.

The model incorporates three aspects of energy poverty: affordability, insulation quality, and the ability to participate. Seven scenarios are evaluated, combining individual or shared investment structures, cost or equity objective functions, and the presence or absence of a CO_2 constraint. Household-level heat demand, income, and housing characteristics were used as inputs, alongside technology parameters and constraints. Outputs include total household costs, installed technology capacities, emissions and energy burden.

The scenario comparison shows several findings. First, shared heating systems consistently reduce total system costs relative to individual systems while achieving identical emission levels under a CO_2 constraint. These benefits are strongest for apartment households, whose smaller demands enable more efficient use of shared technologies. Second, only the lowest-cost scenario without emission constraints meets the affordability criteria of the Dutch Wgiw. While electrified heating reduces annual energy bills due to higher efficiency, the associated investments are too high to be recovered over 30 years when strict emission limits are imposed. Third, stringent emission constraints increase total system costs, up to 2.5 times higher than the gas baseline. This shows that there is a strong trade-off between large emission reduction and costs. Moderate emission reductions can achieved at lower or moderately higher costs than the baseline.

Sensitivity analyses highlight that energy price variations affect costs and emissions less than proportionally, indicating that the system configurations are relatively robust. The equity-based objective functions, designed to minimize income-weighted costs, have only marginal influence on outcomes. This is because optimal configurations under cost minimization already lie close to the equity-weighted optimum, and in shared systems a significant share of the costs are allocated using fixed fractions based on demand, leaving limited flexibility for redistribution. These findings explain why no single scenario fully satisfies affordability, equity, and emission reduction goals simultaneously.

Overall, the results show that achieving both low-carbon and socially equitable heat-

ing outcomes requires more than optimal system design. In particular, insulation upgrades, collective investment structures, targeted subsidies for low-income households, and careful alignment with local grid constraints are essential for reducing energy poverty while meeting emission targets.

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Introduction

1.1. The Dutch heating transition

Climate change mitigation requires a significant reduction in greenhouse gas emissions, with residential heating representing a key challenge. In the Dutch residential sector, natural gas accounts for two-thirds of energy consumption (Eurostat, 2023). Most of these households rely on natural gas as their main source of heat (Conradie & van der Vegt, 2024). In response, the Netherlands has committed to a heating transition toward net zero emissions by 2050 as part of the Dutch Climate Act (Zaken, 2021). This entails switching from fossil fuel-based heating to renewable sources.

The scale of this change is substantial. The Netherlands has the highest dependence on natural gas for heating among all IEA countries. In 2021, space heating accounted for more than 70% of end-use in residential buildings and natural gas covered 84% of this energy demand (IEA, 2024b).

While electrification of heat is expected to play a large role in this transition (IEA, 2024a), it presents significant infrastructure challenges. Large-scale electrification contributes to grid congestion issues, which the Netherlands is already facing. This has led to increased interest in collective heating systems as viable alternatives that can relieve pressure on the electricity grid by reducing the peak demand while still achieving decarbonization goals.

The heating transition is often understood as a technical challenge. Yet it is equally a social transition, reshaping how households access heat and how costs and benefits are distributed in society. Without addressing these social dimensions, the heating transition risks reinforcing existing inequalities instead of alleviating them.

Despite national climate targets, the adoption of renewable heating technologies has been slow. While the majority of Dutch citizens is positive about the energy transition (Cbs, 2023), about one-fifth of the population is unable to participate in the heating transition due to a combination of financial and structural barriers (TNO, 2024). This illustrates that the heating transition is a socio-technical transformation.

1.2. Energy Poverty

The International Energy Agency (IEA) recommends implementing a people-centered approach to the energy transition, addressing distributional impacts (IEA, 2024b). The purpose of this thesis is to aid in a more people-centered approach to the energy transition by addressing distributional impacts in the heating transition. This will be achieved by addressing aspects of energy poverty.

Energy poverty is a critical dimension of the heating transition challenge. According to the European definition, energy poverty is a situation in which households are unable to access essential energy services that support a decent standard of living and health, such as adequate heating (Kashour & Jaber, 2024).

Energy poverty can be characterized by three dimensions: Affordability of energy, the energetic quality of housing, and the ability to participate in the energy transition (Mulder et al., 2023), (TNO, 2024). Affordability of energy describes whether households are able to pay for adequate heating without sacrificing other essential needs. The second dimension, the energetic quality of housing, describes the insulation of dwellings, which determines how much energy is needed to maintain comfortable temperatures. The ability to participate refers to whether households are in a position to take part in the transition to sustainable heating technologies. Participation is determined by access to financial resources, homeownership status, and the physical suitability of the home for technology installations. Energy poverty creates a reinforcing cycle. Living in a poorly insulated house requires a higher energy consumption to achieve adequate warmth, which puts a higher financial strain on the already vulnerable households. Although the Netherlands has a relatively low level of energy poverty, it remains a structural issue and requires targeted policy interventions to alleviate (Conradie & van der Vegt, 2024) (Young & Halleck Vega, 2024).

1.3. The Dutch policy context

A key challenge is that renewable energy technologies require significant upfront investments and specific housing conditions, such as homeownership and adequate insulation (Mulder et al., 2023). These requirements effectively exclude lower-income and rental households. As a result, existing subsidy schemes for renewable energy technologies favor wealthier individuals and widen the economic disparity. An example of these policies is the ISDE (Investeringssubsidie Duurzame Energie), which provides financial support for heat pumps, solar boilers, and other renewable heating systems but requires homeownership to be eligible (Mesdaghi et al., 2025).

In response to the energy crisis, the Dutch government introduced temporary financial support to combat energy poverty. Dutch energy poverty policies can be split into two types. A short overview is given below (Mesdaghi et al., 2025):

1. Energy price ceiling: This measure capped the energy prices for all households

and decreased the number of potential energy-poor households by 277.000. This measure was not aimed at energy-poor households; everyone could benefit from it.

2. Energy allowance: All households that have a maximum income of 120% of the minimum living wage were eligible to receive an allowance of 1300 euros in 2022 and 2023. The measure was aimed at energy-poor households, had a larger effect than the price ceiling and helped decrease the amount of potentially energy-poor households by 365.000.

While these measures offered short-term relief, these policies do not structurally address the drivers of energy poverty in the Netherlands, such as low income, high energy prices, and poor energetic quality of housing. Additionally, not all measures were aimed specifically at energy-poor households, which highlights the inefficient allocation of funds. Such measures primarily promote equality by reducing costs for all households, but do not necessarily improve equity, as they do not account for differences in vulnerability or energy burden.

There is a growing recognition that long-term solutions require more comprehensive and inclusive strategies that address both affordability and structural barriers to participation. Despite national climate targets, the adoption of renewable heating technologies has been slow. Although most citizens are positive about the energy transition, energy poverty prevents widespread participation (Okur et al., 2024).

1.3.1. THE DUTCH COLLECTIVE HEAT ACT

The introduction of the new Dutch Collective Heat Act will replace the current Heat Act. This represents a significant shift in the heating transition in the Netherlands. The law is expected to partially go into action in 2026 and be fully implemented in 2027 (NPLW, 2025). The new law is meant to speed up the development of district heating and increase the affordability, security, and sustainability of the energy supply. Under the new law, municipalities play a larger role in the local heat planning and designing local heat networks. Municipalities face the challenge of selecting heating solutions that are both technically feasible and socially equitable. The feasibility of each configuration depends on local conditions. District heating is suitable for densely populated urban areas, while heat pumps are more appropriate in low-density and well-insulated neighborhoods (Haag, 2022). This approach is becoming increasingly adopted by municipalities as a viable heating transition pathway for suitable neighborhoods. It is also expected that energy communities will emerge more, where groups of households jointly invest in and use energy infrastructure (De Minister voor Klimaat en Energie, 2024). Collective heating systems that integrate renewable heat sources and thermal storage are seen as a viable alternative that can potentially relieve pressure on the electricity grid and increase participation in the heating transition.

1.3.2. MUNICIPAL HEAT TRANSITION INSTRUMENTS ACT

The Municipal Heat Transformation Instruments Act (Wgiw) gives Dutch municipalities a route to phase out natural gas in residential neighborhoods. First promising areas for phasing out natural gas are mapped. The approach is area-based. Solutions are chosen per neighborhood based on local building stock and infrastructure conditions. The Act establishes a structured, area-based approach: municipalities first identify and map promising areas for transitioning away from natural gas, then develop tailored transition plans based on local building stock characteristics, existing infrastructure, and socioeconomic conditions (Ministerie van Volkshuisvesting en Ruimtelijke Ordening, 2025). The Act establishes explicit affordability criteria that proposed heating transition plans must satisfy:

- For at least 70% of the households, they cannot be worse off compared to the natural gas baseline over a 30-year horizon.
- The monthly costs cannot increase too much. This criterion leaves some room for interpretation. It does not directly state how much cost increase is acceptable and for how many households this criterion should hold. In this study, it is assumed that this monthly cost criterion is evaluated in line with the first affordability criterion, meaning that the energy bill should not be higher than the current situation for at least 70% of households.

These affordability criteria are intended as guiding principles for municipal decision-making rather than as strict affordability limits. They reflect the recognition that technically optimal decarbonization pathways may not be socially or politically feasible if they impose substantial financial hardship on residents.

It is important to note that the affordability criteria are not equivalent to energy poverty indicators such as energy burden. The energy burden measures the ratio of energy costs to income and reflects distributional impacts across income groups. The affordability criteria, by contrast, focus on cost comparisons relative to the gas baseline and do not account for household income differences. This means that in theory, a heating transition pathway could comply with the Wgiw criteria, but still impose high energy burdens on low-income households.

1.3.3. THE ROLE OF ENERGY SYSTEM MODELING

Energy system models are analytical tools to simulate how an energy system operates under different technologies, prices, demand and policy constraints. Energy system models are used to compare alternative heating technologies, system configurations and costs to identify technically feasible options through optimization. In the context of the heating transition, energy system models are used to identify cost-effective pathways for reducing greenhouse gas emissions. By exploring alternative configurations of the energy system, these models help policymakers evaluate potential future heating transition pathways and assess the implications of different choices. Insights provided by energy system models are shaped by modeling choices, which means energy system models should be used as support tools that show the tradeoffs between choices and not as a tool that gives a single optimal outcome.

1.4. PROBLEM STATEMENT

The Dutch heating transition is shaped by ambitious national climate targets and legislation aimed at phasing out natural gas. However, previous policy approaches rely heavily on aggregate analyses that overlook the distributional consequences of different heating pathways. These approaches evaluate the average effects of different heating pathways but fail to capture the substantial differences between households in terms of energy demand, housing quality and income. As a result, solutions that appear technically feasible and cost-effective at the system level may still impose disproportionately high energy costs on lower-income or otherwise vulnerable households. Understanding these unequal impacts is essential for ensuring that the transition is not only low-carbon but also socially just.

This research addresses this gap by examining how neighborhood-scale renewable heating systems can be configured to meet both decarbonization objectives and equity goals. A household-level modeling approach is used to identify how different configurations influence cost distribution and affordability across diverse socioeconomic groups. In particular, the contrast between individual and collective investment structures is relevant. Community-owned technologies could potentially increase participation by distributing investment costs across multiple households, reducing the individual investment burden, and potentially enabling participation among groups that are otherwise excluded from individual investment schemes (Young & Halleck Vega, 2024).

To evaluate these investment structures systematically, a simplified representation of a district-level heating system in the Dutch urban context is developed. Energy system modeling serves as an analytical tool that captures the complex interactions between technical, economic, environmental and social aspects of the energy system. Several scenarios will be tested against the criteria for neighborhoods to transition to renewable heat. Social justice principles are embedded directly into the model by incorporating energy poverty indicators into the optimization process.

Through this analysis, this research provides insights into how municipalities and heat companies can design integrated energy systems that are both low-carbon and socially inclusive.

2

Literature review

This chapter provides an overview of the existing literature on energy system modeling with a particular focus on how social dimensions such as energy poverty are addressed. Section 2.1 gives a short introduction to the foundations of energy system modeling. Section 2.2 shows how equity dimensions are incorporated in energy system modeling. Section 2.3 explores how costs are distributed in energy system models. Section 2.4 discusses which research gaps still remain and section 2.5 defines the research questions this thesis will address.

2.1. Energy system modeling

Energy system models are widely used to support decision-making in the energy transition, providing insights into optimal renewable technology pathways (Pfenninger et al., 2014).

Heating makes up a major share of the energy demand of the residential sector in the Netherlands (IEA, 2024c). Accounting for the heating sector in energy system models is therefore essential (Nava Guerrero et al., 2019). It is important to note that heat is inherently local, unlike electricity, which can be transported over long distances. Heat production and consumption must be close to each other, because transporting heat over long distances results in high efficiency losses. Decarbonization of heat relies partly on electrification, which means that heating and power are tightly coupled. To model the heating transition, both are needed.

Traditionally energy system optimization models have a techno-economic focus, aiming to minimize system costs and emissions. However, there is a growing recognition that the energy transition must address social justice and equity concerns. This is particularly relevant in the Dutch heating transition where there is a high dependence on natural gas and unequal capacity to invest. Ignoring the barriers to transitioning to renewable heating technologies risks increasing energy poverty levels further (Huaccha, 2023)(Gürsan et al., 2024).

2.2. EQUITY CONSIDERATIONS IN ENERGY SYSTEM MODELING

Recent studies have begun to incorporate equity dimensions into energy system models, although primarily focused on electricity rather than heating. Understanding how these studies integrate equity into their modeling frameworks is important, because it reveals which approaches already exist and what their limitations are. This review examines the different methods used to incorporate equity considerations in energy system models.

One approach is to modify the objective function so that it accounts for distributional concerns. Sifuentes et al. (2024) introduces a mixed-integer linear optimization model designed to optimize investments that balance the trade-off between reducing the electricity bill for low-income households and minimizing greenhouse gas emissions from electricity generation. The model integrated equity by assigning a targeted fixed investment in community solar projects to communities with high shares of low-income residents, prioritizing locations with greater vulnerability.

Similarly, Xu et al. (2025) did research on energy poverty alleviation by implementing an objective function that includes both energy system cost minimization and emission minimization and balancing these competing objectives. Energy poverty is implicitly taken into account through the cost minimization objective. The underlying assumption is that lower system cost correlates with improved affordability. Both studies demonstrate how multi-objective optimization can steer system outcomes toward more equitable results. In this study and in Sifuentes et al. (2024), a clear tradeoff between cost and environmental benefit is found.

Another modeling strategy is to represent energy poverty explicitly using penalty terms. Heleno et al. (2022) uses a linear programming model to find optimal portfolio energy investments to minimize the energy burden for energy-insecure households. This paper explicitly takes socio-economic factors into account in the model. The objective function minimizes the sum of the intervention costs as well as minimizes energy insecurity.The excess burden is given a penalty cost that corresponds to the social cost of having a population living in energy-insecure conditions.. A mock policy is modeled to illustrate the model and an optimal investment portfolio is found. However, this study is limited by its lack of temporal resolution.

Quitoras (2020) is based on a multi-objective energy system model that determined the optimal configuration for an integrated electrical and thermal energy system. This model incorporates socio-economic factors into the model. The three modeling objectives are: energy security, equity and environmental sustainability. However, equity is measured by the levelised cost of electricity and the levelised cycle cost. These indicators are useful for system-level comparisons, but they do not capture household-level outcomes and therefore cannot assess distributional equity.

2.3. INDIVIDUAL AND COLLECTIVE INVESTMENT STRUCTURES

While traditional energy system models often assume uniform investment capabilities across households, emerging research is also examining how individual and collective investment affect participation rates and distributional outcomes. Collective investment approaches are gaining attention due to the potential to address financial barriers for lower-income households.

Liu et al. (2021) compares individual and district investment in renewable heating technologies. It is found that individual solutions offer the highest energy savings but are also the most expensive, due to the increased insulation upgrades. Collective systems are more cost-effective but achieve lower levels of energy savings. Their analysis highlights a clear trade-off between cost and emissions, but does not account for heterogeneity in household investment capabilities.

Similarly, Aparisi-Cerdá et al. (2024) investigated how integrating energy-poor households into renewable energy communities could alleviate energy poverty through shared photovoltaic systems. Investment in the shared system using an energy subsidy is compared to individuals receiving the subsidy to lower the electricity bill. Their findings suggest that participation in renewable energy communities can reduce emissions as well as reduce the energy bill more effectively than direct financial support measures such as energy checks. This study does not compare shared systems to individual investment strategies within the same modeling framework.

Overall, it can be seen that there is an increase in models integrating social considerations into energy system models and a growing number of models incorporating community-based approaches. However, significant gaps still remain, particularly regarding heating systems that includes both equity considerations and cost-sharing mechanisms. Heating transitions often require substantial upfront investments that many households cannot afford individually. In the Netherlands the insulation levels of houses vary widely and many residents are renters. Collective or shared heating solutions are a way to distribute costs and enable participation for households with limited financial capacity. Investigating how equity concerns interact with different cost-sharing structures is therefore essential for assessing which neighbourhood heating strategies are not only cost-effective, but also feasible for all households. This thesis will address this gap by combining district-level heating system optimization model with equity considerations.

2.4. RESEARCH GAP

Although there is an increasing amount of research on integrating equity considerations into energy system models, there are still gaps remaining in current literature.

1. Small-scale energy system models are increasingly used to assess heating transition pathways, however most studies aggregate households and report average outcomes and do not show gains and losses within communities. Models such as Sifuentes et al. (2024) show optimal fund allocation across several regions and average effects in these regions. This does not show the underlying distribution of costs and benefits within communities. A household-level model, however, would

give insight into the distributional impacts within communities, enabling an analysis of the relative benefits and costs across different income groups.

2. There is a lack of energy system models that compare individual and shared investment structures. While studies such as Aparisi-Cerdá et al. (2024) evaluate the benefits of shared investment, they do not directly compare it to individual investment. Comparing these will show the relative advantages of each approach. While Liu et al. (2021) directly compares individual and shared heating systems, there is a lack of equity and affordability consideration.

3. There is a lack of energy system models that incorporate energy poverty directly into the optimization approach. Most research that takes energy poverty into account minimizes system costs and assesses the affordability afterwards. This treats equity as an output rather than a design constraint. Directly integrating affordability in the energy system design will allow for the exploration of more equitable pathways.

2.5. RESEARCH QUESTION

This research aims to address these gaps by developing a community-level energy system model that compares individual versus shared investment structures for renewable heating technologies, while explicitly incorporating energy poverty considerations. By integrating affordability, income heterogeneity, and policy criteria into the optimization framework, the model provides a way to evaluate how different heating configurations affect households with varying characteristics.The goal is to provide insights into more equitable pathways for the heating transition in the Netherlands. This leads to the question:

How can neighborhood-scale renewable heating systems in Dutch urban areas be designed to achieve low-carbon outcomes while addressing energy poverty?

Hypothesis: Renewable neighborhood heating systems that incorporate shared investment and energy-efficiency measures will achieve lower emissions while improving affordability for low-income households, compared to current energy systems, thereby enabling both low-carbon and socially equitable outcomes in Dutch urban areas.

2.5.1. SUBQUESTIONS

To answer the main research question, the following subquestions are formulated. Together, these subquestions aim to answer the research question in several steps.

Subquestions:

- What renewable heating system configurations emerge as optimal under different modeling objectives, minimizing total system cost or minimizing household energy burden, and how does technology deployment differ across scenarios?
- Which modelled neighborhood heating configurations satisfy the affordability criteria defined by Dutch heating transition policy, and which household groups do not meet these criteria under each scenario?

- What tradeoffs emerge between reducing emissions, minimizing costs and limiting energy burden for low-income households in the Dutch heating transition?

3

METHODOLOGY

This chapter explains how the energy system model is built, what data it uses, how energy-poverty dimensions are embedded in the model, and what output the model gives. First, section 3.1 describes the Calliope-based modeling framework and the elements that make up the model. Section 3.2 describes the model input used. Next, section 3.3 describes which energy poverty elements are taken into account in the model and how. Then, section 3.4 presents the scenarios defined for this model. Finally, section 3.5 shows which results are reported per scenario.

3.1. ENERGY SYSTEM MODELING FRAMEWORK

This section delves into the modeling approach. The modeling framework used will be discussed. The objective function and the formulas used are also explained.

3.1.1. MODELING CONFIGURATION

The energy system optimization model was developed using Calliope version 0.7.0.dev5, which is used to optimize energy system costs as well as equity under different conditions (Pfenninger & Pickering, 2018). The model operates in plan mode, where the capacities are determined by the model. The Gurobi solver was employed to solve the optimization problems. Due to the substantial computational requirements, all model runs were executed on the DelftBlue supercomputer, as the problem size exceeded the capabilities of standard desktop computing resources.

The temporal resolution is hourly over a year. However, as optimizing on an hourly resolution for a whole year is computationally expensive, the operate horizon and window allow for splitting up the optimization into larger parts of the year. The operate horizon defines how long the model looks ahead when optimizing for each iteration. The operate window defines the period of the optimization is kept. The operate horizon and operate window are set to a month and a week, respectively. This means that the model optimizes for a month per iteration and for each iteration only the results of the first week of that month are kept. This allows the model to balance medium-term foresight with moderate computational expense. The spatial resolution is defined on the household level. This shows the consumption patterns on the smallest scale.

The model consists of four main components: the nodes, the technologies, the constraints, and the scenarios. The nodes represent the different household archetypes, while the technology set defines the available heating, conversion, storage, and supply options. The optimization behavior of the model is determined by a set of custom constraints. Scenarios are constructed by combining different constraints and model assumptions. After defining the nodes, technologies, and constraints, the scenarios are run to evaluate how the system performs under different objectives and policy contexts.

An overview of the model setup is shown in Figure 3.1. Household data, technology parameters and constraints serve as the model inputs. The model optimizes either total system costs or energy burden, depending on the scenario. The resulting outputs include total costs, emissions, technology deployment and energy burden per household.

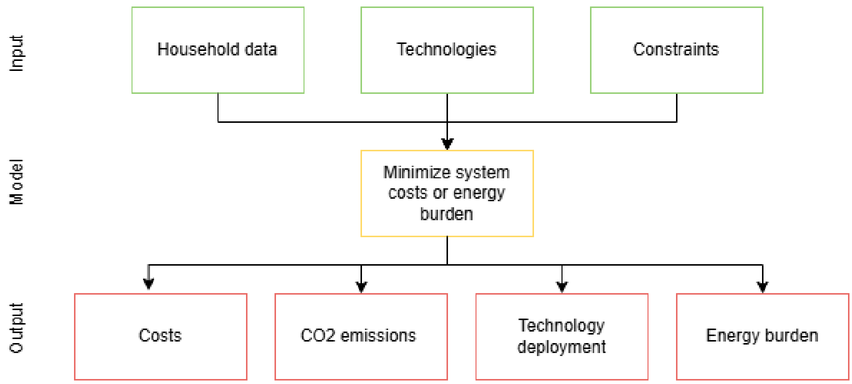


Figure 3.1: Schematic overview of the model setup

3.1.2. OPTIMIZATION APPROACH

In many energy system models, the objective function is to minimize the overall system costs. The goal of this research is not only to minimize costs but also energy poverty, therefore the objective function will be changed. Energy poverty has several aspects, which are discussed in detail in Section 3.3. One objective function will remain as the minimization of overall system costs, which is the default Calliope objective function. The second objective function is formulated to achieve a more equitable distribution of energy burden across the population by minimizing income-weighted costs. In this objective function the cost is minimized but weighted by income, which means that costs for lower incomes should have a higher priority to minimize than costs for higher incomes. Which scenarios use which objective function is explained in Section 3.4.

The objective functions are shown below:

System cost minimization

$$\min \left[\sum_n \sum_m (\text{Capex}_{n,m} + \sum_t \text{Opex}_{n,m,t}) + M \cdot \text{UnmetDemand} \right] \tag{3.1}$$

where n represents the nodes, m the technologies, t the timesteps, Capex is the investment costs, Opex is the fixed and variable operational costs and M is a large penalty value for the unmet demand. The value of M is 1e9. This is to ensure the feasibility of the model, but making the price of unmet demand so high that the demand will be met.

Energy burden minimization individual investment

$$\min \left[\sum_n \frac{\sum_m (\text{Capex}_{n,m} + \sum_t \text{Opex}_{n,m,t})}{\text{Income}_n} + M \cdot \text{UnmetDemand} \right] \tag{3.2}$$

$Income_n$ represents the income per node n.

Energy burden minimization shared investment

$$\min \left[\sum_n \left(\frac{\sum_m (\text{Capex}_{n,m} + \sum_t \text{Opex}_{n,m,t})}{\text{Income}_n} + \text{frac}_n \cdot \text{SharedCost} \right) + M \cdot \text{UnmetDemand} \right] \tag{3.3}$$

$$\text{frac}_n = \frac{\text{demand}_n}{\sum_n \text{demand}_n} \tag{3.4}$$

Where frac_n is the fraction of demand each node uses of the total demand. SharedCost are the costs from the central node N1, where all the shared energy technologies are.

3.1.3. MODEL CONSTRAINTS

There are four different custom constraints used. It depends on the scenario which constraints are turned on. The first three constraints: the insulation level constraint, piecewise costs for heat pumps and power-to-heat ratio for CHP are active for all scenarios. The emission constraint is only active in certain scenarios, which are addressed in Section 3.4.

- The insulation level m can be a base insulation level or an upgraded insulation level. The decision variable $s_{n,m}$ determines the optimal combination of these insulation levels m for each node n. Equation 3.5 ensures that the combination of both insulation levels adds up to one, implying a value of $s_{n,base} = 0.3$ means 30% of the node has base insulation and 70% of the node has upgraded insulation. The insulation level constraint 3.6, at the same time, enforces a consistent insulation choice $s_{n,m}$ for each node over the full modeling horizon. The constraint links the insulation decision variable to the heat supply $q_{n,m,t}$ and the heat demand $D_{n,t}$ for each timestamp. This requires that each insulation level m is responsible for the same share of the heat demand per heat supply over time. This means that with $s_{n,base} = 0.3$, the heat supply $q_{n,base,t}$ to the base insulation level should always be responsible for 30% of the heat demand, resulting in a constant insulation level choice $s_{n,m}$ over time. A small relaxation of ε is considered in the constraint to ensure the feasibility of the model.

$$\sum_{m \in \mathcal{M}_{\text{ins}}} s_{n,m} = 1 \qquad \forall n \in \mathcal{N}. \tag{3.5}$$

$$(1-\varepsilon)\, s_{n,m} D_{n,t} \leq q_{n,m,t} \leq (1+\varepsilon)\, s_{n,m} D_{n,t} \qquad \forall n \in \mathcal{N},\ m \in \mathcal{M}_{\text{ins}},\ t \in \mathcal{T}, \tag{3.6}$$

- A piecewise linear cost constraint is employed to capture economies of scale behavior for heat pumps. The cost curve contains multiple segments, each representing a capacity range with its associated cost per capacity x with the unit [kW].

$$C(x) = \begin{cases} 3500\,x, & x \leq 5, \\ 2500\,x, & 5 < x \leq 10, \\ 1500\,x, & x > 10. \end{cases} \tag{3.7}$$

- Another constraint is to fix the ratios of power and heat over all timesteps for CHP. $q^{\text{heat}}_{n,m,t}$ is equal to space heat and hot water heat. r_m is the heat-to-power ratio for CHP.

$$r_m = \frac{q^{\text{heat}}_{n,m,t}}{q^{\text{el}}_{n,m,t}} \tag{3.8}$$

- A crucial part of this research is the sustainability of the energy systems. This will be integrated as an emission constraint instead of directly in the objective function. Therefore, the last one is the CO_2 emission constraint, where the overall emissions are constrained. The value is based on the reduction in emissions that need to be achieved compared to the base scenario. The goals in the Netherlands are to reduce emissions by 55% compared to 1990 by 2030 and by 95% compared to 1990 by 2050. The goal of 2050 is chosen as the CO_2 limit.

$$\sum_n \sum_m \sum_t \text{CO2}_{n,m,t} \leq E_{max} \tag{3.9}$$

where E_{max} is the emission limit.

3.2. MODEL INPUT

This section discusses the household-related and technological input for the model.

3.2.1. HOUSEHOLD REPRESENTATION

There are 10 different nodes that each represent a household type. These archetypes are defined by two dimensions: income and house type, which together influence demand and affordability. Income is divided into five quintiles, ranging from low to high income. For each quintile, two households are included in the model. The households are assigned to one of three housing archetypes: apartment, terraced house and detached house are not present in the same frequency. The frequency approximately follows the average distribution of these house types in the Netherlands: 3:5:2 (CBS, 2023). The households are connected to a grid which allows unlimited gas and electricity supply. Electricity and gas are modeled as unlimited supply because this study focuses on household-level heating system design rather than upstream network constraints. This simplification allows the model to isolate the effects of technology choice and investment structure without the added complexity of grid capacity limitations. The nodes can be seen as a collection of the same types of households, allowing the model to capture distributional effects across income and housing types while keeping the optimization organized.

3.2.2. HOUSEHOLD CHARACTERISTICS AND DEMAND PROFILES

Households are characterized by demand, income, and housing type. Heat demand consists of demand for space heating and hot water. Open source data from CBS and VNG is used (CBS, 2024a) (VNG, 2024).

Each housing type has unique characteristics. There are three household types with different demands for space heat, hot water and electricity: apartments, terraced houses and detached houses. The household with the largest house has the highest demand. An overview of the heat and electricity demand per house type is shown in Table 3.1. Each household has the same heat demand hourly profile, scaled according to each household's total annual heat demand. It is assumed that each household has 2 people living there, as the average size of a Dutch household is 2.1 persons (CBS, 2024b). The nodes are labeled based on their income level and household archetype. For example, I1H1 means that this node represents a household with an income of the first quintile and the first household archetype, an apartment. The income is the disposable income per household.

Household	Label	Income level	Income (eur)	House	Construction year	Area (m^2)	Space heat (kWh)	Hot water (kWh)	Electricity (kWh)
1	I1H1	20%	23.000	Apartment	Before 1975	90	6,160	1,540	1,970
2	I1H2	20%	23.000	Terraced house	1975–1990	117	8,800	2,200	2,830
3	I2H1	40%	33.000	Apartment	Before 1975	90	6,160	1,540	1,970
4	I2H2	40%	33.000	Terraced house	1975–1990	117	8,800	2,200	2,830
5	I3H1	60%	49.000	Apartment	Before 1975	90	6,160	1,540	1,970
6	I3H2	60%	49.000	Terraced house	1975–1990	117	8,800	2,200	2,830
7	I4H2	80%	69.000	Terraced house	1975–1990	117	8,800	2,200	2,830
8	I4H3	80%	69.000	Detached house	After 2010	186	16,320	4,080	3,950
9	I5H2	100%	139.000	Terraced house	1975–1990	117	8,800	2,200	2,830
10	I5H3	100%	139.000	Detached house	After 2010	186	16,320	4,080	3,950

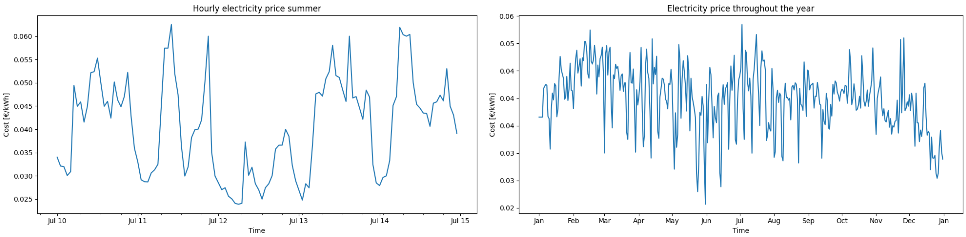
CBS, 2024a TABULA, 2017 Centraal Bureau voor de Statistiek, 2025

Table 3.1: Household typologies and characteristics

3.2.3. ENERGY PRICES

It is assumed that the households have a variable contract for both electricity and gas. Gas prices are quite stable throughout the year and are assumed to be constant. Values are used for consumers from 2025 and includes taxes. Gas prices are from CBS and electricity prices from Ember Energy (CBS, 2025), (Fox, 2024). The cost of district heating is determined by the Dutch Authority for Consumers and Markets (Markt, 2025).

The electricity price pattern is shown in Figure 3.2. The electricity price has a daily pattern. In the morning and in the evening, there are peaks when people are home and using appliances, and demand is highest. The price also depends on demand and the availability of renewables. The peaks throughout the year have large spikes, with the highest being in the winter.



(a) Hourly electricity price during the summer for 2024

(b) Daily electricity price throughout the year 2024

Figure 3.2: Electricity price time series used as model inputs, shown at hourly and and daily resolution

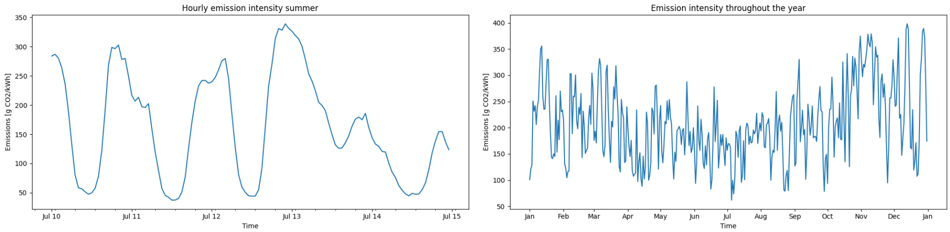
3.2.4. CARBON INTENSITY OF ENERGY SOURCES

The carbon intensity of electricity is 269 grams of carbon dioxide per kWh (Tiseo, 2024) on average throughout the year. This changes throughout the day and seasons, depending on how much energy from renewables is in the mix. The carbon intensity of natural gas is 202 grams of carbon dioxide per kWh (Zijlema, 2024). For district heating, the amount of CO_2 is dependent on the source of heat, however Vattenfall (2025) states that on average heat from district heating emits 55% less CO_2 than natural gas, which gives a value of 91 grams of carbon dioxide per kWh.

Looking at the CO_2 emissions of electricity over a few days in summer, it can be seen that the emissions are higher in the evening and night hours, which is when renewables such as solar are not present. This pattern is daily. The peaks are almost opposite to the solar peaks, which makes sense. Throughout the whole year, there is a lot of variation with the value being between 50 and 450 g CO_2/kWh. The spikes happen when there is a higher demand and less renewables available.

3.2.5. HEATING TECHNOLOGIES

Heat demand can be met by different technologies. Every technology has several characteristics: lifetime, investment cost, operational costs and conversion efficiency. Costs for heat pumps will be different based on the installed capacity to reflect reality more closely. Larger, shared, capacities will have a lower cost per kW compared to smaller, individual



(a) Average CO_2 emissions during the summer of 2024

(b) Average CO_2 emissions throughout the year 2024

Figure 3.3: Average carbon intensity of electricity in 2024 at hourly and daily resolution

installations (IRENA, 2022). Costs for technologies where size has minimal effect on the price, such as electric boilers, electric heaters and solar PV, a fixed price per kW is assumed. Insulation will also be considered a technology that increases energy efficiency. It means that less input is needed, while final demand stays the same. Additionally, it means better heat retention in the home. Insulation is modeled as an efficiency improvement because it directly reduces the final heat demand needed to maintain indoor comfort. Representing insulation as a demand-side efficiency parameter allows the optimization to approximate optimal renovation levels without explicitly modeling thermal dynamics. Each household is assigned a level of insulation based on the construction year, which is an indicator of the thermal quality of the house. The insulation level of households can be upgraded in discrete levels of 0.01 from 0 to 1 with a fixed cost per m2 that increases heat retention by a fixed amount. This cost is dependent on the housing characteristics, which can be seen in Table 3.1. Storage is represented in two forms. Hot water storage tanks and battery storage are included to improve system flexibility. PV generation is also included. The model represents existing infrastructure, with power and gas networks connecting households to the grid. The electricity grid is simplified and can adjust to new connections. For district heating, the secondary net is assumed to be present. Additionally, natural gas boilers are already assumed to be present in the households, serving as a baseline heating option. Data for costs of the technologies are from the Danish Energy Agency unless stated otherwise (DEA, 2024). An interest rate of 5% is assumed. All costs considered in this model represent end-user costs incurred by households, including investment and operating expenses. System-level or public infrastructure costs, such as network expansions or upstream energy infrastructure, are not included.

An overview of the technology characteristics is given in Table 3.2. The technologies include all the technologies from generation to conversion.

There are several types of technologies present in the model:

1. transmission: power lines, gas pipes, and pipes for space heat and hot water that supply energy to each household node. In the sharing scenarios, additional transmission links are included to represent the thermal pipes for shared space heating and hot water, as well as electrical links that allow households to exchange energy.

Technology	Type	Lifetime (years)	Capex	Opex	Conversion efficiency
Power line	Transmission	40	0.006 [eur/kW/m]	-	98%
Gas pipe	Transmission	50	0.011 [eur/kW/m]	-	98%
Space heat pipe	Transmission	25	-	-	100%
Hot water heat pipe	Transmission	25	-	-	100%
Supply grid power	Supply	25	-	400 [eur/y]	100%
Supply gas	Supply	25	-	170 [eur/y]	100%
Solar PV	Supply	25	100 [eur/kW]	10.7 [eur/kW]	85%
District heating	Supply	30	5251 [eur]	760 [eur/y]	100%
Natural gas boiler	Conversion	25	1 [eur/kW]	1.1 [eur/kW]	85%
Electric boiler	Conversion	25	210 [eur/kW]	13.4 [eur/kW]	100%
Electric heater	Conversion	30	873 [eur/kW]	8 [eur/kW]	100%
Heat pump	Conversion	25	1500-3500 [eur/kW]	32.6 [eur/kW]	300%
Chp	Conversion	25	9400 [eur/kW]	84.4 [eur/kW]	41%
Insulation base	Conversion	-	-	-	100%
Insulation upgrade	Conversion	35	85-96 [eur/m2]	-	220%
Hot water storage	Storage	20	120 [eur/kWh]	-	85%
Electricity storage	Storage	20	750 [eur/kWh]	-	90%

(DEA, 2024; Engie, 2025; IRENA, 2021; Kuipers, 2024; Markt, 2025; REEnergizeCO, 2023; Solvari, 2025)

Table 3.2: Heating technology characteristics

2. supply: electricity, gas and solar PV. Electricity and gas are transmitted to households from a distributor, whereas solar PV is generated at the nodes directly.
3. conversion: from gas to heat and just electricity: natural gas boiler, electric heater, electric boiler, heat pump, insulation, CHP (each tech can fulfill one or more demands).
4. storage: for hot water and electricity.

SUPPLY TECHNOLOGIES

Electricity and gas are modeled as an infinite supply. Solar is modeled as a variable, weather-dependent renewable source.

Solar PV

Solar PV provides electricity generation for individual households and reduces dependence on grid-supplied electricity. It can lower operational costs, as the electricity is self-generated and therefore has no additional costs besides investment costs. The generated electricity can be used directly, stored in a battery or transported to other nodes in the sharing scenarios. Solar PV varies throughout the day and across seasons and is modeled based on the solar irradiation pattern in the Netherlands and is seen in Figure A.1. The irradiation is strongest during the day and in the summer months. The average area of a roof in the Netherlands is around 50 m2. However, the useful area for solar PV will be smaller than that (van der Putten, 2025). A maximum flow capacity of 5 kW approximately corresponds to this area. The average cost for solar PV modules in 2024 is around 100 euros per kW installed (Hemetsberger et al., 2024).

CONVERSION TECHNOLOGIES

Conversion technologies transform one form of energy into another. They convert gas and electricity into useful heat for hot water and space heating. Each technology has unique characteristics for how efficiently this is done, and under what cost and emissions. The characteristics of each conversion technology used in the model are described below.

Gas boiler

Gas boilers produce heat by combusting natural gas, typically achieving thermal efficiencies of 85% (Feiken, 2023). It has low investment costs, and is assumed to already be present in this model. It provides reliable heating independent of the electricity infrastructure. However, gas generates high emissions, making it incompatible with the goals of the heating transition.

Electric heater

Electric heating has electricity as input and room heating and or hot water as output. The advantages are that the investment and installation costs are low, however there are losses when converting electricity to heat and the energy price is high. The technology is mature and there are no economies of scale present. The data for this technology is from the DEA (2024).

Electric boiler An electric boiler converts electricity directly into heat with a very high conversion efficiency of 100%. It has low investment costs and simple installation. However, its operational costs depend strongly on electricity prices, and it contributes to higher peak electricity demand because it does not provide efficiency gains like heat pumps. Data for the electric boiler is from (Ramboll, 2022) and (Marsidi, 2018).

Heat pump

Heat pumps are a reliable technology that is able to cover 100% of the residential heating demand. Therefore, in the model, heat pumps can cover both heating and hot water demand. Heat pumps are able to be installed in small sizes (3-5 kW) and large sizes. Larger-scale heat pump installations have the benefit of economies of scale, which is why the capex is modeled in stages for the heat pump. Air source heat pumps are chosen for this model. Heat pumps have been replacing gas boilers since the ban in 2018. Heat pumps are becoming the main heating solution in new buildings. The investment costs are high, but the efficiency is as well. Heat pumps are able to achieve efficiencies of 300%. The data is obtained from IRENA (2022).

Insulation

Insulation is modeled as a technology that reduces the amount of heat required to fulfill the space heat demand. In the model, heat demand represents the theoretical space heating requirement of the home before any efficiency measures are applied. The final heat demand represents the reduced demand after accounting for insulation. Insulation transforms heat demand into a lower final heat demand by improving the thermal efficiency of the building envelope.

The insulation constraint allows the model to select the optimal insulation level for each household, from the existing base insulation level to an upgraded level. It enforces that only one insulation level is chosen per node and that this choice is applied consistently for all timesteps. The price per area of insulation depends on the house type.

Micro-CHP

A combined heat and power (CHP) unit simultaneously produces electricity and heat from a single fuel source. CHP systems achieve higher overall efficiency than separate heat and power production. Their operation is constrained by a fixed heat-to-power output ratio, limiting flexibility in meeting variable heat and electricity demands. The source can be gas, waste heat or biomass.

STORAGE TECHNOLOGIES

Hot water storage

Hot water can be stored in a tank. The water can be heated at times where energy is cheaper and be used at a later time. There is a maximum storage capacity set of 40 kWh, which represents a typical upper bound for a size hot water tank that could be installed in a household (Ease, 2016). The hot water storage tank is typically charged during the day, when solar irradiation is high and the tank is discharged in the evenings when heat demand peaks. This can be seen in Figure A.3. There is seasonal variation in the charging pattern of the hot water tank. In the summer months, the storage tank has a higher net charge value as the heating demand is lower and solar irradiation is higher.

Battery storage

Battery storage makes use of the Tesla Powerwall (2) (Tesla, 2019), which is a home battery. Each household is able to invest in only one battery, which corresponds to a maximum storage capacity of 14 kWh. This limit is assumed based on the space available in the homes. The minimum state of charge of 10% is imposed to ensure technically realistic operation. Real batteries cannot be fully discharged without accelerating degradation, and manufacturers typically specify a restricted usable SOC window. Additionally, the maximum charging and discharging rates are constrained by a fixed ratio between flow capacity and storage capacity for the Tesla Powerwall. This ensures that battery operation remains consistent with realistic technical specifications. The battery charges during the day, when there is excess solar energy and discharges mostly early in the evening. There is no strong seasonal variation. The full profiles are shown in Figure A.2.

3.3. ENERGY POVERTY INDICATORS

In order to answer questions on which system configurations are equitable, we need to define what makes an energy system equitable. The most equitable configuration has the least amount of energy poverty.

Energy poverty in the Netherlands is categorized by three dimensions: affordability, energetic quality of the home and possibilities to make the house more sustainable (TNO, 2024). The model will incorporate these aspects of energy poverty. Affordability is approximated by the energy burden metric and is incorporated directly into the objective function for some scenarios, and is also evaluated in the results. The burden of each household will be calculated by annualized energy cost over income. The energy costs encompass the upfront investment, fixed fees for energy supply from the grid and variable fees for the energy consumed. The objective function will minimize the energy burden to obtain an equitable outcome. An energy burden of 10% is often taken as the threshold of energy poverty (TNO, 2020). Energetic quality of the home is approximated by the level of insulation and relates to the energy efficiency gap. The optimization chooses if and how much a household upgrades its insulation. The insulation level is an output from the model that is measured for each household. The last aspect of energy poverty, the ability to invest, is not taken into account explicitly in this model configuration. It is incorporated in the scenario design. All scenarios except the baseline assume that households have the ability to invest. The baseline scenario represents the situation where no investment in new heating technology occurs.

When assessing these model configurations, the optimal system contains all three elements of equity that the solution gives: a low energy burden, a high insulation level, and the households are able to invest. Based on these criteria, the results of the scenarios are analyzed.

3.4. SCENARIO DESIGN

The base model builds on the Urban Scale template and has been adapted to reflect the neighborhood heating context (Pfenninger & Pickering, 2025). The seven scenarios described in Table 3.3 represent alternative heating system configurations under different modeling and policy assumptions. Together, they allow for an evaluation of how these alternatives perform along the technical, economic, and equity dimensions of the heating transition. All scenarios are modeled without subsidies or other financial support mechanisms.

1. Gas baseline: establishes the reference case, representing the existing energy system where (most) households use natural gas for heating. This scenario disables investment in other technologies, thereby also representing the scenario where households have no say in investment decisions. This scenario gives an emission baseline.

2. Cost-optimal: This scenario represents an unconstrained optimization scenario where the model selects heating technologies to minimize the total system costs.

3. Cost-optimal with CO_2 constraint: introduces a carbon emissions constraint, while maintaining the lowest cost objective. This scenario shows the least-cost pathway to meeting climate targets under individualized energy systems.

4. Equity individual: employs the income-weighted objective function alongside emissions constraints, prioritizing equitable cost distribution across income groups while households continue to operate independently.

5. Equity shared: Extends scenario 4 by enabling energy resource sharing, representing an energy community configuration. This configuration allows for collective

ownership of generation and storage assets, exploring whether cooperation can enhance both economic efficiency and equity outcomes.

6. District heating: is modeled as a centralized thermal energy sharing system. This scenario is a simplified representation that captures the essential characteristics and end-user costs. Only the end-user costs are taken into account. For district heating it is assumed that it is financially beneficial for energy providers to develop the district heating network.

7. Cost-optimal shared: This scenario uses the same configuration as Scenario 5 but applies the cost-minimization objective. This is to test what difference the objective function makes in a sharing configuration.

No.	Scenario Name	Sharing	CO_2 Limit	Objective Function	Heating technology
1	Gas baseline	No	No	Cost	Gas boiler
2	Cost-optimal	No	No	Cost	All
3	Cost-optimal with CO_2 constraint	No	Yes	Cost	All
4	Equity individual	No	Yes	Equity	All
5	Equity shared (energy community)	Yes	Yes	Equity	All
6	District heating	Yes	Yes	Cost	Heating network
7	Cost-optimal shared	Yes	Yes	Cost	All

Table 3.3: Overview of modeled scenarios

The CO_2 limit is based on the CO_2 emissions from scenario 1. In 2030, the goal is to decrease the emissions by 55% compared to 1990 and reduce by 95% by 2050 (NPLW, 2025), which means that the emissions need to decrease by 22% and 91% respectively compared to 2024. For the emission constraint, it was chosen to decrease the emissions to the level set by the 2050 goal.

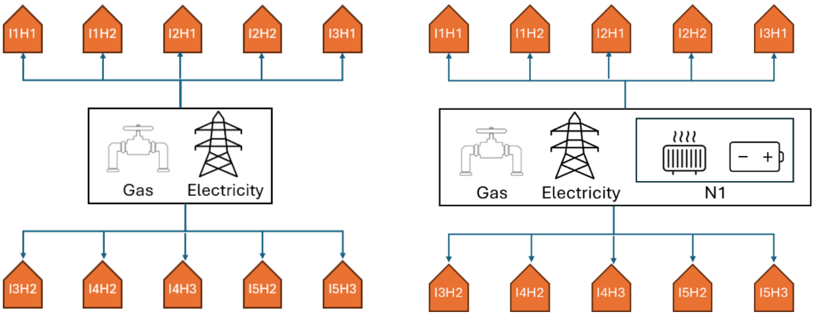
The scenarios described in Table 3.3 are compared to answer the subquestions.

- To evaluate the difference in output when minimizing cost and energy poverty, scenarios 3 and 4 are compared as well as scenarios 5 and 7.
- To evaluate which scenarios fulfill the criteria from the Dutch Wgiw act, the costs of each scenario is compared to the costs of the baseline scenario.
- To evaluate the differences between sharing and individual systems, scenarios 3 and 7 and scenarios 4 and 5 are compared.
- To see what the tradeoffs are between emissions and affordability, results are taken from all scenarios.

Together, these scenarios systematically answer the subquestions: first by comparing system designs, then by evaluating equity impacts, then by testing cost-sharing effects, and finally by analyzing trade-offs. Results will show under what design district-scale energy systems can achieve both climate and equity objectives.

3.4.1. INDIVIDUAL VERSUS SHARED SYSTEM CONFIGURATIONS

The individual and sharing configurations are set up differently. Figure 3.4 gives a simplified representation of the individual and shared configurations. In the individual setup, all nodes are connected to the gas and electricity grid. All heating technologies are located at the household nodes. In the sharing scenarios, all shared technologies are placed at a central node, N1, which delivers energy to the household nodes. The annualized costs of the technologies at the central node are reassigned to the household nodes in proportion to their annual share of demand.



(a) Individual structure

(b) Shared structure

Figure 3.4: Schematic overview of the modeled neighborhood in the individual and shared configuration

3.5. MODEL OUTPUTS

For each scenario, the model outputs the following results:

- Costs: total system costs annualized over a 30-year horizon, split by investment costs and fixed and variable operation costs.
- Technology deployment: the optimal installed capacities of all heating, storage, and generation technologies for each node or shared system configuration.
- Emissions: total CO_2 emissions associated with the energy use from electricity, gas or district heating.
- Equity outcome: energy burden per household type.

4

Results

This chapter presents the results of the developed model. The aim of the analysis is to evaluate how different heating system configurations, cost–sharing structures, and objective functions affect the distribution of costs, energy burden, technology deployment and emissions across households with varying income levels in the model. The chapter is structured as follows:

Section 4.1 presents the main outputs of each scenario, such as technology investments, annual energy bills, total household costs, and resulting CO_2 emissions. Section 4.2 evaluates the results against the affordability criteria set in the Dutch Wgiw. Here, individual household outcomes are compared to the gas-based reference situation to assess whether low-carbon heating options meet policy requirements. Section 4.3 evaluates what the tradeoffs are between costs and emissions. Section 4.4 presents a sensitivity analysis investigating how changes in energy prices and emission constraints affect the optimization outcomes. This analysis is used to understand the robustness of the results. Additionally, it is investigated why the equity objective function produces limited differences compared to the standard cost-minimizing objective.

4.1. Heating system configurations across scenarios

This section will discuss the differences in model output across the scenarios and between household nodes.

Technology deployment

Each scenario has a different technology mix. Scenarios 1 and 6 are not discussed, as their primary heating technology is already predetermined. Across the remaining scenarios, there is no CHP or heat pumps deployed, as can be seen in Figure 4.1. Heat pumps are very efficient, but have a very high investment cost. They are more expensive than other heating technologies. The figure shows the total installed capacity per technology aggregated across all household nodes.

There is a big difference in technology deployment between scenario 2, which has no emission constraint and the other four scenarios with an emission constraint. In Scenario 2, gas boilers remain the dominant technology because gas-based heating is still cost-effective when no emission limit is imposed. In contrast, the scenarios with an emission constraint have a much higher capacity of electric boilers compared to scenario 2. In these constrained scenarios, the deployment of electric heaters, PV and storage is also substantially higher than in Scenario 2. Technologies that use electricity are able to produce fewer emissions. In the model, natural gas has a constant emission factor, whereas the emission intensity of electricity varies hourly depending on the share of renewables in the grid mix. Although electricity has a higher average emission factor than gas, part of the electricity demand can be met by PV, which has zero emissions. In addition, the optimization can shift electric demand toward hours with lower electricity emission intensity by using storage. As a result, in the scenarios with a CO_2 constraint, electric heating technologies can achieve lower total emissions than gas boilers. In the scenario without an emission constraint, gas is used a lot more.

Comparing the individual and sharing scenarios, the biggest difference is that the capacity of the electric boiler and the storage capacity are a lot lower in the sharing scenarios. There is little difference in the amount of PV and the electric heater capacity.

Finally, there is very little difference in the results between the lowest cost scenarios and the equity objective scenarios. Scenarios 3 and 4 have very similar technology deployment. Scenario 4 only has a slightly larger capacity for the boiler. Between the sharing scenarios 5 and 7, there is no difference in technology deployment.

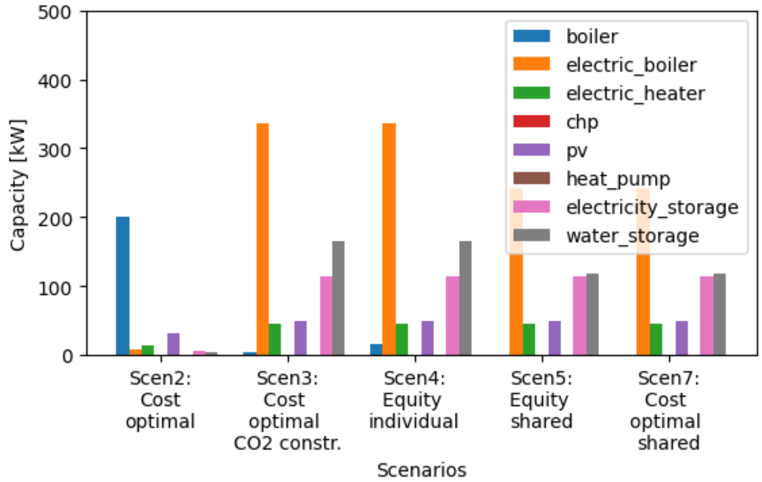


Figure 4.1: Total installed heating, generation and storage capacities across scenarios

COSTS PER HOUSEHOLD FOR INDIVIDUAL AND SHARING CONSTRUCTIONS

The results from the individual scenarios 3 and 4 will be compared to the results from the sharing scenarios 5 and 7. These pairs of scenarios differ only in their objective functions. Comparing the costs per node for the individual and sharing scenarios, the differences are minimal. From Table 4.1, it is clear that between scenarios 3 and 4, there is no difference in costs for the first seven nodes. Only the three highest-income nodes (I4H3, I5H2, I5H3) show any difference, and even there the change is below 1%. The difference in costs between the sharing scenarios 5 and 7 is even less. Here, the difference in cost per node is not even a tenth of a percent. This clearly shows that the equity objective has very little effect on the result. In the individual scenarios, the equity objective does not lower the cost for any node, it only makes the costs for the higher income nodes higher. In the sharing scenarios, the costs are lower for the lower-income nodes and higher for the high-income nodes in scenario 5, where the equity objective is active. This difference is negligible, however. This is largely due to the fact that the majority of the costs are allocated at the shared node, and these costs are allocated through a predetermined fraction that is based on the demand. The objective function does not influence how these shared costs are distributed. Only a very small share of the costs is household-specific, which means the weights in the objective function only have very limited room to adjust the outcome.

When comparing the results of individual and shared configurations, the differences are much larger. For households in apartments, costs are 18 percent lower when sharing. For households in a terraced house, the costs are 5 percent lower, however, for households living in a detached house, the costs are about ten percent higher. The total system costs are 3.5 percent lower in the sharing scenario. This indicates that sharing leads to lower costs and reduces energy burden for households in apartments and terraced houses.

Node	Cost-optimal CO_2 constr. (eur)	Equity individual (eur)	Equity shared (eur)	Cost-optimal shared (eur)	Difference equity individal and shared
I1H1	3611.32	3611.32	2949.61	2950.38	-18%
I1H2	4790.56	4790.56	4562.67	4563.00	-5%
I2H1	3611.32	3611.32	2949.96	2950.30	-18%
I2H2	4790.56	4790.56	4562.89	4563.00	-5%
I3H1	3611.32	3611.32	2950.08	2950.30	-18%
I3H2	4790.56	4790.56	4563.30	4563.00	-5%
I4H2	4790.56	4790.56	4563.35	4563.00	-5%
I4H3	7151.90	7086.38	7861.52	7861.43	11%
I5H2	4790.56	4821.30	4563.47	4563.00	-5%
I5H3	7151.75	7201.03	7861.99	7861.43	9%

Table 4.1: Annual household energy costs per node under individual and shared scenarios

EMISSIONS

Total emissions per scenario are shown in Figure 4.2. Scenario 1 has the highest CO_2 emissions as the source of heat is natural gas. Scenario 2 has significantly lower CO_2 emissions, even though no emission limit is imposed. It shows that partially switching away from natural gas is financially beneficial. Scenarios 3, 4, 5 and 7 have the same CO_2 constraints, which is why the emissions are lower and identical. District heating also has lower CO_2 emissions, but not as low as in scenarios with constraints.

ENERGY BURDEN

Figure 4.3 shows the energy burden per household node per scenario. The total burden is also shown in Table B.1. The energy burden is split into investment costs and the variable energy costs: the energy bill. The energy bill consists of the yearly fixed supply costs for gas, electricity and district heating (depending on the scenario) and the usage. The

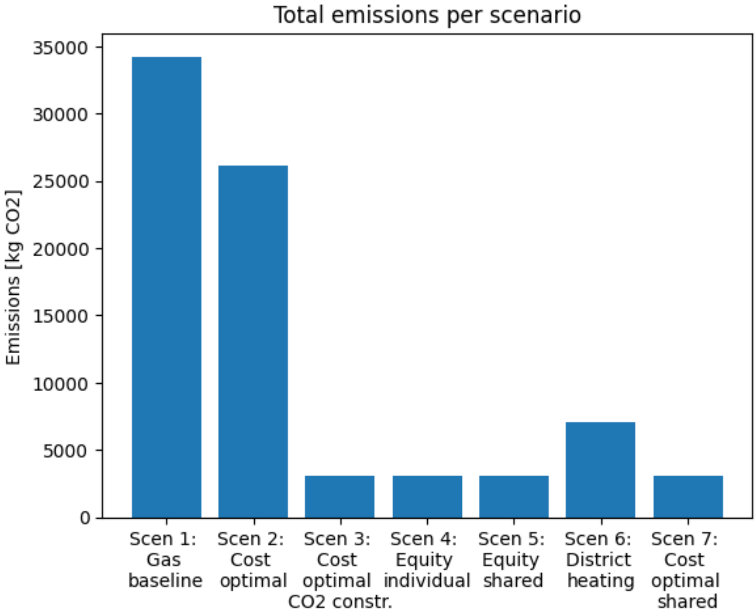
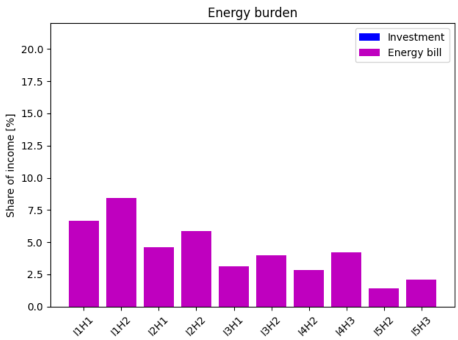
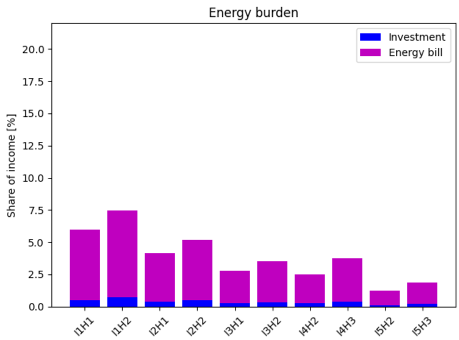


Figure 4.2: Total annual CO_2 emissions per scenario

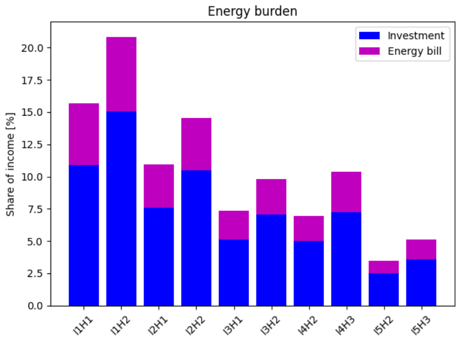
energy burden is higher for households with lower incomes and larger homes across all scenarios. The energy burdens change per scenario, but the distribution is similar. Scenarios 4 and 5 have an objective function that should make the difference between energy burdens smaller, this is not the case, however. The lowest energy burdens are in scenarios 1 and 2. In the baseline scenario, there is no investment possible in renewable technologies, which is why the costs mostly consist of the energy bill. In scenario 2, investment is possible and there are no other constraints present. This leads to a lower energy burden for all nodes compared to the base scenario. There is no emission constraint in the district heating scenario and the energy burden is higher than in the base and lowest cost scenarios, but a little lower than in the scenarios with an emission constraint. In the other scenarios, there is a strict emission constraint, which leads to higher investment costs in renewable technologies. The energy burden increases due to higher investment costs, while the energy bill is mostly lower compared to the baseline. The lower households have the highest energy burden, even under equity objectives. The highest energy burden is for low-income households in terraced houses. An energy burden of 20% is twice the energy burden threshold. This is because this household has the lowest income and a higher heat demand at the same time. District heating has low operational costs, but the fixed yearly fee is high, which increases the energy bill.



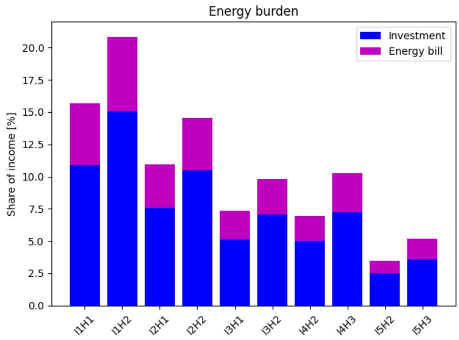
(a) Scenario 1: Gas baseline



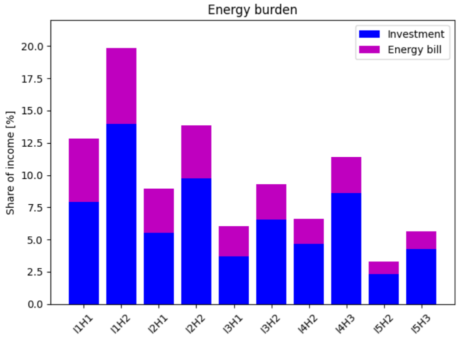
(b) Scenario 2: Cost-optimal



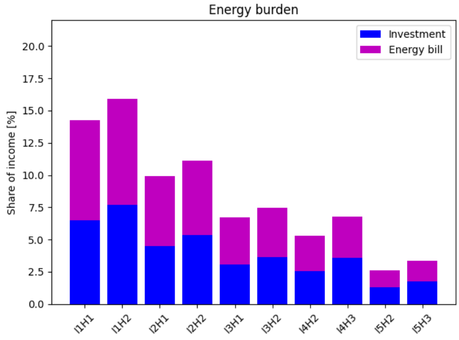
(c) Scenario 3: Cost optimal with CO_2 constraint



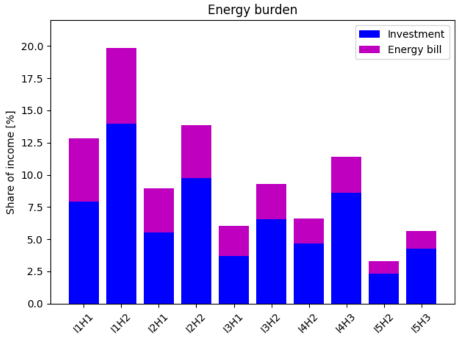
(d) Scenario 4: Equity individual



(e) Scenario 5: Equity shared



(f) Scenario 6: District heating

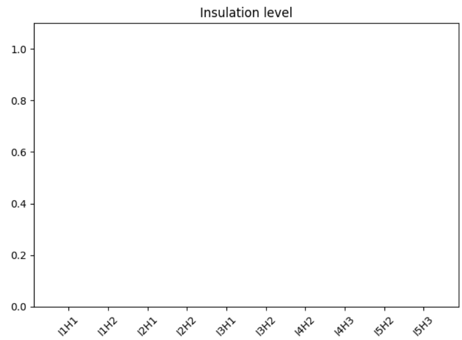


(g) Scenario 7: Cost optimal shared

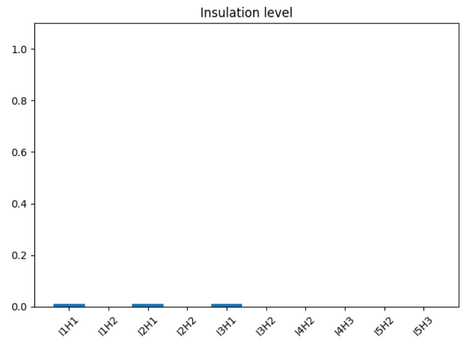
Figure 4.3: Overview of energy burden per household per scenario

INSULATION

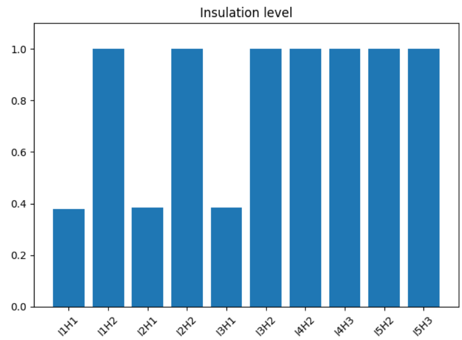
The level of insulation per node for each of the scenarios is plotted in Figure 4.4. In the base scenario, there is no investment in insulation for any household. In the lowest cost scenario, there is barely any insulation, only the apartment households have a small level of insulation. In the scenarios with an emission constraint, the households in terraced and detached houses are insulated fully, while apartment households are insulated partially. This can be explained by terraced and detached houses having a much larger heat demand than apartments, which makes it more financially beneficial to insulate instead of investing in more heat capacity. Only in the district heating scenario is there full insulation for each household. This is more efficient than requiring more heat from the grid. From the perspective of the energetic quality of housing as an energy poverty indicator, the district heating scenario performs best, as it results in full insulation across all household types.



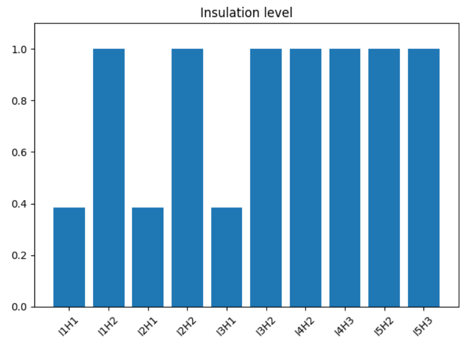
(a) Scenario 1: Gas baseline



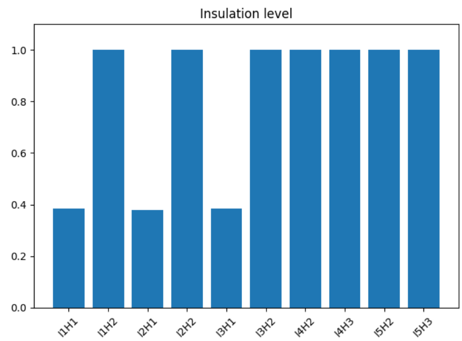
(b) Scenario 2: Cost optimal



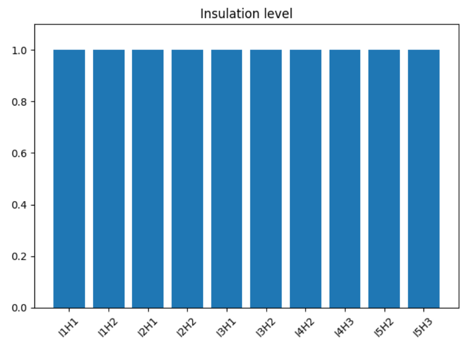
(c) Scenario 3: Cost optimal with CO_2 constraint



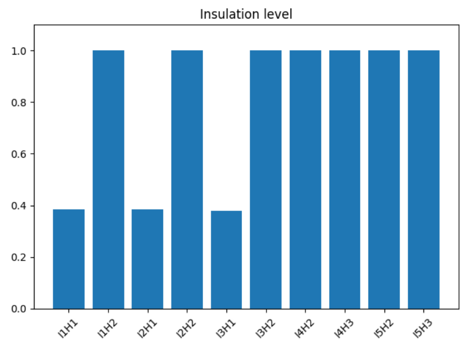
(d) Scenario 4: Equity individual



(e) Scenario 5: Equity shared



(f) Scenario 6: District heating

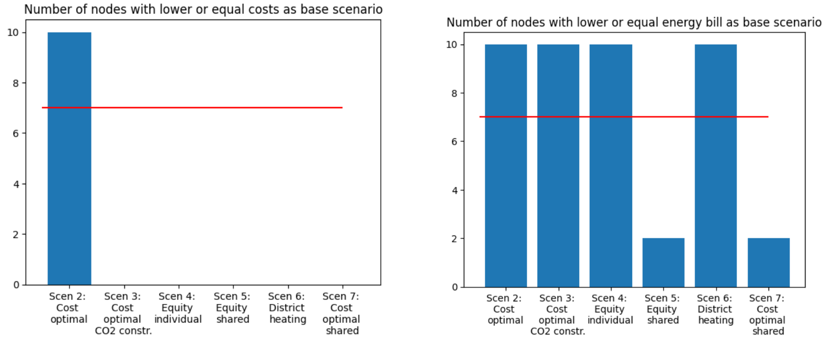


(g) Scenario 7: Cost optimal shared

Figure 4.4: Insulation upgrade level per scenario, expressed as a fraction of the maximum possible upgrade (0-1)

4

4.2. EVALUATION AGAINST DUTCH HEATING TRANSITION AFFORDABILITY CRITERIA (WGIW)



(a) Total costs (b) Energy bill

Figure 4.5: Number of household nodes with equal or lower total costs and energy bills than the gas baseline scenario. The red line indicates the Wgiw affordability threshold, corresponding to at least 70% meeting this criterion.

Throughout this study, energy burden is treated as the primary indicator of energy poverty, while the Wgiw criteria are used as a complementary, policy-oriented benchmark rather than a measure of equity.

There are two criteria for a renewable heating solution to be eligible. The first is that the annualized costs over 30 years cannot be higher than the current situation for 70% of households. The second is that the energy bill cannot be higher than the current situation for 70% of households. Figure 4.5 shows that in the scenario where all technologies are available, both the investment costs and energy bill are lower than currently. In this scenario, the model predominantly invests in relatively cheap technologies and makes minimal changes to the gas-based system. As a result, both annualized costs and energy bills are lower for every household. The total costs are, on average, 12% less per node than in the baseline scenario. The full comparison is shown in Table B.2 in Appendix A. When emissions are unrestricted, traditional heating systems remain financially attractive.

In the individual scenarios with a stringent CO_2 constraint, the energy bill is also lower than in the current situation, however, the total costs are not lower for any node. Meeting the CO_2 target requires substantial investments in electric heating technologies and insulation, which significantly increase annualized capital costs. Although these investments reduce operational costs by lowering energy use and shifting consumption to cheaper electricity hours, the savings are not large enough to offset the much higher investment expenditures. As a result, even with a lower energy bill, the total annual costs remain higher for every household. The total costs are almost 2.5 times higher than in the baseline scenario. Therefore,all nodes in these scenarios fail to meet the Wgiw criteria.

4

Within the sharing scenarios, the only nodes that do not experience an increase in their energy bill are the two high-income households in the detached houses. The total costs for these nodes are, on average, 2.3 times higher than in the baseline scenario. There is a large difference between the nodes. The total costs increase the most for high-income households at 2.7 times higher than the baseline, while total costs for low-income households are almost 2 times higher. These scenarios also fail the criteria. In the district heating scenario, all households experience a lower energy bill, but higher total costs compared to the baseline. District heating requires a high yearly connection fee, which funds the substantial upfront investment costs of the grid.

From the modeled scenarios, only scenario 2 meets the Wgiw affordability requirements. All scenarios that impose a strong emission constraint or rely on centralized infrastructure, fail on at least one of the two criteria. The failure to meet the Wgiw affordability criteria indicates the need for policy intervention rather than a rejection of the corresponding heating pathway.

4.3. TRADEOFFS BETWEEN EMISSION REDUCTION AND COSTS

Understanding the tradeoffs between emissions system costs is essential for evaluating the feasibility of different heating system configurations. The emissions and costs across the scenario are shown in Figure 4.6. The baseline scenario has the highest emissions, but not the lowest costs. The district heating scenario achieves low emissions, however, also at relatively high costs. Scenario 2 has both lower emissions and costs than the baseline, indicating that moderate emission reductions can be realized through cost-efficient technologies. It is clear that there is no linear relationship between emissions and costs. It shows that a well-designed system is able to reduce emissions and costs simultaneously.

The emissions are the same for the individual and sharing scenarios, but the costs are lower in the sharing scenarios. Cost reductions in sharing scenarios result from lower required capacity. Emissions are lowest in scenarios where a stringent CO_2 constraint is employed. This sharp decrease in emissions comes at a high cost. The total system costs for achieving 91% less emissions than currently are almost 2.5 times the cost of the current system. While moderate emission reductions can be achieved at relatively low cost, further reductions require disproportionately higher investments. Low-cost abatement options such as electrification are not enough to satisfy the stringent emission constraint alone. Overdimensioned heating and storage capacity is needed to meet the requirements, which are expensive.

The sharp cost increase is driven by the requirement to reach the imposed CO_2 constraint within a fixed technology set rather than the emission reduction requirement itself. These results suggest that reducing the costs of high levels of decarbonization requires additional flexibility and cost-reduction measures.

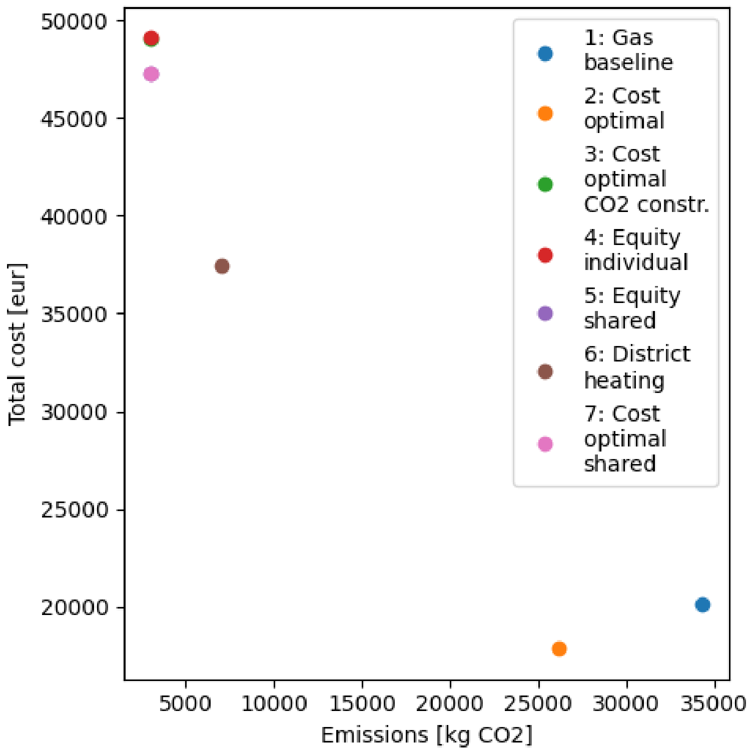


Figure 4.6: Tradeoff between total system costs and CO_2 emissions across scenarios. Scenarios 3 and 4 overlap, as well scenarios 5 and 7, indicating identical outcomes.

4.4. SENSITIVITY ANALYSIS

This section evaluates the robustness of the model by examining how changes in input parameters influence model outcomes. Energy prices, emission constraints and the objective function will be tested.

4.4.1. ENERGY PRICE VARIATION

This model evaluates costs over 30 years, which means that price volatility is especially important. Both the electricity and gas prices are increased and decreased simultaneously, while all other inputs stay constant. A decrease and an increase of 10% were chosen. Scenario 2 is chosen for the price sensitivity analysis. This scenario has no constraints and investment in technologies is allowed. This makes it a suitable baseline for examining how changes in energy prices influence the resulting configuration, as it isolates the effect of price variation without being affected by other constraints such as emission limits.

COSTS

The total costs decrease when the energy prices decrease by 10% and increase when the energy prices increase by 10% as well. This response is not proportional, however. A 10% energy price change leads to only a 7% change in costs, both when prices increase and when they decrease. This is shown in Table B.3. This suggests that the system is relatively cost-robust, as changes in energy prices lead to smaller changes in total costs. This implies that a share of the costs is driven by fixed costs and/or investment costs, which do not scale with the energy prices and dampen the effect of the price variability.

The effect on the cost composition is not proportional. The total cost breakdown is shown in Tables B.4 and B.5. With low energy prices, the investment costs decrease by 33% and the energy bill by 5%. At the high energy prices, the investment cost increase 42 % and the energy bill increases by 4%. This shows that investment decisions are more sensitive to changes in energy prices than to changes in the energy bill. High energy prices make investment-heavy configurations more attractive.

EMISSIONS

Emissions follow a similar pattern. Lower prices lead to a higher gas consumption and, therefore, higher emissions. The change is again disproportional. Emissions increase by 7% at higher energy prices and decrease by 7% at lower energy prices. This shows that the emissions are also relatively cost-robust, as they change less than the energy prices. This is shown in Table B.6.

TECHNOLOGY DEPLOYMENT

The technology deployment changes only marginally when the energy prices are increased or decreased by 10%. The full deployment is visualized in Figure B.1. The gas boiler capacity increases at the lower prices and decreases slightly when prices rise. Gas boilers operate at lower efficiencies than electric boilers, which means a decline in energy prices reduces their operating costs more substantially. This shows that gas is somewhat more attractive when energy prices are lower. This also means that electric heating technologies such as the electric boiler, electric heater, PV and storage are more attractive at higher energy prices. These technologies are able to take advantage of operational flexibility. PV can generate part of the electricity demand on-site, and storage can shift consumption to cheaper hours. Even though their energy use becomes more expensive, this flexibility allows them to avoid the high price periods, which partially offsets the increase in costs.

4.4.2. CO_2 EMISSIONS IN THE OBJECTIVE FUNCTION

This section examines how changing the weights in the objective function affects the trade-off between total system costs and CO_2 emissions, while keeping the underlying system configuration unchanged. The aim is to assess whether the main insights on emissions–cost trade-offs are sensitive to the choice of optimization objective. The objective function can have different weights for costs. In the run scenarios the objective function has a weight of 1 for monetary costs and therefore minimizes monetary costs only. To explore the emissions and cost tradeoff, the objective function is extended to include both monetary costs and CO_2 emissions, weighted by y (monetary) and x (emissions) adding up to 1. Below is the updated equation with two weights in the objective function.

$$\min \begin{bmatrix} 0.5(\sum_{n}\sum_{m}(\text{Capex}_{n,m} + \sum_{t}\text{Opex}_{n,m,t})) + \\ 0.5(\sum_{n}\sum_{m}\sum_{t}\text{Opex}_{n,m,t}) + M\cdot\text{UnmetDemand} \end{bmatrix} \tag{4.1}$$

The previous section showed that there is no strong relationship between emissions and costs across scenarios. To check whether this is also the case when only the objective cost weights in the objective function change, different CO_2 constraints and objectives are tested. To explore this trade-off, scenarios are run with different objective functions, including cost minimization, emission minimization, and a balanced objective that assigns equal weights to costs and emissions. In addition, a scenario with a very stringent emission constraint (Scenario 3) is included for comparison. In Figure 4.7, these runs are shown.

Scenario 2 represents the minimization of costs. The emissions are the highest and the costs are the lowest. The opposite, the run with the emission minimization objective has very low emissions, but at extremely high costs. The balanced run, with a weight of 0.5 for cost minimization and 0.5 for emission minimization, achieves intermediate outcomes with a slight increase in costs relative to the cost-minimizing case and substantially lower emissions. As a comparison, the results from scenario 3 are shown. Scenario 3 achieves even lower emissions than the emission-minimizing objective, at considerably lower cost.

When taking the baseline value of emissions as 1 for the run that minimizes emissions and the baseline value of costs as 1 for the run that minimizes costs there are some interesting results. As seen in Table 4.2, the costs are almost 90 times as high in the minimizing emissions run. However, the emissions are 4 times as high for the minimum cost run. This indicates a disproportionate response, where cost increases are large relative to the achievable emission reductions. The minimum CO_2 run represents an extreme solution in which emissions are reduced as much as possible. As a result, the system relies on expensive overdimensioned technologies to eliminate the residual emissions, which leads to a sharp increase in total system costs. While emissions are bounded by minimum heat demand, costs are not similarly constrained, which causes marginal abatement costs to rise steeply as emissions approach the lowest values.

It is also clear that the minimum CO_2-emission run is not as cost-efficient as some other scenarios. The same emissions are achieved at lower costs in the balanced run, and even lower emissions can be reached at lower costs in Scenario 3. In contrast, the minimum CO_2 objective reduces emissions through marginal adjustments without a binding structural constraint, which can result in less effective system-wide decarbonization.

Overall, this analysis shows that extreme objective functions lead to unbalanced cost-emission reduction outcomes, while a balanced objective function achieves substantial emission reductions at comparatively low additional cost.

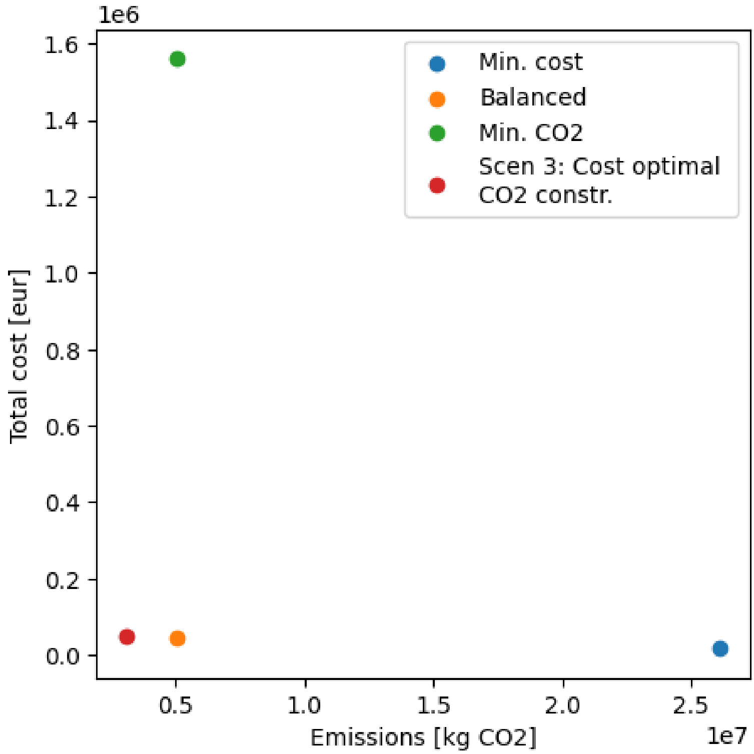


Figure 4.7: Costs and emissions comparison under different objective function weights

4.4.3. EQUITY OPTIMIZING OBJECTIVE FUNCTION

To understand why the equity-based objective function does not substantially change the optimization outcomes compared to the lowest-cost objective, two sensitivity tests were performed. Specifically, the income levels were modified and the CO_2 emission constraint was varied. These tests reveal which inputs actually influence the objective function and which do not. Because the purpose of these tests was solely to isolate the effect of the objective function, the model was run over a representative one-month period rather than a full year. The results are shown in Tables B.7 and B.8.

Scenario	**Emissions (kg)**	**Costs (eur)**	**Increase emissions**	**Increase costs**
Min. cost	26137477	17851	417%	0%
Balanced	5055071	43538	0%	144%
Min. CO_2	5053769	1560087	0%	8640%
Scen 3: Cost optimal CO_2 constr.	3081600	49090	-39%	175%

Table 4.2: Costs and emissions under different objective function weights

varying Income

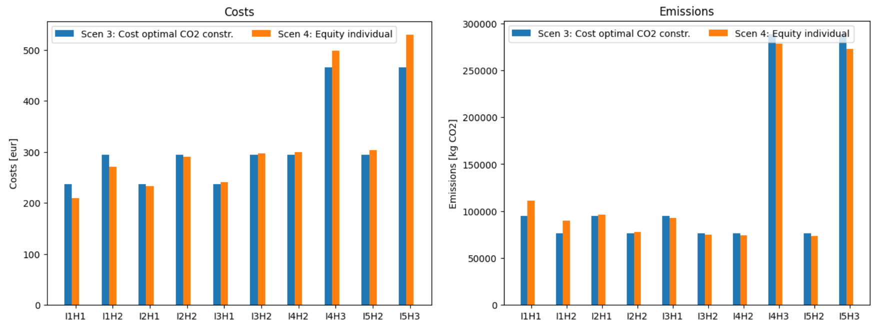
In the first test, the income values were adjusted by reducing the lowest five incomes by 50% and doubling the highest five incomes. The intention was to create a wider spread in income levels and examine whether this would lead to different outcomes under the equity objective. The results show that this modification had almost no effect on the optimization. System costs, investments, dispatch decisions, and emissions remained effectively identical across scenarios.

For the individual scenarios, the largest difference in costs is 0.04% lower with the equity objective function active, showing a marginal reduction in costs. In the sharing scenarios, there is no difference in costs. The equity objective function minimizes the total weighted energy burden, which is still a linear weighted sum of costs. Costs are not explicitly redistributed between households. Even when the income differences are larger, the resulting differences are insignificant. This indicates that the solution that minimizes total system costs also approximates the solution that minimizes the income-weighted energy burden. Within the constrained solution space, there is little flexibility to shift costs away from lower-income households without increasing total system costs. The shared equity objective has similar characteristics. The shared costs are divided according to a fixed fraction that does not change with the objective function. This cost allocation does not depend on income or on the objective function, which means that the shared equity objective has no influence on the shared costs. These shared costs make up the majority of the total costs, and since they are unaffected by the equity weights, the results are almost identical with or without the equity objective active.

Varying Emission constraint

Changing the emission constraint had a much larger effect on the results from the run with the equity objective function. The emission constraint was changed to a decrease of 57% compared to the baseline, as opposed to a decrease of 91% used in the CO_2 limit scenarios. A decrease of 57% was chosen, because this decrease is halfway between the emission reduction targets of 2030 and 2050. With a lower emission constraint, the feasible solution space becomes larger. This gives the model greater flexibility to reallocate both costs and emissions across households. Under these looser constraints, the optimization shifts more costs toward higher-income households while reducing costs for lower-income households. At the same time, the emissions assigned to lower-income households increase, even though total system emissions remain fixed by the constraint. This effect is visible in Figure 4.8. Under the equity objective in scenario 4, lower-income households experience lower costs and higher emissions, whereas higher-income households face higher costs and lower emissions. Relaxing the emissions limit creates more room for redistribution without affecting the overall totals. This effect is only present in the individual scenarios. In the sharing scenarios, the costs and emissions are the exact same. This is seen in Table B.10. In the sharing scenarios, costs and emissions are allocated based on the predetermined fraction of the demand of each household, leaving no room for redistribution across households when the emission constraint changes. As a result, the outcomes for the sharing scenarios remain identical regardless of the strictness of the emission limit.

The equity optimizing objective functions are designed to prioritize affordability for lower-



(a) Costs (b) Emissions

Figure 4.8: The effect of a looser emission constraint on costs and emissions under the equity objective

income households, however, they lead to only marginally different outcomes compared to the cost minimization scenarios. This is due to certain structural characteristics of the model.

First, the stringent emission constraint restricts the feasible solution space. Only a narrow set of technology configurations is able to satisfy the emission requirements. Within this solution space, the income-weighted optimum and cost-minimizing optimum are close to each other, leaving little room for lowering costs for lower-income households. This is confirmed by the fact that when the emission constraint is relaxed, the feasible solution space is larger and affordability for lower-incomes is higher.

Additionally, the cost-minimization and equity objectives are linear functions. While the equity objective increases the relative importance of lower costs for lower-income households, costs cannot be actively reallocated between households. As a result, total system costs are reduced in a similar way under both objectives. This is confirmed by altering the income distribution, which had minimal effect on the results.

Lastly, in the sharing scenario with the equity objective, the majority of the costs are incurred at the shared node due to technology investment. The costs are allocated using a fixed fraction. This allocation is based on demand and not income. Therefore, the objective has limited influence on the outcomes, as the way the costs are distributed is not altered.

5

Discussion and conclusion

This chapter reflects on the results presented in Chapter 4 in the broader context of the Dutch heating transition and discusses the answers to the research questions. Section 5.1 discusses the implications of the assumptions made in the model and the limitations of the modeling approach. Section 5.2 answers the subquestions, which together answer the main research question. It also highlights some recommendations based on the findings. Lastly, Section 5.3 outlines directions for future research.

5.1. Discussion

This section reflects on the implications of the assumptions on the results. It is also highlighted what the main model limitations are. Lastly, the effect of certain modeling choices is analyzed.

5.1.1. Model assumptions and limitations

The model developed in this thesis provides insights into the technical, economic and distributional aspects of potential heating transition pathways. However, several limitations should be acknowledged. Energy poverty is a social issue. The underlying drivers of energy poverty cannot be captured fully through an optimization model. The model, therefore, offers an analysis for identifying inequitable outcomes, but addressing energy poverty requires targeted policy interventions beyond the scope of modeling.

Simplified representation of energy poverty

Energy poverty in the model is characterized by three dimensions: energy burden, housing quality and ability to invest. While these indicators capture important structural aspects of energy poverty, they remain simplified representations. The model does not include demographic variables such as age or gender, even though there are correlations with vulnerability to energy poverty.

Presence of unmet demand

Unmet demand is present in all objective functions and is included in the model formulation to ensure feasibility under strict emission constraints. The unmet demand is penalized with a very high cost, making it only an option when demand cannot be met without violating the active constraints. The presence of nonzero unmet demand is, therefore, driven by the strict emission constraint. Unmet demand can be interpreted as load shedding. The model does not directly implement flexibility options such as demand response, but represents the result of demand reduction needed to achieve emission constraints. The presence of unmet demand, therefore, indicates that meeting the imposed emission targets would require some degree of demand reduction or flexibility in practice. Although households may have limited flexibility in their heating demand, using this flexibility would come at a cost, which is represented in the model by the high penalty assigned to unmet demand.

Cost assumptions

The model relies on several simplifying assumptions to reduce model complexity. For example, the technology costs assumptions are based on current estimates. While these costs are subject to change over time due to factors such as market development and policy support, these changes would mainly influence the relative attractiveness of specific technologies. Heat pumps, for example, currently have high investment costs but might decrease in price over time as deployment becomes more widespread. Still, the qualitative insights are driven by the structure of the model rather than the technology prices. In particular, the strong trade-off between stringent emission constraints and affordability is expected to remain even under different technology cost assumptions, even if the optimal technology mix changes. Similarly, changes in insulation costs would shift the balance between efficiency investments and supply-side technologies, without altering the conclusion that high upfront investments remain a key barrier for low-income households.

Absence of subsidies

An important modeling assumption is the absence of subsidies or other forms of financial support. In the model, households are assumed to pay the full investment and operational costs of heating technologies. In practice, subsidies can substantially reduce upfront investment barriers, particularly for low-income households, and may alter the relative attractiveness of different heating technologies.

Including subsidies would likely improve affordability outcomes and could enable higher emission reductions without increasing household costs. Modeling subsidy schemes would require additional assumptions about eligibility, funding sources, and allocation mechanisms, which are beyond the scope of this study.

Simplified representation of district heating

District heating in this model is represented as a centralized thermal energy sharing system with simplified characteristics. In reality, district heating encompasses diverse configurations with varying heat sources, distribution networks, and connection technologies, each with distinct cost structures and performance characteristics. While the model captures essential characteristics and end-user costs, it does not represent the full spectrum of possibilities.

In the model, it is assumed that there are no subsidies or public financial support for district heating. In reality, there are subsidies for connecting to a heating network. Including subsidies would lower the connection fees for households and could improve the relative performance of district heating compared to individual or other shared heating solutions. However, modeling subsidy schemes would require additional assumptions such as subsidy levels, and allocation that are beyond the scope of this study.

ELECTRIFICATION AND GRID CONGESTION

Many renewable heating solutions require electricity, including the solutions in the model. The model assumes unlimited access to gas and electricity supply and does not include grid capacity constraints. Scenarios with high emission constraints deploy higher capacities of electric boilers, electric heaters, and battery storage. If these solutions were implemented on a large scale, this would have a large impact on the electricity grid. Grid congestion is a big problem in the Netherlands and will remain a challenge in the foreseeable future. Therefore, switching from gas to all-electric solutions is not necessarily a feasible solution. Collective heating systems, such as district heating or a shared structure, have the potential to electrify without burdening the grid too much. The heating transition requires creative thinking and joint effort to achieve both goals of sustainability and affordability for all.

5.1.2. EFFECT OF STRINGENT CO_2 CONSTRAINT

The CO_2 constraint used in this study is arbitrary. It is based on the Dutch 2050 emission reduction targets, which are a policy-informed but ultimately arbitrary threshold. The sensitivity analysis examining different weights for cost minimization versus emission minimization revealed that the relationship between costs and emissions is highly non-linear. When comparing the baseline emissions to the cost-optimized scenario, emissions were four times higher, while costs in the emission-minimized scenario were nearly 90 times higher than the cost-optimal solution. This disproportionate relationship suggests that there may be expensive technologies that can dramatically increase costs without proportionally reducing emissions, while emission reductions are ultimately bounded by demand. Households always require a minimum level of heat. Even with maximum insulation and full electrification, the model must still supply this heat, which sets a lower bound on achievable emissions.

A more comprehensive exploration of the emission-cost frontier would require testing multiple constraint levels and objective function weights. The current analysis provides valuable insights into extreme cases such as pure cost minimization, pure emission minimization, and heavily constrained scenarios. The intermediate space remains less explored. Future research should systematically map this trade-off space to identify efficient solutions that balance climate goals with economic feasibility.

The emission constraint applied in this model represents a system-wide reduction target derived from national climate objectives. The emission reduction is treated as a collective requirement and does not differentiate emission limits at the household level.

Income-dependent emission limits require additional assumptions about fairness and increase model complexity beyond the scope of this study.

5.1.3. Limited effect of equity objective function

The effect of the income-weighted objective function on equity outcomes is limited. The model is constrained by emission requirements and technology choices. Under these conditions, changing the objective function has little influence on the system configuration or cost distribution. This highlights the difference between what can be achieved through system optimization and what requires policy intervention. While the model can identify configurations that reduce overall costs, emissions, or energy burden, it cannot resolve structural inequities such as unequal access to capital or tenure status.

Equitable outcomes could be more effectively addressed through explicit model design choices, such as alternative shared cost allocation rules, affordability constraints, or targeted subsidies.

5.2. Conclusion

This research investigated how neighborhood-scale renewable heating systems in Dutch urban areas can be designed to achieve low-carbon outcomes while addressing energy poverty. Through optimization modeling of different technology configurations, cost-sharing structures, and equity objectives, several key findings have emerged. These are used to answer the research questions.

What renewable heating system configurations emerge as optimal under different objectives, minimizing total system cost or minimizing household energy burden, and how does technology deployment differ across scenarios?

Shared heating systems outperform individual heating systems. While achieving the same emission target, in a sharing scenario, the costs for all households are lower than in an individual scenario. These benefits are the largest for households living in apartments. Apartments benefit disproportionately from collective investment since shared system costs are allocated proportionally to demand rather than requiring each household to invest in its own heating technology. Technology deployment differs most between scenarios without and with emission constraint. With the strict emission constraint, there is a shift away from gas boiler capacity and an increase in electric boiler capacity and electric and water storage. This transition is necessary to meet decarbonization goals, but comes with a significant cost increase, particularly due to the high upfront investment associated with electric heating technologies and insulation measures.

Which modeled neighborhood heating configurations meet the criteria defined by Dutch heating transition policy and which groups fail to meet these criteria?

Only the cost-minimization scenario without emission targets meets the Wgiw policy criteria that states that households should not be worse off than in the natural gas baseline. Almost all scenarios achieve lower energy bills due to increased efficiency from electric heating technologies, however these heating technologies require a large investment that is not earned back in 30 years. The energy burden is highest for low-income households. This makes it clear that to meet climate targets and decrease energy poverty, targeted subsidies for low-income households are needed. According to the Wgiw, affordability is defined as maintaining post-transition energy costs at or below current levels. Based on this criterion, achieving a reduction in overall emissions of 95% in the individual scenario would require an annual subsidy between €2100 and €2850 euros per household. In the sharing scenario, this range is lower, between €1400 and €2600 per household per year. This estimate is restricted to the households with the lowest 40% of incomes, as higher income households have an energy burden of 10% or lower and therefore do not face affordability constraints under the modeled scenarios.

What tradeoffs emerge between reducing emissions, minimizing costs and limiting energy burden for low-income households in the Dutch heating transition?

The results indicate a non-linear relationship between costs and emissions, where moderate emission reductions can be achieved at low cost, while further reductions become increasingly costly within the model framework. Achieving a 91% reduction in emissions increases the total costs by 2.5 times. These cost differences are based on current price assumptions and represent relative scenario comparisons rather than future cost projections. Emission-constrained scenarios give consistently higher costs within the model framework. The sharp cost increase observed under these stringent CO_2 constraints reflects the structure of the optimization problem. Once low-cost abatement options are exhausted, the model relies on increasingly expensive technologies to achieve additional emission reductions. This outcome is therefore a property of the modeled system under static assumptions, and not a general statement about the cost-effectiveness of emission reductions in real-world heating transitions.

5

Together, these subquestions answer the main research question: **How can neighborhood-scale renewable heating systems in Dutch urban areas be de- signed to achieve low-carbon outcomes while addressing energy poverty?**

Renewable heating systems that achieve both reduced emissions and energy poverty require shared energy systems, insulation, the ability to invest and no increase in costs. There is no single scenario from this research that is able to achieve all these goals at the same time.

The findings show that achieving a low-carbon and socially just heating transition requires more than an optimal technology configuration. It requires a combination of a collective heating system, insulation upgrades, financial capacity to invest and targeted policy support for vulnerable households. In particular, measures that support low-income households and reduce upfront investment barriers are needed.

5.2.1. RECOMMENDATIONS

Trying to put equity explicitly in the objective function had minimal effect. Energy poverty is not a problem that can be solved with a better model. The model results show that model configurations with sharing, the ability to invest in technologies, and a high level of insulation lower energy poverty. Scenarios with high affordability had low levels of insulation, which contradict each other in the criteria for an equitable heating transition. There is no one scenario that has all these characteristics. There are targeted subsidies needed to effectively decrease emissions and speed up the heating transition. These subsidies should target those who are most in need, low-income households in low energetic quality housing. Existing forms of support often fail to target these groups effectively, and the model results indicate that such targeted subsidy design is essential for reducing discrepancies between households. As renewable heating technologies are able to reduce energy bills but have high investment costs, subsidies should address the upfront investment.

Furthermore, the results highlight the consistent benefits of shared or collective heating systems, which reduce overall system costs, require less installed capacity due to demand diversity, and distribute investment more evenly across participating households. Policymakers should therefore promote and enable shared ownership models, such as heat cooperatives and energy communities. These structures are particularly valuable for households that cannot individually finance high-efficiency technologies. However, enabling collective systems may require legal and regulatory adaptations to ensure that renters and low-income residents can participate without facing disproportionate financial risk.

Another key recommendation concerns insulation, which emerges from the model as a prerequisite for both cost-effective and low-emission electrified heating technologies. Better-insulated homes require smaller electrified heating capacities and achieve lower long-term energy costs, while the associated investment remains substantial. Insulating the building stock should therefore be treated as a priority in the heating transition, supported by financial instruments.

In addition, grid congestion must be addressed proactively. Electrification-based heating solutions increase electricity demand, particularly during peak hours. Without sufficient grid reinforcement or local flexibility solutions, widespread electrification can exacerbate existing congestion challenges. Smart solutions that introduce demand shifting or energy hubs are needed to reduce peak loads. Municipalities need to take these challenges into account in their heating transition plans. It is also important to take the local conditions into account.

5.3. FUTURE RESEARCH

Future research should explore a broader range of emission constraints and cost minimization objectives. This study mainly explores extreme cases with high emission constraints and single-weight objective functions. Mapping more intermediate solutions could help identify pathways that are cost-effective and still achieve high emission reductions, while maintaining affordability for the most vulnerable.

This study assumes identical hourly demand profiles across households scaled with the total demand. Demand-side flexibility could reduce peak demand and potentially reduce system costs. Future research could incorporate heterogeneous demand profiles and behavioral demand response to assess the role of peak shaving in cost and grid congestion reduction.

The current model does not account for electricity grid constraints, despite this being a large issue in the Netherlands. Incorporating grid capacity limits and potentially load shifting would show whether solutions are compatible with the current electricity grid.

Lastly, the implementation of potential policy instruments that address energy poverty should be incorporated. Modeling different subsidy schemes and testing their effectiveness would help identify what measures are most effective in reducing energy poverty.

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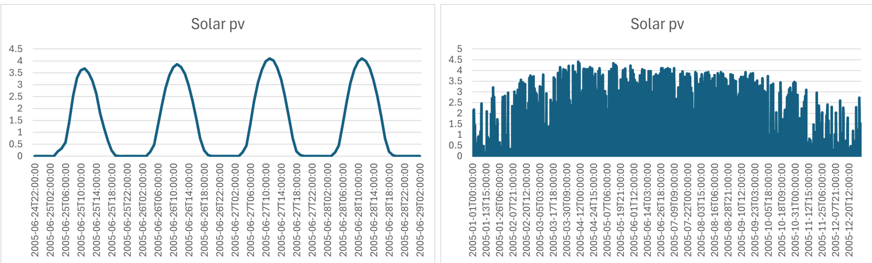
A

Appendix A: Supplementary input data and profiles

A.1. Solar PV irradiation profiles



(a) Solar summer

(b) Solar year

Figure A.1: Solar irradiation throughout the year

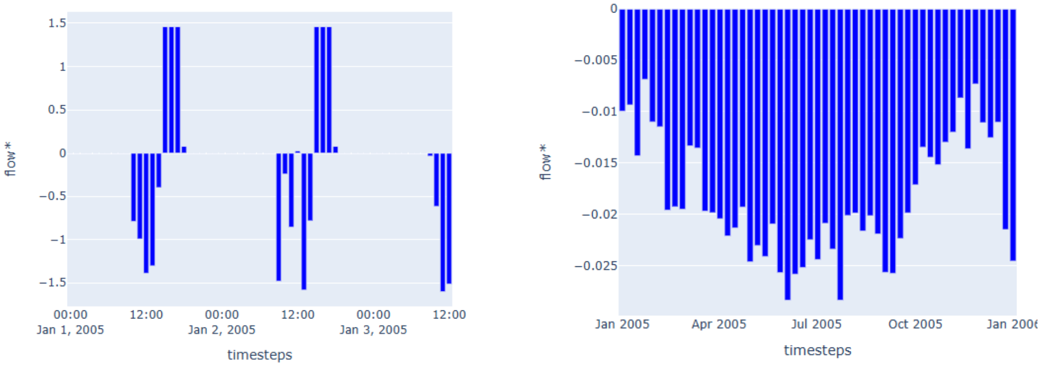
A

A.2. BATTERY STORAGE PROFILES

(a) Hourly (b) Weekly

Figure A.2: Battery charge and discharge behavior

A.3. HOT WATER STORAGE PROFILES



(a) Hourly (b) Weekly

Figure A.3: Hot water tank charge and discharge behavior

B

Appendix B: Supplementary model and sensitivity analysis results

B.1. Energy burden

Node	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7
I1H1	7%	6%	16%	16%	13%	14%	13%
I1H2	8%	7%	21%	21%	20%	16%	20%
I2H1	5%	4%	11%	11%	9%	10%	9%
I2H2	6%	5%	15%	15%	14%	11%	14%
I3H1	3%	3%	7%	7%	6%	7%	6%
I3H2	4%	4%	10%	10%	9%	7%	9%
I4H2	3%	2%	7%	7%	7%	5%	7%
I4H3	4%	4%	10%	10%	11%	7%	11%
I5H2	1%	1%	3%	3%	3%	3%	3%
I5H3	2%	2%	5%	5%	6%	3%	6%

Table B.1: Energy burden per household node per scenario

B.2. TOTAL COST PER NODE AND COMPARISON TO BASE SCENARIO

Node	Scen 1 (eur)	Scen 2 (eur)	Scen 3 (eur)	Scen 4 (eur)	Scen 5 (eur)	Scen 6 (eur)	Scen 7 (eur)	Scen 2 diff	Scen 3 diff	Scen 4 diff	Scen 5 diff	Scen 6 diff	Scen 7 diff
I1H1	1528	1372	3611	3611	2950	3280	2950	-10%	136%	136%	93%	115%	93%
I1H2	1942	1717	4791	4791	4563	3661	4563	-12%	147%	147%	135%	89%	135%
I2H1	1528	1372	3611	3611	2950	3280	2950	-10%	136%	136%	93%	115%	93%
I2H2	1942	1717	4791	4791	4563	3661	4563	-12%	147%	147%	135%	89%	135%
I3H1	1528	1372	3611	3611	2950	3280	2950	-10%	136%	136%	93%	115%	93%
I3H2	1942	1717	4791	4791	4563	3661	4563	-12%	147%	147%	135%	89%	135%
I4H2	1942	1717	4791	4791	4563	3661	4563	-12%	147%	147%	135%	89%	135%
I4H3	2911	2576	7152	7086	7862	4662	7861	-12%	146%	143%	170%	60%	170%
I5H2	1942	1717	4791	4821	4563	3661	4563	-12%	147%	148%	135%	89%	135%
I5H3	2911	2576	7152	7201	7862	4662	7861	-12%	146%	147%	170%	60%	170%

Table B.2: Household cost comparison with gas baseline

B.3. Sensitivity analysis: energy price variation

Node	Scenario 2 (eur)	-10% (eur)	+10% (eur)	Difference -10%	Difference +10%
I1H1	1372	1284	1453	-6%	6%
I1H2	1717	1591	1833	-7%	7%
I2H1	1372	1284	1453	-6%	6%
I2H2	1717	1591	1833	-7%	7%
I3H1	1372	1284	1453	-6%	6%
I3H2	1717	1591	1833	-7%	7%
I4H2	1717	1591	1833	-7%	7%
I4H3	2576	2350	2788	-9%	8%
I5H2	1717	1591	1833	-7%	7%
I5H3	2576	2350	2788	-9%	8%

Table B.3: Difference in costs and energy burden per node under energy price changes

Node	Scenario 2 investment (eur)	Scenario 2 energy bill (eur)	-10% investment (eur)	-10% energy bill (eur)	+10% investment (eur)	+10% energy bill (eur)
I1H1	117	1255	78	1206	165	1288
I1H2	167	1550	112	1479	236	1596
I2H1	117	1255	78	1206	165	1288
I2H2	167	1550	112	1479	236	1596
I3H1	117	1255	78	1206	165	1288
I3H2	167	1550	112	1479	236	1596
I4H2	167	1550	112	1479	236	1596
I4H3	277	2298	177	2173	348	2440
I5H2	167	1550	112	1479	236	1596
I5H3	277	2298	177	2173	348	2440

Table B.4: Total cost breakdown and changes per node under energy price changes

Node	Scen 2 inv.	Scen2 bill	-10% inv.	-10% bill	+10% inv.	+10% bill	Diff inv -10%	Diff inv +10%	Diff bill -10%	Diff bill +10%
I1H1	1	5	0	5	1	6	-33%	42%	-4%	3%
I1H2	1	5	0	4	1	5	-33%	42%	-5%	3%
I2H1	0	4	0	4	1	4	-33%	42%	-4%	3%
I2H2	1	3	0	3	1	3	-33%	42%	-5%	3%
I3H1	0	3	0	2	0	3	-33%	42%	-4%	3%
I3H2	0	2	0	2	0	2	-33%	42%	-5%	3%
I4H2	0	2	0	2	0	2	-33%	42%	-5%	3%
I4H3	0	2	0	2	1	2	-36%	25%	-5%	6%
I5H2	0	1	0	1	0	1	-33%	42%	-5%	3%
I5H3	0	10	0	9	0	11	-36%	25%	-5%	6%

Table B.5: Energy burden per node under energy price changes

Node	Scenario 2 (kg)	-10% (kg)	+10% (kg)	Difference -10%	Difference +10%
I1H1	1711	1833	1576	7%	-8%
I1H2	2446	2621	2253	7%	-8%
I2H1	1711	1833	1576	7%	-8%
I2H2	2446	2621	2253	7%	-8%
I3H1	1711	1833	1576	7%	-8%
I3H2	2446	2621	2253	7%	-8%
I4H2	2446	2621	2253	7%	-8%
I4H3	4388	4725	4218	8%	-4%
I5H2	2446	2621	2253	7%	-8%
I5H3	4388	4725	4218	8%	-4%

Table B.6: Emissions per node under energy price changes

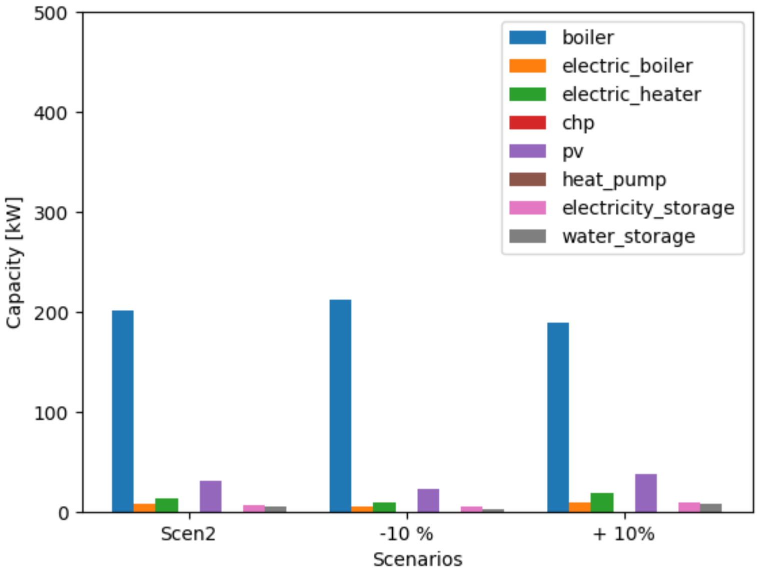


Figure B.1: Flow capacity of technologies per scenario under energy price changes

B.4. SENSITIVITY ANALYSIS: OBJECTIVE FUNCTION TESTING

Node	Income (eur)	Scen 3 (eur)	Scen 4 (eur)	Scen 5 (eur)	Scen 7 (eur)
I1H1	959	243	243	92	92
I1H2	959	303	303	160	160
I2H1	1375	243	243	92	92
I2H2	1375	303	303	160	160
I3H1	2042	243	243	92	92
I3H2	8166	303	303	160	160
I4H2	11500	303	303	160	160
I4H3	11500	486	486	247	247
I5H2	23166	303	303	160	160
I5H3	23166	486	486	247	247

Table B.7: The effect of varying income on energy costs. The lowest 5 incomes are halved and the highest five incomes are doubled compared to the run scenarios. The values are based on a one month period.

Node	Scen 3 (kg)	Scen 4 (kg)
I1H1	94540	111000
I1H2	288359	272498
I2H1	76173	89593
I2H2	94540	96263
I3H1	76173	77855
I3H2	94540	92683
I4H2	76173	74938
I4H3	76173	74218
I5H2	288359	278586
I5H3	76173	73565

Table B.8: The effect of varying income on emissions. The lowest 5 incomes are halved and the highest five incomes are doubled compared to the run scenarios. The values are based on a one month period.

Node	Income (eur)	Scen 3 (eur)	Scen 4 (eur)	Scen 5 (eur)	Scen 7 (eur)
I1H1	1917	237	209	98	98
I1H2	1917	294	271	170	170
I2H1	2750	237	233	98	98
I2H2	2750	294	290	170	170
I3H1	4083	237	241	98	98
I3H2	4083	294	297	170	170
I4H2	5750	294	299	170	170
I4H3	5750	466	498	261	261
I5H2	11583	294	303	170	170
I5H3	11583	466	530	261	261

Table B.9: Cost per node while testing CO_2 constraint. The constraint is set to a 57% reduction compared to the 91% emission reduction in the scenarios. The values are based on a one month period.

Node	Income (eur)	Scen 3 (kg)	Scen 4 (kg)
I1H1	1917	94540	111000
I1H2	1917	76173	89593
I2H1	2750	94540	96263
I2H2	2750	76173	77855
I3H1	4083	94540	92683
I3H2	4083	76173	74938
I4H2	5750	76173	74218
I4H3	5750	288359	278586
I5H2	11583	76173	73565
I5H3	11583	288359	272498

Table B.10: Emissions per node testing CO_2 constraint. The constraint is set to a 57% reduction compared to the 91% emission reduction in the scenarios. The values are based on a one month period.