Materializing the Demand Response Potential from Heat Pumps in the Netherlands

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Materializing the Demand Response Potential from Heat Pumps in the Netherlands

Investigating the Role of Consumer Behavior

by

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EXECUTIVE SUMMARY

In the age of the energy transition, balancing the supply and demand of electricity on the power grid is expected to become an increasingly difficult task due to a sharp increase in renewable energy sources. The supply and demand of electricity must be matched at all times in order to ensure a reliable and stable power grid (Ngondya & Mwangoka, 2017). Traditionally, supply has followed demand: increasing the electrical output of conventional gas-fired plants was all that was required in order to satisfy a spike in electrical demand. However, due to the intermittent availability of renewable resources such as solar radiation and wind, the Netherlands must transition to a situation in which the electrical demand follows supply; this principle is called demand-response (DR) (Villar et al., 2018).

At a consumer level, a product which is able to provide a demand response in the form of electrical flexibility is a heat pump. A heat pump is a device capable of providing indoor heating by making use of the temperature differential between the indoor and outdoor climatic conditions of the home in combination with electricity. The heat pump has been selected as a subject of interest given the Dutch government's climate ambitions: approximately half of all residential dwellings are to be fitted with one by 2050 (Rijksoverheid, 2019). Studies have demonstrated that it is technically feasible for heat pumps to provide electrical flexibility (Accenture, 2021; Carroll et al., 2020; Dodds et al., 2015; ElementEnergy, 2017; TenneT, 2021). The common denominator shared amongst the above-mentioned studies is that the effect of consumer behavior on the total flexibility potential of heat pumps is absent in all approaches taken.

Drawing upon ideas by Chappin et al. (2017) and Kahneman and Tversky (1979), this research hypothesizes that the demand response potential of heat pumps is much more subject to consumer behavior than has been assumed up to now. This research has been conducted with the intention of understanding how consumer behavior affects the demand response potential of heat pumps. By doing so, the research can aid policy makers with the comparison of policy options when aiming to maximize the demand response potential of heat pumps. Furthermore, the research aims to pinpoint which behavioral factors which should receive policy attention when focusing on consumer behavior. This research objective translates into the following research question:

How can we materialize the potential for demand response from residential heat pumps in The Netherlands until 2050?

The main research question has been answered by using a multi-method approach combining qualitative behavioral findings with a quantitative optimization model. A literature review revealed two types of consumer behavior to have an effect on the demand response potential of heat pumps: consumer adoption behavior and consumer user behavior. With regards to consumer adoption behavior, a classification of consumer groups has been created consisting of a convenient, distrusting and proactive consumer. With regards to consumer user behavior, a similar approach is taken and a classification has been made consisting of conservers, spenders, cool dwellers, warm dwellers and an average group. For each of the consumer groups belonging to the respective typologies, accompanying behavioral characteristics have been identified which are deemed to affect the heat pump flexibility potential of each consumer type. The research has been structured as such that these underlying behavioral characteristics serve as policy targets once the effect of each consumer type in the typology on the flexibility potential of heat pumps has been established.

Proceeding the consumer adoption and user types identified in the literature review, a linear optimization model has been developed capable of modelling the flexibility potential of heat pumps for each identified consumer type. In addition, technical characteristics such as residential dwelling composition in the Netherlands, insulation levels, electricity prices and ambient temperatures are considered. The data collection for the optimization followed a multi-method approach: results from a survey, sub-model and mathematical calculations all served as model input in order to obtain the most accurate flexibility estimate.

The results from the linear optimization model reveal consumer adoption behavior to have the most effect on the collective demand response potential of heat pumps. For homes which have been undergone one renovation or that were constructed after 1990, by the year 2050, the model estimates an average demand response of 3.2 GW per demand response event that can be offered by heat pumps assuming 100% market penetration. This number declines to 2.4 GW of electrical flexibility at 75% market penetration and 1.6 GW of electrical flexibility in the case a mere 50% market penetration, assumed to be the minimum market penetration level. Therefore, the study estimates that gains of up to 1.6 GW in 2050 can be realized by increasing consumer adoption from 50% market penetration to 100% market penetration. For policy makers, this means that consumer behavior should be an area of focus when the benefits from gaining 1.6 GW of extra flexibility from heat pumps in 2050 proportionally outweigh the policy costs incurred to increase consumer adoption.

Should the above cost-benefit analysis generate a positive result, the potential for demand response by heat pumps can be maximized when policy focuses primarily on the convenient consumer group created in the consumer adoption typology. This recommendation is based on the finding that the convenient consumer group represents more than half of all households eligible for a heat pump and as such large gains in the demand response potential of heat pumps can be made by targeting this consumer group. Policy should specifically focus on behavioral characteristics such as existing inertia, the availability bias, ignorance and satisficing behavior. In summary, by decreasing the ’hassle’ factor for convenient consumers, substantial gains in the demand response potential of heat pumps can be achieved. Additionally, policy makers are encouraged to target behavioral factors such as trust, the availability bias and loss aversion when developing policy aimed at increasing the adoption of heat pumps by the distrusting consumer. While the gains in the flexibility potential of heat pumps will not be as large compared to the convenient consumer, targeting the distrusting consumer group is necessary in order to reach the 100% heat pump market penetration desired by the Dutch government by 2050.

From the model results, it has emerged that user behavior has a lesser effect on the demand response potential of heat pumps. However, this does not mean that policy should forego targeting user behavior altogether. The results from the model indicate that altered user behavior could increase the demand response potential of heat pumps by 21% in case of upward flexibility regulation, and by 5% in case of downward flexibility regulation. Moreover, unregulated user behavior could lead to a a decrease in demand response potential of heat pumps by 12% in the case of upward flexibility regulation and by 5% in the case of downward flexibility regulation.

One of the most significant results derived from the model is that it not necessarily the user type influencing the demand response potential of the heat pump, rather it is the temperature range at which the user does not experience any loss in thermal discomfort. In addition, a notable finding of the research is that while user behavior has a limited effect on the average flexibility provision of heat pumps, it does have an effect on the frequency at which the heat pump is able to provide a demand response. This means that at a system level, individual user behavior can have a notable impact on the flexibility provision of heat pumps when a frequent demand response event is desired. Nevertheless, policy makers should prioritize developing policy focusing on consumer adoption behavior should the benefits of gaining an additional 1.6 GW of flexibility from heat pumps in 2050 proportionally outweigh its policy costs.

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PREFACE

"Work hard in silence, let your successes be your noise" (F. Ocean)

What lies before you is the document marking the end of my time as a student in Delft. It is a period in my life that I will cherish forever; I have had the pleasure of spending these years surrounded by some of the most talented, kind and considerate human beings I have ever met.

Embarking on this project, I knew next to nothing about heat pumps and doubted several times if the project would come to a success. Thankfully, I was not on my own and had a wonderful support team guiding me through the process. I am beyond grateful for my supervisors Dr. de Vries and Dr. ir. Chappin for their everlasting support. Gerdien: thank you for the weekly catch-up sessions and providing me with new perspectives on climate psychology. Emile: thank you for advising me on sound modelling practices and your critical attitude on my (sometimes) unsupported statements.

I would also like to express my gratitude towards the Fundamental Analysis department at Eneco. Robert, Divya, Roald, Paul and Jeroen: I could not have done it without you. Due to our catch-up moments I never felt truly alone during the thesis-writing process. Your passion for the energy transition is unequivocal: there is so much to learn from all of you. I am so thankful to have been your intern.

Now on to friends; where to start? To the Potvissen: thank you so so much for taking my mind off of the project every now and then and joining me on bike rides and walks; THERE WERE SO MANY! Michela, Amila, Mateo, Ronny and Lotte: you guys know what it is like; thank you for being able to share our thesis struggles. To my roommate Saskia: thank you for your ever-lasting patience and understanding. I would also like to thank Katherina, Pauline, Lidha and project partner in crime Mirjam. And of course to everybody else: you know who you are.

Finally, I would like to thank my family: mom, dad, Liv: I love you so much. River: thank you for enduring all the hugs when I needed them. I am excited for what the future has in store for me, enjoy the thesis!

Merel Louise Schumacher
Delft, 11-08-2021

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INTRODUCTION

1.1. RESEARCH PROBLEM

As the penetration of renewable energy sources in the Dutch electricity system increases, systematic changes are called for in order to accommodate the unconventional characteristics of renewable energy sources. The intermittent nature of renewable energy sources is making it more difficult to maintain a balance between the supply and demand of electricity, leaving no choice but to increase reserves and ramping needs from fossil-fueled conventional power assets (Villar et al., 2018). The intermittency challenge is driving a push for more flexible power load availability within the Dutch electricity system (Smale et al., 2017). The value of such a flexible power load is very uncertain, yet likely to increase. The International Energy Agency defines flexibility in a power system as: "the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system to maintain reliable supply in the face of rapid and large imbalances, whatever the cause."(International Energy Agency, 2011, p.35).

The flexible power load problem is not the only challenge the Netherlands faces in light of the energy transition. At this point in time, more than 90 percent of Dutch households are heated with the use of natural gas (Oxford Institute For Energy Studies, 2019). As stated in the Climate Accord, all 7.7 million Dutch households are to be supplied with more sustainable sources of heating by 2050 (Rijksoverheid, 2019). Sustainable sources of heating include various types of heat pumps and district heating networks that make use of residual heat, geothermal sources and E-Boilers. Replacing the primary source of heat energy for almost all households poses a considerable challenge, especially since thermal comfort is a good all households already own.

Research has identified heat pumps to be a potential source of flexible power load (TenneT, 2020). This is where both the flexible load challenge and the heating transition challenge meet: perhaps one problem could be solved by the other. The extent to which heat pumps could contribute to increasing flexible load is not only dependent on the technical demand-response characteristics of the heating technology. Rather, it is suspected that the flexibility potential of heat pumps will also depend to a large extent on behavioral characteristics portrayed by households. Therefore, in order to fundamentally understand how heat pumps can contribute to the flexibility search by providing a demand response, the behavioral dynamics of heat pump adoption and user behavior by households must be investigated in relation to the value a flexible load will have in the future.

1.2. RESEARCH OBJECTIVE

The research objective of this thesis is to capture consumer behavior related to heat pumps in a computational demand response model that is able to optimize the dispatch of heat pumps. By understanding how consumer behavior influences the demand response potential of heat pumps, a more comprehensive estimate of the flexibility value of heat pumps can be made. In addition, policy can be developed in order to target the identified consumer behavior. Not only is this suspected to be a cost-effective way of materializing the demand response potential from heat pumps, doing so will lead to a more stable and reliable Dutch power system.

This research objective will be investigated with the following main research question:

How can we materialize the potential for demand response from residential heat pumps in The Netherlands until 2050?

1.3. SOCIETAL AND SCIENTIFIC RELEVANCE

The research conducted in this thesis aims to contribute to society and science by providing a previously unexplored insight into how behavior is able to influence the demand response potential of heat pumps. Subsection 1.3.1 describes how the research aims to contribute to society, subsection 1.3.2 describes how the research aims to contribute to the scientific community.

1.3.1. SOCIETAL RELEVANCE

The Dutch Climate Accord envisions that 7.7 million houses and around 1 million other buildings will have switched to a more sustainable source of heating by 2050 (Rijksoverheid, 2019). It is estimated that heat pumps will play a role in the heating systems of half these dwellings, amounting to approximately 4.5 million heat pumps which are to be installed by 2050. (Oxford Institute For Energy Studies, 2019). However, because heat pumps require electricity in order to provide heating, a rise in the number of installed heat pumps is expected to have a significant effect on the residential electricity demand. This poses an issue during times of peak demand and low renewable power availability, leaving no choice but to increase reserves and ramping needs from fossil-fueled conventional power assets. Luckily, when provided with the right control strategy, heat pumps are able to flexibly draw electricity from the power grid, lowering the electricity required during peak hours. As a result, it is both possible that an increase of installed heat pumps in the Netherlands can either aggravate the flexibility problem or play a key role in solving it. By materializing the demand response potential of heat pumps as much as possible, the societal costs associated with the future necessity of more electrical flexibility can be reduced.

1.3.2. SCIENTIFIC RELEVANCE

At this point in time, no hourly demand response model has been developed targeting the flexibility potential of heat pumps that is able to incorporate consumer behavior. Calculations of the estimated flexibility potential of heat pumps have been performed, however these do not consider behavioral factors such as adoption behavior and user behavior. By capturing these behavioral dimensions in an optimization model, the behavioral elements, which are qualitative in nature, can be captured quantitatively. This will result in a more comprehensive system understanding and better reflect the true flexibility potential heat pumps are able to offer.

1.4. KNOWLEDGE GAP

This section aims to introduce several core concepts relevant to the research and explicate the identified knowledge gap. The section begins with an introduction on the technical flexibility potential of heat pumps, establishing that up to this point, consumer behavior has not been incorporated into the modelling practices present in the studies. The section proceeds to provide precedents demonstrating how behavior has been incorporated in energy research before, arguing that it should be technically possible to apply similar techniques in this thesis study.

1.4.1. TECHNICAL FLEXIBILITY POTENTIAL OF HEAT PUMPS

This subsection aims to investigate the existing available literature available on the provision of electrical flexibility by heat pumps. This investigation has been conducted with the intention of establishing if a behavioral dimension has been captured in the demand response modelling of heat pumps before. In addition, the subsection aims to provide a brief introduction into the relationship between heat pumps and the provision of electrical flexibility.

The potential for heat pumps to provide flexibility in power systems has been explored by Arteconi et al. (2013), their research finds that when heat pumps are coupled with Thermal Energy Storage (TES) systems, electrical energy can be curtailed between the peak hours (16:00 - 19:00) with little cost to thermal comfort for households. A similar approach is taken by Bhattarai et al. (2014), who demonstrate that heat pump flexibility can contribute significantly to providing both local network and system level flexibility. A study which produced mixed results was conducted by Zhang et al. (2019), their findings conclude that while heat pumps can indeed provide a flexible load, there are side effects from this form of demand response such as payback and comfort loss, which might diminish their potential. Zhang et al. (2019) also find that which these side effects largely depend on the level of thermal inertia of the buildings. Therefore, it can be hypothesized that the degree of insulation of households buildings might play a large role in the potential for flexible load of heat pumps. Love et al. (2017) tell a more cautionary tale: their study finds that if 20 percent of households would be reliant on a heat pumps in Great-Britain, without flexible curtailment the peak electrical demand would increase by 14 percent, thereby exerting more pressure on the power systems instead of relieving it of it.

The common denominator shared amongst the studies reviewed above is that while a potential for flexible load has certainly been identified for heat pumps, the extent to which these technologies can collectively contribute to solving the flexibility problem is highly uncertain. This can be attributed to the fact that the collective contribution is dependent on the way the technologies are integrated into the fabric of society. While thermal comfort is mentioned several times, it is unknown what role this factor plays into the willingness of households to adopt to a new and more sustainable heat pump. In addition, none of the studies reviewed above incorporate consumer behavior into their modelling practices.

1.4.2. CAPTURING BEHAVIOR IN ENERGY MODELS

Although none of the studies investigating the demand response potential of heat pumps have incorporated consumer behavior in their modelling practices, several studies in the energy field have succeeded in establishing a relationship between consumer behavior and quantitative modelling. Capturing a behavioral dimension in a technical model can lead to a more comprehensive and accurate understanding of the modelled system. This is because in engineering, foregoing any consideration of a behavioral dimension risks a significantly different empirical outcome compared to the modelled system. This subsection aims to provide an insight in how behavior and energy-modelling have been united in previous scientific works.

Research on by Schleich et al. (2019) has demonstrated that time discounting, risk aversion, loss aversion, and present bias all have an effect on household adoption of energy-efficient technologies. In addition, studies are increasingly conveying that behavioral factors play an important role in renewable energy investment decision making (Masini & Menichetti, 2012; Mogles et al., 2018).

Some studies such as Mohajeryami et al. (2015) take it one step further and attempt to incorporate behavioral characteristics of consumers in order to gain a better estimate of the potential of demand response by consumer appliances. While their work does not focus sustainable heating technologies, they consider consumer loss-aversion in the evaluation of two demand response pricing schemes (Mohajeryami et al., 2015). It is demonstrated that an inherent behavioral characteristic of consumers is loss-aversion, and that this must be taken into account when selecting an appropriate demand response scheme (Mohajeryami et al., 2015). A similar approach is taken by Good (2019), where he models the effects of several behavioral biases on the effectiveness of demand response schemes. The studies reviewed demonstrate that it is possible to incorporate the behavioral characteristics of consumers into energy modelling, hence it is the expectation that this can also applied to models estimating the flexibility potential of heat pumps.

1.5. THESIS STRUCTURE

This thesis is structured in the following way: directly following this introduction, chapter 2 introduces the research approach which has been taken in order to answer the main research question. Chapter 3 then provides an exploratory review of the factors influencing the demand response potential of heat pumps. The theory used in order to formalize these factors in introduced in chapter 4. Subsequently, typologies are created in chapter 5 which will aid in the operationalization of a mathematical model capable of calculating the demand response potential of heat pumps. Chapter 6 then provides a formal introduction to the mathematical optimization model used to answer the main research question with. The model results are analyzed in chapter 7. The research conclusion is presented in chapter 8, finalizing with a reflection provided in chapter 9.

2

RESEARCH APPROACH

This chapter introduces the research approach which will be used to answer the main research question: "How can we materialize the potential for demand response from residential heat pumps in The Netherlands in 2050?". The research methods which will be applied in the project are argued for in section 2.1. Subsequently, the sub-questions that will be used in order to answer the main research question are presented in section 2.2. The chapter concludes by introducing a research flow diagram in section 2.3, which will make the coherency between the sub-questions explicit.

2.1. RESEARCH METHODS AND CHARACTERIZATION

This study aims to utilize a combination of qualitative and quantitative approaches in order to research how the demand response potential from heat pumps can be materialized until 2050. The first step taken in this study is exploratory in nature. At present, it is unknown how consumer behavior is able to influence the demand response potential of heat pumps. A literature review is a suitable tool in order to scope out the existing literature on the subject, and can be used in order to structure and classify the information acquired. By understanding the factors and theories underlying the flexibility potential of heat pumps, an attempt can be made to formalize these factors in a mathematical model. The demand response potential of heat pumps can be calculated by using a modelling approach. More specifically, a linear programming approach can be applied in order to determine the flexibility potential of a heat pump. Linear programming techniques are often applied to energy optimization problems as it almost always the objective to minimize the total costs of the energy system given the system boundary conditions (Bordin et al., 2017; Lauinger et al., 2016). There exist a variety of linear programming tools which allow for energy system modelling. While it can already be established that linear programming is a suitable technique for determining the demand response potential of heat pumps, it can not be determined yet which tool can be applied to meet the research goal of this thesis. This is because the tool in question must be able to process the data shape emerging from the qualitative section of this thesis. Therefore, the decision regarding which linear programming tool to use will be taken later in this research.

2.2. SUB-QUESTIONS

In order to answer the main research question, the research will be approached with the use of six sub-questions. The motivation of each sub-question is explained below, as well as the desired information aimed to

1. What factors contribute to the demand response potential of heat pumps?

This sub-question focuses on identifying which factors affect the demand response potential of heat pumps and is exploratory in nature. Initial research from section 1.4.1 has indicated that the technical characteristics of heat pumps influence the demand response potential the heat pumps are able to offer. In addition, section 1.4 introduced a knowledge gap indicating that the behavioral dimension in the flexibility provision by heat pumps has yet to be integrated with the existing technical research. Therefore, this sub-question aims to unite the technical and behavioral dimensions related to the demand response potential of heat pumps and explore this relationship. The way this relationship is defined will serve as a structure for the remainder of the thesis.

2. What information is required in order to capture the heterogeneity present in the factors affecting the demand response potential of heat pumps?

Once the technical and behavioral factors influencing the demand response potential of heat pumps has been defined, further information is required to allow for the factors to be operationalized in a mathematical model. To illustrate, a factor such as consumer adoption behavior encompasses a variety of sub-factors and internal variations. Literature is required that is able to conceptualize how behavioral factors influence the flexibility potential of heat pumps. This sub-question focuses on providing and presenting the theoretical information required in order to capture the heterogeneity present in the identified factors influencing the demand response potential of heat pumps. A variety of theories, data bases and methods will be presented and the sub-question will investigate how this information can be used in order to operationalize the factors identified in sub-question 1.

3. How can the heterogeneity present in the factors affecting the demand response potential of heat pumps be captured and formalized in a typology?

This study aims to make use of several typologies in order to determine how consumer behavior can influence the demand response potential of heat pumps. According to research conducted by Doty and Glick (1994), typologies are complex theoretical constructs which are able to specify a set of relationships among concepts, constructs or variables. Such concepts, constructs and variables have been introduced in sub-question 2. Therefore, this sub-section will attempt to draw upon the framework created in sub-question 1 and use the insights derived from sub-question 2 to create typologies which are able to capture the heterogeneity present when modelling the demand response potential of heat pumps. The sub-question has been answered when typologies capturing the factors affecting the demand response potential of heat pumps have been created and are formalized to the degree they can be operationalized for use in a mathematical model.

4. How can factors influencing the demand response potential of heat pumps be formalized in a mathematical model?

In this sub-question, a linear optimization model will be formalized in which the hourly flexibility load of residential heat pumps can be estimated. The sub-question will investigate which tool is appropriate for the modelling of the demand response potential of heat pumps. It will have to be ensured that the formalized typologies derived from sub-question 3 can serve as model input. Furthermore, additional data might have to be collected depending on the selected modelling tool. Choices will have to be made regarding the model configuration and which scenarios will be modelled. This sub-question is complete when a parametric model has been developed which is able to estimate the collective flexible load potential of heat pumps given the behavioral characteristics of households.

5. How does behavior influence the demand response potential of heat pumps?

This sub-question aims to analyze the results generated from the linear optimization model developed in sub-question 4. By comparing the flexible load potentials inherent to the technical and behavioral characteristics serving as input for the model, it can be determined what characteristics offer the largest demand response potential and how this potential is influenced by consumer behavior. In addition, an initial value can be given regarding the total flexible load potential heat pumps are able to offer in 2050. This number can be used in order to determine the cost-effectiveness of policy measures targeting consumer behavior in order to increase the flexibility potential of heat pumps.

2.3. RESEARCH STRUCTURE

The research approach taken is presented in figure 2.1. The research has been designed to be conducted in a three-phase approach: exploratory and theoretical review, modelling and analysis. The first phase of this research consist of an exploratory and theoretical review and concerns itself with answering sub-questions 1 and 2. During this phase, the most important theoretical frameworks will be established and presented. The second phase of this thesis concerns itself with the development of a model capable of calculating the demand response potential of heat pumps. A typology capable of capturing heterogeneity present in the factors influencing the demand response potential of heat pumps will be created and a mathematical model will be developed. As a result, the second phase: modelling, encompasses sub-questions 3 and 4. The final phase in the research approach is the analysis of the model results. During this phase, the behavioral factors which have the greatest influence on the demand response potential of heat pumps are identified. Understanding the relationship between consumer behavior and the flexibility potential of heat pumps will provide a starting point for policy makers with regards to how the demand response potential of heat pumps can be materialized. As such, the final phase: analysis will encompass sub-question 5.

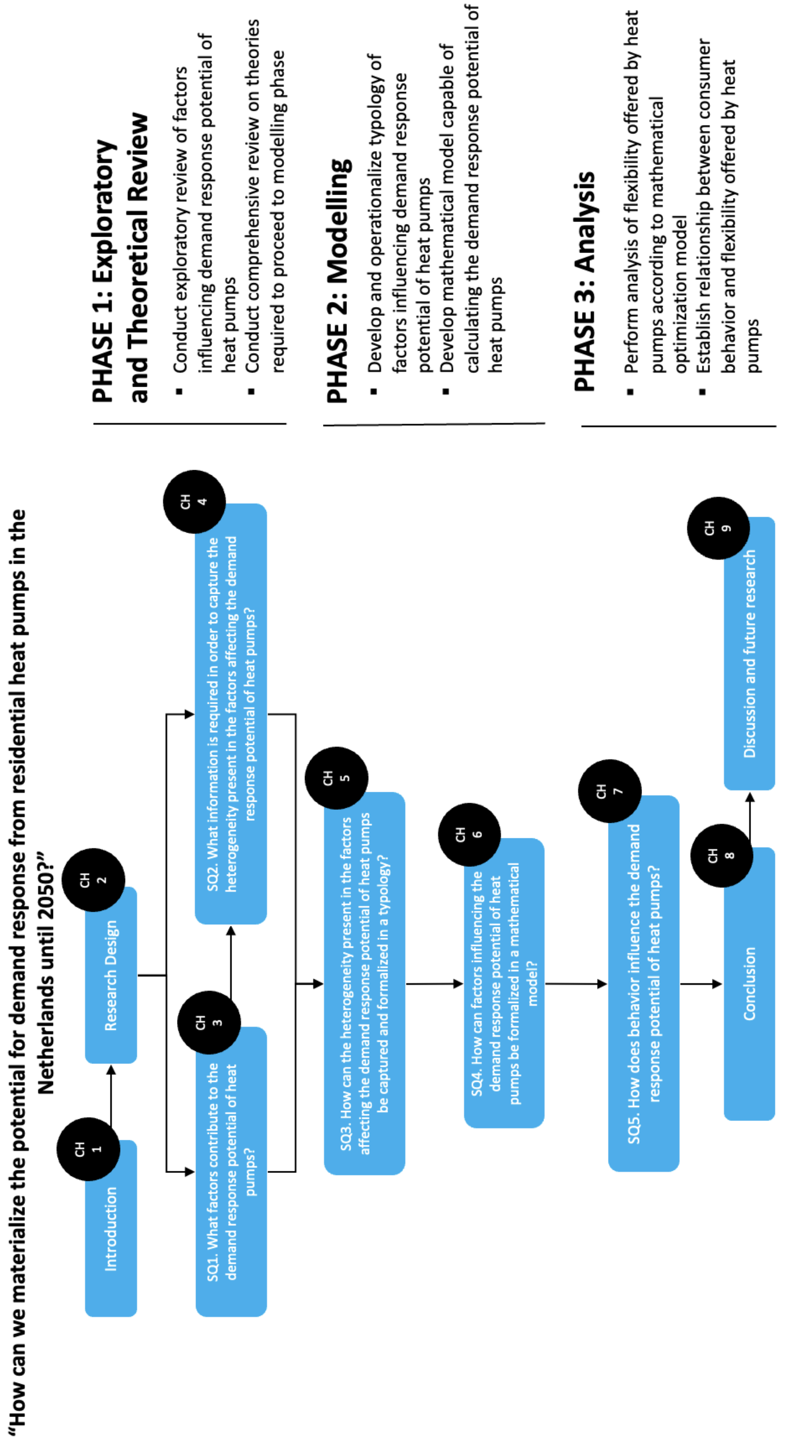

Figure 2.1: Research Flow Diagram of Conducted Research

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EXPLORATORY REVIEW

This chapter answers the following sub-question:

What factors contribute to the demand response potential of heat pumps?

An exploratory review has been conducted in order to obtain a general classification of factors influencing the flexibility potential of heat pumps. The chapter will specifically focus on defining a typology for technical factors and behavioral factors. Other relevant factors such as financial, politicial and institutional elements are not taken into consideration within the scope of this thesis. An overview of the classification is provided is table 3.1 below. This chapter begins by presenting the selection of chosen factors in section 9.1 indicating why the factors have been chosen and how the factors relate to each other. The chapter proceeds by presenting two exploratory studies researching the influence of technical factors on the flexibility provision of heat pumps. Hereafter, the focus is shifted to the influence of behavioral factors on the flexibility provision of heat pumps, where it is established that further research is required.

Table 3.1: Categorical classification of factors influencing the flexibility potential of heat pumps

Technical Factors	Behavioral Factors
Heat Pump Characteristics	Consumer User Characteristics
Dwelling Characteristics	Consumer Adoption Characteristics

3.1. SELECTION OF FACTORS

The first step in the investigation of how the demand response potential of heat pumps can be materialized in 2050 is to identify which factors have an influence on the flexibility potential of heat pumps. In order to reach this goal, exploratory research was conducted looking into the technical and behavioral factors underlying the flexibility potential of heat pumps. Four factors emerged from the exploratory research: heat pump characteristics, residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics. Before proceeding to the results of the exploratory research however, it must be clear why these four factors were selected and what their relation is to one another.

3.1.1. SELECTION OF FACTORS

The first step taken by the author to identify what factors determine the flexibility provision of heat pumps was to conduct an exploratory study into the different types of heat pumps available on the market. Fundamentally, the flexibility potential of a heat pump is determined by the characteristics of the heat pump and the characteristics of the residential dwelling it is placed in. Since this study aims to investigate how consumer behavior influences the demand response potential of heat pumps, consumer user characteristics and consumer adoption characteristics will also be considered in the scope of this thesis. These factors emerged from the knowledge gap identified in section 1.4 and are more hypothetical in nature. Factors such as the regulatory environment, the infrastructure in place responsible for the dispatch of the heat pump and the energy market conditions are of no doubt also important to consider when materializing the demand response potential from heat pumps. However, the novel contribution of this study is that the relationship between consumer behavior and the flexibility potential of heat pumps is investigated, Therefore, the latter mentioned factors will not be taken into account. An overview of the considered factors is given in figure 3.1.

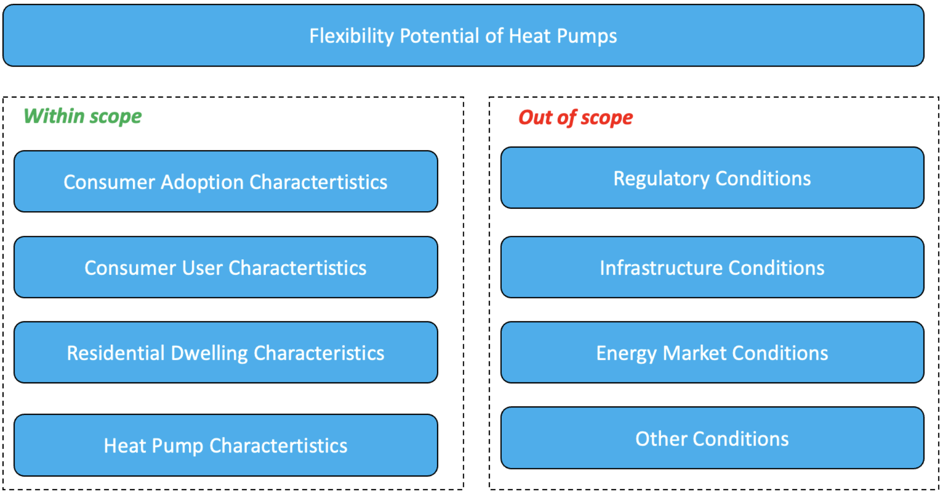


Figure 3.1: Overview of Research Scope

3.1.2. RELATIONSHIP BETWEEN FACTORS

Figure 3.2 depicts how the four selected factors relate to one another when placed in the context of flexibility provision from heat pumps. The figure has intentionally been created to resemble an individual home.

Heat Pump Characteristics At the heart of the home one can find the heat pump characteristics. These characteristics are technical in nature and include factors such as heat pump type and installed capacity. The flexibility potential of an individual heat pump is largely dependent on these characteristics, a relationship which is further explained in section 3.2.

Residential Dwelling Characteristics A heat pump can be installed in many different home environments, represented by the second layer: residential dwelling characteristics. Within the Netherlands, there exist a variety of residential dwellings ranging from a detached home to a terraced home. In addition, each home has varying degrees of home insulation, affecting the flexibility potential that the heat pump is able to provide, explained in section 3.3.

Consumer User Characteristics The red dashed line represents the separation between the technical and behavioral dimension of flexibility provision by heat pumps. The behavior of a home owner can not influence the home size or heat pump capacity, however the behavior of a home owner can have an impact on the indoor temperature of the home. This behavior is captured in the third layer: consumer user characteristics, further explained in section 3.4.

Consumer Adoption Characteristics The final layer in the conceptual framework is deliberately placed outside the home structure depicted in the figure and regards consumer adoption characteristics. While the aforementioned factors have the ability to affect the demand response potential of heat pumps on an individual basis, consumer user behavior is considered to impact to flexibility potential on a collective scale. Section 5.8 will further explain the motivation for considering the consumer adoption characteristics.

3.2. HEAT PUMP EXPLORATORY STUDY

Essentially, a heat pump is an umbrella term describing a device which is able to generate heat by making use of a temperature gradient and electricity. There are several types of heat pumps are available on the market which heat homes using various techniques. This section presents two types of heat pumps classified according to their heating source: electricity only (all-electric) or a combination of electricity and natural gas (hybrid). This section is exploratory in nature: it aims to provide the reader with an overview of the existing heat pump technology and attempts to identify in which manner the heat pump is able to provide electrical flexibility.

The exploratory research on heat pump characteristics was conducted by consulting

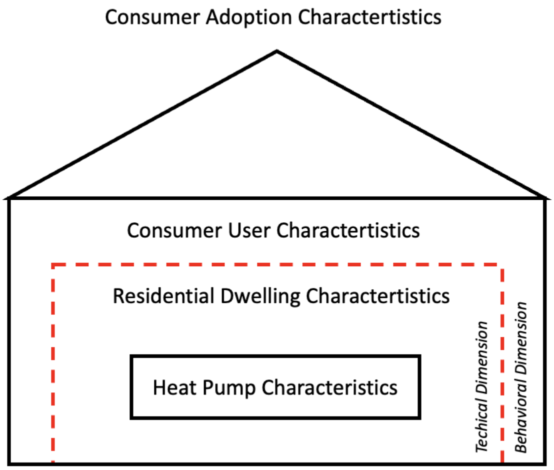


Figure 3.2: Framework demonstrating the relationship between the selected factors

Scopus, Web of Science and Google Scholar in order to find the most relevant papers relating heat pump characteristics to flexibility provision. Search terms such as “All-electric heat pump” AND “Flexibility potential”, "Hybrid heat pump” AND “Flexibility potential”, and “Heat pump" AND "Control Strategy” were used in order to identify relevant articles.

3.2.1. ALL-ELECTRIC HEAT PUMP

A heat pump works by transferring heat from an outside ambient source to the air or water circuits present in buildings (Carroll et al., 2020). All-electric heat pumps require electricity to perform this work (Carroll et al., 2020). Although electricity can be directly converted into heat by means of an electric heater, heat pumps are able to perform this task much more efficiently (Carroll et al., 2020). While there exist a great variety of heat pump technologies, all-electric heat pumps can be categorized into broadly two categories: air source heat pumps and ground source heat pumps (Staffell et al., 2012).

Air-Source Heat Pump Air-source heat pumps work by drawing heat from the outside air and come in two varieties: air-to-air heat pumps and air-to-water heat pumps (Staffell et al., 2012). An advantage of air-to-air based heat pumps is that they are able to provide both heating and cooling, thereby increasing the suitability of the heat pump to provide climate control in all seasons (Staffell et al., 2012). In the Netherlands however, homes are typically heated through a hydronic (water-based) central heating system. This means that the air-to-water heat pump would be the more suitable technology as they are able to connect to the existing central heating infrastructure in the Dutch homes. While air-to-water heat pumps are not able to offer cooling services, they are easier for technicians to install as they are fabricated with a closed refrigerant loop (Staffell et al., 2012). Therefore, technicians require less training to install air-to-water based heat pumps than air-to-air based heat pumps. A significant drawback of air-source heat pumps is that their Coefficient of Performance (COP) declines considerably when the home requires more heat (TenneT, 2021). The COP describes the relationship between the kW of produced heat and the kW of electricity the heat pumps requires to produce this heat. As the outside temperature decreases, more electricity is required in order to produce the desired units of heat (TenneT, 2021). During cold winter weeks this could mean that air-source heat pumps could contribute to a significantly higher electrical peak load (TenneT, 2021). At a consumer level, this will result in a higher electricity than the consumer might be used to. At a system level, more flexibility will be required of the Dutch power system should all electric air-source heat pumps become the dominant residential heating technology. This could be mitigated by installing heat pumps which are tuned to the flexibility requirements of the power grid.

Ground-Source Heat Pump Ground-source heat pumps work by extracting heat from the soil below. Two variations of ground-source heat pumps are available for the domestic heat pump market: open-loop and closed-loop systems. In an open-loop system water is extracted directly from groundwater or a nearby water stream (TenneT, 2021). However, due to strong regulations surrounding the direct use of groundwater, closed-loop systems are much more prevalent (Staffell et al., 2012). In a closed-loop system, heat is generated by means of a heat exchange with the soil below (Staffell et al., 2012). A refrigerant is circled through a series of vertical pipes that have been inserted into the ground (TenneT, 2021). Because the soil temperature in the Netherlands is relatively constant throughout the year (10 - 12 degrees), there is very little variation in the Coefficient of Performance throughout the year (TenneT, 2021). This means that during cold winter days, ground-source heat pumps do not increase the need for flexibility in the Dutch power system nearly as much compared to the air-source heat pump. One of the main disadvantages of a ground-source heat pump is the heavy digging and disruption of the property site caused during installation (Staffell et al., 2012). It is possible that consumers might experience thermal discomfort should they opt for a smaller underground collector to make the installation process less disruptive. This is because the heat generated by the ground-source heat pump is directly related to the size of the underground collector, hence there exists a risky trade-off between installation discomfort and thermal discomfort of the heat pump (Staffell et al., 2012). Therefore, ground-source heat pumps are perhaps best suited for newly-built homes. However, depending on the location of the home, a localized district-heating networks might be more cost-effective than fitting every individual home with a ground-source heat pump (TenneT, 2021). Ground-source heat pumps are typically only suitable for hydronic central heating systems, this means that their application in the Netherlands must not be ruled out even when taking the disruptive installation process into account.

Flexibility Potential of All-Electric Heat Pumps The potential for all-electric heat pumps to provide flexibility in power systems has been explored by Arteconi et al. (2013), their research finds that when all-electric heat pumps are coupled with Thermal Energy Storage (TES) systems, electrical energy can be curtailed between the peak hours (16:00 - 19:00) with little cost to thermal comfort for households. A similar approach is taken by Bhattarai et al. (2014), who demonstrate that heat pump flexibility can contribute significantly to providing both local network and system level flexibility. A study which produced mixed results was conducted by Zhang et al. (2019), their findings conclude that while all-electric heat pumps can indeed provide a flexible load, there are side effects from this form of demand response such as payback and comfort loss, which might diminish their potential. Zhang et al. (2019) also find that which these side effects largely depend on the level of thermal inertia of the buildings. Therefore, it can be hypothesized that the degree of insulation of households buildings might play a large role in the potential for flexible load of all-electric heat pumps. Love et al. (2017) tell a more cautionary tale: their study finds that if 20 percent of households would be reliant on all-electric heat pumps in Great-Britain, without flexible curtailment the peak electrical demand would increase by 14 percent, thereby exerting more pressure on the power systems instead of relieving it of it.

The manner in which heat pump heat production is optimized is called the *control strategy*, this is the term used to describe the decision rules for the system indicating when to turn on and off (ElementEnergy, 2017). The literature reviewed above all describe a grid-signal responsive control strategy. This is the only control strategy available for all-electric heat pumps, a description is provided in table 3.2 below.

Table 3.2: All-electric heat pump control strategy description

Control Strategy	**Description**	**Advantages**	**Disadvantages**
Grid-signal responsive	By taking into account localized electricity line congestion levels and the required electrical flexibility in the power system, the all-electric system will turn off when facing high levels of congestion or an electricity supply squeeze. An electricity supply squeeze can be identified by peaking electricity prices in the day-ahead energy market. When such a price spike has been identified, the all-electric heat pump can produce extra heat in the hours prior and turn off during the electricity supply squeeze. The residential dwelling in which the all-electric heat pump is placed then acts as a temporary thermal buffer.	Provides electrical system flexibility, helpful for Distribution System Operator and Transmission System Operator	Difficult to coordinate, required integrated smart grid system

The common denominator shared amongst the studies reviewed above is that while a potential for flexible load has certainly been identified for heat pumps, the extent to which these technologies can collectively contribute to solving the flexibility problem is highly uncertain. It appears all-electric heat pumps can be either part of the flexibility problem or play a part in solving it. This can be attributed to the fact that the collective contribution is dependent on the way the technologies are integrated into the fabric of society. While thermal comfort and user behavior is mentioned several times, it is unknown what role this factor plays into the flexible power load all-electric heat pumps are able to provide. Insights into consumer behavior are required in order to determine whether all-electric heat pumps will aggravate the flexibility problem or can be part of the solution.

3.2.2. HYBRID HEAT PUMP

In essence, a hybrid heat pump is little more than a combination between an air-source heat pump and a traditional gas boiler. Even though emissions are not eliminated when making use of a hybrid heat pump system, the technology has been identified as a suitable transitional technology as the Netherlands aims for all residential dwellings to be free from natural gas by 2050 (Rijksoverheid, 2019). The hybrid heat pump has been dubbed a suitable transitional technology because of a crucial advantage the hybrid heat pump has over all-electric systems: hybrid heat pumps are able to switch to natural gas during periods of high electrical demand. Since the hybrid system can make use of either electricity or natural gas in order to generate the heat, flexibility can be provided by switching to natural gas during cold periods when wind and solar power are in short supply (TenneT, 2021). Inversely, the hybrid heat pump can make efficient use of electricity when wind and solar power are abundant (TenneT, 2021).

Flexibility Potential of Hybrid Heat Pumps Hybrid heat pumps can be configured in three ways. An air-source heat pump can be installed next to an existing gas boiler, the hybrid heat pump can be sold as an integrated product or the boiler and air-source heat pump can be packaged together (ElementEnergy, 2017). This makes the hybrid heat pump an appealing option for Dutch residential lots as most homes are currently fitted with a traditional gas boiler. While it is also possible to replace the gas boiler completely, the hybrid heat presents less of a radical technology change for consumers and its installation typically takes less time than an all-electrical heat pump since the natural gas boiler does not require removal.

Similar to all-electric heat pumps, hybrid heat pumps perform best when operating continuously and at low temperatures (ElementEnergy, 2017). However, there exist are a variety of arguments why hybrid heat pump output should be controlled intelligently and in a variable manner. For the hybrid heat pump, four control strategies have been identified which are presented in an overview in table 3.3. The four control strategies are able to optimize on aspects such as heat pump efficiency, fuel cost, CO_2 emissions and flexibility response to the electricity grid (ElementEnergy, 2017).

Hybrid Heat Pumps and Fuel Cells Aside from the flexibility potential hybrid heat pumps are able to offer, the technology has one more advantage over all-electric heat pumps: the possibilities for fuel cell integration. Dodds et al. (2015) argue that while fuel cells and heat pumps have been presented as rivaling technologies in literature, combining the two technologies could actually offer system flexibility benefits. The authors demonstrate how a combined heat pump and fuel cell system could flatten the load duration curve of dwellings, depicted in figure 3.3. Although the study is small-scale and considers only 46 residences, Dodds et al. (2015) find that an increase of all-electric heat pumps in just 20% of residences already significantly elevates the load duration curves. When the heat pumps are installed in combination with a (hydrogen) fuel cell, this load duration curve is significantly flattened (Dodds et al., 2015). A flatter load duration curve

Table 3.3: Hybrid heat pump control strategies

Control Strategy	**Description**	**Advantages**	**Disadvantages**
External temperature set-point	During cold winter days, the Coefficient of Performance of an air-source heat pump declines. Therefore, the air-source heat pump becomes less efficient and demands more electricity from the grid to heat the residence. The decision-making mechanism of the hybrid heat pump is therefore based upon an external temperature set-point (outside ambient temperature). Once the temperature declines below this set-point the system will switch to producing heat by dispatching the natural gas boiler.	Very simple control strategy to implement, fuel cost savings	Does not take into account variability in fuel cost prices and CO_2 emissions
CO_2 optimized	In order to minimize the produced CO_2 emissions, the hybrid system will switch to the air-source heat pump or gas boiler based upon real-time CO_2 emissions, which can vary by fuel source. During periods with an abundance of wind and solar energy the electricity is used to power the air-source heat pump, whereas the natural gas boiler is used during cold and windless winter days. This is a strategy similar to and compatible with the fuel cost-optimized control strategy	Low CO_2 emissions, better environmental case for the use of hybrid technology in heating	Requires an hourly estimation of CO_2 emitted per kWh of electricity consumed
Fuel cost-optimized	When faced with a high dynamic electricity price, the hybrid system will automatically engage the natural gas boiler in order to decrease fuel costs. Similarly, when electricity prices are low the air-source heat pump is dispatched. This strategy is similar to and compatible with the CO_2 optimized control strategy.	Fuel cost savings	For Dutch residential electricity consumers, “time-of-use” and dynamic electricity pricing is not yet available
Grid-signal responsive	By taking into account localized electricity line congestion levels and the required electrical flexibility in the power system, the hybrid system will resort to dispatching its gas boiler when facing high levels of congestion or an electricity supply squeeze.	Provides electrical system flexibility, helpful for Distribution System Operator and Transmission System Operator	Difficult to coordinate, required integrated smart grid system

is typically preferable for DSOs and TSOs since it allows for a more efficient electrical dispatch. The higher the peak in the load duration curve, the more installed peak capacity is required of the system. In the case of the Netherlands, this would likely mean that expensive gas plants would have to remain in commission should all-electric heat pumps become a dominant technology. Although hydrogen is currently not available as a hybrid technology, the results of Dodds et al. (2015) do demonstrate that hybrid heat pumps add stability to the electrical system and are able to offer a flexible load.

Dodds et al. (2015) present another important argument for the hybrid heat pump which can be related to consumer adoption. Since a natural gas boiler is a strong incumbent technology in Dutch households, it could be difficult to displace with alternatives such as an all-electric heat pump. A hybrid heat pump might then strike the right balance as an intermediary technology Dodds et al. (2015). Moreover, should the natural gas network in the Netherlands be converted into a hydrogen network, the hybrid heat pump will be able to transition along with it and keep providing a similar service to households Dodds et al. (2015).

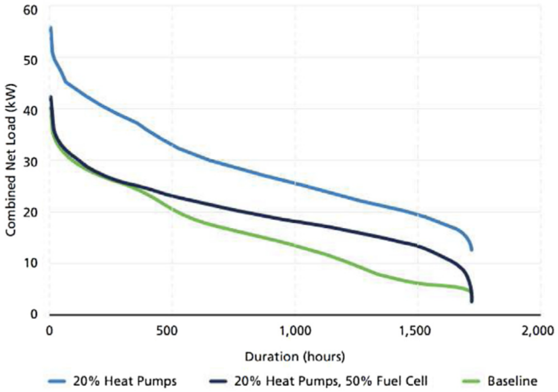


Figure 3.3: Load duration curve demonstrating the impact of heat pumps on a low-voltage feeder with 46 residential dwellings (Dodds et al., 2015, p.2077)

3.2.3. PRELIMINARY CONCLUSION

Table 3.4 depicted below provides a qualitative evaluation with regards to the flexibility potential of the heat pumps discussed in the section above. From the review, it can be concluded that while ground-source heat pumps do not aggravate the flexibility problem due to their limited electrical consumption, they thus also play a very small role in solving it. While the hybrid heat pump offers promising flexibility potential due to its ability to transition to natural gas in periods of high electricity demand, a significant caveat of the technology is that natural gas consumption of the residential dwelling is not ceased completely. Since this study aims to materialize the demand response potential of heat pumps until the year 2050, the remainder of this research will focus on evaluating the electrical flexibility of all-electric air-source based systems.

Up to this point it has been determined that the type of heat pump and control strategy play a significant role in the total flexibility potential heat pumps are able to offer. There is one final factor influencing the flexibility potential of the heat pump: the installed capacity of the heat pump. A heat pump with a high installed capacity can provide more flexible variation due to its ability to provide more heating within a shorter amount of time. The installed capacity is especially relevant to the all-electric air-source heat pump, since the hybrid heat pump is able to switch to natural gas and consumers will not experience any thermal discomfort as a result.

3.3. TECHNICAL CHARACTERISTICS OF DWELLINGS

This section will explore another relevant factor with regards to the total contribution heat pumps can provide towards offering a demand response: the characteristics of the

Table 3.4: Technical selection on the basis of estimated flexibility value

	Air-Source Heat Pump	**Ground-Source Heat Pump**	**Hybrid Heat Pump**
Initial flexibility potential	+	0	++
Control strategy	Grid-responsive only	Grid-responsive only	External temperature set point, CO$_2$ optimized, fuel cost optimized and grid responsive
Future flexibility potential	0	-	+

residential dwelling the heat pump is placed in. It will be argued why home characteristics play a large role in modelling the flexibility potential of heat pumps, as well as why the composition of houses in the Netherlands will have an impact on the cumulative demand response potential of heat pumps.

In order to identify how the technical characteristics of residential dwellings influence the flexibility potential of heat pumps, search terms such as “Residential thermal storage” AND “Heat pumps” and "House characteristics” AND “Thermal modelling” were used in order to identify relevant articles. For this exploratory research, Google Scholar was consulted most frequently.

3.3.1. Building Specific Characteristics

The demand response potential heat pumps can offer is not only dependent on the technical characteristics of the heat pump itself. Rather, the characteristics of the dwelling in which the heat pump is placed also have a large influence on the flexibility potential. Wang and Xu (2006) have indicated that when evaluating a thermal mass control strategy, it is essential to have an appropriate reference model of the building for load prediction or cost saving estimation. In order to analyze the flexibility potential of heat pumps, data about the energy performance of Dutch residential buildings must therefore be collected. Several studies have attempted to develop a thermal mass model of residential dwellings that calculate the thermal storage potential in such detail that they are able to provide a reference value per house (Reynders et al., 2017; Wang & Xu, 2006; Zhang et al., 2019). Zhang et al. (2019) also find that the flexibility potential of heat pumps following a demand response event can vary substantially with different types of dwellings. The two factors most relevant to the flexibility potential a dwelling is able to provide are the *thermal interia* and the *heat transfer* of the building (Zhang et al., 2019). Thermal inertia refers to the rate at which a building is able to retain heat. For example, a building with an underfloor heating system will have higher thermal inertia than a building which does not poses this feature. The heat transfer of a building refers to the rate at which the building loses its heat through thermal radiation. The heat transfer coefficient of a building can be lowered with improved insulation.

3.3.2. Dwelling Composition Characteristics

When attempting to scope the flexibility potential of heat pumps in the Netherlands, it is important to also gather data on the composition of house types next to the thermal inertia and heat transfer coefficients. Reynders et al. (2014) have conducted such a study for Belgian residential dwellings. While the characteristics of Dutch residential dwellings are likely to vary from their Belgian counterparts, the study provides the most comprehensive overview available and includes data on thermal inertia and the heat transfer coefficient of each building (Reynders et al., 2014). Reynders et al. (2014) find that the thermal characteristics of residential dwellings depend amongst others on the type of building: terraced houses experience a higher thermal inertia than fully detached homes. Furthermore, the age of the dwelling and whether the dwelling has undergone renovation also influences the amount of thermal energy the building is able to retain (Reynders et al., 2017). Therefore, in order to determine the total available flexibility potential heat pumps can offer, the residential dwelling composition in the Netherlands must be taken into account and the various dwelling types must be modelled accordingly.

3.4. CONSUMER USER BEHAVIOR

This research hypothesizes that consumer user behavior could have a significant effect on the collective flexible load potential of heat pumps. Section 3.2 highlighted how there exist several heat pump control strategies which are able to influence the heat pump flexibility potential. In line with this reasoning, the way in which users respond to such a control strategy is also of great importance when estimating the collective flexible load potential of heat pumps. This research hypothesizes that the assumption can not be made that every consumer will respond to a control strategy in the same way. The flexibility potential of heat pumps is not only influenced by several behavioral factors related to heat pump usage, but also on the existing behavior of the consumer with respect to their heating preferences. Not every behavioral factor will influence each consumer in the same way, as is illustrated in the study below:

The energy consumption of households can vary significantly due to differences in dwelling characteristics and economic factors such energy type and household characteristics (family size, age of household members, race/ethnicity, etc.). A study by Gyamfi et al. (2013) finds that even when these factors are controlled for, the energy consumption in the individual houses can still not be predicated. When attempting to materialize the flexibility potential that can be derived from heat pumps, it must be understood how user behavior can influence this potential.

The research conducted by Gyamfi et al. (2013) highlights just how heterogeneous the user behavior of demand response participants can be. This heterogeneity of household consumers must be considered when aiming to develop policy in order to materialize the demand response potential of heat pumps. As a result, research must be conducted identifying the underlying behavioral effects which are deemed to have a large effect on the way users interact with their heat pump. Furthermore, it will be useful to create a characterization of heat pump user types in order to capture the heterogeneity of consumer characteristics with respect to user behavior.

3.5. CONSUMER ADOPTION BEHAVIOR

While a single heat pump is able to provide electrical flexibility, materializing the demand response potential from heat pumps is only possible when this flexibility is provided *en masse*. Therefore, in contrast to the heat pump characteristics and residential dwelling characteristics which can influence the flexibility potential of the heat pump on an individual basis, consumer adoption behavior is a factor whose influence can have a multiplicative effect.

To illustrate how adoption behavior could affect the flexibility potential of heat pumps, consider the following example. Households face a significant amount of uncertainty when deciding to transition to a new and more sustainable heating technology such as a heat pump. When faced with the decision to adopt a heat pump, it can be assumed that a rational consumer will evaluate the prospects of installing the heat pump in comparison to the prospects of retaining a traditional boiler system. Table 3.5 presents an overview of the yearly energy savings households experience when installing hybrid or all electric heat pump (2 variants considered). In addition, payback periods are presented. For the hybrid heat pump, this means consumers can expect a return of investment within 8 years. This is a similar return of investment to installing solar panels on a home (Consumentenbond, 2021), yet in 2020 there were an estimated 166 000 households with a heat pump compared to around 1 million households with solar panels (CBS, 2020). The numbers presented in table 3.5 do not take into account potential earnings from providing flexibility, and as such it can be concluded that at present there is a large under investment in heat pump technology by households.

Table 3.5: Overview of average energy savings heat pump installation in the Netherlands (Thuiscomfort.nl, 2021)

	Hybrid Heat Pump	**Air-Source Heat Pump (Air-Water)**	**Air-Source Heat Pump (Air-Air)**
Average Cost (including installation, excluding subsidy) [euros]	4000	16000	6000
Average Subsidy Received [euros]	1500	1500	0
Average Savings (including subsidy) [euros]	300	500	500
Payback Period (including subsidy) [years]	8	16	12

It is suspected that there is no single identifiable behavioral cause for this under investment in heat pumps. Potential heat pump adopters are part of a heterogeneous group and present different behavioral characteristics. Therefore, not all behavioral factors related to heat pump adoption will apply to every consumer. In order to understand how the demand response potential of heat pumps is influenced by consumer adoption behavior, underlying behavioral factors relevant to this behavior must be identified. In addition, it will be helpful to create a consumer typology of potential heat pump adopters in order to capture the suspected heterogeneity in the heat pump adopter group. This thesis will first further investigate the behavioral theory required in order to create such a heat pump consumer adoption typology in section before presenting the typology in section 5.8.

3.6. CONCLUDING FINDINGS

This chapter has presented four factors which are deemed to have an effect on the demand response potential of heat pump when focusing on the relationship between the demand response potential of heat pumps and consumer behavior. The four identified factors are: heat pump characteristics, residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics. Furthermore, it has argued how each of these factors has the potential to influence the total flexibility potential of heat pumps.

With regards to the technical factors, the exploratory review conducted concludes that the demand response potential is dependent on the technical characteristics of the installed heat pump and on the characteristics of the residential dwelling. With respect to the technical character tics of the heat pump, the type of heat pump (air-source, ground-source or hybrid) has a large influence on the flexibility potential. Furthermore, the installed heat pump capacity and the control strategy applied to the heat pump all influence the flexibility potential. The characteristics of the residential dwelling in which the heat pump is placed also influence the total potential for demand response. Thermal inertia and thermal heat transfer are the most important factors influencing the flexibility potential. Lastly, the dwelling composition of the Netherlands plays a role in the total cumulative flexible load heat pumps are able to offer, and as such must also be taken into consideration. Table 3.6 provides an overview of the technical factors which will be considered in the development of the linear optimization model.

With regards to the behavioral factors, the explanatory review concludes that there exist two distinguishable factors influencing the total demand response potential of heat pumps: consumer user characteristics and consumer adoption characteristics. However, unlike with the technical characteristics, further research is required in order to identify the underlying behavioral structures which explain how the consumer behavior is able to influence the demand response potential of heat pumps. In addition, the underlying behavioral structures are unlikely to apply to all consumer user and adoption characteristics, as it is suspected that the consumers are part of a heterogeneous group. Therefore, further research is necessary in order to understand how consumer heterogeneity could affect the demand response potential of heat pumps.

Table 3.6: Overview of factors most relevant to the flexibility potential of heat pumps

Heat Pump Characteristics	Heat Pump Type	Heat Pump Capacity	Heat Pump Control Strategy
Residential Dwelling Characteristics	Thermal Inertia	Thermal Heat Transfer	Dwelling Composition
Consumer User Characteristics	Consumer Heterogeneity		
Consumer Adoption Characteristics	Consumer Heterogeneity		

The next chapter will delve further into the theory required to transform the factors relevant to the flexibility potential of heat pumps into variables which can be operationalized in an optimization model.

4

Conceptualization and Data

This chapter is written with the intention of answering the following sub-question:

What information is required in order to capture the heterogeneity present in the factors affecting the demand response potential of heat pumps?

After defining the four factors influencing the demand response potential of heat pumps in chapter 3, it was established that for some of the factors, further information is required before these can be formalized in a mathematical model. This chapter presents the information which has been consulted in order to proceed with the conceptualization of variables. Table 8.2 presents an overview of the four factors considered in this thesis along with the type of information which has been consulted in their operationalization.

Table 4.1: Overview of Information Consulted for Model Conceptualization

Factor	**Information**	**Type**
Heat Pump Characteristics	Installed Capacity	Equation
	COP	Equation
Residential Dwelling Characteristics	Dwelling Composition	Database
	TABULA Project	Database
Consumer User Characteristics	Behavioral Factors	Literature
	User Types	Literature
Consumer Adoption Characteristics	Behavioral Factors	Literature
	Bass Model of Innovations	Method
	Otte's Lifestyle Topology	Literature

4.1. Heat Pump Characteristics

While there are many technical factors influencing the demand response potential of heat pumps, this study will take into account two different variables which are deemed to influence this potential the most: installed capacity and coefficient of performance.

These two factors are considered to be of importance as the more power the heat pump consumes, the higher the potential for a demand response when turned off. Heterogeneity is present in the installed capacity since a larger installed capacity can provide a stronger demand response. Heterogeneity is present in the coefficient of performance since a heat pump is less efficient at lower temperatures, also influencing the potential for demand response. The information required to capture the heterogeneity present in the installed capacity of the heat pump is explained in subsection 5.1.2. Subsection 4.1.2 explains why the coefficient of performance is dependent on the ambient temperature and presents an equation which is able to account for this factor.

4.1.1. INSTALLED CAPACITY

In section 3.6, it was established the installed heat pump capacity influences the flexibility potential of the all-electric heat pump. This heat pump capacity is in turn influenced by the characteristics of the residential dwelling the heat pump is placed in. For example, one can imagine that less heating capacity is required to heat a smaller well-insulated home compared to a larger poorly-insulated home. In order to determine the appropriate installed capacity, a general guideline can be utilized (Warmtepompverwarming.net, 2021). This guideline consists of a power factor PF multiplied by the home area A, and is displayed in equation 4.1.

$$P_{hp} = PF * A \tag{4.1}$$

The power factor is a constant dependent on when the home was built. For homes built before 2000, a power factor of 0.08 m^2/kW is advised, for homes built between 2000-2010 a power factors of 0.06 m^2/kW is considered and for homes built between 2010 and the present the power factor is 0.04 m^2/kW. The power factors are also of influence in relation to home renovation level. For homes which have not been renovated, a power factor of 0.08 can be considered m^2/kW. This power factor increases to 0.06 m^2/kW when a home has undergone one renovation. After a thorough renovation, a power factor of 0.04 m^2/kW can be considered. This empirical theory regarding power factors will be utilized when determining the appropriate installed heating capacity of the modelled heat pumps.

4.1.2. COEFFICIENT OF PERFORMANCE

The more efficient the heat pump, the higher its coefficient of performance (COP) will be due to the technical characteristics inherent to its design. However, the COP is not a constant number in itself. Rather, it is a variable number dependent on two factors: the ambient temperature and the partial load ratio. Equation 4.2 displays a simplified equation of the COP as a factor of ambient temperature (Quintel Intelligence, 2021a). This formula will be applied when modelling the flexibility potential of heat pumps year round: it will be ensured that the COP of the heat pump is dependent on the ambient temperature.

$$COP_h(T) = 3.25 + 0.0875 * T \tag{4.2}$$

A second factor relevant to the COP of a heat pump is the partial load ratio (PLR) (Piechurski et al., 2017). The PLR is a number indicating the share of power used by the heat pump compared to its maximum power capacity. For example, if a heat pump has a maximum heating capacity of 10 kW, in the case it is only providing 5 kW of heating then its PLR is 0.5. Figure 4.1 demonstrates that for an air-water heat pump, when the PLR drops below 0.5, the partial load factor (PLF) also significantly declines. The PLF is a measure of the heat pump efficiency, and affects its COP in the following way: if the PLR drops below 0.2, the heat pump experiences a significant decline in its COP. In the analysis of the results emerging from the optimization model, it will have to be evaluated if the heat pump operates frequently below a PLR of 0.2. In this case, the efficiency of the heat pump declines significantly and the results can appear more favourable than they really are.

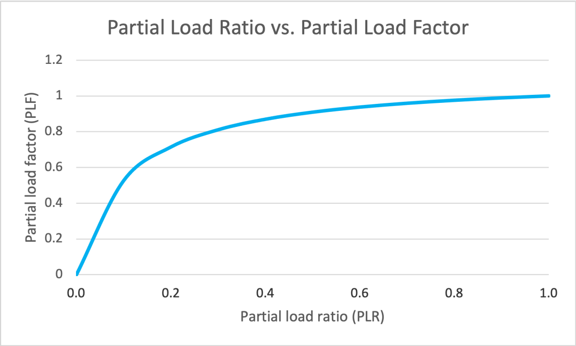


Figure 4.1: Partial Load Ratio vs. Partial Load Factor

4.2. RESIDENTIAL DWELLING CHARACTERISTICS

Chapter 3 revealed how the dwelling composition and dwelling characteristics can significantly influence the flexibility potential of the heat pump installed in a residential dwelling. With regards to residential dwelling characteristics, heterogeneity is present in the composition of dwellings of the Netherlands. Section 4.2.1 will reveal there to be three types of residential dwellings eligible for heat pump installation and provide an estimation of how many of each type are present in the Netherlands. Heterogeneity is also present in the thermal characteristics of each dwelling type, section 4.2.2 presents the TABULA project, a database in which these thermal characteristics can be retrieved.

4.2.1. DWELLING COMPOSITION

According to CBS (2016), residential dwellings can be categorized according to the following composition: apartments, terraced houses, semi-detaches houses and detached houses. The share of home compositions in the Netherlands is depicted in table 4.2. The absolute number of each home type is mentioned as well as the percentage of homes suitable for a heat pump. For example, heat pumps are not suitable for apartment buildings. Terraced homes are more likely to be situated in densely packed residential neighborhoods in cities and suburbs. This means that alternative heating technologies such as district heating will also be a sustainable source of heating for these homes. As a result an estimate has been made that 50 percent of terraced homes are eligible for a heat pump. As the homes increase in size, they are less likely to be located in densely population areas and district heating becomes less and less economically feasible. Therefore it will be assumed 75 percent of semi-detached homes will be eligible for a heat pump, and 100 percent of detached homes are to be fitted with a heat pump.

It must be noted that while these assumptions are significant and highly simplified, according to this estimation, the total number of homes eligible for a heat pump is 4.4 million. This number is consistent with the expectation mentioned in Oxford Institute For Energy Studies (2019), where it has been identified that around half the homes in the Netherlands are to be fitted with a heat pump, amounting to 3.9 million. This means that the estimate provided in table 4.2 is on the slightly higher side with around half a million more homes eligible for a heat pump than the estimate made by Oxford Institute For Energy Studies (2019). While this is deemed a shortcoming of the estimation method, the gap is small enough to proceed on the basis of this estimation. The estimated composition of homes eligible for a heat pump will be used in the conceptualization of the model in the following way: the composition of homes will be taken into account when calculating the collective flexibility potential provided by heat pumps.

Table 4.2: Share of home composition from (CBS, 2016)

	Apartment	**Terraced**	**Semi-Detached**	**Detached**
Share of houses in the Netherlands	15.0	42.5	19.6	23.0
Absolute number of houses (million)	1.2	3.3	1.5	1.8
Percent eligible for heat pump	0	50	75	100
Number of homes eligible for heat pump (million)	0	1.6	1	1.8

4.2.2. TABULA PROJECT

The thermal inertia and thermal heat transfer coefficients of a home depend on the characteristics of the residential dwelling such as floor area and insulation. Since this research is investigating the demand response potential of heat pump installed in residential dwellings located in the Netherlands, technical data must be retrieved reflecting the home composition of the Netherlands.

The European TABULA project is a database which can be consulted in order to retrieve these technical characteristics. As a part of the project, home typologies have been developed for thirteen European countries. For each typology, a national classification has been made, grouping the buildings based upon characteristics such as their age, size and insulation parameters. An example typology for the Netherlands is given in figure 4.2.

4.3. CONSUMER USER CHARACTERISTICS

In order to capture the heterogeneity present with respect to consumer user behavior, subsection 4.3.1 begins by identifying behavioral factors which are suspected to under-

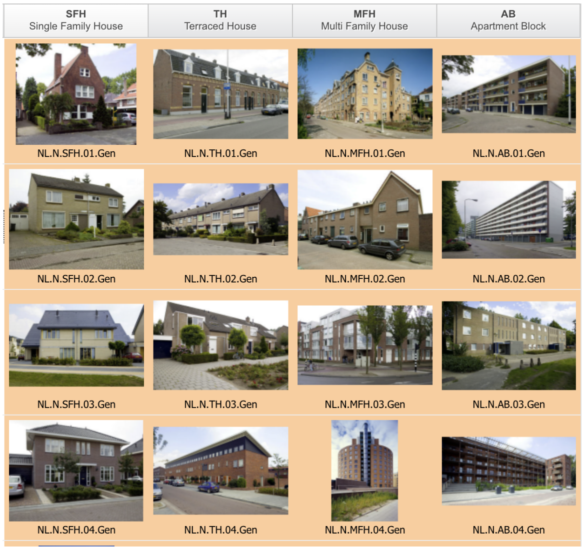


Figure 4.2: Home typology in the Netherlands according to the European TABULA project

lie the way users control their heat pump should their heat pump be technically capable to provide a demand response. Subsection 4.3.2 provides an initial characterization of home users based upon a study conducted by Van Raaij and Verhallen (1983), who managed to capture this heterogeneity nearly four decades ago.

4.3.1. USER BEHAVIOR AFFECTING THE DEMAND RESPONSE POTENTIAL OF HEAT PUMPS

Three behavioral effects have been identified that are deemed to be relevant when evaluating the flexibility response from heat pumps taking into account user behavior. The behavioral effects are: adaptive thermal comfort, the rebound effect and the endowment effect. While there are many behavioral factors relating to user behavior which can influence the demand response potential of heat pumps, these three factors have been selected as they capture three distinct phenomena related to user behavior. The endowment effect and adaptive thermal comfort have been selected based on their prevalence in the articles encountered during the search for literature. The rebound effect has been selected based on advice provided by the supervision of this thesis. These effects are relevant for the conceptualization of user behavior for the optimization model as they can provide guidance regarding which behavior to target when developing policy in order to materialize the demand response potential of heat pumps. Each effect will be discussed in a paragraph below, while highlighting the implications for the flexibility potential of heat pumps.

Adaptive thermal comfort One of the main concerns that arises when flexibly controlling a heat pump to provide a demand response is the loss of thermal comfort. While this poses not so much an issue for a hybrid heat pump, a dissatisfaction factor can be identified as a result of thermal comfort loss when providing a demand response with an all-electric heat pump (Vellei & Le Dréau, 2019). More recently, research has focused on the concept of adaptive thermal comfort, a principle defined by Nicol and Humphreys (2002, p.564) as follows: "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". According to the adaptive approach, the dissatisfaction from thermal comfort loss as a result of a demand response from a heat pump might be lower than initially believed. Estimating the range of comfortable conditions is difficult to define, however Nicol and Humphreys (2002, p.570) find that: "adaptive thermal comfort is a function of the possibilities for change as well as the actual temperatures achieved". The research by Nicol and Humphreys (2002) finds that the range of thermal comfort will be determined by the balance between these two factors. In addition, the study establishes that if there is no possibility of changing clothing or ventilating the room, the width of the thermal comfort zone is merely around ±2 °C. However, if the adaptive opportunities are more plentiful, the study argues that the width of the thermal comfort zone might be significantly wider. Therefore, it can be concluded that if the adaptive opportunities for mitigating thermal dissatisfaction are increased, the demand response potential offered by a heat pump might also increase.

Rebound effect Another behavioral factor relevant to user behavior and heating technologies is the rebound effect. This effect occurs when improved energy efficiencies are compensated by increased energy spending and consumption. Hens et al. (2010) find that rebound effects are very much present in the energy consumption of households for heating. For example, after energy efficiency measures such as improved insulation are implemented, households may conserve less energy than initially expected. This could be attributed due a rebound occurring where households now pay less attention to the heat escaping their home since: "the dwelling has improved insulation anyway" (Hens et al., 2010). When applied to the demand response potential of heat pumps, the rebound effect might cause the participant of the flexibility scheme to increase the desired indoor temperature on their thermostat since the participant might be under the impression they are already doing something to help the environment. As a result, the heat pump might require even more power in order to heat the dwelling at the desired temperature than without the energy conserving measures.

Endowment effect The final behavioral factor related to the way user behavior impacts the flexibility potential of heat pumps is the endowment effect. First identified by Kahneman and Tversky (1979), the effect causes people to place a higher value on things merely because they currently own them or have done so in the past (Luo et al., 2016). In the Netherlands, households have been able to heat their homes with use of natural gas for decades. Therefore, the conclusion can be drawn that a Dutch resident has an expectation to have their thermal comfort needs met. In other words, a resident may feel as if they ’own’ thermal comfort. This hypothesis is confirmed in a paper written by Good (2019) and is problematic since households might value thermal comfort much higher than they would have had should they not experienced such a unique situation in which their thermal comforts were met at an acceptably low price. Therefore, the financial incentive offered to households as a result of flexibly dispatching their heat pump might have to be higher than initially expected. In addition, the further the deviation from the thermal comfort standard, the more compensation households might need to receive in order to join the response scheme.

4.3.2. CHARACTERIZATION OF USER TYPES

When attempting to characterize the consumer types relevant to user behavior, research conducted by Van Raaij and Verhallen (1983) proves to be an incredibly suitable starting point with respect to making an initial classification. Since 1983, the study has been cited over 460 times, and in addition recent notable studies have continued to cite the work published almost forty years ago (Brounen et al., 2012; Stephenson et al., 2010; Wood & Newborough, 2003). Van Raaij and Verhallen (1983) point to *home temperature* and *ventilation* as two important indicators of home energy use. Using these two indicators, Van Raaij and Verhallen (1983) have identified five behavioral clusters relevant to home energy use. The clusters are: conservers, spenders, cool, warm and average and are depicted in figure 4.3. Van Raaij and Verhallen (1983) found that the energy consumption of these clusters varied significantly, with spenders consuming the most energy of all. Next comes the average cluster, after which the cool and warm clusters follow. The conservers consume the least energy of all. The classification of these consumer types will be used as a starting point for the evaluation of how a heterogeneous group of consumers might respond to offering a flexible demand response should a heat pump be installed in their dwelling.

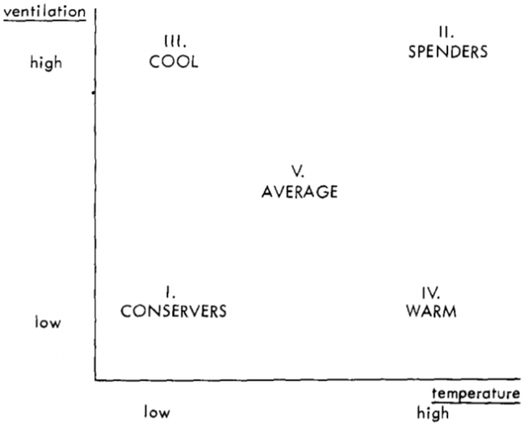


Figure 4.3: Five behavioral clusters depending on ventilation and temperature, adapted from Van Raaij and Verhallen (1983)

4.4. CONSUMER ADOPTION CHARACTERISTICS

This section begins by presenting behavioral factors which are suspected to influence the heat pump adoption behavior of consumers in subsection 4.4.1. The heterogeneity present in the uptake of heat pumps through time can be determined according to the Bass model of innovations, which is presented in subsection 4.4.2. The Bass model of innovations has been selected The section concludes by presenting Otte's lifestyle typology, a model which captures heterogeneity by dividing the general population in several lifestyles, and attaches values to the share of the population belonging to each group.

4.4.1. ADOPTION BEHAVIOR AFFECTING THE DEMAND RESPONSE POTENTIAL OF HEAT PUMPS

Several behavioral effects can be identified that are deemed to be relevant when evaluating the flexibility potential from heat pumps taking into account adoption behavior. In the subsection below, an overview will be provided of the processes and behaviors influencing the decision to adopt a heat pump. The literature has been selected on the basis of number of citations, the extent of specificity on heat pumps and after direction of the thesis supervision. These effects are relevant for the conceptualization of user behavior as they can aid in the development of a typology of consumer adoption types. These consumer adoption types can then be operationalized in the optimization model by estimating the heat pump uptake depending on the adoption rate by consumer type.

Chapter 3 argued that presently, an under investment in heat pump technologies by consumers can be observed. Hesselink and Chappin (2019) provide an explanation as to why an under investment in heat pump technologies might be occurring. They do this by investigating the underlying barriers leading to an energy efficiency gap, which they define as: "the slower than optimal adoption of energy efficient technologies" (Hesselink & Chappin, 2019, p. 31). Hesselink and Chappin (2019) find that the barriers can be structural, economic, behavioral and social in nature. A study conducted on heat pump adoption in the United Kingdom by Snape et al. (2015) confirms that heat pump uptake is slower than expected when evaluated on the basis of optimal energy efficiency. Financial incentives aimed at increasing the adoption rate do not always prove effective, which can largely be attributed to a "hassle factor". (Snape et al., 2015). The "hassle factor" encompasses a variety of non-financial barriers that can withhold households from investing in green energy measures such as a heat pump (de Vries et al., 2019; Snape et al., 2015). One of most influential of these non-financial barriers was identified to be one of convenience, as it was found that 61 % of households only replace their heating system when it has broken down or is on the verge of doing so (Snape et al., 2015). Another important barrier contributing to the "hassle" factor was the complicated administrative process associated with qualifying for a subsidy. The barriers present in the subsidy application process can act as a micro-stressor, causing households to withhold from adopting a heat pump altogether (de Vries et al., 2019; Snape et al., 2015).

While not focusing on the adoption of heat pumps specifically, García-Maroto et al. (2015) provide a generalised framework on the decision making process of a consumer adopting an innovative heating system, presented in figure 4.4. In stage 1, a consumer evaluates the need for a new heating system by weighing the pros and cons of a set of internal (personal) factors, as well as taking into consideration external ones such as government subventions and marketing actions (García-Maroto et al., 2015). Once the need of a new system has been established, the consumer will consult information sources that they perceive as reliable before making the decision to purchase in stage 2 (García-Maroto et al., 2015). In stage 3, the final choice of the heating system is made based upon its perceived advantages (García-Maroto et al., 2015). García-Maroto et al. (2015, p.209) conclude that: "the adoption of an innovative heating system may imply doubts about the level of satisfaction or the urgency that such a decision would entail. Such uncertainty could be related with physical yield, energy savings,economic savings, availability of supply and services, etc.".

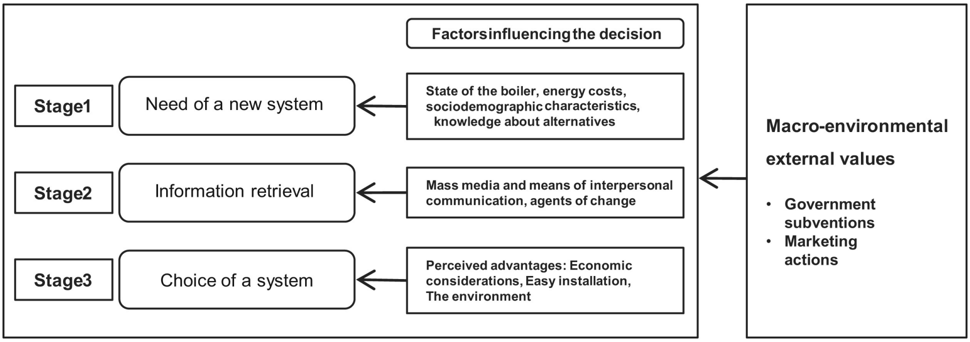


Figure 4.4: Decision process of adopting a new heating technology (García-Maroto et al., 2015, p.209), adapted from (Mahapatra & Gustavsson, 2009; Nair et al., 2010)

4.4.2. BASS MODEL OF INNOVATION

In order to determine the collective flexibility potential that heat pumps are able to provide, the Bass model of Innovation can be applied in order to determine the uptake of heat pumps through time. According to the theory of diffusion of innovations, diffusion is a process through which an innovation is communicated over time towards potential consumers of a product (Rogers, 1962). In this case the heat pump is considered the innovation, and according to the theory, the adoption of heat pumps is likely to follow an S-shaped growth curve. The Bass model is a widely validated tool which can make a forecast of the S-shaped adoption curve based on the coefficient of innovators and coefficient of imitators (Bass, 1969). According to the Bass model, innovators decide to adopt new technology independently whereas imitators are influenced by the decisions of others (Bass, 1969). While the model has been widely verified and praised for its predictive accuracy, a frequent criticisms is that it considers the population to be homogeneous, therefore authors such as Kiesling et al. (2012) instead argue for an agent-based modelling approach in order to capture the heterogeneity of the population. Nevertheless, given the accuracy of the Bass model without taking into account behavioral decision factors, in addition to the limited time scope of the thesis, the Bass model is considered a suitable tool for predicting the total heat pump adoption (Bass et al., 1994). Moreover, behavioral factors can be factored in when estimating the total market pool of potential adopters, which will be explained in the paragraph below. An example of what a potential S-shaped adoption curve of heat pumps could look like is given in figure 4.5.

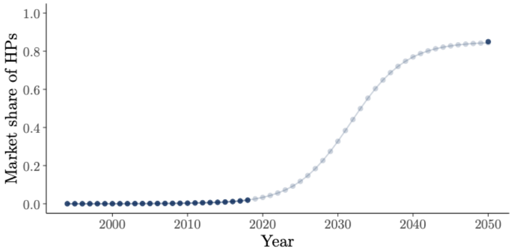


Figure 4.5: Potential adoption S-curve of heat pumps in the Netherlands, retrieved from de Waardt (2020)

The Bass model requires four parameters: starting time $t0$, coefficient of innovators p, coefficient of imitators q, and the total market size m. The Bass model has a differential structure, equation 4.3 shows how $f(t)$ is the change of installed base fraction of heat pumps and $F(t)$ is the installed base fraction of heat pumps at time t. Equation 4.4 displays how to calculate the total number of heat pump adoptions A at time t. The trajectories determined from the applying the Bass model of innovation will be used in order to determine the collective demand response potential of heat pumps.

$$\frac{f(t)}{1-F(t)} = p + q * F(t) \tag{4.3}$$

$$A(t) = m * \frac{1-e^{-(p+q)(t-t0)}}{1+\frac{p}{q} * e^{-(p+q)(t-t0)}} \tag{4.4}$$

4.4.3. OTTE'S LIFESTYLE TYPOLOGY

After a typology capturing the consumer adoption behavior has been developed, the next step is to quantify how many households belong to each group in order to provide a collective estimate of the total demand response potential of heat pumps. Making such an estimate is not straightforward and raises numerous questions. Can consumer lifestyles be related to their willingness to adopt a heat pump? Are certain types of consumers more likely to live in a detached house than other types?

A tool which can be applied in order to estimate the amount of households belonging to consumer groups is Otte's lifestyle typology, depicted in table 4.3. Otte's lifestyle typology has been selected as a relevent piece of information since a similar approach to capturing the socio-demographic and psychological heterogeneity of households was used in research on German insulation activity by Friege et al. (2016). In table 4.3, nine different lifestyles are characterized with the share of each consumer group belonging to each lifestyle given in brackets. The 'level of living' refers to the economic and cultural resources of each consumer type. The consumer type can be related to the household values, ranging from traditional, partially modern to modern.

Table 4.3: Otte's lifestyle typology, adapted from (Friege et al., 2016)

		Consumer type			Total share level of living
		Traditional/ Distrusting consumer	**Partially Modern/ Convenient consumer**	**Modern/ Proactive consumer**	
Level of living	**High**	Established Conservatives (5.7)	Established Liberals (15.9)	Reflectives (6.9)	28.5
	Middle	Conventionals (9.9)	Adaptive Mainstream (26.9)	Hedonists (10.0)	46.8
	Low	Traditional Workers (6.6)	Domestically Centered (14.7)	Entertainment Seekers (3.4)	24.7
Total share consumer type		22.2	57.5	20.3	100/100

4.5. CONCLUDING FINDINGS

This chapter has presented the information required in order order to capture heterogeneity within the heat pump characteristics, residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics. Chapter 5 will use this information in order to create typologies which will serve as input for the optimization model.

5

TYPOLOGY FORMALIZATION

This chapter is written with the intention of answering the following sub-question:

How can the heterogeneity present in the factors affecting the demand response potential of heat pumps be captured and formalized in a typology?

Drawing upon the information collected in chapters 3 and 4, this chapter aims to create a typology which is able to capture the heterogeneity present in residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics. For each of the characteristics, a selection of types capturing the heterogeneity present in the charactertistics is made. Next, data is collected in order to ensure that the typology can be operationalized in a mathematical model capable of calculating the demand response potential of heat pumps. Section 5.1 applies this method to the residential dwelling characteristics, section 5.2 applies this method to the consumer user characteristics and section 5.3 applies this method to the consumer adoption characteristics. The chapter concludes by explaining the next steps in the operationalization of the optimization model in section 5.4.

5.1. TYPOLOGY OF RESIDENTIAL DWELLINGS

Chapter 3 revealed how the dwelling composition and heat pump characteristics can significantly influence the flexibility potential of the heat pump installed in each dwelling. In order to capture the heterogeneity present in residential dwellings, a selection of homes is made and a typology is created in subsection 5.1.1. Subsection 5.1.2 will then formalize this typology by estimating the required installed heating capacity in each type of residential dwelling. This way, the typology can be incorporated into the optimization model which has been developed as part of this study.

5.1.1. SELECTION OF HOMES

In order to calculate the full flexibility potential of heat pumps in the Netherlands, the heterogeneity in residential dwelling types can be captured by creating a typology. It is necessary to create such a typology since the thermal inertia and thermal heat transfer coefficients of a home depend on the characteristics of the home such as floor area and insulation. Three residential dwelling types will be taken into account when modelling the flexibility potential of heat pumps: detached, semi-detached and terraced dwellings. Data is retrieved from the European TABULA project, whose theoretical origins have been presented in section 4.2.

The homes characteristic for the detached, semi-detached and terraced home types of the Netherlands are presented in figure 5.1. While there are many types of detached, semi-detached and terraced homes, the author made this selection on the basis of how representative each home type seemed for average home type. While this selection is without a doubt subjective, the TABULA project offers thermal heat transfer coefficients based upon how many times each home has been renovated. Table 5.1 presents the thermal characteristics of each home type. How the thermal heat transfer coefficient and thermal inertia are calculated is detailed in appendix B. Each residential dwelling type has been given a code. The letters D, SD and T represent the type of house: detached, semi-detached or terraced. The numbers 1,2 and 3 represent the renovation level of the home: poor, medium or good.

(a) Detached home, (NL.N.SFH.01.Gen)

(b) Semi-detached home, (NL.N.SFH.03.Gen)

(c) Terraced home, (NL.N.TH.02.Gen)

Figure 5.1: House types selected from the Tabula project, Tabula reference code in brackets

While the thermal characteristics of the three selected home types depend on the level on insulation, a characteristic which is also very important for the required heat pump capacity is the home area. For example, some detached homes in the Netherlands have areas much larger than 200 m^2. Meanwhile, small terraced homes may only have an area of 75m^2. Therefore, assuming home areas of 143, 135 and 117m^2 respectively for the detached, semi-detached and terraced homes is an assumption which should be investigated in further research.

Table 5.1: Thermal characteristics of chosen homes

	Detached home (NL.N.SFH.01.Gen)			**Semi-detached home (NL.N.SFH.03.Gen)**			**Terraced home (NL.N.TH.02.Gen)**		
Renovation	Poor (D1)	Medium (D2)	Good (D3)	Poor (SD1)	Medium (SD2)	Good (SD3)	Poor (T1)	Medium (T2)	Good (T3)
Area (m^2)	143	143	143	135	135	135	117	117	117
Building heat transfer R (°C / kW)	1.5	4.5	6.9	3.1	5.5	8.4	2.3	5.6	9.0
Building thermal inertia C (kWh/ °C)	6.4	6.4	6.4	6.1	6.1	6.1	5.2	5.2	5.2

5.1.2. FORMALIZATION OF DWELLING TYPES

Besides the thermal characteristics of each home type, an estimation regarding the maximum heat pump capacity installed in the home is required as the heating capacity of the heat pump is dependent on thermal characteristics of the home. This estimation must be made in order to formalize the created typology in the optimization model which has been developed. Section 5.1.2 presented the theory required in order to estimate the necessary heat pump heating capacity for residential dwellings in the Netherlands. For the home types chosen, a power factor of 0.08 has been considered for homes which have not been renovated. This power factor increases to 0.06 m^2/kW when the renovation that has been conducted has been given the medium level. After a thorough renovation, a power factor of 0.04 m^2/kW is considered. Table 5.2 displays the estimated heat pump heating capacities suitable for each home type. These capacities do not represent the power required by the heat pump because of the COP characteristic of the heat pump. Therefore, the actual power consumption will be the heating output power divided by the COP at a given time.

Table 5.2: Assumed heat pump installed capacity

	Detached home (NL.N.SFH.01.Gen)			**Semi-detached home (NL.N.SFH.03.Gen)**			**Terraced home (NL.N.TH.02.Gen)**		
Renovation	None	Medium	Thoroughly	None	Medium	Thoroughly	None	Medium	Thoroughly
Power Factor (m^2/kW)	0.08	0.06	0.04	0.08	0.06	0.04	0.08	0.06	0.04
Maximum heat Capacity (kW)	11.4	8.6	5.7	10.8	8.1	5.4	9.3	7.0	4.7

5.2. TYPOLOGY OF USER BEHAVIOR

Chapter 4 revealed how the heterogeneity present in user groups is suspected to significantly influence the flexibility potential of the heat pump installed in each dwelling. In order to capture the heterogeneity present within consumer user groups, a typology of user groups is created in section 5.2.1. Subsection 5.2.2 then formalizes this typology by combining the literature reviewed with a conducted survey. This way, the consumer user typology can be incorporated into the optimization model which has been developed as part of this study.

5.2.1. SELECTION OF USER TYPES

Section 4.3 introduced an initial typology of home user types created by Van Raaij and Verhallen (1983). The classification of these consumer types has been used as a starting point for the evaluation of how a heterogeneous group of consumers might respond to offering a flexible demand response should a heat pump be installed in their dwelling. Table 5.3 provides an overview of each user type and presents the hypothesized implications with respect to the user behavior should each consumer type adopt a heat pump. These implications have been evaluated on the basis of the behavioral factors identified in section 4.3.1.

Table 5.3: Characterization of home energy users and implications for flexibility potential from heat pump

Home User Type	Explanation (From Van Raaij and Verhallen (1983))	Implications for heat flexibility response
I. Conservers	Conservers (I) maintain a low temperature and a low level of ventilation in their homes. They are characterized by a higher level of education, a smaller family size as compared with the other segments. Their energy use is lower than all other segments; and large individual differences are observed in the summer period. Although there are some effects of their house characteristics, a major explaining factor is their positive attitude toward energy conservation: a high level of energy concern and a low level of comfort concern. This segment shows the desired behavior and energy use. In an energy conservation campaign the goal should be to reinforce this type of energy behavior.	Conservers are likely to participate in a demand response scheme for heat pumps and are willing to accept a considerable loss of thermal comfort in exchange for environmental conservation gains and financial profits. They demonstrate a high degree of adaptive thermal comfort while the rebound effect and endowment effect play a lesser role.
II. Spenders	The spenders (II) maintain a high temperature and a high level of ventilation in their homes. They have a lower educational level and are more often at home. Their energy use is higher than all other segments and we observe large individual differences in the summer period. The proportion of superior insulated homes is rather low for this segment (36 percent). Attitudes do not explain their high levels of energy use. Attitudinal campaigns will probably not be very successful for this segment. Behavioral recommendations to lower their thermostat settings, to ventilate less, and to insulate their homes may be the best campaign strategy. Changing the energy behavior of the spenders will remain a difficult task. Home insulation might be more feasible.	Spenders are unlikely to participate in a demand response scheme for heat pumps since they are not willing to accept a loss in thermal comfort and are not motivated by financial incentives. Spenders demonstrate a low degree of adaptive thermal comfort and feel a strong entitlement to thermal comfort. Therefore the endowment effect plays a large role in the spender consumer profile. The rebound effect is not as apparent for this consumer since they are not willing to alter their behavior in the first place.
III. Cool	The cool segment (III) maintains a low temperature but a high level of ventilation. Their energy use is intermediate. The proportion of superior insulated homes is high for this segment (65 percent). Attitudes do not explain their energy use. The cool segment uses less energy in a standard-insulated home than in a superior insulated home as compared between the two types of home insulation and as compared with the other segments. Home insulation has either no effect or an adverse effect on this segment. The high level of ventilation of the cool counteracts the positive effects of home insulation. In an energy conservation campaign the adverse effects of high ventilation levels should be stressed. Reduction of the level of ventilation or heat recovery in their ventilation systems may help this segment.	When targeted with the right incentives, the flexibility potential derived from the demand response of heat pumps installed in the residences of cool dwellers is very large as they display a high degree of adaptive thermal comfort. The endowment effect is not as strong for the cool dweller since they are not used to owning thermal comfort. However, the effects from a rebound can not be ignored since the cool dweller already displays high levels of ventilation. This may increase when participating in the demand response scheme.
IV. Warm	The warm segment (IV) maintains a high temperature and a low level of ventilation. Their energy use is intermediate. This segment is generally older and they emphasize comfort more than the other segments. It is well-known (Newman and Day 1975) that older people prefer a higher temperature. Energy conservation campaigns should de-emphasize comfort or should advocate that good clothing instead of high temperature may not reduce comfort.	The heat pump installed in the residence of the warm dweller can offer a limited demand response since the endowment effect of owning thermal comfort is particularly type for this home user type. However when targeted with the right marketing campaign, the adaptive thermal comfort factor for this type of home user can be increased. Unfortunately, the warm dweller is susceptible to rebound as they might increase the temperature of their home even more after participating in the scheme for some time.
V. Average	The average segment (V) is by definition not deviating in its characteristics. Again we observe large individual differences in the summer period. In energy-conservation campaigns, an attempt should be made to move this segment in the direction of the conservers. The average segment requires no specific treatment but could benefit from information about lower temperatures and less ventilation.	For the average home user type, adaptive thermal comfort, the rebound effect and the endowment effect all influence the potential of the demand response derived from a heat pump installed at their dwelling. However, the effects are mild and therefore more easy to influence and control. Therefore, the flexibility potential derived from heat pumps installed at the average dweller must not be underestimated.

Table 5.4 presents an overview in which home user types are ranked on the basis of the the three identified behavioral factors relevant to the flexibility potential inherent to heat pump user behavior. When creating policy in order to increase the flexibility potential of heat pumps, the strength of these effects must be considered in order to create the most effective policy. On the basis of the literature, the following hypothesis has been developed with respect to the flexibility potential from heat pumps installed in the homes of each user type:

The flexibility potential of heat pumps installed in homes of conservers is very high as this can be considered the desired flexibility behavior. The flexibility potential of cool dwellers and average dwellers is both high. For cool dwellers this is due to their high adaptive thermal comfort and low endowment effect, however the rebound effect must be guarded. The flexibility potential for the average dweller will be high when incentivized with the right policy. Warm dwellers are more difficult to convince and the rebound effect must be guarded for this user type. Gaining a significant flexibility potential from spenders will be difficult and it is the expectation that this user type will not be able to contribute much to meeting the flexibility demand in the Dutch electricity system since this consumer group displays low adaptive thermal comfort and the endowment effect is strongly present.

Table 5.4: Overview of behavioral effect strength on flexibility potential of identified user types

	I. Conservers	**II. Spenders**	**III. Cool**	**IV. Warm**	**V. Average**
Adaptive thermal comfort	++	–	+	-	0
Rebound effect	–	-	+	++	0
Endowment effect	–	++	-	+	0

5.2.2. FORMALIZATION OF USER TYPES

In the subsection above, five types of consumers with respective to home heating behavior have been identified: average, conservers, spenders, warm dwellers and cool dwellers. It has been established that heat pump user behavior has the potential to affect the flexibility potential, and that this is directly related to the thermal insulation of the home as well as the thermal comfort bounds of users. Therefore, in order to determine the total flexibility potential of heat pumps in relation to user behavior, an estimation must be made of these thermal comfort bounds in addition to determining the share of home users belonging to each user type. From the literature review conducted in section 4.3.2, it emerged that consumers have differing preferences with respect to home temperature as well as the temperature range in which they are able to experience thermal comfort. The larger the temperature range in which a resident is able to experience thermal comfort, the higher the flexibility potential of the heat pump. This subsection will describe how the typology of user types has been formalized using the results a survey which was conducted in order to identify clusters of consumers along with their typical range of thermal comfort. This method was selected as to the author's knowledge, there exist no data regarding the minimum and maximum temperature bounds for consumers with regards to home heating preferences. In addition, by conducting a survey, a cluster analysis could be performed on the collected data points. This would make it possible to identify different consumer types in the data and provides a more comprehensive behavioral component than only making use of an average.

Survey Respondents The survey has been conducted with the aim to collect as many data points on the thermal comfort bounds of consumers as possible. Therefore, the survey has intentionally been designed to be very short in order to generate a high number of respondents, which is necessary when performing a cluster analysis on the data points. Due to this decision, consumers are not asked about demographic characteristics such as their age, educational background or home type. This means that it can not be verified whether the survey is representative for the whole Dutch population. On the other hand, the 1 minute duration of does increase the chance to receive a response and in addition no privacy concerns are raised.

For the distribution of the survey, two distribution links have been created in order to keep track of how many respondents each distribution channel would receive. The first distribution link has generated 73 responses and has been sent through communication platform Whatsapp to acquaintances of the author. This means that the population of the responses collected through distribution link 1 is more than likely to consist of students, in addition to the parents of these students. The second distribution link has been posted on the social media platform LinkedIn, a social media platform used by energy utility company Eneco called Yammer and posted in the weekly newsletter to Eneco employees. The employees of Eneco were approached as this thesis research has been conducted in corporation with the company. The second distribution link has generated 108 responses, and is likely to consist of highly educated adults that are part of the workforce since this is the demographic the author has connected with most closely during the writing of this thesis. Given the distribution means of the survey, groups which are underrepresented are likely to be elderly adults and adults with a low level of education.

In total, the survey gathered 181 respondents within the time span of a week. Data cleaning of the recorded responses has been performed by removing the response if questions 1 or 2 had been answered with "No". Of the 181 initial responses, 154 responses remained. When performing an initial analysis of these responses, two outliers were identified. Two respondents indicated that the maximum indoor temperature at which they would be willing to heat their home without experiencing a loss in thermal comfort was 27 degrees centigrade. This number was deemed unrealistically high, especially since the second highest recorded data point was 25 degrees centigrade, two whole degrees lower. Therefore, data cleaning was performed which removed these two responses. This meant that in total 152 responses were considered for the estimation of consumer home heating preferences.

Survey Procedure In order to estimate the thermal comfort bounds of consumers, the survey respondents have been presented with the following questions:

1. Do you live in the Netherlands?
2. Are you able to control your home indoor temperature by using a thermostat?

3. At what temperature do you typically heat your home? (answer in degrees centigrade using one decimal point)
4. What is the maximum indoor temperature you would be willing to heat your home at without experiencing a loss in thermal comfort? (answer in degrees centigrade using one decimal point)
5. What is the minimum indoor temperature you would be willing to heat your home at without experiencing a loss in thermal comfort? (answer in degrees centigrade using one decimal point)

Questions 1 and 2 have been designed as checks in order to determine the eligibility of the consumer to take part in the survey. Since the thesis investigates the flexibility potential of heat pump users in the Netherlands, the home heating preferences of users in countries with different climates will not be considered. In addition, if a consumer is not able to control their home indoor temperature by using a thermostat, the hypothesis is that it will be much more difficult to estimate the preferred indoor temperature. Therefore, if the respondent would answer "no" to either question 1 or 2, their response will not be taken into account for the data analysis.

Questions 3, 4, and 5 have been designed with the intention of providing direct input to the linear optimization model that has been developed as part of this thesis. For the average respondent, answering question 3 is presumed to be rather straightforward as this is the temperature the respondent will usually set their thermostat at. It is expected that estimating the thermal comfort bounds for questions 4 and 5 is more challenging, especially since the formulation of the questions might be difficult to understand and is potentially ambiguous. The term "Experiencing a loss in thermal comfort" might invoke a different meaning to each respondent. While this is a shortcoming of the survey, a different formulation would still have made it difficult for the consumer to estimate the thermal comfort bounds, which will serve as crucial input for the linear optimization model. The interface of the survey that was presented to consumers can be found in appendix A.

Survey Processing In total, the survey gathered 181 respondents within the time span of a week. Data cleaning of the recorded responses has been performed by removing the response if questions 1 or 2 had been answered with "No". Of the 181 initial responses, 154 responses remained. When performing an initial analysis of these responses, two outliers were identified. Two respondents indicated that the maximum indoor temperature at which they would be willing to heat their home without experiencing a loss in thermal comfort was 27 degrees centigrade. This number was deemed unrealistically high, especially since the second highest recorded data point was 25 degrees centigrade, two whole degrees lower. Therefore, data cleaning was performed which removed these two responses. This meant that in total 152 responses were considered for the estimation of consumer home heating preferences.

Each response in the survey consists of three data points: the average temperature at which the respondent typically heats their homes, the maximum temperature at which they still experience thermal comfort and the minimum temperature at which they are still able to experience this comfort. From these data points, a data-framework in Python was created and the k-means clustering algorithm was applied in order to group data points with similar characteristics together.

The K-means clustering algorithm is a method which can be applied when aiming to cluster numerous data points on the basis of similar characteristics. Chapter x will present the results of a survey and the k-means algorithm will be applied in order to cluster the obtained data. As the name might suggest, the k-means clustering algorithm aims to partition a number of observations n into k clusters, in which each data point belongs to the cluster with the nearest mean. Each cluster has a cluster center which is representative for the cluster. The k-means clustering algorithm is useful when intending to define clusters within data points based upon similar characteristics. Given a set of observations (x1, x2, ..., xn), where each observation is a d-dimensional real vector, the k-means clustering aims to separate the n observations into k (n) sets S = S1, S2, ..., Sk so as to minimize the within-cluster sum of squares.

A frequent criticism of the k-means algorithm is that it clusters the data points based upon an arbitrary cluster number that is determined by the modeller. A k number can be selected on the basis of subjective suitability, a number derived from literature or by applying a rule of thumb developed by Qiu and Joe (2006). Qiu and Joe (2006) recommend that the sample size should amount to a minimum of 10 times the number of dimensions times the number of clusters in cases where the clusters are of equal size. Equation 5.1 shows the mathematical formulation of this recommendation. For example, if a clustering is performed along three dimensions, amounting to a d of 3 and a k of 5 clusters is chosen, the total number of data points that must be collected before the k-means clustering can be applied is 10 * 3 * 5 = 150.

$$n = 10 * d * k \tag{5.1}$$

For the clustering analysis of the survey, a k of 5 has been applied, as this is considered to be in line with the number of groups defined by Van Raaij and Verhallen (1983). This means that the algorithm has been set-up in such a way it would create 5 clusters based on the average, maximum and minimum temperature of the data points (in a three-dimensional space). According to the theory presented by Qiu and Joe (2006) in section 4, with 5 clusters identified, the total number of data points that must be collected before the k-means clustering can be applied is 10 * 3 * 5 = 150. Since 152 responses are considered for the analysis, the sample size just about meets this threshold and it can be concluded that enough data points have been gather in order to apply the k-means clustering algorithm.

Survey Results Figure 5.2 presents the clusters created by applying the k-means clustering algorithm to the 152 data points considered. In the three-dimensional space, each axis represents the value of the data point given the indicated value of average, minimum and maximum acceptable indoor temperature. In addition, the center of each cluster is presented by a black dot. In general, it can be established that the k-means clustering algorithm has adequately defined five consumer user type cluster centers on the basis of the survey. Ideally, the distance between the cluster center and all surrounding data points is as small as possible, however the from the figure it can be determined that there are clear locational differences between the clusters. For example, the cool dweller and warm dweller groups are clearly located in different areas of the plot.

The results of the clustering computation are presented in table 5.5. For each cluster, an attempt has been made to match the characteristics of the cluster (average, maximum and minimum) to the typology created by Van Raaij and Verhallen (1983). Doing so enables the typology of user characteristics to be formalized in the optimization model Two groups keep their home on the cooler side with average temperatures of 19.6 and 19.0 degrees centigrade. Based on the Van Raaij and Verhallen (1983) typology, the conservers and cool dwellers both fit these characteristics. Since one group was willing to accept minimum temperatures of 16.3 degrees centigrade, this group was identified to be the cool dwellers. The average cluster was identified based upon their average corresponding to the average of the survey collectively. Two groups keep their home on the warmer side with average temperatures of 21.0 and 20.7 degrees centigrade. Again, based upon the typology created by Van Raaij and Verhallen (1983), the conservers and spenders fit these cluster characteristics. Since one group was willing to accept a maximum temperature of 24.2 degrees centigrade, this cluster was deemed to be part of the warm dweller user group. In addition, each cluster name has been given a code C1 representing the average user group, C2 representing the conserver user group, C3 representing the spender user group, C4 representing the warm dwellers and C5 representing the cool dwellers.

Table 5.5: Results of K-clustering algorithm applied to survey results

Group	Maximum Temperature	Minimum Temperature	Average Temperature
C1 - Average	22.1	18.6	20.0
C2 - Conservers	20.6	18.7	19.6
C3 - Spenders	22.2	20.4	21.0
C4 - Warm Dwellers	24.2	18.4	20.7
C5 - Cool Dwellers	21.1	16.3	19.0

Discussion of Survey Results When applying the k-means clustering algorithm, the modelled results can differ slightly per run as the algorithm uses heuristics in order to determine the final clusters. Therefore, a significant drawback of the algorithm is that the clusters might be slightly differently defined per run. In addition, it is important to verify if the chosen k of 5 based on the results found by Van Raaij and Verhallen (1983) indeed creates 5 separate clusters that can be aligned with their findings. Table 5.6 does exactly this by presents by comparing the results from Van Raaij and Verhallen (1983) with the results generated by the algorithm based upon the survey data.

Figure 5.2: Clustering of consumer groups based on average, minimum and maximum acceptable temperature

For the shares of average, spenders and cool dweller groups, the share of the group has less than a 5 percentage point delta between the shares found by Van Raaij and Verhallen (1983) and those generated from the clustering algorithm. The percentage point delta between the conservers and warm dweller is the highest, it seems that in the survey results many warm dwellers have moved to the user conserver group. There are multiple possible explanations for this. Since the 1980s environmentalism has started to play a more dominant role in our heating behavior and many consumers are now more environmentally cautious. A second reason is similar to this but not motivated by environmentalism: gas prices in the Netherlands have increased significantly since the 1980s. Lastly, the discrepancy could be due to the survey being distributed mostly amongst students and adults up to the age of 50. Therefore, results could have been skewed since students tend to be more environmentally cautious and elderly people tend to heat their home at higher temperatures. Nevertheless, the discrepancy between the user groups can be explained and it can therefore be concluded that the k-means clustering algorithm is an adequate method for determining the temperature comfort ranges of the different user types. For the calculation of the flexibility potential from heat pumps per user type, the distribution as presented in the second-to last column in table 5.6 will thus be used.

Table 5.6: Comparison between results Van Raaij and Verhallen (1983) and conducted survey

Group	Samples study van Raaij and Verhalen (1983)	Share as percent of total	Samples from survey study	Share as percent of total	Percentage delta (Literature study subtracted from survey study)
Average	37	25.5	40	26.3	0.8
Conservers	18	12.4	47	30.9	18.5
Spenders	22	15.2	30	19.7	4.6
Warm Dwellers	45	31.0	16	10.5	-20.5
Cool Dwellers	23	15.9	19	12.5	-3.4
Total	145	100	152	100	

5.3. TYPOLOGY OF ADOPTION BEHAVIOR

Chapter 4 revealed how the heterogeneity present in consumer adoption groups is suspected to significantly influence the collective flexibility potential that heat pumps are able to provide. In order to capture the heterogeneity present within consumer user groups, a typology of consumer adoption groups is created in section 5.3.1. Subsection 5.3.2 then formalizes this typology by combining reviewed literature and the Bass model of innovations. By doing so, the consumer adoption typology can be incorporated into the optimization model which has been developed as part of this study.

5.3.1. SELECTION OF ADOPTION TYPES

From the theoretical analysis conducted in section 4.4.1, it can be concluded that many behavioral factors are at play for the consumer when making the decision to adopt a heat pump. Circling back to the framework created by García-Maroto et al. (2015), for each stage in the adoption process several relevant behavioral factors mentioned in Hesselink and Chappin (2019) have been identified. Table 5.7 provides an overview of these factors and places them in relation to heat pumps specifically. This table will serve as a reference framework for the characterization of heat pump adopters, which will be discussed in the remainder of this subsection.

On the basis of table 5.7, a typology of consumer adoption types has been created consisting of the convenient, distrusting and proactive consumer. The typological overview is given in table 5.8 below. In addition, a description is provided for each adoption consumer type.

Convenient consumer For this type of consumer, inertia is an important behavioral factor with respect to the adoption of a heat pump system. A need for a new heating system must present itself in order for this consumer type to consider adopting a heat pump, directly relating to stage 1 of the heat pump adoption process: need for a new system. An opportunity for heat pump adoption arises when the existing heating system breaks down or the residential dwelling must undergo a renovation. Secondly, the availability bias is of relevance since this type of consumer will not actively seek out information online, consuming what he/she will come across haphazardly. Thirdly, ignorance/a priori beliefs play a role in the heat pump adoption behavior of the convenient consumer since the consumer will be repelled by a complicated administrative process when applying for a subsidy. Last but not least, this consumer portrays a high degree of satisficing behavior. The convenient consumer will consider adopting a heat pump as long as the transaction costs and "hassle" factor are brought to a minimum.

Table 5.7: Behavioral framework with implications for heat pump adoption

Stage	Behavioral Factor	Explanation (From Hesselink and Chappin (2019, p.33).	Heat Pump Implications
1. Need for a new system	Inertia	People have a tendency to want to stick with the status quo rather than having to change for practical reasons and for convenience; as they like to avoid hidden costs associated with a switch.	Heat pumps are most often installed as a replacement when the existing heating system breaks down or when signaled with non-emergency indicators that the heating system is reaching the point of breakdown. (Snape et al., 2015)
2. Information Retrieval	Availability bias	People primarily draw on knowledge and information that is easily accessible. Lack of information may mean that some opportunities are missed.	While much information on heat pumps is available online, the nature of the information can differ depending on where the information is retrieved. See appendix A.
	Ignorance/ A priori beliefs	Lack of knowledge, understanding or education aboutenergy efficiency.	There is "hassle" factor associated with the complicated administrative process when qualifying for a heat pump subsidy. (Snape et al., 2015)
	Trust	People seek information and judgement from those that they trust. People may also trust information from specific people or institutions more than others.	Spacial adoption can play a major role in the adoption of the heat pump. Residents are more likely to install a heat pump when their neighbor has done so. (Snape et al., 2015)
3. Choice of a system	Discounting/irrational response to monetary incentives	People's response to incentives are often short-lived and unpredictable and may crowd out intrinsic motivations	It can take 8 to 16 years to earn back a return on investment for a heat pump, this may lead households to discount the rate of return. (CBS, 2020)
	Satisficing behavior	People do not tend to optimize their decision but rather aim to satisfy a small set of criteria, i.e. the minimum requirements	The comparative reliability and perceived effectiveness of the heat pump versus the boiler system are the main factors driving the adoption.(Masini & Menichetti, 2012)
	Loss aversion	People weight losses more than gains when making decisions and people tend to avoid the prospect of a loss even with the prospect of certain gains, and tend to accept a gamble in order to avoid a loss.	The loss of thermal comfort as a result of a switch to a heat pump is a concern for many households. Therefore, retaining the boiler system is a more 'certain' bet.

Table 5.8: Factor characterization of heat pump adopters

Convient Consumer	Distrusting Consumer	Proactive Consumer
Inertia	Trust	Discounting/irrational response to monetary incentives
Availability bias	Availability bias	A priori beliefs
Ignorance	Loss Aversion	Loss Aversion
Satisficing		

Distrusting consumer Stage 2: information retrieval takes a central position for the distrusting consumer during the heat pump adoption decision-making process. Trust in the information he/she receives is crucial for persuasion. For example, if a neighbor of a distrusting consumer installs a heat pump and has a negative experience, this will have a large effect on the decision-making process of this consumer. In addition, the availability bias also influences this consumer's negative opinion of heat pumps. Social media posts such as those presented in appendix A will stay with this consumer for some time. Another reason for the distrust can be attributed to loss aversion: the prospect of transitioning to a heat pump system is uncertain. Therefore, this consumer type will opt-for the more certain option and will tend to stick to the existing heating system. Overall, this consumer type is characterized by a general distrust in the heat pump technology and is unlikely to adopt a heat pump spontaneously.

Proactive consumer This consumer type actively seeks out a new heating system and consults many different sources of information on which he/she will base their decision.

Therefore, during the heat pump decision-making process stage 3: choice of a system will be the stage where most behavioral factors are of relevance for this consumer. While the chance of this consumer type adoption a heat pump is high, discounting behavior and irrational response to monetary incentives can still influence their final decision. For example, this consumer might want to adopt a heat pump due to sustainability concerns, but forego adoption if this sustainable motivation is short-lived. In addition, a priori beliefs can also play an important in the decision-making process of this consumer type. If this consumer type has already made up their mind, they might not be open to listening to an installation technician regarding the most suitable heat pump type for their house type. Lastly, even the proactive consumer is not immune to loss aversion. If they have doubts about the expected pay-off of switching to a heat pump system, they might forego the adoption of the system until a higher degree of certainty is reached.

Adoption behavior An overview of the consumer characterizations and the most important behavioral factors in their heat pump decision-making process is provided in table 5.8 below. Consumers can be split into three types with respect to heat pump adoption: the convenient consumer, the distrusting consumer and the proactive consumer. The flexibility potential of heat pumps will depend on how many consumers belong to which category in the typology and how they are able to be influenced in order to install a heat pump. The proactive consumer is most likely to install a heat pump, whereas the convenient consumer might be open to installing one should their existing heat pump system break down. The distrusting consumer will be most difficult to convince, with trust and the availability bias playing a large role in their willingness to adopt a heat pump. When developing policy in order to materialize the demand response potential of heat pumps with respect to user behavior, the factors displayed in table 5.8 provide a good starting point with respect to which behavioral factor the policy should target. In Chapter 5, an estimate regarding how many consumers belong to each consumer type mentioned this typology will be made.

5.3.2. FORMALIZATION OF ADOPTION TYPES

Subsection 5.3.1 defined three consumer types with varying behavioral attitudes regarding heat pump adoption. This subsection aims to formalize the behavioral characteristics of heat pump adopters into heat pump adoption curves which can be implemented in combination with the linear optimization model. First, an estimation is made regarding the number of consumer types living in each type of dwelling (terraced, semi-detached and detached). Second, the Bass model of innovation is implemented in order to estimate the adoption growth curves of heat pumps until 2050.

Assumptions composition heat pump adopters Given the limited time scope of the thesis research, an estimate of the amount of households in each of the consumer groups was made based upon Otte's lifestyle typology. This typology has been presented as supporting theory in section 4.4.3. The 'level of living' refers to the economic and cultural resources of each consumer type. The consumer type can be related to the household values, ranging from traditional, partially modern to modern. These three household values have been related to the identified consumer types defined in subsection 5.3.1. Therefore a traditional household is assumed to belong to the distrusting consumer group, the partially modern household to the convenient consumer group and the modern household to the proactive consumer group. This means that it will be assumed that the distrusting consumer makes up 22.2 percent of the population, the convenient consumer makes up 57.5 percent of the population and the modern consumer 20.3 percent of the population. An updated version of Otte's lifestyle typology is given is table 5.9 below, it can be observed that the consumer types have been related to the lifestyle types.

Table 5.9: Otte's lifestyle typology, adapted from (Friege et al., 2016)

		Consumer type			Total share level of living
		Traditional/ Distrusting consumer	**Partially Modern/ Convenient consumer**	**Modern/ Proactive consumer**	
Level of living	**High**	Established Conservatives (5.7)	Established Liberals (15.9)	Reflectives (6.9)	28.5
	Middle	Conventionals (9.9)	Adaptive Mainstream (26.9)	Hedonists (10.0)	46.8
	Low	Traditional Workers (6.6)	Domestically Centered (14.7)	Entertainment Seekers (3.4)	24.7
Total share consumer type		22.2	57.5	20.3	100/100

While an estimate has been made on the share of each consumer group making up the collective heat pump adoption population, the question remains how to approach the notion that one consumer type might be more likely to live in a certain type of house than the other. In chapter 4 it was determined that the characteristics of the dwelling have a large influence on the potential of flexibility a heat pump can provide. Therefore, in order to estimate how many residential dwellings belong within each consumer type we again refer to Otte's lifestyle typology. Table 5.9 identifies three levels of living: high, middle and low. According to the typology, 28.5 percent of the population has a high level of living, 46.8 percent a middle level of living and 24.7 percent a low level of living. An abstraction that will be made is that consumers with a high level of living are more likely to live in detached homes and semi-detached homes, consumers with a middle level of living are more likely to live in semi-detached and terraced homes, and consumers with a low level of living more likely to live in terraced homes and apartments. While this is a significant abstraction, it has been based on the notion that people with more economic and cultural resources are more likely to live in larger homes.

The share of home compositions in the Netherlands has been discussed in the theoretical section 5.2.2, where it has been argued how many home types are eligible for a heat pump. Table 5.10 has been used as a tool to calculate how many types of homes belong to each identified consumer type. On the horizontal the share of home types as provided in table 4.2 is displayed. Vertically it is displayed which share of consumers belong to which level of living. The contents of the cells demonstrate the share of homes belonging to each level of living. The assumption works as follows: consumers with a low level of living make up 24.7 percent of the population. Apartments make up 15 percent of the homes in the Netherlands. It will be assumed that consumers with a low level of living will first occupy all the apartments, with the remainder 9.7 percent occupying a terraced home. This same line of reasoning has been applied to consumers with a medium and high level of living.

Table 5.10: Share of homes in each level of living

	Apartment	**Terraced**	**Semi-detached**	**Detached**	Total (Percent)
High	0	0	5.5	23	28.5
Medium	0	32.8	14	0	46.8
Low	15	9.7	0	0	24.7
Total (Percent)	15	42.5	19.5	23	

The final step in the estimation is to calculate how many homes eligible for a heat pump belong to which identified consumer type. This calculation has been made based upon the nine consumer types displayed in table 5.9. The calculation works as follows: established conservatives make up 5.7 percent of all consumers and enjoy a high level of living. This means that of the 1.8 million detached homes eligible for a heat pump, in which 28.5 percent of the population lives (see table 5.10), 5.7/28.5 * 1.8 = 0.36 million detached homes eligible for a heat pump are occupied by distrusting consumers. Table 5.11 displays the results of the final calculation: the absolute number of dwelling types eligible for a heat pump occupied with which consumer type (distrusting, convenient, proactive).

Table 5.11: Composition of dwellings occupied by consumer types

	Distrusting	**Convenient**	**Proactive**	**Total**
Detached (million)	0.36	1.00	0.44	1.80
Semi-Detached (million)	0.21	0.57	0.22	1.01
Terraced (million)	0.37	0.95	0.32	1.64

Application of Bass Model Now that the estimation of the number of dwelling types eligible for a heat pump occupied by each consumer type has been made, an second estimation must be made regarding the adoption curves of heat pumps in taking into account the composition of these consumers (distrusting, convenient and proactive) before the data has reached an appropriate level of formalization which can be applied in the developed optimization model.

Subsection 4.4.2 introduced the theoretical background of the Bass model, which can be used in order to create adoption curves of a new technology such as heat pumps. The strength of the bass model is that despite just requiring four parameters, the S-shaped curves that are produced by the model can take very differing shapes based on the parameter values inserted. Therefore, in order to create heat pump adoption curves, an estimation of these parameters must be made. The four parameter required by the Bass model are: starting time $t0$, coefficient of innovators p, coefficient of imitators q, and the total market size m.

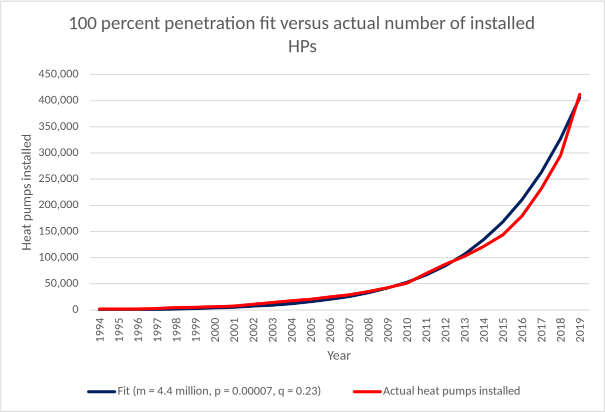
According to data from the Dutch Central Bureau of Statistics, the first heat pumps were installed in 1994 (CBS, 2020). Therefore, $t0$ is considered to start at this base year. Estimating market size m is not as straightforward, however in table 4.2 we learn that in total 4.4 million houses are suitable for a heat pump, which means that m can not exceed 4.4 million. Should 4.4 million heat pumps be installed by 2050, the goal mentioned in the climate accord by Rijksoverheid (2019), it will entail that all identified consumer groups fully adopt a heat pump. It is difficult to estimate the market penetration of heat pumps within each identified consumer group, however from the research conducted in section **??**, it emerged that the proactive consumer is most likely to adopt a heat pump, followed by the convenient consumer and finally the distrusting consumer. Table 5.12 demonstrates three scenarios of heat pump market penetration based on these behavioral insights. The ideal scenario is 100 percent adoption by all consumer groups, leading to 100 percent market penetration. In this scenario m is 4.4 million installed heat pumps in 2050. When assuming that the potential adoption market for heat pumps for the distrusting consumer is 50 percent adoption, 75 percent for convenient consumers and 100 percent for proactive consumers, the total market penetration of heat pumps will amount to approximately 75 percent and 3.3 million heat pumps will be installed in 2050. The final scenario assumes 25 percent of distrusting consumers eventually adopting a heat pump, 50 percent of convenient consumers adopting one and 75 percent of proactive consumers adopting a heat pump. Based on these assumptions the total market penetration is around 50 percent, leading to an estimated m of 2.2 million heat pumps.

Table 5.12: Estimation of total market side m based on the identified heat pump adopter groups

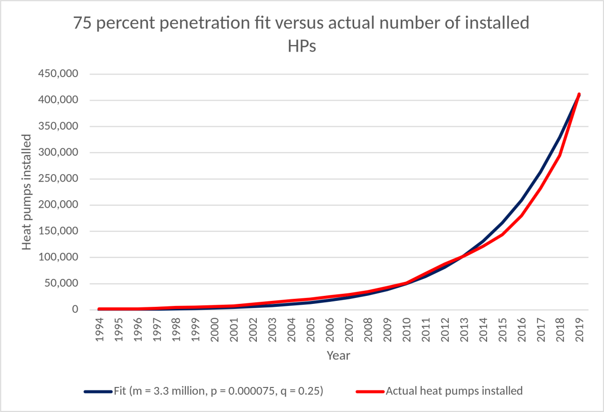
	Adoption grade distrusting consumer	**Adoption grade convenient consumer**	**Adoption grade proactive consumer**	**Estimation of variable m**
100 Percent Market Penetration	100	100	100	4440000
75 Percent Market Penetration	50	75	100	3340000
50 Percent Market Penetration	25	50	75	2230000
Houses Eligible for Heat Pump	940000	2520000	980000	

Now that variables m and $t0$ have been identified, the coefficient of innovators p and coefficient of imitators q must be estimated. These coefficients can be estimated by making use of the heat pump growth data thus far retrieved from CBS (2020). There has been a market for Dutch heat pumps for 26 years, and by plugging in the estimated maximum market sizes m we can find p and q by choosing values which lead to a fitted Bass curve most closely resembling the existing heat pump growth so far. The results for the fitted curves are depicted in figure 5.3.

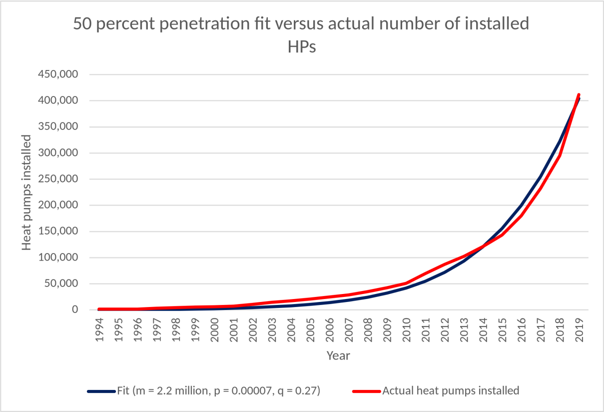
Table 5.13 presents the results of the fitted parameters for each market penetration scenario. These parameters have been inserted into the Bass model with a time horizon starting in 1994 and ending in 2050, thereby spanning 56 years. Figure 5.4 shows the result of the heat pump adoption curves fitted using the parameters from table 5.13. The adoption curves will be used when estimating the total collective flexible load heat pumps are able to provide. The linear optimization which will be used will model the demand response capacity of a single heat pump. The collective flexible load potential



(a) Fit for 100 percent market penetration



(b) Fit for 75 percent market penetration



(c) Fit for 50 percent market penetration

Figure 5.3: Fits of curves based upon estimates for p and q

can be determined by scaling these values with the amount of heat pumps installed in year t according to the adoption curves presented in figure 5.4.

Table 5.13: Estimation of parameters

	t0	m estimate	p estimate	q estimate	R-squared
100 Percent Market Penetration	1994	4440000	0.00007	0.23	95.8
75 Percent Market Penetration	1994	3340000	0.000075	0.25	95.8
50 Percent Market Penetration	1994	2230000	0.00007	0.27	95.8

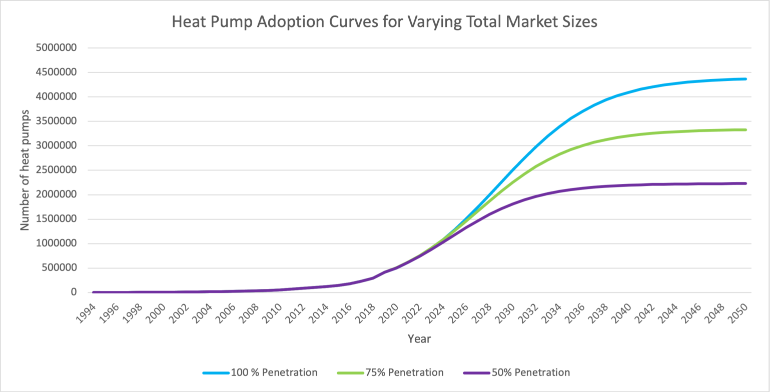


Figure 5.4: Adoption curves created using the Bass model

5.4. CONCLUDING FINDINGS

This chapter has created three respective typologies surrounding residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics. For each typology, theories, literature and other methods have been applied in order to make the typologies suitable for the modelling phase of this research.

In total, 5 consumer types have been identified with respect to thermal comfort bounds and user behavior. In addition, 3 home types have been identified which can respectively be split into three further sub-groups depending on the state of home renovation. For each home, the linear optimization model will be run in combination with the 5 user types, leading to a total of 45 runs. The linear optimization model will provide output for 1 consumer type living in 1 home type. Therefore, the results must be scaled in ratio to the user type and residential dwelling composition. After this has been completed, the results will be scaled yet again according to the estimated yearly adoption curves generated from the Bass model. Upon completion of this step, an estimate of the total flexibility potential of heat pumps can be made. The next chapter will proceed to discuss the inner workings of the linear optimization model.

6

OPTIMIZATION MODEL

After establishing and formalizing the typology of residential dwellings, consumer user types and consumer adoption types in chapter 5, this chapter is written with the intention of answering the following sub-question:

How can factors influencing the demand response potential of heat pumps be formalized in a mathematical model?

The chapter begins by introducing the mathematical model which has been utilized for determining the demand response potential of heat pump in section 6.1. The specifications for the model are discussed in section 6.2, after which the model dynamics are discussed in section 6.3. The set-up of the model is further specified in section 6.4.

6.1. OPEN MODEL DESCRIPTION

This sections begins by providing a motivational description as to why OPEN model has been selected in order to answer the main research question in subsection 6.1.1. Subsequently, a general introduction to the model structure is provided in section 6.1.2.

6.1.1. MODEL MOTIVATION

The demand response potential of heat pumps can be calculated by using a linear programming approach. Linear programming techniques are often applied to energy optimization problems as it is often the objective to minimize the total costs of the energy system given the system boundary conditions (Bordin et al., 2017; Lauinger et al., 2016). There exist a variety of linear programming tools which allow for energy system modelling. Examples of linear programming tools include the python PICOS package and the software package Linny-R. While both tools are suitable for the development of a heat pump demand response optimization model, the choice was made to use OPEN: An open-source platform for developing smart local energy system applications (Morstyn et al., 2020).

OPEN was selected is it possesses over a key set of advantages compared to the PICOS package and Linny-R software. OPEN provides an extensible platform for developing local energy systems and is pre-loaded with the optimization software required for solving the dispatch of the local energy system assets. While such a predefined structure can be problematic as it can lead to a poor understanding underlying 'black box' structure, OPEN is accompanied by extensive user guide and comes loaded with two examples: a case study for a building with an all-electric heat pump and solar panels on its roof, and a case study for a local electric vehicle charging network optimization. A key advantage of the OPEN model is that the thermal dynamics of a building are already built-in in the BuildingAsset class. The selection for the OPEN model was made based on this feature in addition to the simple heat pump case example already provided. Finally, OPEN has been developed with modularity and customization in mind. This means that integrating the quantitative behavioral elements into the model is technically possible and not constrained by software architecture.

6.1.2. INTRODUCTION OPEN MODEL

The main elements of OPEN can be represented in a UML class diagram, depicted in figure 6.1. The model exists of four key components: the EnergySystem, Assets, Market and Network. In the EnergySystem class, the optimization horizon and solving configurations are defined. The assets which are to be optimized within the energy system can be defined according to the several asset classes consisting of a NondispatchebleAsset, a StorageAsset or a BuildingAsset. An example of an asset belonging to the NondispatcheableAsset class is a solar panel, an example of an asset belonging to the StorageAsset class is an electric vehicle and an example belonging to the BuildingAsset class is a heat pump. The energy market prices which will serve as input for the optimization are defined in the Market class. If desired, export prices can also be defined, this is the compensation a non-dispatchable asset such as a solar panel would receive for feeding electricity back onto the grid. Finally, in the Network asset class the physical local network configuration and constraints can be defined. This feature is particularly useful when faced optimizing a local energy network that is facing congestion issues. Now that the general structure of the OPEN model is clear, the next section will discuss how the model has been configured in order to calculate the demand response potential of heat pumps in the Netherlands.

6.2. MODEL SPECIFICATIONS

While the OPEN model comes pre-loaded with a heat pump demand response case study, the case study only takes into account the thermal dynamics of one building during a 24-hour time period in summer and in winter. Therefore, in order to calculate the total demand response potential of heat pumps in the Netherlands, the underlying structure must be modified in such a way that it is able to optimize the heat pump dispatch over a full year. Therefore, the model will be optimized for 365 time periods of 24-hours. In addition, the identified house types and consumer types must be considered in order to capture the behavioral dimension of the demand response potential. Table 6.1 displays all the input variables required for the optimization model. Each input variable is

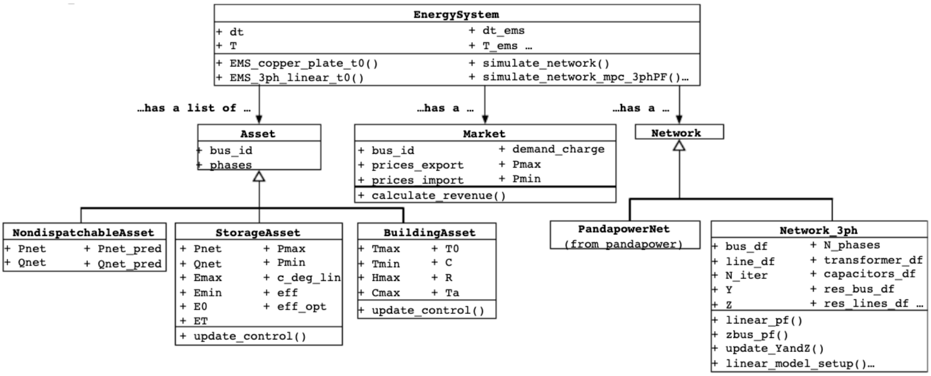


Figure 6.1: Overview of OPEN model structure, from (Morstyn et al., 2020)

further specified individually in the paragraphs below.

Table 6.1: Required model input

Variable	**Value**
Allowed temperature range	5 Consumer Types, Table 5.5
Initial temperature	Table 5.5
Ambient temperature	Time Series
HVAC capacity	Table 5.1.2
COP	Calculation
Building heat transfer	9 home types, Table 5.1
Building thermal mass	9 home types, Table 5.1
Energy price	Time Series
EMS time-series resolution	1 hour
Optimization horizon	24 hours
Simulation time-series resolution	15 mins

Allowed temperature range The allowed temperature range of the consumer types is derived based on the work conducted in chapter 4. In total 5 consumer types have been identified (C1,C2,C3,C4,C5), the allowed temperature ranges per consumer type are found in table 5.5.

Initial temperature The value for the initial temperature at the start of the optimization *t0* is defined as the typical indoor temperature as indicated by the respondents in the survey, displayed in table 5.5. For every 24-hour period, the *t0* value is updated with the final temperature value of the home in the previous time series. How this has been implemented in the model code can be found in appendix E.

Ambient Temperature The outside temperature can significantly influence the power required by the heat pump to provide heating to the home. For example, the heat pump will have to provide more output heating when it is 5 °C outside compared to an ambient temperature of 15 °C. At an ambient temperature of 20 °C the heat pump might not have to provide any heating at all, whereas at temperatures above 25 °C the cooling mechanism will have to be instated. The time series used as ambient temperature input is the weather year 2010. The weather year 2010 was selected as it is considered an average weather year in the Netherlands and used as the default weather year in an energy transition model developed by Quintel Intelligence (2021b). The weather time series used as input for the optimization model is depicted in figure 6.2.

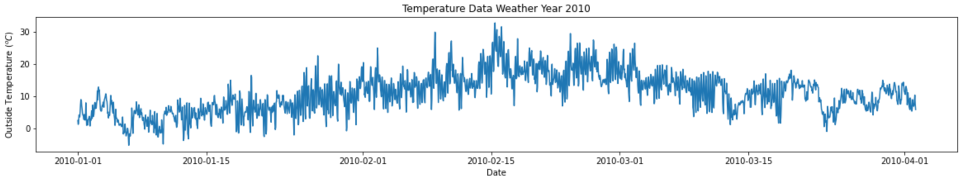


Figure 6.2: Outside temperature weather year 2010

HVAC capacity The installed heat pump capacity suitable per home type has been calculated in section 5.1.2. For the heating capacities of the heat pumps, the data from table 5.2 will be used as input for the optimization model.

COP The COP of the heat pump can be calculated according to the theory presented in subsection 4.2.

Building thermal mass Input for the thermal mass of the chosen building types has been calculated in section 5.1 and for each home type (D1, D2, D3, SD1, SD2, SD3, T1, T2, T3) the thermal mass is displayed in table 5.1.

Building heat transfer Input for the building heat transfer coefficient of the chosen building types has been calculated in section 5.1 and for each home type (D1, D2, D3, SD1, SD2, SD3, T1, T2, T3) the building heat transfer coefficient is displayed in table 5.1.

Energy price The electricity prices series used for this modelling work is based on the Eneco electricity outlook of the scenario "existing policy" in the year 2030.

EMS time-series resolution The energy management system (EMS) time-series resolution describes the update rate of the Asset references in the optimization model (Morstyn et al., 2020). In other words, it describes the rate at which the asset can adapt to changing prices and other energy system conditions. In the case of the heat pump, an EMS resolution of 1 hour has been chosen. This means that the heat pump can change its power output on an hourly basis. The value of 1 hour has been chosen due to two reasons. Firstly, the run time of the model decreases significantly at a higher resolution due to the increase in optimization steps. Secondly, experts have raised concerns about the lifetime of a heat pump when it experiences a significant increase in start-stop cycles. With an EMS time-series resolution of 1 hour, the heat pump can only change its power output on an hourly basis. While it is estimated that this will have a limited impacted on the heat pump lifetime, this modelling choice does impact the type of flexibility the heat pump is able to offer. In the Netherlands, the flexibility required on the balancing market operates within a time frame of 5 minutes. Therefore, this modelling choice means that the demand response potential of heat pumps on the balancing market can not be evaluated. This is not necessarily problematic because the individual power consumed by a heat pump is very low; heat pumps could only play a role in the demand response on the balancing market if they are turned on and off collectively throughout the Netherlands. Within a time frame of 5 minutes, it might be more efficient to turn off an industrial production process that consumes a large amount of electricity such as a steel production site.

The EMS time-resolution of 1 hour is more suitable for evaluating the potential for demand response on the day-ahead power market in the Netherlands. Since these power prices are known a day in advance, heat pumps could provide an hourly demand response to these prices and the flexibility potential could be traded on the intra-day market.

Simulation time-series resolution The resolution of the simulation time-series describes the update rate of the data referenced by the assets and model elements (Morstyn et al., 2020). In other words, it is the resolution of the data which it plugged into the optimization model. Since the electricity price time-series has a time resolution of 15 minutes, a time resolution of 15 minutes was chosen as the value for the simulation time-series resolution. Because the ambient temperature resolution has a resolution of 1 hour, this data set was split into 15-minute intervals in order to comply with the simulation time-series resolution requirement.

Optimization horizon A 24-hour optimization horizon was selected for the optimization model. This means that the BuildingAssets optimize their heat pump over a 24 hour time period and that the optimization is run ahead of the 24 hour time period. The BuidingAssets have full knowledge of the expected electricity price and ambient temperature during this period, which is given in a 15-minute simulation time-series resolution. The heat pumps can respond to the energy system data on an hourly basis, and are optimized over this 24 hour time horizon. The optimization horizon of 24 hours is chosen as the day-ahead electricity prices are only known one day in advance and are updated in 24 hour time increments. Therefore, the heat pump is able to provide a demand response once the day-ahead prices are known and the heat pump can optimise its power consumption based on these values.

6.3. MODEL DYNAMICS

This section discuses the OPEN model optimization dynamics and displays the formalization of the optimization problem regarding the dispatch of the heat pump. First, the thermal dynamics of the building itself are discussed, after which the optimization dynamics are presented.

Thermal dynamics of building The thermal characteristics of the home types are modelled by a first order discrete time temperature model which is included when modelling the asset class BuildingAsset. The model can be represented by means of equation 6.1:

$$\tau_{jt+1} = \frac{\Delta t}{R_j C_j}(\tau^a_{jt} - \tau_{jt}) + \frac{\Delta t}{C_j}(\eta^{he}_j p^{he}_{jt} - \eta^{co}_j p^{co}_{jt}) \tag{6.1}$$

For each building j and time interval t, τ_{jt} is the internal building temperature, τ^a_{jt} is the ambient temperature, p^{he}_{jt} is the forced heating power and p^{co}_{jt} is the forced cooling power. The power values are multiplied by the coefficients of performance: $h^{he}_j$and h^{co}_j are the coefficients of performance for heating and cooling respectively, which are defined as a function of the ambient temperature described in section 6.2. $R_j$and C_j are constants which respectively model the heat transfer and thermal mass of the building. Equation 6.1 allows for the internal thermal dynamics of the building to be modelled (Morstyn et al., 2020, p.9). The constraints under which the model optimizes are defined by the minimum and maximum allowed temperatures.

Optimization Dynamics The objective function of the chosen OPEN model configuration is given in equation 6.2. From subsection 6.2 it was established that the optimization horizon encompasses a 24 hour period, this means that the optimization horizon T can be captured by stating $T = \{1, 2, ..., 24\}$. For time interval tT and interval duration Δt^{ems}, the goal is to minimize the costs associated with the power consumption of the heat pump, defined by import price λ^{imp}_t multiplied by the power consumption of the heat pump p^{imp}_t.

$$\min \sum_{t\in} \Delta t^{ems} (\lambda^{imp}_t p^{imp}_t) \tag{6.2}$$

The first constraint the model must take into account is that the power consumed p^{he}_{jt} by the heat pump installed in building j can not be greater than the total heating capacity of the installed heat pump $p^{he}_{j,max}$. This constraint is represented by equation 6.3. In this configuration, $j = \{T1, T2, T3, SD1, SD2, SD3, D1, D2, D3\}$

$$0 \leq p^{he}_{jt} \leq p^{he}_{j,max} \tag{6.3}$$

Similarly to the constraint related to the heating capacity of the heat pump, the power consumed for cooling purposes p^{co}_{jt} by the heat pump installed in building j can not be greater than the total cooling capacity of the installed heat pump $p^{co}_{j,max}$. This constraint is represented by equation 6.4.

$$0 \leq p^{co}_{jt} \leq p^{co}_{j,max} \tag{6.4}$$

Equation 6.5 is an extension of equation 6.1, the internal temperature of building j at time $t+1$ is calculated by taking the current temperature into account and applying the thermal dynamics equation. This equation is subject to the constraint represented by equation 6.6. For each consumer type c, part of set $c = \{C1, C2, C3, C4, C5, C6\}$, the internal building temperature τ_{jt} can not exceed the acceptable temperature bounds set for each consumer type.

$$\tau_{jt+1} = \tau_{jt} + \frac{\Delta t^{ems}}{R_j C_j}(\tau^a_{jt} - \tau_{jt}) + \frac{\Delta t^{ems}}{C_j}(\eta^{he}_j p^{he}_{jt} - \eta^{co}_j p^{co}_{jt}) \tag{6.5}$$

$$\tau_{ct,min} < \tau_{jt} < \tau_{ct,max} \tag{6.6}$$

6.4. MODEL SET-UP

Appendix D provides an overview of the variable configurations which will be utilized as input for the linear optimization model. In total, 5 consumer types have been identified with respect to thermal comfort bounds and user behavior. In addition, 3 home types have been identified which can respectively be split into three further sub-groups depending on the state of home renovation. For each home, the linear optimization model will be run in combination with the 5 user types, leading to a total of 45 runs. Moreover, in order to determine The linear optimization model will provide output for 1 consumer type living in 1 home type. Therefore, the results must be scaled in ratio to the user type and residential dwelling composition. After this has been completed, the results will be scaled yet again according to the estimated yearly adoption curves generated from the Bass model. Upon completion of this step, an estimate of the total flexibility potential of heat pumps can be made.

6.5. CONCLUDING FINDINGS

This chapter has presented the OPEN model, a mathematical optimization tool which can be utilized in order to determine the demand response potential of heat pumps. The model specifications surrounding the model input have been presented, as well as the inner model dynamics. The chapter has concluded with presenting the model set-up. The model will be run in this set-up and the results will be analysed in the next chapter - chapter 7.

7

MODELLING RESULTS

This chapter has been written with the intention of answering the following sub-question:

How does behavior influence the demand response potential of heat pumps?

The chapter is structured as follows: section 7.1 begins by providing a verifcation and validation of the model itself. Section 7.2 then provides an initial analysis of the raw output derived from the linear optimization model. Subsequently, the data gathered from the individual heat pump output is scaled and manipulated in order to determine the collective flexibility potential in section 7.3. The chapter concluded by providing a synthesis of the effects of consumer behavior on the flexibility provision of heat pumps in section 7.4.

7.1. MODEL VERIFICATION AND VALIDATION

In order to increase confidence in the model output and ensure that policy can be created based on its output, the model developed in this study must be verified and validated. Model verification refers to the process of evaluating if the model functions as intended in the model conceptualization. Model validation concerns itself with evaluating if the results derived from the model are reliable enough to base policy on. The verification is conducted subsection 7.1.1 and the validation is conducted in subsection 7.1.2.

7.1.1. VERIFICATION

Verification of the optimization model is conducted by investigating if the model dynamics function as intended, as well as determining if the model is fit for its intended purpose. The raw source code of the model has been provided in appendix E.

Verification Model Dynamics As part of the model verification, a semi-detached residential dwelling that has undergone a medium renovation (SD2) and the average consumer type (C1) have been selected in order to verify if the model behavior functions as described in section 6.1. House type SD2 was selected as this is a semi-detached home which has undergone one renovation and is a house for which a heat pump installation should be economically feasible. In order to determine if the optimization model functions as intended, the difference is model dynamics between the average consumer type C1 will be evaluated for the reference case - in which the heat pump is not able to provide any flexibility, and for the flexible bounds as indicated by the consumer type, which ranges between 18.6 and 22.1 °C.

Figure 7.1 displays the heat pump electrical power consumption of house consumer type SD2C1 - reference case. The heat pump selected has both a heating and a cooling mechanism. The green line represents the power consumed by the heat pump and the blue line represents the outdoor temperature. It can be observed in the February and December months that when the outdoor temperature decreases the power required by the heat pump increases significantly. This is in line with the COP formula presented in equation 4.2, which states that the heat pump requires more power as the ambient temperature decreases.

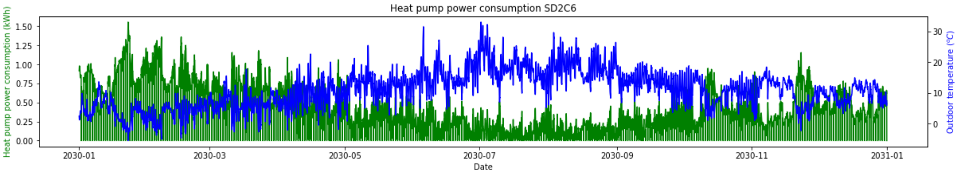


Figure 7.1: Hourly load profile of heat pump in modelled year 2030

Figure 7.2 displays the indoor temperature of the home belonging to consumer type C1 - reference. Throughout the year, it can be observed that a stable indoor temperature of 20.0 degrees centigrade is maintained. This means that the heat pump indeed functions as would be expected in order to heat or cool the home to achieve this steady indoor temperature.

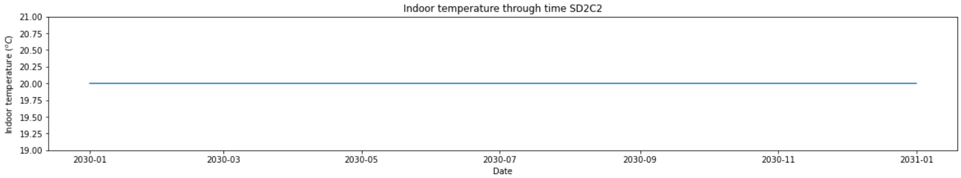


Figure 7.2: Indoor temperature of consumer type C6 in home SD2

Now that is has been confirmed that the model functions as would be expected without implementing any flexible dispatch, it must be assessed if the heat pump is able to respond to flexibility correctly. Figure 7.3 plots the power consumption of the heat pump against the electricity prices during a week in February. It can indeed be observed that the heat pump consumes additional power when the electricity price is low, and turns off when the electricity price is high. This is in line with expectations, and therefore it can be concluded that the flexible dispatch of the heat pump within the model functions correctly.

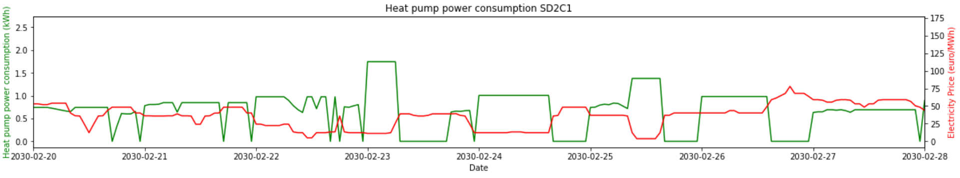


Figure 7.3: Heat pump power consumption profile of consumer type C1 plotted against electricity prices

Finally, it can be observed that the indoor temperature is indeed variable when flexible upper and lower bounds are instated. Figure 7.4 displays the indoor temperature through time for consumer type C1 in residential dwelling type SD2. It can be observed that the indoor temperature is variable through time - in line with expectations. During the winter time the indoor temperature is a little on the cooler side, this is likely because it is more economical to use as little power as possible when the power price is high. Therefore, while the indoor temperature varies as expected, it must be taken into account that consumers will experience a slightly cooler home when participating in a demand response scheme.

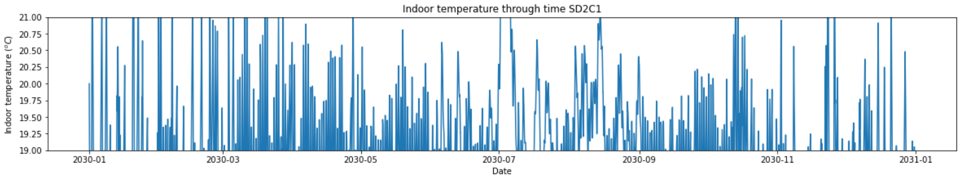


Figure 7.4: Indoor temperature of consumer type C1 in home SD2

Verification Model Purpose Another important aspect of model verification is assessing if the model developed is fit for its intended purpose. Therefore, it must be verified if the linear optimization model can be used in order to assess the flexibility potential of heat pumps. Moreover, the model has to incorporate the behavioral factors in order to explore the effect of behavior on the total flexibility output. Ultimately, this insight is intended to lead to an advice on which behavior to target in order to materialise the demand response potential from heat pumps.

The linear optimization model has been developed with the purpose in mind of determining the flexibility potential per consumer type. Because each consumer type has a different indoor temperature range, the power consumed by the heat pump will depend on the bounds of this range. For example, when assessing the flexibility potential of consumer type C5 (who has a lower temperature bound of 16.7 degrees centigrade), this consumer can not be compared to a consumer who wishes to maintain a constant indoor temperature of 21 degrees centigrade. In order to make a fair comparison, the results from the survey have been used to identify consumer type pairs. For every consumer type identified from the survey, a reference consumer type has been created who wishes to maintain their home at a steady indoor temperature equal to the value at which they heat their homes at on average. This way, the total flexibility potential can be determined by comparing each consumer type to their own reference type. Moreover, the upward flexibility and downward flexibility potential can also be calculated. Therefore, it can be concluded that the flexibility potential of the consumer types can be calculated by making use of the model and that the model is fit for its intended purpose in this regard.

7.1.2. VALIDATION

Ensuring that the output generated by the model matches real-world observations is a crucial element in the validation of the linear optimization model. When assessing the model's validity, it is important to consider factors such as the order of magnitude of the numerical output as well as assessing the internal variation between the generated results. The validity of the model is assessed on the following points: total power consumed by the heat pumps according to the model, variation within insulation types and the order of magnitude of the average flexibility provision.

Total Power Consumed by Heat Pumps The first check that can be carried out in order to assess the model's validity is the total power consumption of the heat pumps installed in the different home types. The model optimizes a a year by carrying out the computations in 24-hour consecutive time periods. If the power consumed during these 24-hour time periods is summed, the total power consumption of the heat pump over the full year is obtained. Validating whether the total power consumption of the heat pumps approaches real-world values would mean that this 24-hour period optimization adequately predicts heat pump power consumption. According to Vattenfall (2021), the a heat pump which is installed in a well-insulated home consumes on average 4000 kWh of power a year. For a heat pump with a slightly better COP, this number is estimated to be around 3000 kWh of power a year (Nibe, 2021).It will be assumed that the well-insulated home mentioned in the sources above match the type 2 homes which have undergone one renovation. Therefore, the expectation is that for these homes the annual power consumption by the heat pumps will range between 3000-4000 kWh. Figure 7.5 displays the yearly power consumption of the heat pump installed in homes with insulation level 2. The red lines depict the averages mentioned in the sources of Vattenfall (2021) and Nibe (2021). On the basis of the graph, it can be concluded that the total power consumption of the heat pumps indeed fall within the ranges derived from the sources above. In addition, it can be observed that the heat pumps installed in detached homes on average consume more electrical power than heat pumps installed in semi-detached or terraced homes. This too is in line with expectations. The final observation which can be made on the basis of the graph is that the difference in heat pump power consumption between the semi-detached and terraced homes is very small. In reality you would perhaps expect this gap to be slightly bigger, however in general it can be concluded that the total power consumption of the heat pumps derived from the model matches real-world values quite closely.

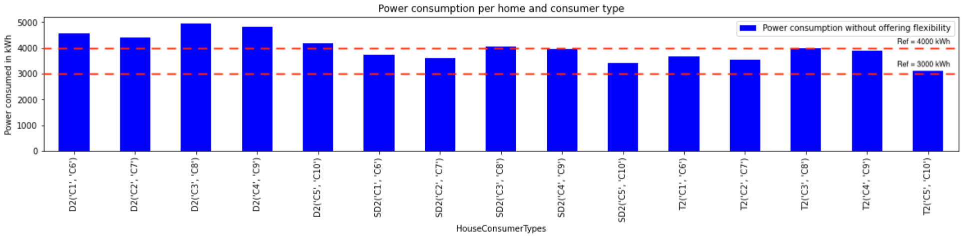


Figure 7.5: Yearly power consumption of heat pumps with no flexibility offered

Variation Within Insulation Level A second check which can increase the model's validity is establishing if the total heat pump power consumption of the homes differs depending on the degree of insulation. According to the data from the TABULA project, homes annotated with a 1 have not undergone any renovation. Homes marked with a 2 have undergone one renovation, and homes with a 3 have undergone two renovations. With regards to energy saving measures such as insulation, the expectation would be that the savings in total energy usage are larger when comparing home types 1 and 2 than when comparing home types 2 and 3. Figure 7.6 displays the annual power consumption of heat pumps installed in home types SD1,SD2 and SD3 for the different consumer types without offering any flexibility. The graph indeed confirms that the heat pump power consumption significantly declines when the home has undergone one renovation. A semi-detached home which has not undergone any renovation is expected to consume more than 6000kWh of electricity annually when installing a heat pump. This is in line with data derived from Regionaal Energieloket (2021), who recommend such a home to be fitted with improved insulation first before installing the heat pump. The results derived from the model support this recommendation, and as such it can be concluded that the different levels of home insulation indeed reflect real-world values.

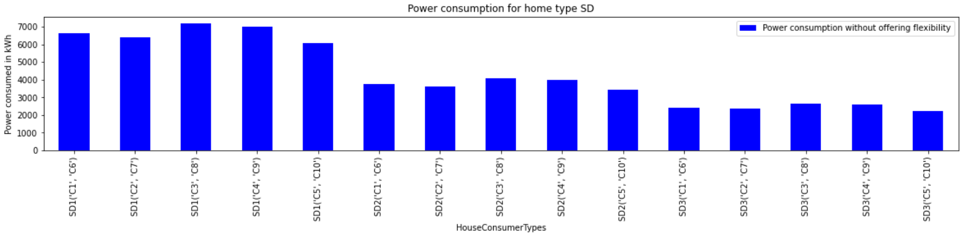
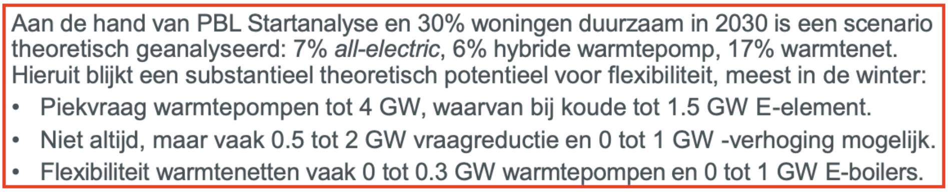


Figure 7.6: Yearly power consumption of heat pumps with no flexibility offered

Order of Magnitude Average Flexibility Provision The final check which has been conducted in order to increase the confidence in the model is to verify if the order of magnitude of the average flexibility provision as presented in figures 7.12 and 7.13 provides an appropriate estimate of the flexibility provided by heat pumps. Figure 7.7 below presents the conclusion reached regarding the flexibility potential of heat pumps by TenneT (2020). The first observation which can be made is that the order of magnitude - GW, is indeed in line with the results generated in this study. The study by TenneT (2020) assumes a market penetration of 13% of heat pumps in 2030, however this market penetration level is calculated by also taking into account homes which are eligible for a connection to the district heating network. Since the market penetration level in this study is defined as a ratio of homes with a heat pump installed compared to the total share of homes eligible for a heat pump, the market share of 13% derived in the TenneT study corresponds to a market penetration of 26% in this study under the assumption that approximately half of all residential dwellings are eligible for a heat pump.

In figures 7.12 and 7.13, the trajectories which assume a total market penetration of heat pumps in 50% in 2050 of all eligible homes most closely matches the assumptions made by the TenneT (2020) study, although the assumed market penetration of heat pumps is slightly higher than assumed in the TenneT (2020) study. In 2030, the average upward flexibility provision ranges between approximately 1.3 GW and 2.5 GW, while the average downward flexibility ranges between 1.3 GW and 3 GW depending on the degree of market penetration and home insulation level. In figure 7.7 below, it is concluded that the average flexibility provision from upward regulation ranges between 0 and 1 GW, whereas the average flexibility provision from downward regulation ranges between 0.5 and 2 GW. This means that the TenneT study is slightly more conservative than the results generated from this study. However, considering this study assumes a higher level of market penetration, the order of magnitude is matched and the aim of this study is to understand how behavior can affect the total demand response potential of heat pumps, the flexibility results are deemed appropriate valid as to serve as a support for creating policy.



Aan de hand van PBL Startanalyse en 30% woningen duurzaam in 2030 is een scenario theoretisch geanalyseerd: 7% *all-electric*, 6% hybride warmtepomp, 17% warmtenet. Hieruit blijkt een substantieel theoretisch potentieel voor flexibiliteit, meest in de winter:

- Piekvraag warmtepompen tot 4 GW, waarvan bij koude tot 1.5 GW E-element.
- Niet altijd, maar vaak 0.5 tot 2 GW vraagreductie en 0 tot 1 GW -verhoging mogelijk.
- Flexibiliteit warmtenetten vaak 0 tot 0.3 GW warmtepompen en 0 tot 1 GW E-boilers.

Figure 7.7: Conclusion flexibility report by TenneT (2020)

7.2. FLEXIBILITY RESULTS LINEAR OPTIMIZATION MODEL

7.2.1. FLEXIBILITY CALCULATION METHOD

Output from the linear optimization model includes the power usage of the heat pump at each time step, as well as the indoor temperature of the home at each time step. In chapter **??** several consumer types were defined with respect to flexible indoor preferences. In order to calculate the flexible power which each consumer type can provide, the model was run twice per consumer type: with and without flexibility. In the runs with flexibility, the temperature bounds as defined in table **??** were used as input. In the runs without flexibility, the average indoor temperature as derived from the survey was considered as both the lower and upper acceptable bound with respect to indoor temperature. This enables a fair comparison to be made for each consumer type. Table 7.1 provides an overview of the temperature bounds used for each flexible consumer type, as well as the static reference consumer type.

Table 7.1: Temperature bounds per consumer type, flexibility vs. reference

Group	**Maximum Temperature**	**Minimum Temperature**	**Average Temperature (indicated by survey)**	**Maximum Temperature Reference**	**Minimum Temperature Reference**
C1 - Average	22.1	18.6	20.0	20.0	20.0
C2 - Conservers	20.6	18.7	19.6	19.6	19.6
C3 - Spenders	22.2	20.4	21.0	21.0	21.0
C4 - Warm Dwellers	24.2	18.4	20.7	20.7	20.7
C5 - Cool Dwellers	21.1	16.3	19.0	19.0	19.0

7.2.2. CALCULATION OF FLEXIBILITY

Equation 7.1 displays how the initial flexibility for each home type j and consumer type c is calculated. $P_{c0,j}$ refers to the electrical power consumed by the heat pump in building j by each consumer type $c0$ that has been assigned flexible temperature bounds. $P_{c1,j}$ refers to to the electrical power consumer by the heat pump in building j by the corresponding consumer type who has been assigned a single indoor temperature. The difference in electrical power consumer can then be considered to be the flexibility potential.

$$P_{flex,j,c} = P_{c0,j} - P_{c1,j} \tag{7.1}$$

Figure 7.8 displays equation 7.1 in practice: for each time step the delta power consumption of the flexible heat pump versus the static heat pump has been calculated and plotted across all runs. Based upon this figure, the following observations have been made:

- The graph density is especially high between a power delta of 0.5 and -0.5 kW. This can be attributed due to the fact that for the reference consumer types, the average temperature the consumers themselves indicated by means of the survey was considered instead of taking the average of the derived minimum and maximum temperature bounds. While these values lie close to one another, they are not the same. For most consumer types, this means that the average temperature inside the home is slightly cooler when offering flexibility and that the heat pump will have to produce slightly less power regardless. This modelling choice has been made in order to calculate the true flexibility of each consumer type compared to their own reference, however noise in the data is created as a result. Therefore, only delta values exceeding 0.5kW and -0.5kW have been considered as offering true flexibility. The total flexibility offered is sensitive to the chosen parameters, and will be discussed in the discussion.

- All values exceeding 0.5 kW are considered to be flexibility in the form of *upward regulation*. This means that because the heat pump is expecting an increase in prices, it will consume extra power compared to the static heat pump.
- All values exceeding -0.5 kW are considered to be flexibility in the form of *downward regulation*. Because of an increase in power prices, the heat pump lowers its power consumption or turns off completely depending on the leeway the heat pump has with respect to meeting the minimum bounds of the indoor temperature.

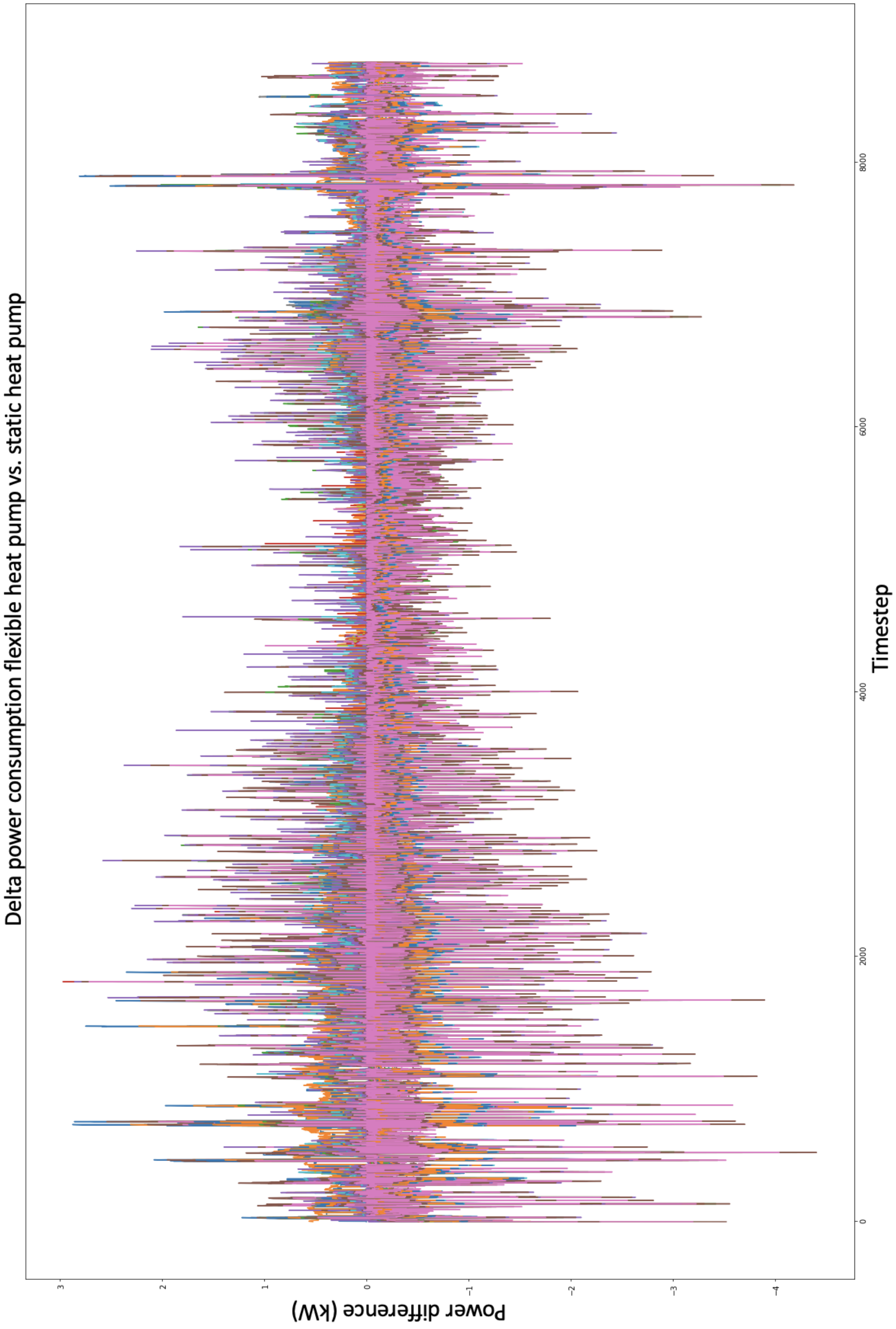


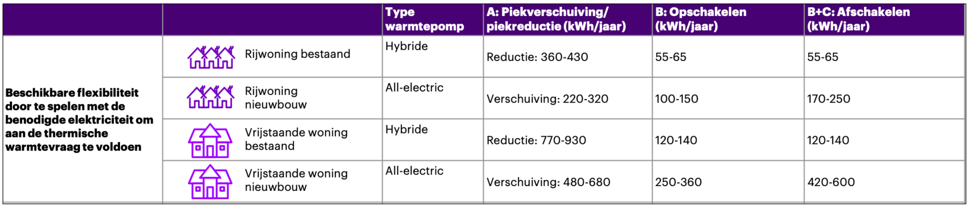
Figure 7.8: Differential between reference consumer user type and flexible consumer user type for all runs

7.2.3. SUM OF TOTAL FLEXIBILITY

From the hourly flexibility differential derived from figure 7.8, it can be calculated what the sum of total flexibility offered is. Figure 7.10 displays the total flexibility offered for each house and consumer type combination as a measure of upward and downward regulation. Based upon this figure, the following observations can be made:

- The total flexibility potential of the heat pump decreases significantly when the level of insulation increases. Homes indicated with 1 are considered to have poor insulated, homes indicated with 2 are considered to have medium insulation and homes indicated with 3 are considered to be well-insulated. Sharp declines in both upward and downward regulation can be observed when the level of insulation of the home increases. This can largely be attributed due to the fact that the maximum installed heating capacity of heat pumps in poorly insulated homes is much higher. In practice, not many heat pumps will be installed in poorly insulated homes without also taking insulation measures due to the high electricity bill home owners will face.

- For all house and consumer type combinations, the total flexibility potential of downward regulation is higher than the total flexibility potential of upward regulation. This is consistent with an analysis conducted by Accenture (2021), which found that the potential for downward regulation is higher than upward regulation. The results from the analysis conducted by Accenture (2021) are displayed in figure 7.9, It can also be observed that the values derived from the model results match quite closely with the values displayed in figure 7.9. This confirms that considering flexibility only above bounds of 0.5 and -0.5 kW is an adequate approach with regards to determining the true flexibility offered.



		Type warmtepomp	A: Piekverschuiving/ piekreductie (kWh/jaar)	B: Opschakelen (kWh/jaar)	B+C: Afschakelen (kWh/jaar)
Beschikbare flexibiliteit door te spelen met de benodigde elektriciteit om aan de thermische warmtevraag te voldoen	Rijwoning bestaand	Hybride	Reductie: 360-430	55-65	55-65
	Rijwoning nieuwbouw	All-electric	Verschuiving: 220-320	100-150	170-250
	Vrijstaande woning bestaand	Hybride	Reductie: 770-930	120-140	120-140
	Vrijstaande woning nieuwbouw	All-electric	Verschuiving: 480-680	250-360	420-600

Figure 7.9: Yearly flexibility offered according to Accenture (2021)

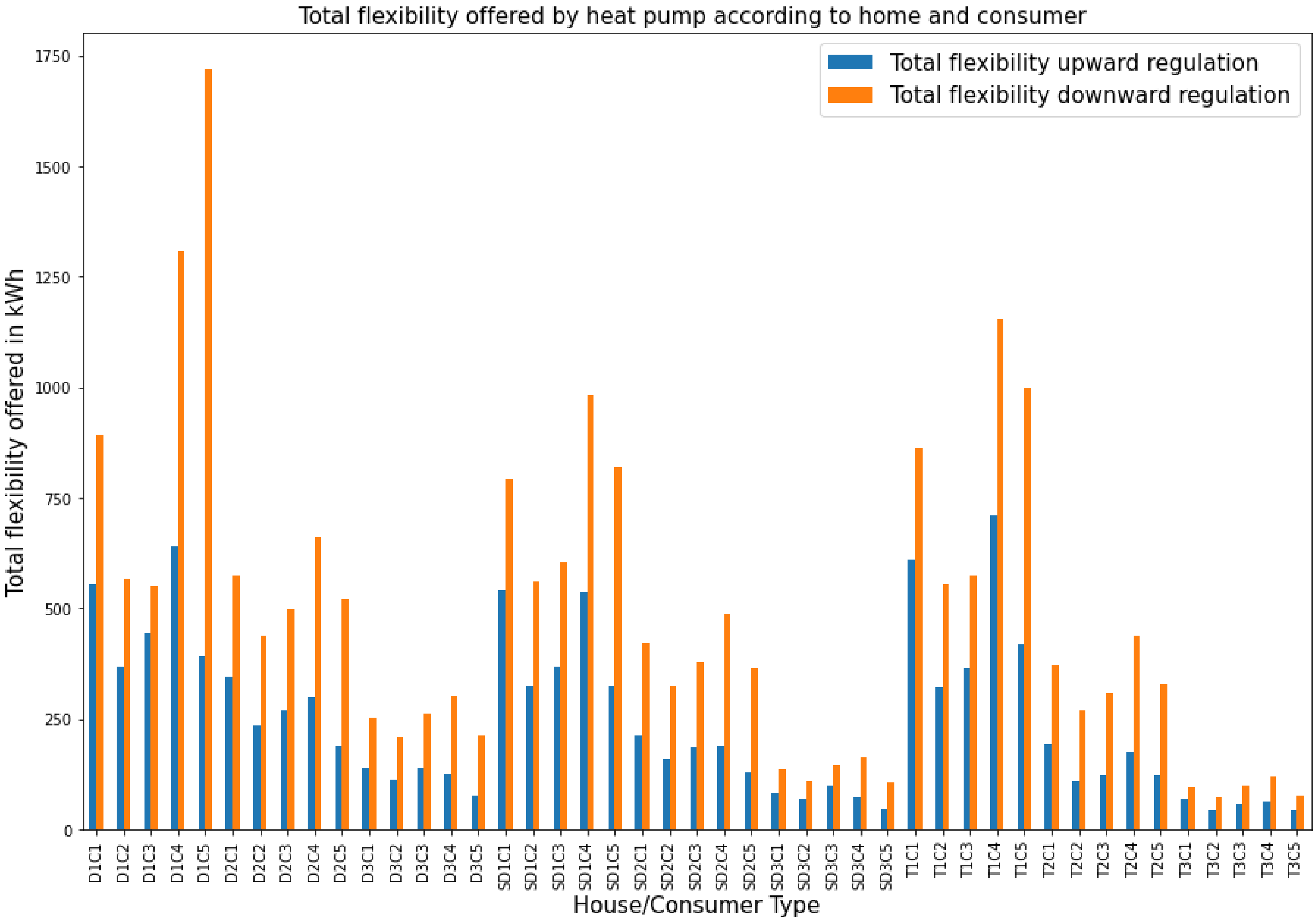


Figure 7.10: Sum of average flexibility offered by each house/consumer type combination

7.2.4. AVERAGE PROVISION OF FLEXIBILITY

While the sum of flexibility provided is an important figure with respect to estimating the demand response potential of heat pumps, the average flexibility in kW that can be provided per demand response event perhaps provides a better measure of flexibility. This is because, when there is a need for a demand response event, it is useful for the TSO and DSO to know just how much heat pumps can contribute to maintaining a balance on the electricity grid. Figure 7.11 displays the average flexibility the modelled heat pumps can offer per demand response event. Based upon this figure, the following observations can be made:

- Interestingly, while the sum of upward regulation is lower than the sum of downward regulation, the average power consumed during an upward regulation event is in some cases higher than the flexibility offered during a downward regulation event. This is especially true for homes with a high degree of insulation.
- Unlike the total sum of flexibility offered over a year, the range of average flexibility offered by heat pumps in the house/consumer configurations is relatively small and more dependent on consumer user type than residential dwelling type. This means that if the average flexibility provision of heat pumps has a priority over the total sum of flexibility provided by DSOs, consumer user type could become a potential target when looking to materialize the demand response potential from heat pumps.

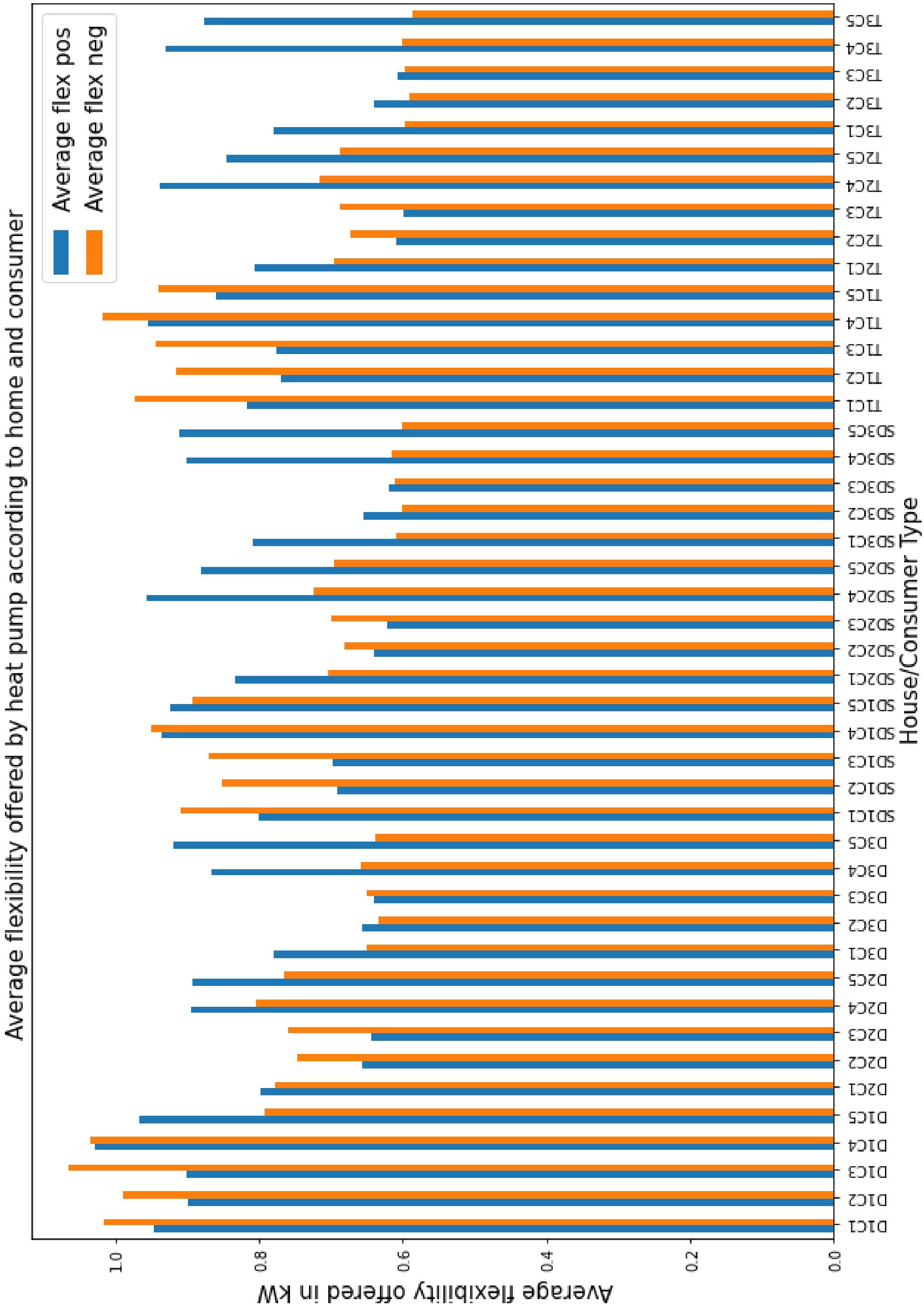


Figure 7.11: Average flexibility offered by each house/consumer type combination

7.3. SCALING OF FLEXIBILITY

Now that the average flexibility potential per home and consumer type has been calculated, the ratio of home types and consumer types can be used in order to compute the collective flexibility potential of heat pumps per demand response event. The ratio of home and consumer types used is derived respectively from tables 5.10 and 5.11. Using these tables, an average flexibility value has been computed per insulation type. These average flexibility values have been multiplied with the Bass adoption curves developed in chapter 5. Figure 7.12 displays the average upward flexibility offered by heat pumps according to the different levels of market penetration and the insulation level of the home. In order to determine the influence of insulation level on the flexibility provision, the flexibility potential of each trajectory assumes that all residential dwellings in the Netherlands are of that insulation type. In reality, the insulation levels of homes will be a mix between poor insulation, medium insulation and good insulation. Based upon the figure, the following observations can be made:

- The level of market penetration is the most important factor for determining the total average upward flexibility potential. The potential is highest for homes with poor insulation and a 100% market penetration, followed by homes with medium and good insulation at 100% market penetration.
- It makes no difference if the home has medium insulation or good insulation. The total average upward flexibility potential offered by heat pumps in houses with these insulation levels is the same and determined by the total level of market penetration.
- From the year 2025 onward, large differences in the collective upward flexibility offered by heat pumps can be observed, indicated by the gap between trajectories moving further away from one another. This means that no matter the level of insulation by the homes, market penetration is a very important factor determining the flexibility potential of heat pumps during a demand response event. Since the trajectories lie closely together until the year 2025, it will be difficult for policy makers to assess if heat pump adoption is following the desired trajectory until this year.

Figure 7.13 displays the average downward flexibility offered by heat pumps according to the different levels of market penetration and the insulation level of the home. Based upon the figure, the following observations can be made:

- Just as with the case for upward regulation, the level of market penetration is the most important factor for determining the total average downward flexibility potential. While the potential is still the highest for homes with poor insulation and a 100% market penetration, the average downward flexibility potential is similar for poorly insulated homes with 75% market penetration and medium-insulated homes with 100% market penetration.
- The total average downward regulation of well-insulated homes is lower than medium-insulated homes, yet once again it can be established that the level of market pen-

etration has a larger influence on the total average downward flexibility that can be offered.

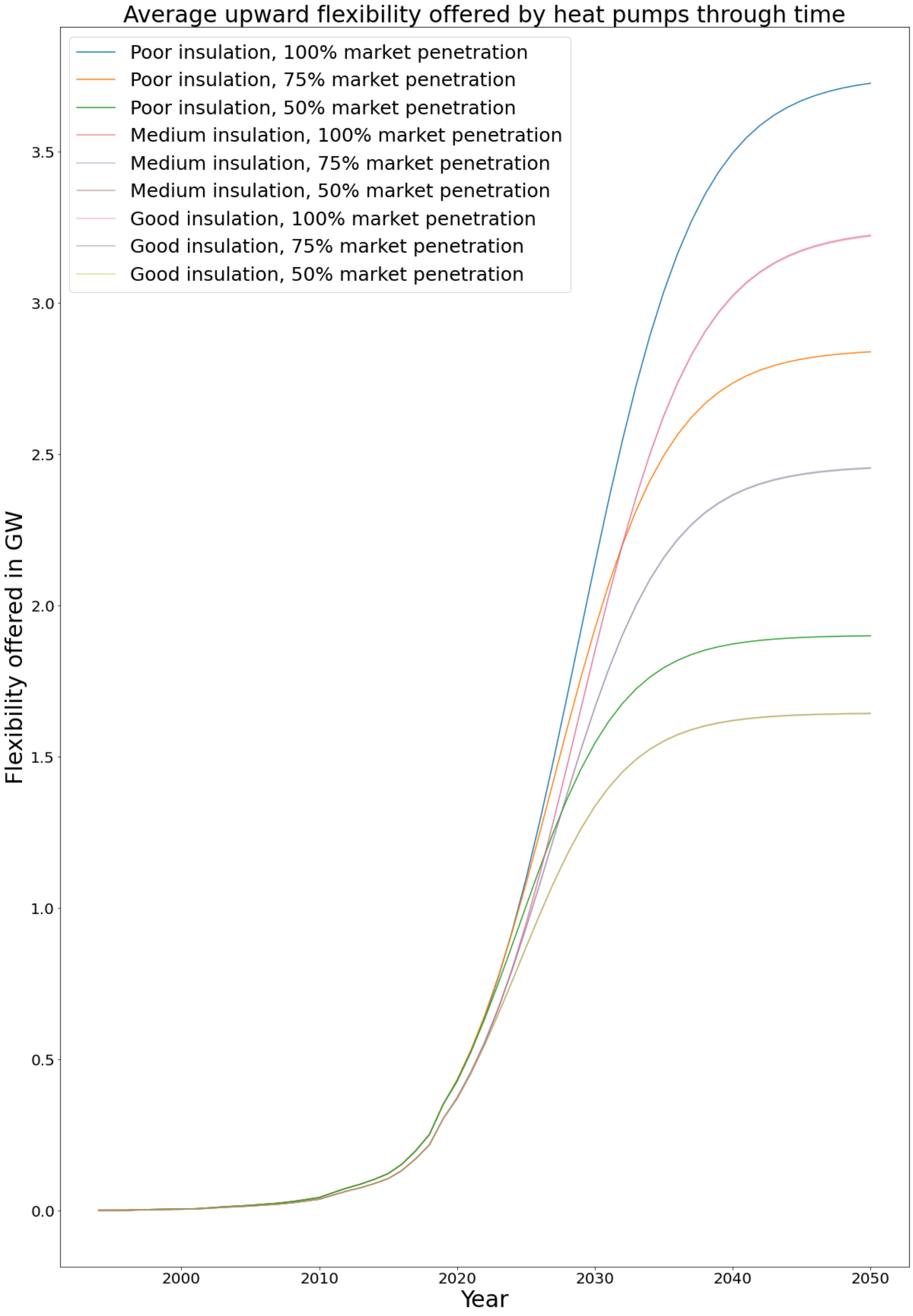


Figure 7.12: Flexibility potential according to insulation level, upward regulation

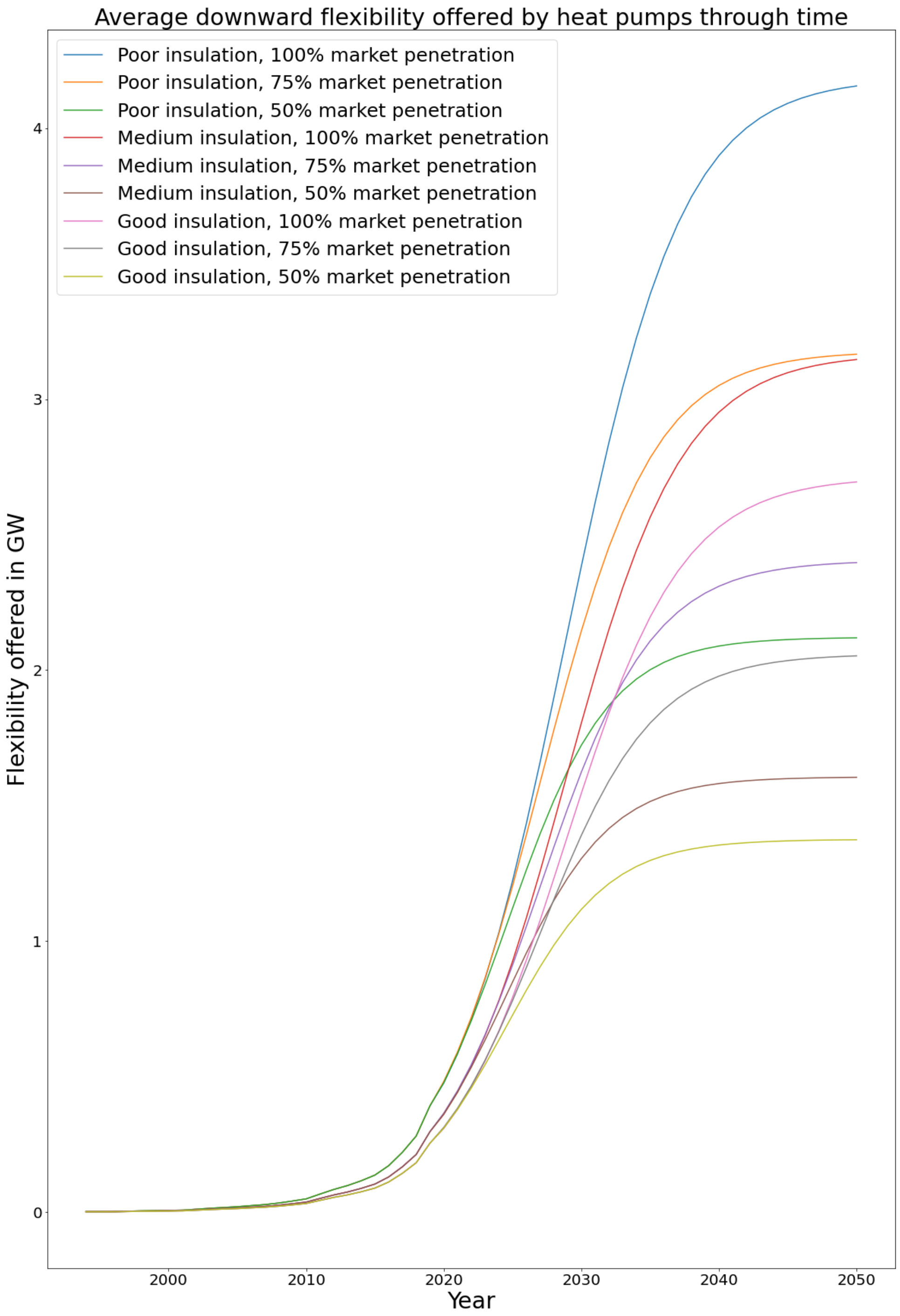


Figure 7.13: Flexibility potential according to insulation level, downward regulation

7.4. EFFECT OF USER BEHAVIOR

It has been established that consumer adoption behavior, especially regarding the total market penetration of heat pumps, is a very important factor affecting the total flexibility potential that heat pumps are able to offer. However, in chapter 5.2 it is hypothesized that user behavior also significantly affects the total flexibility potential of heat pumps. This section will explore how much altering user behavior can affect the flexibility potential of heat pumps. To achieve this, the different user profiles have been ranked based on the average flexibility potential that they are able to offer. For each type of residential dwelling, it has been determined how much more average flexibility potential can be gained by switching to a different user profile. The results are displayed in tables 7.2, 7.3 and 7.4.

Table 7.2: Detached home: effect user behavior

	Additional upward flexibility potential	**Additional downward flexibility potential**
C1 (Average)	1.2	1.1
C2 (Conservers)	1.0	1.1
C3 (Spenders)	1.0	1.1
C4 (Warm Dwellers)	1.3	1.1
C5 (Cool Dwellers)	1.3	1.0

Table 7.3: Semi-detached home: effect user behavior

	Additional upward flexibility potential	**Additional downward flexibility potential**
C1 (Average)	1.0	1.0
C2 (Conservers)	1.0	1.0
C3 (Spenders)	1.4	1.1
C4 (Warm Dwellers)	1.4	1.0
C5 (Cool Dwellers)	1.2	1.0

Table 7.4: Terraced home: effect user behavior

	Additional upward flexibility potential	**Additional downward flexibility potential**
C1 (Average)	1.2	1.0
C2 (Conservers)	1.0	1.0
C3 (Spenders)	1.0	1.0
C4 (Warm Dwellers)	1.4	1.1
C5 (Cool Dwellers)	1.3	1.0

In order to explore the effect of user behavior in contrast to to adoption behavior, the influence of user behavior versus adoption behavior has been plotted in graphs 7.14 and 7.15, plotting the average upward and downward flexibility for homes which have undergone one renovation. For each adoption curve, a band with has been created demonstrating how much the flexibility potential changes when users switch to a different type of user behavior using the data represented in tables 7.2. 7.3 and 7.4. Based upon the the figures, the following conclusions can be drawn:

- In the case of upward flexibility provision, the flexibility which can be offered by heat pumps depends both on the market penetration of the heat pumps and on the type of user behavior. This becomes particularly evident from the year 2040 onward, where it can be observed that user behavior can influence the average flexibility offered by around +1 GW or -0.5 GW. This maximum is reached when consumers maintain a C4 - warm dweller profile. It is not surprising that the warm dweller profile offers the most upward flexibility potential: since consumers are willing to accept a high indoor temperature, the heat pump is able to ramp up considerably when electricity is cheap.

- In the case of downward flexibility provision, the flexibility which can be offered by heat pumps is even more dependent on the market penetration of heat pumps. Even in 2050, the differences in average downward flexibility offered are very small, approximately +0.1 GW or -0.1 GW of average downward flexibility offered can change depending on the user profile. While this initially may seem surprising, especially in contrast to the average upward flexibility offered, there does exist an explanation: the graph considers average downward flexibility offered and not the total yearly flexibility that can be offered. When a home receives better insulation (as is the case with the homes displayed in the graph of type 2), the installed heat pump capacity becomes smaller. Therefore, the differences offered in average flexibility offered amongst user types does not vary as much.
- However, when looking at the yearly flexibility heat pumps are able to offer, significant differences can be observed between the consumer types. This phenomenon is visible in figure 7.10. Consumer types C1 (average), C4 (warm dwellers) and C5 (cool dwellers) offer more downward flexibility over a year than consumer types C2 (conservers) and C3 (spenders). An explanation for this is that for the aforementioned group, the acceptable temperature range is significantly larger than for the latter mentioned group. This means that the heat pump can turn off for longer periods of time, providing more cumulative downward flexibility over a year.
- Therefore, while the effects of user behavior on the average flexibility provided are relatively small, the effects of user behavior on the total flexibility provided through a year are of interest to a DSO, TSO or energy utility should heat pumps undergo a widespread adoption. On this regard, the flexibility potential per user group is determined by the temperature range the user group is willing to accept, the larger the range, the more potential for flexibility there will be.

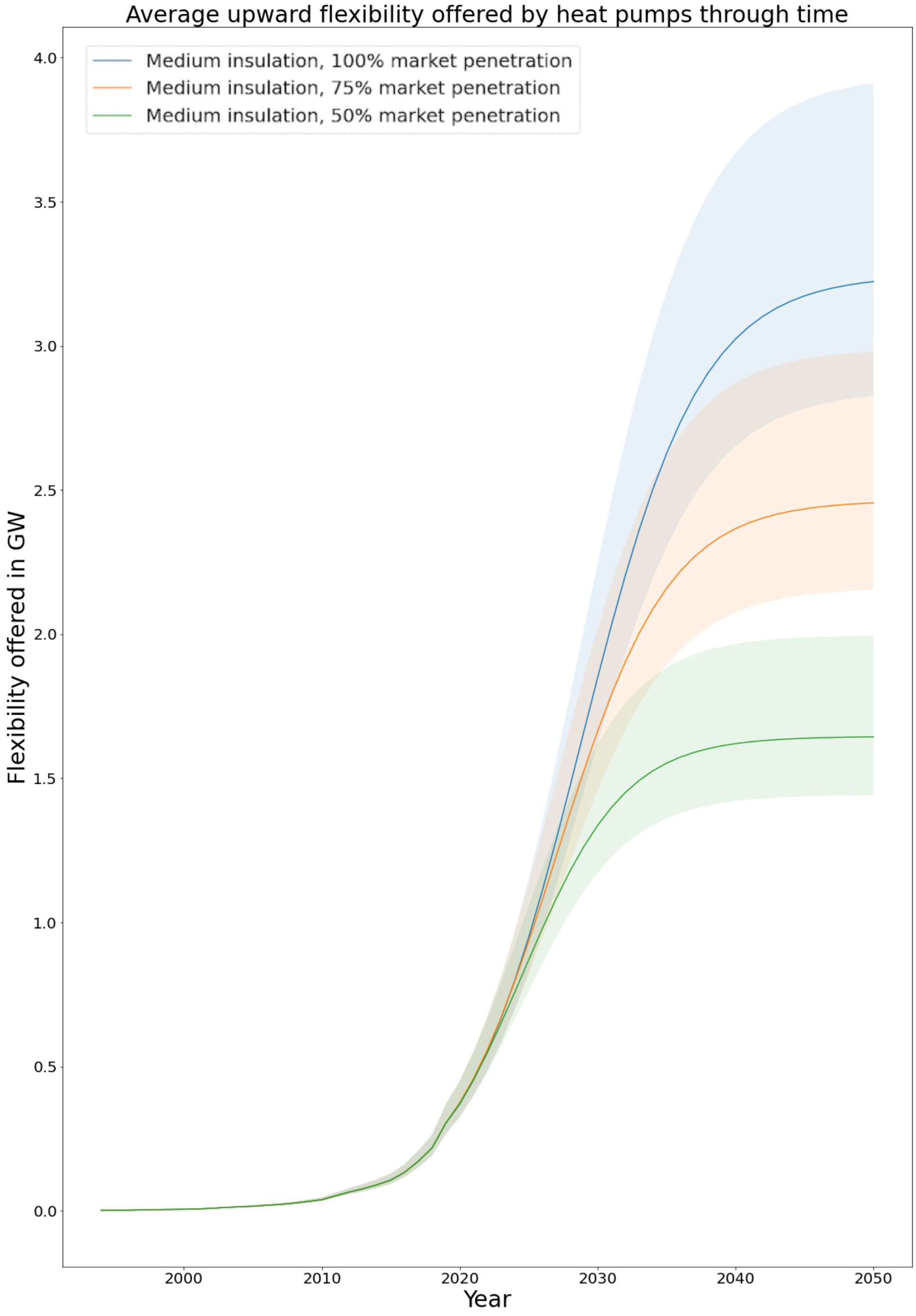


Figure 7.14: Effect adoption versus user behavior, upward regulation

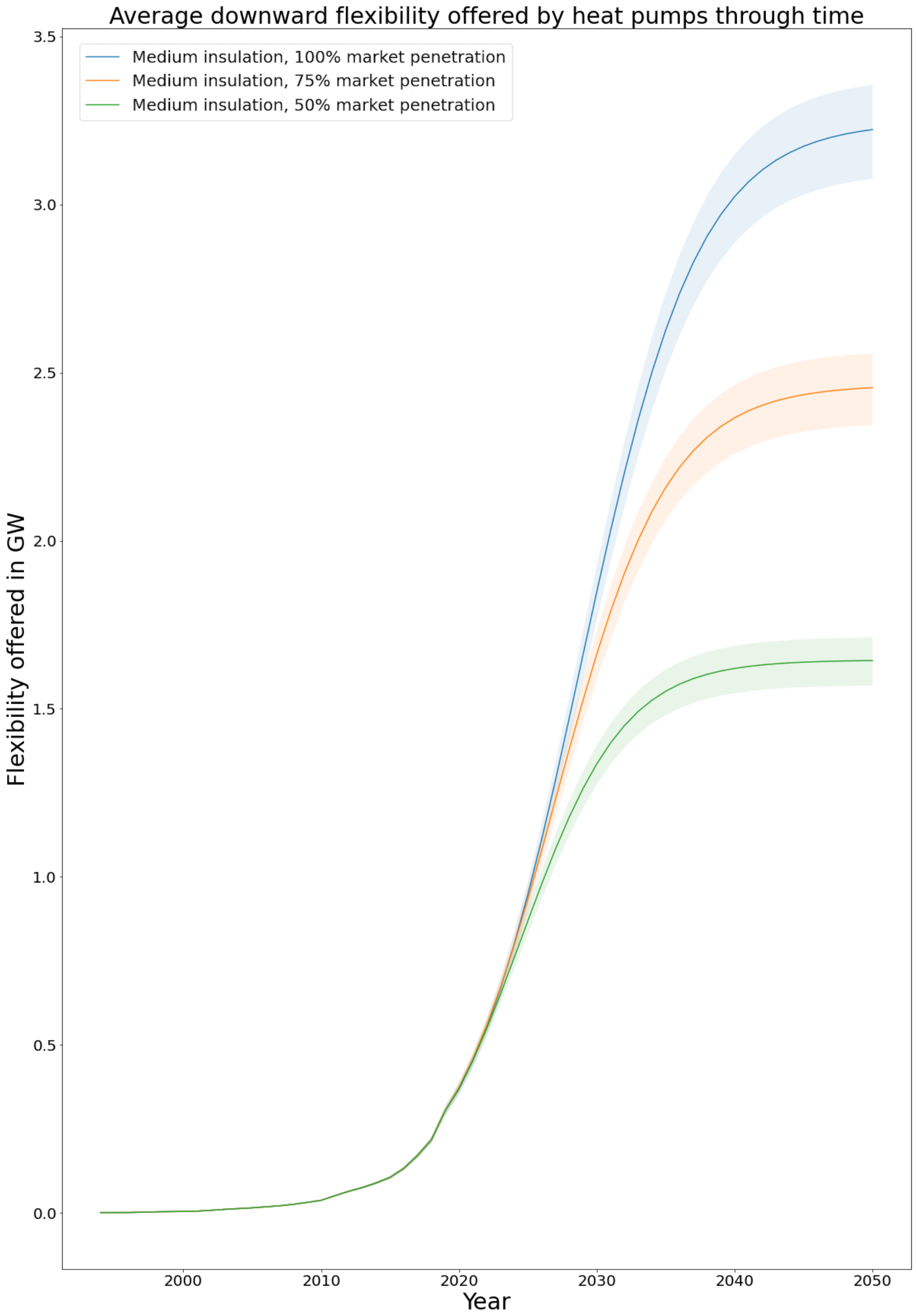


Figure 7.15: Effect adoption versus user behavior, downward regulation

7.5. POLICY CONSEQUENCES

First and foremost, it has been established that under the assumption that the technical architecture supporting the flexibility provision by heat pumps is realized, the model results indicate that additional gains in flexibility amounting to 1.6 GW can be realized by targeting consumer adoption behavior. Therefore, in order to materialize the demand response potential from heat pumps, policy should aim to maximize the consumer uptake of heat pumps as much as possible.

Table 7.5 provides an overview of the scenarios which have been run with respect to the final market penetration achieved by heat pumps. In addition, table 7.6 displays the share of consumers deemed to belong to each of the distrusting, convenient and proactive consumer types. Since this study has estimated the convenient consumer type to make up 63% of the population, this group should be the primary target when aiming to materialize the demand response potential of heat pumps.

Table 7.5: Overview of Market Penetration Scenarios

	Adoption grade distrusting consumer	**Adoption grade convenient consumer**	**Adoption grade proactive consumer**	**Estimation of total number of heat pumps**
100 Percent Market Penetration	100	100	100	4440000
75 Percent Market Penetration	50	75	100	3340000
50 Percent Market Penetration	25	50	75	2230000
Houses Eligible for Heat Pump	940000	2520000	980000	

Table 7.6: Share of Consumer Types

	Distrusting Consumer	**Convenient Consumer**	**Proactive Consumer**
Share	13%	63%	24%

Based on the findings of this research, it is recommended that for policy to be effective, behavioral factors characteristics for the convenient consumer group such as inertia, the availability bias, ignorance and satisficing behavior should be targeted. As such, policy should primarily focus on decreasing the ’hassle’ factor by lowering the threshold to install a heat pump as much as possible.

While the gains in the flexibility potential of heat pumps will not be as large compared to the convenient consumer, targeting the distrusting consumer group is necessary in order to reach the 100% heat pump market penetration desired by the Dutch government by 2050. Therefore, policy makers are also encouraged to target behavioral factors such as trust, the availability bias and loss aversion when developing policy aimed at increasing the adoption of heat pumps by the distrusting consumer.

Furthermore, from the model results, it can be concluded that user behavior has a lesser effect on the demand response potential of heat pumps than consumer adoption behavior. However, this does not mean that policy should forego targeting user behavior altogether. The results from the model indicate that altered user behavior could increase the demand response potential of heat pumps by 21% in case of upward flexibility regulation, and by 5% in case of downward flexibility regulation. Moreover, unregulated user behavior could lead to a a decrease in demand response potential of heat pumps by 12% in the case of upward flexibility regulation and by 5% in the case of downward flexibility regulation. This means that policy targeting user behavior could be developed in order to materialize an increase in the flexibility provision in the form of upward regulation, however the gains from developing policy to increase the flexibility provision in the form of downward regulation are limited.

When aiming to materialize the demand response potential of heat pumps from user behavior, it can be concluded that it is not necessarily the behavioral traits of the identified consumer user types (Average, Conservers, Spenders, Warm Dwellers, Cool Dwellers) affecting the flexibility potential of heat pumps, but rather the temperature range at which the consumer feels comfortable inside their home. Increasing this range will not have a significant effect on the average flexibility provided by heat pumps, but it will affect the total demand response potential which can be offered by heat pumps over the course of a year.

Three behavioral effects have been identified relating to consumer behavior: adaptive thermal comfort, the endowment effect and the rebound effort. In order to materialize the total yearly demand response potential of heat pumps, policy is recommended which aims to increase the acceptable indoor temperature range of a consumer as much as possible.

7.6. CONCLUDING FINDINGS

Verification and validation of the model conclude that is enough confidence in the obtained results to provide this policy advice. The analysed results derived from the optimization model indicate the flexibility potential of heat pumps to be strongly influenced by the degree of home insulation and the degree of obtained market penetration. In homes with poor insulation, the capacity of the installed heat pump is often larger, enabling a higher demand response potential. However, for these homes, the utility bill will also be much higher due to an increased consumption of electricity. Because it is unlikely that the financial gain from providing flexibility will outperform the financial gain from increasing the insulation level of the home, the degree of market penetration by heat pumps is considered the primary target when aiming to materialize the demand response potential of heat pumps. Perhaps not all that surprising, flexibility gains of up to 1.6 GW can be achieved by increasing the market penetration level from 50% total market penetration in 2050 to 100% total market penetration in 2050.

The results indicate that the effect of user behavior on the average flexibility provision of heat pumps is limited. This means that at an individual level, users have little influence on the average demand response potential of heat pumps. Only for the average, warm dweller and cool dweller consumer groups, the results from the model indicate that altering the indoor heating patterns to match these user groups could increase the average upward flexibility regulation of heat pumps with about 21%. With respect to providing an average downward flexibility regulation, the effects of user behavior are negligible.

An interesting finding is that user behavior does influence the total flexibility which can be provided by heat pumps over a year due to the frequency at which a demand response event can be provided. This means that the total yearly flexibility provision can be influenced by individual user behavior. The total flexibility offered is the largest for the warm dwelling consumer types, followed by the cool dweller groups, average, conservers and finally spenders. When evaluating the user types based on the provided range of minimum and maximum temperature preferences within the home, this order of flexibility provision corresponds directly to the size of the range provided. Table 7.7 displays the acceptable temperature range assumed for each user group.

Table 7.7: Range of acceptable temperature bounds by consumer user type

Consumer Type	Temperature Range in °C
C4 - Warm Dwellers	5.8
C5 - Cool Dwellers	4.8
C1 - Average	3.5
C2 - Conservers	1.9
C3 - Spenders	1.8

In section 5.2, the following hypothesis was made with regards to the effects of user behavior on the flexibility potential of heat pumps:

The flexibility potential of heat pumps installed in homes of conservers is very high as this can be considered the desired flexibility behavior. The flexibility potential of cool dwellers and average dwellers is both high. For cool dwellers this is due to their high adaptive thermal comfort and low endowment effect, however the rebound effect must be guarded. The flexibility potential for the average dweller will be high when incentivized with the right policy. Warm dwellers are more difficult to convince and the rebound effect must be guarded for this user type. Gaining a significant flexibility potential from spenders will be difficult and it is the expectation that this user type will not be able to contribute much to meeting the flexibility demand in the Dutch electricity system.

From the results gathered from the optimization model, it can be established that the hypothesis above is falsified. While the qualitative research indicated conservers to be able to provide a high degree of flexibility, their small temperature range with respect to the minimum and maximum acceptable indoor temperature is the main reason as to why the flexibility provision of conservers is limited. This is not only the case for the conserver user group, for all user groups the acceptable temperature range is the leading factor in determining the total flexibility provision of the heat pump of each user group. This does not mean that the underlying behavioral effects are negligible, these effects are reflected upon in chapter 9.

8

CONCLUSION

In this chapter, the sub-questions presented in each of the chapters are revisited. A concise conclusion to each sub-question is provided in section 8.1. In section, 8.2, a synthesis of the research process is provided and the main research question posed in this study is answered.

8.1. SUB-QUESTION CONCLUSIONS

1. What factors contribute to the demand response potential of heat pumps?

Heat pump characteristics, residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics are the four identified factors deemed to affect the demand response potential of heat pumps. A framework has been created relating the four factors to one another. Within the technical dimension, heat pump characteristics and residential dwelling characteristics are both of relevance in determining the flexibility potential of heat pumps. Within the behavioral dimension, consumer user characteristics and consumer adoption characteristics are both of relevance in determining the flexibility potential of heat pumps.

The exploratory review concludes that the demand response potential of heat pump is dependent on the technical characteristics of the installed heat pump and on the characteristics of the residential dwelling. With respect to the technical characteristics of the heat pump, the type of heat pump (air-source, ground-source or hybrid) has a large influence on the flexibility potential. Furthermore, the installed heat pump capacity and the control strategy applied to the heat pump all influence the flexibility potential. The characteristics of the residential dwelling in which the heat pump is placed also influence the total potential for demand response. Thermal inertia and thermal heat transfer are the most important factors influencing the flexibility potential. Lastly, the dwelling composition of the Netherlands plays a role in the total cumulative flexible load heat pumps are able to offer, and as such must also be taken into consideration. Table 8.1

provides an overview of the technical factors which will be considered in the development of the linear optimization model.

With regards to the behavioral factors, the explanatory review concludes that there exist two distinguishable factors influencing the total demand response potential of heat pumps: consumer user characteristics and consumer adoption characteristics. The exploratory review concludes that further research is required in order to capture the heterogeneity present in consumer behavior before the effect of consumer behavior on the demand response potential of heat pumps can be determined.

Table 8.1: Overview of factors most relevant to the flexibility potential of heat pumps

Heat Pump Characteristics	Heat Pump Type	Heat Pump Capacity	Heat Pump Control Strategy
Residential Dwelling Characteristics	Thermal Inertia	Thermal Heat Transfer	Dwelling Composition
Consumer User Characteristics	Consumer Heterogeneity		
Consumer Adoption Characteristics	Consumer Heterogeneity		

2. What theoretical information is required in order to capture the heterogeneity present in the factors affecting the demand response potential of heat pumps?

In order to operationalize the four factors selected for this study in a mathematical model capable of calculating the flexibility potential of heat pumps, further data collection and conceptualization was warranted. Table 8.2 presents an overview of the information and data collected in order to conceptualize each factor.

Equations are an appropriate tool in order to determine the appropriate installed capacity and coefficient of performance (COP) of a heat pump. The heterogeneity present in residential dwellings can be captured using two databases: the CBS data base for determining the dwelling composition in the Netherlands and the TABULA project database for determining the residential dwelling characteristics of Dutch residential dwellings. A combination of literature and the application of the K-means clustering algorithm form an appropriate combination in order to develop typologies concerning consumer user behavior. A combination of literature and the application of the Bass Model of Innovations form a suitable combination for the development of a consumer adoption typology. To conclude, it can be established that the theories and information presented are suitable tools which can be used to capture the heterogeneity present in the identified factors influencing the demand response potential of heat pumps.

3. How can the heterogeneity present in the factors affecting the demand response potential of heat pumps be captured and formalized in a typology?

In this study, a choice has been made to exclusively model the flexibility potential of all-electric heat pumps as this is in line with the government aim of transitioning completely

Table 8.2: Overview of Theories/Information Consulted for Model Conceptualization

Factor	Theory/Information	Type
Heat Pump Characteristics	Installed Capacity	Equation
	COP	Equation
Residential Dwelling Characteristics	Dwelling Composition	Database
	TABULA Project	Database
Consumer User Characteristics	Behavioral Factors	Literature
	User Types	Literature
Consumer Adoption Characteristics	Behavioral Factors	Literature
	Bass Model of Innovations	Method
	Otte's Lifestyle Topology	Literature

away from the use of natural gas by 2050. Therefore, the typology of heat pump characteristics is based on the thermal characteristics of the dwelling the heat pump is installed in. For the remaining factors of residential dwelling characteristics, consumer user characteristics and consumer adoption characteristics, a typology has been created which is displayed in table 8.3. In total, three residential dwelling types are selected, which are split further in varying levels of insulation level: poor insulation, medium insulation and good insulation. Five consumer user types have been identified with respect to thermal comfort bounds and user behavior. Three consumer adoption types have been identified who each posses different behavioral characteristics that they take into account when posed with the decision to adopt a heat pump or not.

To conclude, the typology can be formalized for implementation in a mathematical model in the following way: for each residential dwelling type, a linear optimization model capable of modelling the demand response potential of heat pumps will be run in combination with the 5 user types, leading to a total of 45 runs. The linear optimization model will provide output for 1 consumer type living in 1 home type. In order to determine the collective demand response potential of heat pumps, the results can be be scaled in ratio to the user type and residential dwelling composition. After this has been completed, the results can yet again be scaled yet again according to the estimated yearly adoption curves generated from the Bass model, capturing the heterogeneity in consumer adoption types.

Table 8.3: Typology capturing the heterogeneity of characteristics influencing the demand response potential of heat pumps

Residential Dwelling Types	Consumer User Types	Consumer Adoption Types
Detached	Average	Distrusting Consumer
Semi-Detached	Conservers	Convenient Consumer
Terraced	Spenders	Proactive Consumer
	Warm Dwellers	
	Cool Dwellers	

4. How can factors influencing the demand response potential of heat pumps be formalized in a mathematical model?

In order to model the demand response potential of heat pumps, a linear optimization model called OPEN has been selected. OPEN provides an extensible platform for developing local energy systems and is pre-loaded with the optimization software required for solving the dispatch of the local energy system assets, providing it with an edge over other linear optimization models. In addition, OPEN has been developed with modularity and customization in mind, allowing for a highly customized implementation of the factors influencing the demand response potential of heat pumps.

Table 8.4 displays the input variables required for the OPEN model. For each input variable, the input data is gathered by referencing a value retrieved from a table, an equation or a constant. The data has been prepared in such a way that it is possible for the OPEN model to reference all inputs, therefore it can be concluded that the input variables have been adequately operationalized. The raw source code of how the formalization is implemented is found in appendix E.

Table 8.4: Required model input

Variable	**Value**
Allowed temperature range	5 Consumer Types, Table 5.5
Initial temperature	Table 5.5
Ambient temperature	Time Series
HVAC capacity	Table 5.1.2
COP	Calculation
Building heat transfer	9 home types, Table 5.1
Building thermal mass	9 home types, Table 5.1
Energy price	Time Series
EMS time-series resolution	1 hour
Optimization horizon	24 hours
Simulation time-series resolution	15 mins

5. How does behavior influence the demand response potential of heat pumps?

The analysed results derived from the optimization model indicate the flexibility potential of heat pumps to be strongly influenced by the degree of home insulation and the degree of obtained market penetration. The degree of market penetration by heat pumps is considered the primary target when aiming to materialize the demand response potential of heat pumps. At 50% market penetration, the model results indicate an estimated average flexibility potential of heat pumps of 1.6 GW in 2050. The flexibility potential can be increased to 2.4 GW at 75% market penetration and 3.2 GW at 100% market penetration.

The results indicate that the effect of user behavior on the average flexibility provision of heat pumps is limited. For the average, warm dweller and cool dweller consumer groups, the results from the model indicate that altering the indoor heating patterns to match these user groups could increase the average upward flexibility regulation of heat pumps with about 21%. With respect to providing an average downward flexibility regulation, the effects of user behavior are negligible.

An interesting finding is that user behavior does influence the total flexibility which can be provided by heat pumps over a year due to the frequency at which a demand response event can be provided. The total flexibility offered is the largest for the warm dwelling consumer types, followed by the cool dweller groups, average group, conservers and finally spenders. The results reveal that the main variable determining to total flexibility provision is related to the provided range of minimum and maximum temperature preferences within the home of each consumer type.

It can be concluded that consumer adoption behavior has a much larger influence on the collective flexibility provision of heat pumps than consumer user behavior. Consumer user behavior can affect the demand response potential of a given heat pump, however this behavior is mostly related to the acceptable temperature range given by each consumer.

8.2. MAIN RESEARCH CONCLUSION

This research has been conducted in light of answering the following main research question:

How can we materialize the potential for demand response from residential heat pumps in The Netherlands until 2050?

The knowledge gap addressed in this study concerns the investigation of how consumer behavior is able to influence the demand response potential of heat pumps. The main research question has been answered by using a multi-method approach combining qualitative behavioral findings with a quantitative optimization model. After developing a general framework relating four factors influencing the flexibility potential of heat pumps to one another, further research was conducted in order to collect the required data necessary to capture the heterogeneity present in the four considered characteristics. This heterogeneity has been formalized by creating consumer typologies using the information gathered from the theoretical research. Subsequently, the factors influencing the demand response potential of heat pumps have been formalized in a mathematical model which is able to calculate the flexibility potential of heat pumps. From the results, it can be established that consumer adoption behavior has significantly more impact on the demand response potential of heat pumps than consumer user behavior. Therefore, when looking to materialize the demand response potential from heat pumps, the policy focus should be directed at consumer adoption behavior as opposed to consumer user behavior. The results from the linear optimization model reveal consumer adoption behavior to have the most effect on the collective demand response potential of heat pumps. For homes which have been undergone one renovation or that were constructed after 1990, by the year 2050, the model estimates an average demand response of 3.2 GW per demand response event that can be offered by heat pumps assuming 100% market penetration. This number declines to 2.4 GW of electrical flexibility at 75% market penetration and 1.6 GW of electrical flexibility in the case a mere 50% market penetration, assumed to be the minimum market penetration level. Therefore, the study estimates that gains of up to 1.6 GW in 2050 can be realized by increasing consumer adoption from 50% market penetration to 100% market penetration. For policy makers, this means that consumer behavior should be an area of focus when the benefits from gaining 1.6 GW of extra flexibility from heat pumps in 2050 proportionally outweigh the policy costs incurred to increase consumer adoption.

In order to maximize the heat pump market penetration and thus the potential for demand response by heat pumps, policy should primarily focus on the convenient consumer group created in the consumer adoption typology. This recommendation is based on the finding that the convenient consumer group represents more than half of all households eligible for a heat pump and as such large gains in the demand response potential of heat pumps can be made by targeting this consumer group. Policy should specifically focus on behavioral characteristics such as existing inertia, the availability bias, ignorance and satisficing behavior. In summary, by decreasing the 'hassle' factor for convenient consumers, substantial gains in the demand response potential of heat pumps can be achieved. Additionally, policy makers are encouraged to target behavioral factors such as trust, the availability bias and loss aversion when developing policy aimed at increasing the adoption of heat pumps by the distrusting consumer. While the gains in the flexibility potential of heat pumps will not be as large compared to the convenient consumer, targeting the distrusting consumer group is necessary in order to reach the 100% heat pump market penetration desired by the Dutch government by 2050.

While the most gains in be realized by increasing the market penetration level of heat pumps, user behavior has a lesser effect on the demand response potential of heat pumps. However, this does not mean that policy should forego targeting user behavior altogether. The results from the model indicate that altered user behavior could increase the demand response potential of heat pumps by 21% in case of upward flexibility regulation, and by 5% in case of downward flexibility regulation. Moreover, unregulated user behavior could lead to a a decrease in demand response potential of heat pumps by 12% in the case of upward flexibility regulation and by 5% in the case of downward flexibility regulation. One of the most significant model results concludes that it not necessarily the user type influencing the demand response potential of the heat pump, rather it is the temperature range at which the user does not experience any loss in thermal discomfort. When aiming to materialize the demand response potential of heat pumps from user behavior, policy makers should aim to increase the adaptive thermal comfort of consumer, while safeguarding the influence of the rebound effect and the endowment effect.

9

REFLECTION

The final chapter in this thesis consists of a reflection touching upon the biggest limitations and assumptions which have been made during the research process. A reflection on the general methodology is provided in section 9.1. Hereafter, the biggest limitations of the linear optimization model are discussed in section 9.2. The external factors of most significant to this study are elaborated upon in section 9.3. Finally, two recommendations for future research are given in section 9.5.

9.1. REFLECTION ON GENERAL METHODOLOGY

This study has combined several qualitative and quantitative methods in order to analyze how the demand response potential of heat pumps can be materialized.

The research approach commenced with two literature reviews. First, an evaluation of the technical characteristics of heat pumps and residential dwellings was conducted in order to gain a better understanding of the technical characteristics related to the flexibility provision of heat pumps. Second, the behavioral characteristics related heat pump consumer adoption and consumer user behavior were identified by means of a qualitative literature review. The results of the literature reviews were then used as input for the linear optimization model, which in turn were multiplied with the Bass

A critique which can be delivered on the research approach is how the level of detail of each research element does not always match the level of detail required. For example, the data collection with respect to the residential dwelling characteristics was performed very thoroughly, and eventually three home types were selected with varying degrees of insulation. While insulation has a very large effect on the flexibility provision of the heat pump, perhaps is would have sufficed to only consider homes which have been renovated at least once, since consumers living in homes with poor insulation will face a significant energy bill if they do not improve their home insulation when installing a heat pump. While this level of detail has increased the confidence in the average upward and downward flexibility figures, the main goal of this research is to understand how the demand response potential of heat pumps can be materialized, specifically with respect to consumer behavior.

9.2. REFLECTION ON OPTIMIZATION MODEL

The verification and validation of the optimization model which was developed demonstrated that the results generated from the model quite closely match the total power consumption of heat pumps when compared to a real-world situation. Before implementing the model, a technical literature review was conducted revealing the most relevant technical characteristics related to the flexibility provision of heat pumps. From the study, it emerged that the insulation size of the home have a large influence on the flexibility potential of the home. While these factors were considered for the linear optimization model, there are several improvements which could have been made in order to increase the accuracy of the optimization model.

First and foremost, the optimization model was run with a single electricity price series and one ambient temperature series. As the primary goal of this research was to discover the effects of consumer behavior on the provision of flexibility, the limited variation in scenarios is deemed acceptable. However, for future improvements, it is recommended that more scenarios are run.

A second factor up for discussion with regard to the linear optimization model is that no sensitivity analysis was performed. In light of the limited time scope of this thesis, the decision was taken to forego conducting this analysis and instead focus on the verification and validation of the model. In order to improve the model's validity, it is recommended for a sensitivity analysis to be performed on the threshold at which a heat pump is deemed to provide electrical flexibility. The chosen threshold in this study was set at -0.5 kw and 0.5kw of flexibility provision, however the results of this study might have been different had a different threshold been selected.

9.3. REFLECTION ON EXTERNAL FACTORS

There exist a variety of external factors that are able to influence consumer behavior with respect to the demand response potential of heat pumps that were not considered in the scope of this research. This section will discuss the external factors deemed to be of most significance with respect to the materialization of demand response potential.

9.3.1. NATIONAL LEGISLATION

In recent years, environmental groups and renewable utilities have called for a ban on the installation of natural gas boilers (NOS, 2018). For the 95% of households which are currently heated using a natural gas boiler, this would mean that once this boiler breaks down, either a hybrid or all-electric heat pump would have to be installed in order to meet the heating demands of the home. Should such a ban be imposed by the national government, the heat pump adoption curves developed in this study would likely change significantly in shape and size, possibly affecting the flexibility potential inherent to heat pumps.

While new legislation could significantly impact the assumed heat pump adoption curves, it is a far stretch to require a consumer to participate in a demand response scheme when a heat pump has been installed. Therefore, while requiring households to adopt a heat pump is legally possible, this would not automatically enhance the total flexibility potential of heat pumps. In order to materialize this potential, it should be considered to focus both on the adoption of the heat pump itself, in combination with the adoption of the demand response scheme.

Therefore, it will be assumed that new legislation requiring households to adopt a heat pump in the case of their natural gas boiler breaking down can increase the total flexibility potential of heat pumps, but this is not a given. If anything, such legislation will have the potential to significantly speed up the technological innovation necessary in order for heat pumps to provide this demand response.

9.3.2. TECHNOLOGICAL INNOVATION

At this point in time, the technology required in order to facilitate the demand response potential of heat pumps is not ready to be implemented on a large scale. There exist several hurdles with respect to the implementation of the demand response scheme that have effect on both the behavior of consumers and the total flexibility potential of heat pumps.

According to a report by Accenture (2021), the two main reasons why heat pumps are not able to offer flexibility to the grid today are the lack of standardisation and the lack of transparency in the costs of flexibility provision. With respect to standardisation, there exists no standardized platform which connects the heat pump with the Transmission System Operator. The reason why such a platform has not been developed yet is related to the price paid for the power consumed by the heat pump. While the day-ahead price of power varies significantly within 15 minute time increments, this variation is not reflected in the flat fee a consumer pays for their power. This means that no incentive can be provided to a heat pump to alter their power consumption. In addition, the heat pump must be fitted with a technology that is smart-grid ready, a feature that most heat pumps currently do not possess over.

Therefore, technical innovation is an external factor that has the potential to have a large impact when aiming to materialize the demand response potential of heat pumps. Applied specifically to consumer behavior, a consumer will have to be well-informed if their heat pump is smart grid ready or not in case they are open to providing flexibility with their heat pump. In addition, innovation with respect to the interaction between the home energy management system and the consumer is required in order to ensure a smooth adoption. Should it the technical feasibility of heat pump flexibility provision be realized, smart grid developers will have to consider if the heat pump should indeed be integrated into the grid. Since this study has not looked into the flexibility provision of other technologies such as electricity storage in electric vehicles or home batteries, it could be the case that the flexibility gained from these technologies is much larger than the flexibility which can be provided by heat pumps. Therefore, while the research has identified the most important behavioral aspects relevant to the materialization of demand response of heat pumps, it could be the case that the research is overshadowed should the benefits of demand response from electric vehicles and home batteries far exceed those of heat pumps. Lastly, it is expected that the potential fee a consumer will receive in exchange for providing flexibility will influence the total flexibility that heat pumps are able to provide. These uncertainties with respect to technical innovation surrounding heat pumps have not been taken into account in this study.

9.4. POLICY RECOMMENDATIONS

The primary purpose of this study has been to gain insight on the effect of consumer behavior on the demand response potential of heat pumps. While the conclusions in chapter 8 present the insights which have emerged from the optimization model results, no concrete policy advice has been given as of yet. This section provides a series of policy recommendations policy makers can consider in order to increase the demand response potential from heat pumps. These recommendations do not always follow from the model results directly, however they can provide policy makers with a starting point when developing policy aimed at increasing the flexibility potential of heat pumps that targets consumer behavior. The recommendations have been specified to the extent that they are able to be taken up by policy makers present in governments, corporations and utilities alike.

9.4.1. POLICY TARGETING ADOPTION BEHAVIOR

In chapter 7, it was recommended that for policy targeting consumer adoption behavior to be effective, behavioral factors characteristics for the convenient consumer group such as inertia, the availability bias, ignorance and satisficing behavior should be targeted. As such, policy should primarily focus on decreasing the 'hassle' factor by lowering the threshold to install a heat pump as much as possible. Each of the behavioral characteristics can be targeted in the following way:

- Existing inertia can be targeted when the natural gas boiler of the convenient consumer breaks down. This is a suitable moment to present the possibility of adopting a heat pump to a convenient consumer. Therefore, policy is recommended in which a heat pump is automatically installed after disposal of a natural gas boiler, unless stated otherwise by the consumer.

- The availability bias can be targeted by developing policy aimed at making information about heat pumps more accessible to consumers. Presently, consumers must actively look for information of heat pumps in order to become more knowledgeable. Examples of how to make information more available to the convenient consumer is to actively approaching this consumer with information regarding the heat pump. The consumer does not have to install the heat pump right away, however the idea of installing the heat pump will have crossed this consumer's mind, leading to a higher chance of installing a heat pump in the future.

- Ignorance can be targeted by providing the convenient consumer with a more straightforward process regarding the acquisition of a subsidy. Presently, this subsidy can only be obtained after the heat pump has already been installed. Policy is recommended that simplifies this process. For example, the subsidy can be subtracted from the price of the heat pump at the time of purchase.

- Satisficing behavior is perhaps the most difficult behavioral factor to target when developing policy in order to convince the convenient consumer to adopt a heat pump. In the end, it can be assumed that the convenient consumer would like to heat their home in the simplest and most cost-effective manner possible. It is recommended that policy is developed looking into the compensation scheme that the convenient consumer can participate in when their heat pump provides a demand response. This thesis has not investigated the set-up of such a scheme, however if the benefits of the scheme vastly outweigh retaining the natural gas boiler, the convenient consumer might be more inclined to adopt a heat pump

9.4.2. POLICY TARGETING USER BEHAVIOR

Three behavioral effects have been identified relating to consumer behavior: adaptive thermal comfort, the endowment effect and the rebound effort. In order to materialize the total yearly demand response potential of heat pumps, policy is recommended which aims to increase the acceptable indoor temperature range of a consumer as much as possible. The policy could be materialized in the following way:

- A possible policy measure in order to increase the acceptable indoor temperature range of a consumer is to target an increase in the adaptive thermal comfort factor. Consumers tend to restore their comfort should a change occur diminishing their thermal comfort. By offering plenty of adaptive opportunities, the width of the thermal comfort zone can be increased. Therefore, policy is recommended which focuses on increasing the adaptive opportunities within the home. Examples of adaptive opportunities range from increasing the ventilation possibilities of the home, to installing floor heating (lowering the thermal heat transfer coefficient of the home), to acquiring a thicker sweater. It is recommended that the effect of each of these measures on the acceptable indoor temperature range is explored, and that consumers are also made aware of the opportunities following an efficient marketing campaign.

- For consumers who are not willing to increase the boundaries of their acceptable indoor temperature range, policy is recommended which explores if perhaps these boundaries can be extended by providing a financial incentive. During the development of this policy, the endowment effect must be kept in mind: since consumers feel as if they already 'own' thermal comfort, a higher compensation might be required in order to extend these thermal boundaries. It is recommended that the costs of this compensation are evaluated compared to the costs incurred by not providing a demand response. It could be the case that the latter policy (not undertaking any action) could be more cost-effective due to the endowment effect.

- Last but not least, policy is recommended which is able to safeguard the endowment effect. The results above consider the acceptable temperature range of the consumer to be constant year round. However, it could be the case that a consumer is willing to lower their indoor temperature just once a week, after which the minimum acceptable indoor temperature by the consumer significantly increases. Therefore, further research is recommended investigating if the acceptable temperature ranges provided by consumers is a static or dynamic.

9.5. RECOMMENDATIONS FOR FUTURE RESEARCH

While section 9.4 has presented several pieces of concrete policy advice which could be helpful for policy makers aiming to materialize the demand response potential of heat pumps by targeting consumer behavior, the policy recommendations could be more refined. This section presents two methods which could allow for a more thorough understanding of the behavioral characteristics related to consumer adoption: discrete choice modelling and agent-based modelling. Conducting this research would enable for more suitable policy to be developed, materializing the demand response potential of heat pumps as much as possible.

The results from the study reveal that up until 2030, the consumer adoption of heat pumps has the largest effect on the collective demand response potential of heat pumps. For the distrusting consumer, who is not as likely to adopt a heat pump, factors such as trust, availability bias and loss aversion are major reasons why a heat pump is not adopted. For the convenient consumer, factors such as inertia, the availability bias, ignorance and satisfying behavior are particularly relevant. The proactive consumer, while likely to adopt a heat pump, could still be held back by an irrational response to monetary incentives, a priori beliefs and loss aversion. While all these biases and factors have been identified, it is uncertain what the contribution of each factor is with respect to the decision of adopting a heat pump. In addition, it is likely that the identified consumer groups in turn consist of individual consumers with heterogeneous characteristics. Therefore, when developing policy aiming to increase the consumer adoption of heat pumps, this heterogeneity must be taken into account. Both discrete choice modelling and agent-based modelling are appropriate methods which are able to take into account this heterogeneity.

9.5.1. DISCRETE CHOICE MODELLING

Future research is recommended that will explore the effect each identified behavioral factor has on the likelihood of a consumer to adopt a heat pump. A research approach which could be taken in order to quantify the influence of the behavioral factors on the individual decision to adopt a heat pump is discrete choice modelling. During the this master thesis research, it was established that consumers can be split into the three identified groups: the distrusting, convenient and proactive consumer. A discrete choice model could be created in order to statistically relate the choice to adopt a heat pump to the behavioral factors of each identified consumer group. It can then be established which factors have the largest influence on the likelihood of consumer adoption, and policy can be developed accordingly.

9.5.2. AGENT-BASED MODELLING

Another research approach which could be applied in order attain a more thorough understanding of the effect of the behavioral biases with respect to the adoption of a heat pump is agent-based modelling. In future work, an agent-based model could be developed in which agents are split into agent types reflecting the three identified consumer groups. For each agent-type, sliders for the identified behavioral factors could be created that indicate how much of an influence each behavioral bias has on the likelihood of adoption. Variations between the number of agents belonging to each agent-type could be created in order to understand how a different composition of consumer types affect the collective heat pump adoption. In addition, variations within the sliders values could be made whose levels could respond to several policy options. This could lead to an understanding of how much each policy affects each identified behavioral factor, and in turn how this would alter the total collective demand response potential of heat pumps related to consumer adoption.

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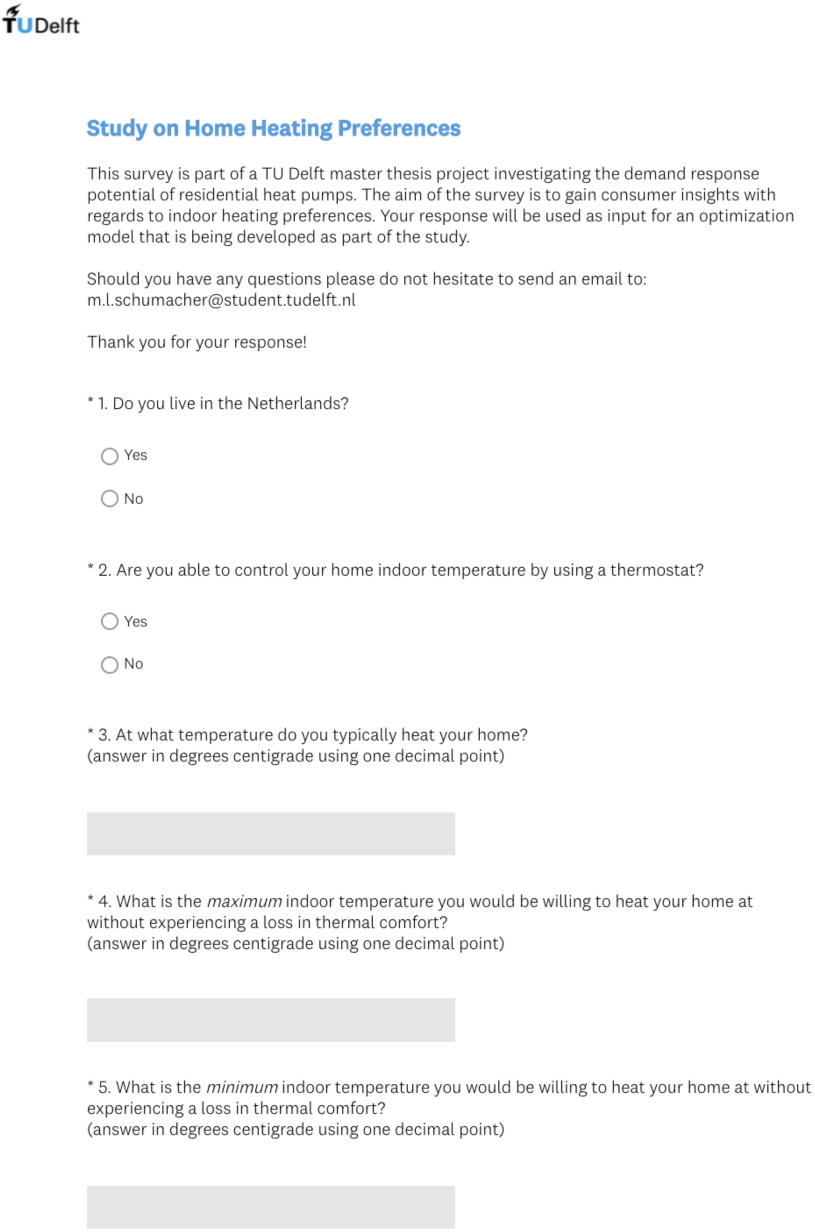
A

APPENDIX SURVEY

This appendix presents the raw results gathered from the survey discussed in chapter 5. Figure A.1 depicts the survey interface as presented to the respondents. Table A.1 presents all the raw collected data points, amounting to a total 181 responses. All data points with a "no" in either question 1 or 2 were removed from the data set. In addition, respondent numbers 55 and 145 were removed as 27 degrees centigrade were considered significant outliers in the survey results and it is believed that most heat pumps users would find such an indoor temperature to cause a considerable loss in thermal comfort.



Study on Home Heating Preferences

This survey is part of a TU Delft master thesis project investigating the demand response potential of residential heat pumps. The aim of the survey is to gain consumer insights with regards to indoor heating preferences. Your response will be used as input for an optimization model that is being developed as part of the study.

Should you have any questions please do not hesitate to send an email to:
m.l.schumacher@student.tudelft.nl

Thank you for your response!

* 1. Do you live in the Netherlands?

○ Yes

○ No

* 2. Are you able to control your home indoor temperature by using a thermostat?

○ Yes

○ No

* 3. At what temperature do you typically heat your home?
(answer in degrees centigrade using one decimal point)

* 4. What is the *maximum* indoor temperature you would be willing to heat your home at without experiencing a loss in thermal comfort?
(answer in degrees centigrade using one decimal point)

* 5. What is the *minimum* indoor temperature you would be willing to heat your home at without experiencing a loss in thermal comfort?
(answer in degrees centigrade using one decimal point)

Figure A.1: Lay-out of the distributed survey

Table A.1: Raw collected responses from survey

Respondent	**Q1**	**Q2**	**Q3 (avg temp)**	**Q4 (max temp)**	**Q5 (min temp)**
1	No	Yes	21	22	18
2	Yes	Yes	19.5	19.5	18
3	Yes	Yes	20.5	21	19.5
4	Yes	Yes	21	22	20
5	Yes	Yes	19	20	17
6	Yes	Yes	20	22	19
7	Yes	Yes	19.5	20	19
8	Yes	Yes	18	22	17
9	Yes	Yes	20	21	19
10	Yes	Yes	19	21	20
11	Yes	Yes	19	22	19
12	Yes	Yes	20	21	20
13	Yes	Yes	21.5	22.5	20
14	Yes	Yes	20	22	19
15	Yes	Yes	19	21	20
16	Yes	No	19	22	16
17	Yes	Yes	20	22	20
18	Yes	Yes	20	21	18
19	Yes	Yes	21	24	20
20	Yes	Yes	20	21	19.5
21	Yes	Yes	20.5	22	20.5
22	Yes	Yes	19	20	18
23	No	No	20	21	18
24	Yes	Yes	19.5	21	19
25	Yes	Yes	20.5	22	21
26	Yes	Yes	21.5	23.5	18.5
27	Yes	Yes	20	21.5	19
28	Yes	Yes	20.5	22.5	18
29	Yes	Yes	19	23	19
30	No	Yes	19	20	15
31	Yes	Yes	19	21	18
32	Yes	Yes	21	22	20
33	Yes	Yes	20	21.5	19
34	Yes	Yes	20	22	19
35	Yes	Yes	21	25	16
36	Yes	Yes	20	22	19.5
37	Yes	Yes	19.5	19.5	19.5
38	Yes	Yes	20	25	18
39	Yes	No	22	23	21
40	Yes	Yes	20	20	17

41	Yes	Yes	19	21	19
42	Yes	Yes	20	23	19.5
43	Yes	Yes	19.5	21	19
44	Yes	Yes	20	24	18
45	Yes	Yes	20	23	19
46	Yes	Yes	19	21	19
47	Yes	Yes	18	22	17
48	Yes	Yes	18	21	15
49	No	Yes	21	23	20
50	Yes	Yes	19.5	21	19
51	Yes	Yes	20.5	21	19
52	Yes	Yes	21	21	20
53	No	Yes	23	30	29
54	Yes	Yes	18.5	22	18.5
55	Yes	Yes	21.5	27	21.5
56	Yes	Yes	20	25	18
57	Yes	Yes	20	22	18
58	Yes	Yes	19	22	15
59	Yes	Yes	20	22	19
60	Yes	Yes	20	22	18
61	Yes	Yes	20.5	22	20.5
62	Yes	Yes	21	24	20
63	Yes	Yes	20	20	19
64	Yes	Yes	19.5	20.5	19
65	Yes	Yes	20	22.5	15
66	Yes	Yes	21	21	21
67	Yes	Yes	21	22	21
68	Yes	Yes	21	25	17
69	Yes	Yes	21	21	21
70	Yes	Yes	21	22	19
71	Yes	Yes	20	22	19
72	Yes	Yes	20	22	18
73	Yes	Yes	20.5	22	20.5
74	Yes	Yes	20	21	19
75	Yes	Yes	21	22	20
76	Yes	Yes	22	23	21
77	Yes	Yes	21	22	20
78	Yes	Yes	20	21	19.5
79	Yes	Yes	21.5	20	18
80	Yes	Yes	18.5	21	18
81	No	Yes	22	23	21
82	Yes	Yes	22	23	21
83	No	Yes	20.5	24	19

84	Yes	Yes	18	20	18
85	Yes	Yes	21	22	18
86	No	Yes	21	25	18
87	No	Yes	23.5	24	20
88	Yes	Yes	20.5	22	19.5
89	Yes	Yes	20	20	19
90	Yes	Yes	19	22	19
91	Yes	Yes	21.5	22.5	20.5
92	Yes	Yes	21	22	18
93	Yes	Yes	21	19	19
94	Yes	Yes	21	21	19
95	Yes	Yes	21	22.5	20
96	Yes	Yes	21	21	19
97	Yes	Yes	19	24	18
98	Yes	Yes	21	21	20
99	Yes	Yes	20	22	18
100	Yes	Yes	19.5	20.5	17
101	Yes	Yes	19.5	22	19
102	Yes	Yes	21	22	19
103	Yes	Yes	22	22	21
104	No	Yes	21	23	18
105	Yes	Yes	20.5	21.5	20
106	No	No	21	23	20
107	Yes	Yes	18	19	17
108	Yes	Yes	22	22	18
109	Yes	Yes	19.5	20.5	19
110	Yes	Yes	18	21	16
111	Yes	Yes	19	21	18
112	Yes	Yes	21	22	19
113	Yes	Yes	19.5	22	17
114	Yes	Yes	20	21.5	18
115	Yes	No	20	22	18
116	No	Yes	22.3	25	20
117	Yes	Yes	21	22	20
118	Yes	Yes	20	21	18.5
119	Yes	Yes	19.5	21	19
120	Yes	Yes	19.5	20	19
121	No	No	26	28	22
122	Yes	Yes	19	20	18
123	Yes	Yes	19.5	23	18
124	Yes	Yes	20.5	22	20
125	Yes	Yes	20	21	18
126	Yes	Yes	20	22.5	19

127	Yes	Yes	20	21	19
128	Yes	Yes	18.6	19	18
129	Yes	Yes	19	21	17
130	Yes	Yes	19	21	18
131	Yes	No	20.5	22.5	19
132	Yes	Yes	21.5	23	20.5
133	Yes	Yes	21	22	16
134	Yes	Yes	19	20	18
135	Yes	Yes	21	24	16
136	Yes	Yes	19.6	21	17.6
137	Yes	Yes	19.5	22	17.5
138	Yes	Yes	21.5	22	21
139	Yes	No	20.5	22	19.5
140	Yes	Yes	19	21	18
141	Yes	Yes	19.5	22	18
142	Yes	Yes	22	23.4	18
143	No	Yes	18	21	18
144	Yes	Yes	20	24	19.5
145	Yes	Yes	23	27	18
146	Yes	Yes	20	22	16
147	Yes	Yes	19.5	21	17
148	Yes	No	19.5	23	12
149	Yes	Yes	19	22	19
150	Yes	Yes	18.5	20	17
151	Yes	No	19	22	15
152	Yes	No	19	22	19
153	Yes	No	18	20	16.5
154	Yes	Yes	21	25	21
155	Yes	Yes	18	21	17
156	Yes	Yes	22	24	19
157	Yes	No	19	21	18.5
158	Yes	Yes	19	22	18
159	Yes	Yes	21	23	18
160	Yes	Yes	20	20	17.5
161	Yes	Yes	18	20	15.5
162	Yes	Yes	20	21	18
163	Yes	Yes	20	22	18
164	Yes	Yes	21.5	22	21
165	Yes	Yes	20	22	15
166	Yes	Yes	21	25	20
167	Yes	Yes	18.5	20	18
168	Yes	No	20	25	18
169	Yes	Yes	19.5	23	19

170	Yes	Yes	19	22	18
171	Yes	Yes	21.5	22	19
172	Yes	Yes	21	22	20.5
173	Yes	Yes	20	22	19
174	Yes	No	21	24.5	21
175	Yes	No	21	21	18.5
176	Yes	Yes	19	21	18
177	Yes	Yes	19.5	21	18.5
178	Yes	Yes	20	23	18
179	Yes	Yes	20.5	23	19
180	Yes	Yes	21	21.5	20.5
181	Yes	Yes	20	21.5	18.5

B

APPENDIX HOME CHARACTERISTICS

This appendix presents the data used in order to calculate the thermal heat transfer coefficient and thermal inertia coefficient of the residential home types selected from the TABULA project.

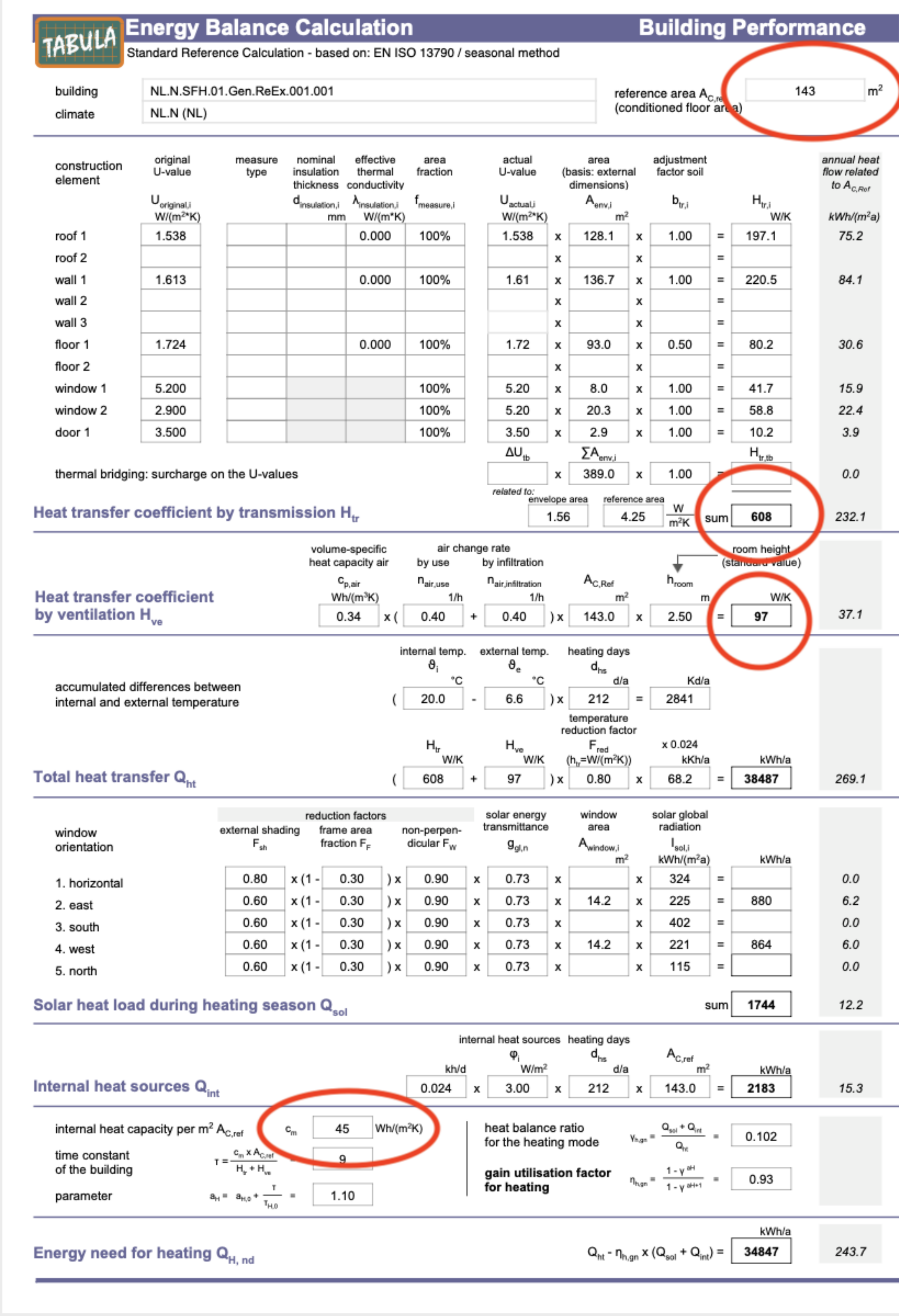
For each home type, the thermal heat transfer coefficient was calculated by adding the heat transfer coefficient by transmission H_{tr} and the heat transfer coefficient by ventilation H_{ve}, as displayed in equation B.1. This would amount to a coefficient with units in W/K, however the OPEN model asks for a thermal heat transfer with units in °C / kW, therefore the value was divided by 1000 and then inverted in order to comply with the expected units.

$$R = H_{tr} + H_{ve} \tag{B.1}$$

The building thermal inertia coefficient was calculated by multiplying the internal heat capacity C_m with the area of the chosen building $A_{C,ref}$, as displayed in equation C. The internal heat capacity has the same value for every selected building: 45 Wh/(m^{2}K). This value was thus multiplied by the area of the building and divided by 1000 in order to get the desired unit of kWh/(°C) desired for the OPEN model.

$$C = C_m * A_{C,ref} \tag{B.2}$$

Figures 1 to 9 display the individual data retrieved from the TABULA project page. The red circles in figure 1 present the values used as input for the equations above, for each of the figures these 4 values were consulted. The data of each calculation sheet was retrieved using: https://webtool.building-typology.eu/#bm.



Energy Balance Calculation **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.SFH.01.Gen.ReEx.001.001	reference area $A_{C,ref}$ (conditioned floor area)	143	m²
climate	NL.N (NL)			

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	annual heat flow related to $A_{C,Ref}$ kWh/(m²a)
roof 1	1.538			0.000	100%	1.538	x	128.1	x	1.00	=	197.1	75.2
roof 2							x		x		=		
wall 1	1.613			0.000	100%	1.61	x	136.7	x	1.00	=	220.5	84.1
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	1.724			0.000	100%	1.72	x	93.0	x	0.50	=	80.2	30.6
floor 2							x		x		=		
window 1	5.200				100%	5.20	x	8.0	x	1.00	=	41.7	15.9
window 2	2.900				100%	5.20	x	20.3	x	1.00	=	58.8	22.4
door 1	3.500				100%	3.50	x	2.9	x	1.00	=	10.2	3.9
						ΔU_{tb}		$\Sigma A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	389.0	x	1.00	=		0.0

Heat transfer coefficient by transmission H_{tr}

related to: envelope area 1.56 reference area 4.25 W/(m²K) sum **608** 232.1

Heat transfer coefficient by ventilation H_{ve}

volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
0.34	x (	0.40	+	0.40	) x	143.0	x	2.50	=	**97**	37.1

accumulated differences between internal and external temperature

	internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a
(	20.0	-	6.6	) x	212	=	2841

Total heat transfer Q_{ht}

	H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
(	608	+	97	) x	0.80	x	68.2	=	**38487**	269.1

window orientation	reduction factors: external shading F_{sh}		reduction factors: frame area fraction F_F		reduction factors: non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.73	x		x	324	=		0.0
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.73	x	14.2	x	225	=	880	6.2
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.73	x		x	402	=		0.0
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.73	x	14.2	x	221	=	864	6.0
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.73	x		x	115	=		0.0

Solar heat load during heating season Q_{sol} sum **1744** 12.2

Internal heat sources Q_{int}

kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
0.024	x	3.00	x	212	x	143.0	=	**2183**	15.3

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}} =$ 9

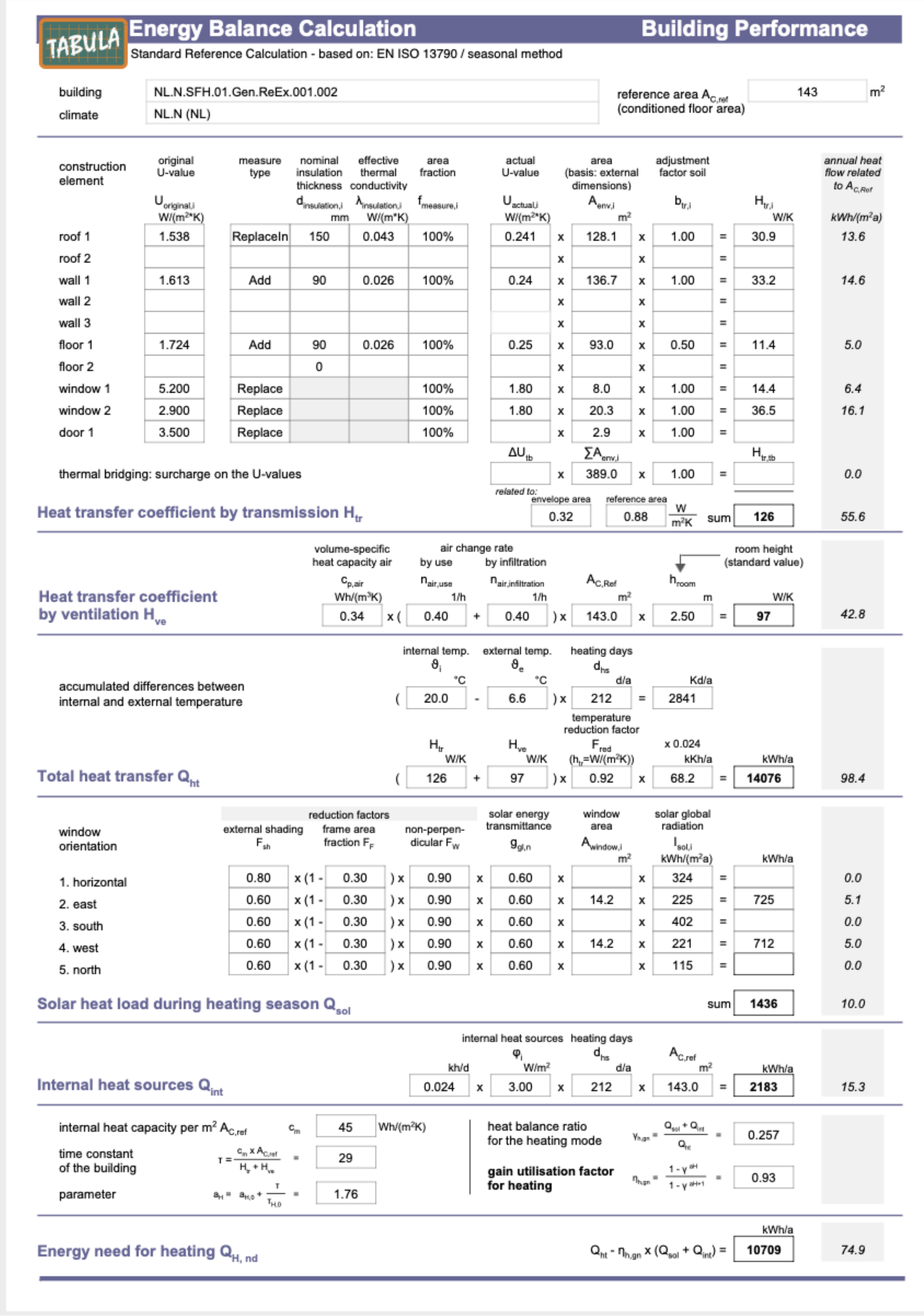
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}} =$ 1.10

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}} =$ 0.102

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}} =$ 0.93

Energy need for heating $Q_{H,nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int}) =$ **34847** kWh/a 243.7

Figure B.1: Home characteristics Detached home with no renovation



Energy Balance Calculation **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.SFH.01.Gen.ReEx.001.002	reference area $A_{C,ref}$ (conditioned floor area)	143 m^2
climate	NL.N (NL)		

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$* *kWh/(m²a)*
roof 1	1.538	ReplaceIn	150	0.043	100%	0.241	x	128.1	x	1.00	=	30.9	*13.6*
roof 2							x		x		=		
wall 1	1.613	Add	90	0.026	100%	0.24	x	136.7	x	1.00	=	33.2	*14.6*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	1.724	Add	90	0.026	100%	0.25	x	93.0	x	0.50	=	11.4	*5.0*
floor 2			0				x		x		=		
window 1	5.200	Replace			100%	1.80	x	8.0	x	1.00	=	14.4	*6.4*
window 2	2.900	Replace			100%	1.80	x	20.3	x	1.00	=	36.5	*16.1*
door 1	3.500	Replace			100%		x	2.9	x	1.00	=		
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	389.0	x	1.00	=		*0.0*

	related to: envelope area	reference area				
Heat transfer coefficient by transmission H_{tr}	0.32	0.88	$\frac{W}{m^2K}$	sum	**126**	*55.6*

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.40	) x	143.0	x	2.50	=	**97**	*42.8*

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a		
accumulated differences between internal and external temperature	(	20.0	-	6.6	) x	212	=	2841		
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a
Total heat transfer Q_{ht}	(	126	+	97	) x	0.92	x	68.2	=	**14076**

Total heat transfer: 98.4

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	324	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	14.2	x	225	=	725	*5.1*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	402	=		*0.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	14.2	x	221	=	712	*5.0*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	115	=		*0.0*

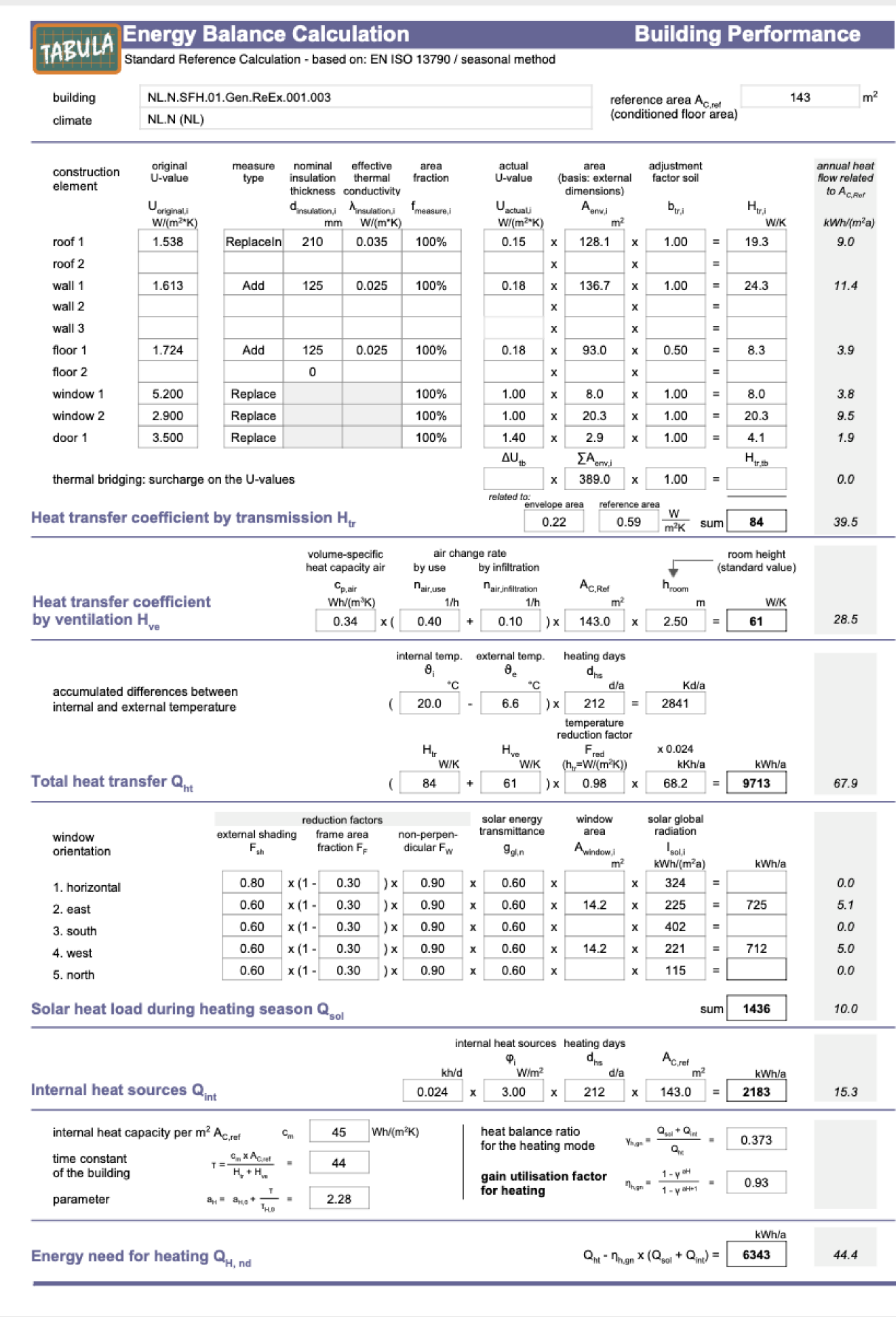
Solar heat load during heating season Q_{sol} sum **1436** *10.0*

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	212	x	143.0	=	**2183**	*15.3*

internal heat capacity per m² $A_{C,ref}$	c_m	45 Wh/(m²K)	heat balance ratio for the heating mode	$\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$	=	0.257
time constant of the building	$\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ =	29	**gain utilisation factor for heating**	$\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$	=	0.93
parameter	$a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ =	1.76				

		kWh/a	
Energy need for heating $Q_{H,nd}$	$Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ =	**10709**	*74.9*

Figure B.2: Home characteristics Detached home with a medium renovation



Energy Balance Calculation **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.SFH.01.Gen.ReEx.001.003	reference area $A_{C,ref}$ (conditioned floor area)	143 m^2
climate	NL.N (NL)		

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$ kWh/(m²a)*
roof 1	1.538	ReplaceIn	210	0.035	100%	0.15	x	128.1	x	1.00	=	19.3	*9.0*
roof 2							x		x		=		
wall 1	1.613	Add	125	0.025	100%	0.18	x	136.7	x	1.00	=	24.3	*11.4*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	1.724	Add	125	0.025	100%	0.18	x	93.0	x	0.50	=	8.3	*3.9*
floor 2			0				x		x		=		
window 1	5.200	Replace			100%	1.00	x	8.0	x	1.00	=	8.0	*3.8*
window 2	2.900	Replace			100%	1.00	x	20.3	x	1.00	=	20.3	*9.5*
door 1	3.500	Replace			100%	1.40	x	2.9	x	1.00	=	4.1	*1.9*
						ΔU_{tb}		$\Sigma A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	389.0	x	1.00	=		*0.0*

related to: envelope area 0.22 reference area 0.59 W/(m²K)

Heat transfer coefficient by transmission H_{tr} sum **84** *39.5*

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.10	) x	143.0	x	2.50	=	**61**	*28.5*

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a			
accumulated differences between internal and external temperature	(	20.0	-	6.6	) x	212	=	2841			
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
Total heat transfer Q_{ht}	(	84	+	61	) x	0.98	x	68.2	=	**9713**	*67.9*

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpen-dicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	324	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	14.2	x	225	=	725	*5.1*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	402	=		*0.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	14.2	x	221	=	712	*5.0*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	115	=		*0.0*

Solar heat load during heating season Q_{sol} sum **1436** *10.0*

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	212	x	143.0	=	**2183**	*15.3*

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 44

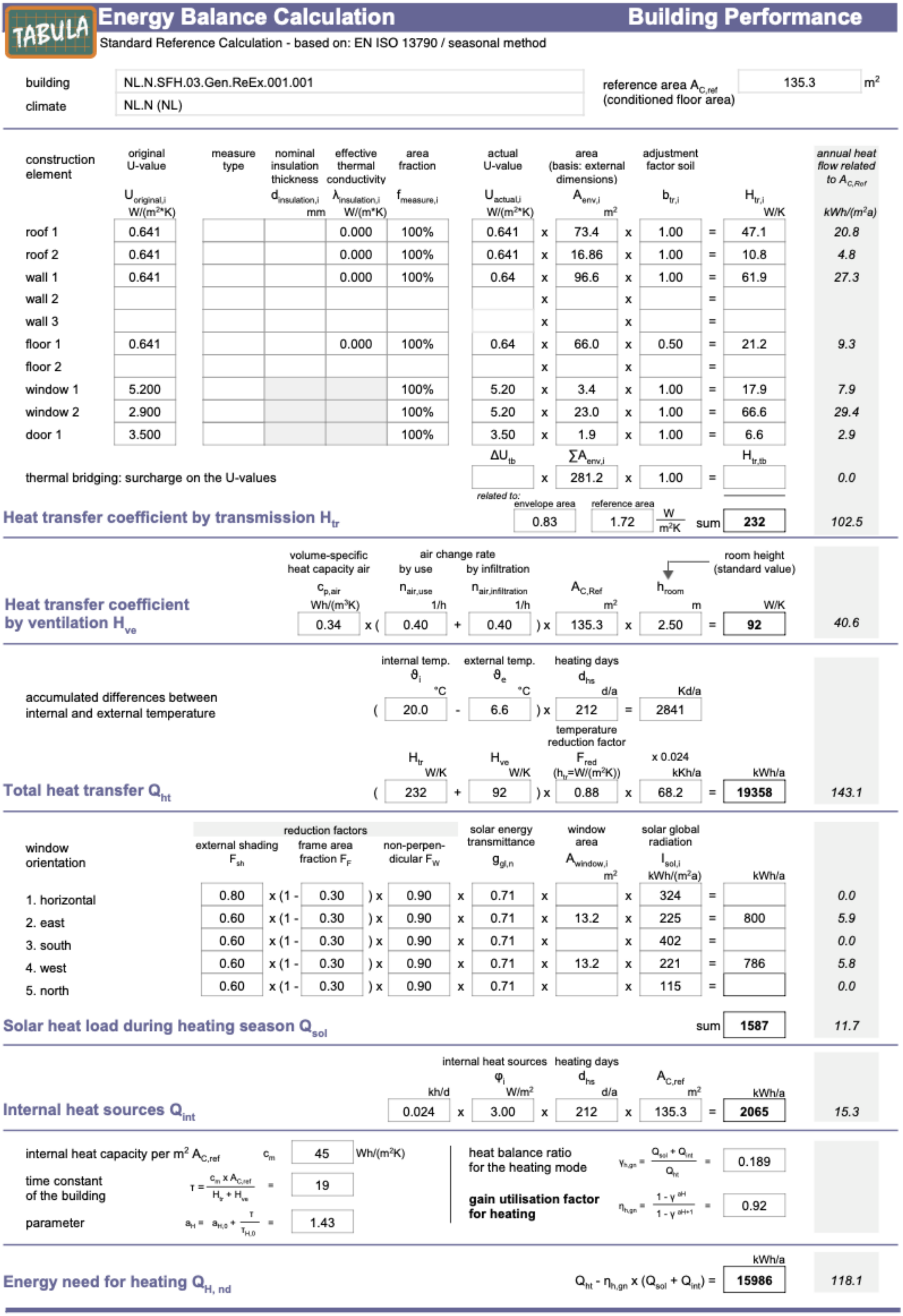
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 2.28

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.373

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.93

Energy need for heating $Q_{H,nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **6343** kWh/a *44.4*

Figure B.3: Home characteristics Detached home with a thorough renovation



Energy Balance Calculation **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.SFH.03.Gen.ReEx.001.001	reference area $A_{C,ref}$ (conditioned floor area)	135.3	m^2
climate	NL.N (NL)			

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$* *kWh/(m²a)*
roof 1	0.641			0.000	100%	0.641	x	73.4	x	1.00	=	47.1	*20.8*
roof 2	0.641			0.000	100%	0.641	x	16.86	x	1.00	=	10.8	*4.8*
wall 1	0.641			0.000	100%	0.64	x	96.6	x	1.00	=	61.9	*27.3*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	0.641			0.000	100%	0.64	x	66.0	x	0.50	=	21.2	*9.3*
floor 2							x		x		=		
window 1	5.200				100%	5.20	x	3.4	x	1.00	=	17.9	*7.9*
window 2	2.900				100%	5.20	x	23.0	x	1.00	=	66.6	*29.4*
door 1	3.500				100%	3.50	x	1.9	x	1.00	=	6.6	*2.9*
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	281.2	x	1.00	=		*0.0*

related to: envelope area 0.83 reference area 1.72 $\frac{W}{m^2K}$ sum **232** *102.5*

Heat transfer coefficient by transmission H_{tr}

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		h_{room} m room height (standard value)		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.40	) x	135.3	x	2.50	=	**92**	*40.6*

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a			
accumulated differences between internal and external temperature	(	20.0	-	6.6	) x	212	=	2841			
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
Total heat transfer Q_{ht}	(	232	+	92	) x	0.88	x	68.2	=	**19358**	*143.1*

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpen-dicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.71	x		x	324	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.71	x	13.2	x	225	=	800	*5.9*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.71	x		x	402	=		*0.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.71	x	13.2	x	221	=	786	*5.8*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.71	x		x	115	=		*0.0*

Solar heat load during heating season Q_{sol} sum **1587** *11.7*

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	212	x	135.3	=	**2065**	*15.3*

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 19

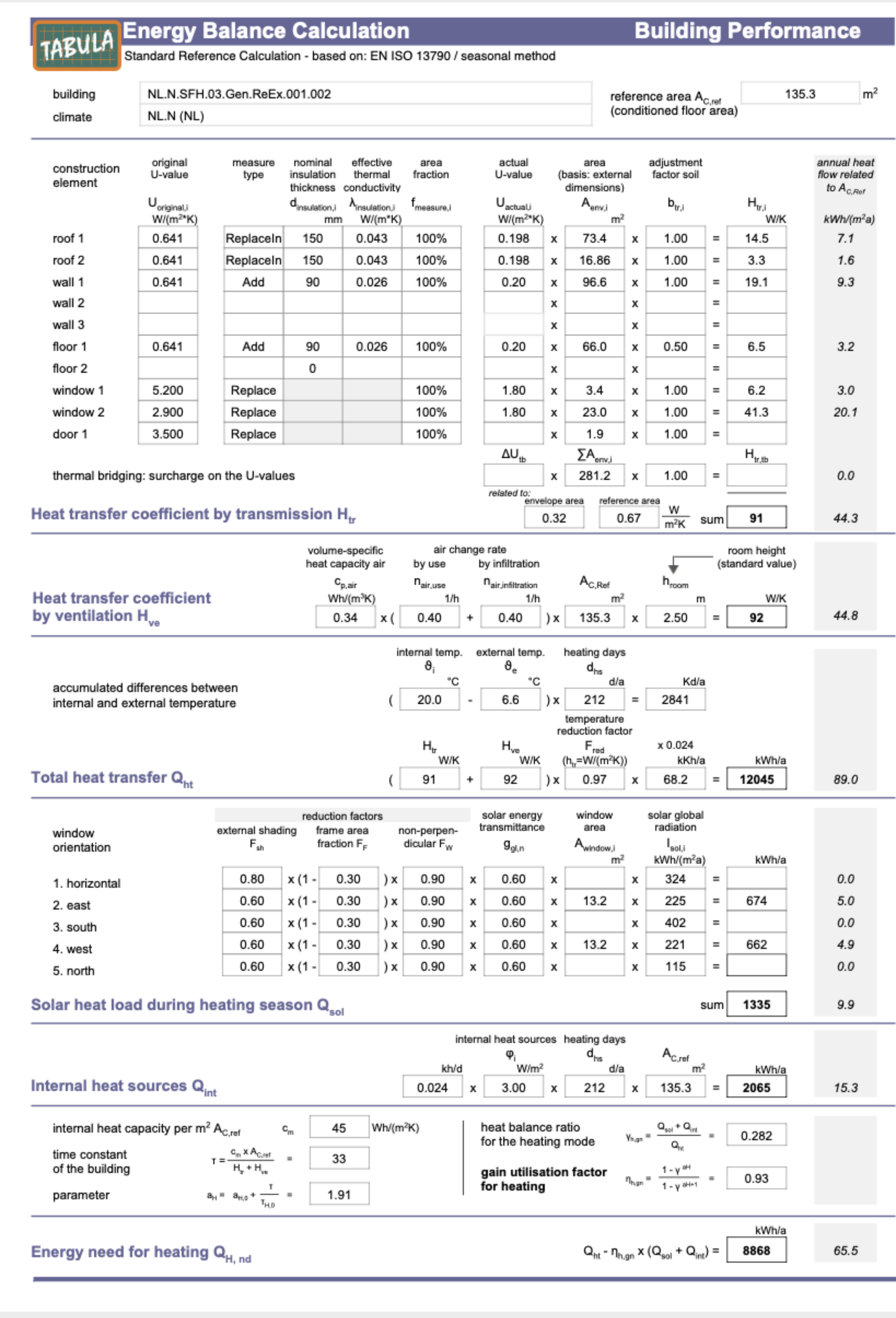
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.43

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.189

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.92

Energy need for heating $Q_{H, nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **15986** kWh/a *118.1*

Figure B.4: Home characteristics semi-detached home with no renovation



TABULA

Energy Balance Calculation **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building NL.N.SFH.03.Gen.ReEx.001.002

climate NL.N (NL)

reference area $A_{C,ref}$ (conditioned floor area) 135.3 m^2

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	annual heat flow related to $A_{C,Ref}$ kWh/(m²a)
roof 1	0.641	ReplaceIn	150	0.043	100%	0.198	x	73.4	x	1.00	=	14.5	7.1
roof 2	0.641	ReplaceIn	150	0.043	100%	0.198	x	16.86	x	1.00	=	3.3	1.6
wall 1	0.641	Add	90	0.026	100%	0.20	x	96.6	x	1.00	=	19.1	9.3
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	0.641	Add	90	0.026	100%	0.20	x	66.0	x	0.50	=	6.5	3.2
floor 2			0				x		x		=		
window 1	5.200	Replace			100%	1.80	x	3.4	x	1.00	=	6.2	3.0
window 2	2.900	Replace			100%	1.80	x	23.0	x	1.00	=	41.3	20.1
door 1	3.500	Replace			100%		x	1.9	x	1.00	=		
thermal bridging: surcharge on the U-values						ΔU_{tb}	x	$\Sigma A_{env,i}$ 281.2	x	1.00	=	$H_{tr,tb}$	0.0

related to: envelope area 0.32 reference area 0.67 W/(m²K) sum 91 44.3

Heat transfer coefficient by transmission H_{tr}

Heat transfer coefficient by ventilation H_{ve}

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
	0.34	x (	0.40	+	0.40	) x	135.3	x	2.50	=	92	44.8

accumulated differences between internal and external temperature

	internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a
(	20.0	-	6.6	) x	212	=	2841

Total heat transfer Q_{ht}

	H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
(	91	+	92	) x	0.97	x	68.2	=	12045	89.0

window orientation	reduction factors: external shading F_{sh}		reduction factors: frame area fraction F_F		reduction factors: non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	324	=		0.0
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.2	x	225	=	674	5.0
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	402	=		0.0
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.2	x	221	=	662	4.9
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	115	=		0.0

Solar heat load during heating season Q_{sol} sum 1335 9.9

Internal heat sources Q_{int}

kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
0.024	x	3.00	x	212	x	135.3	=	2065	15.3

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 33

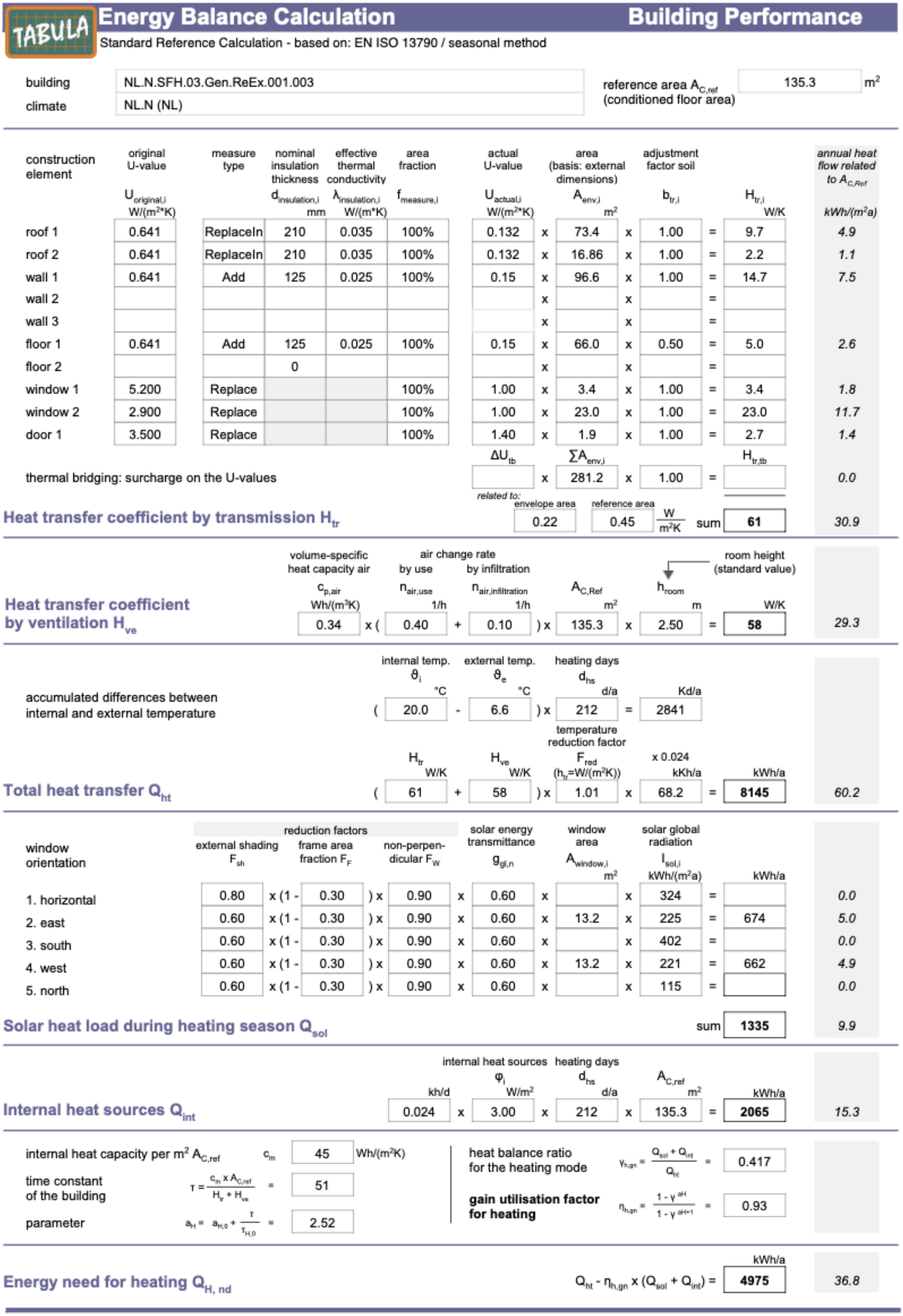
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.91

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.282

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.93

Energy need for heating $Q_{H,nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = 8868 kWh/a 65.5

Figure B.5: Home characteristics semi-detached home with a medium renovation



Energy Balance Calculation **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.SFH.03.Gen.ReEx.001.003	reference area $A_{C,ref}$ (conditioned floor area)	135.3 m^2
climate	NL.N (NL)		

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$ kWh/(m²a)*
roof 1	0.641	ReplaceIn	210	0.035	100%	0.132	x	73.4	x	1.00	=	9.7	*4.9*
roof 2	0.641	ReplaceIn	210	0.035	100%	0.132	x	16.86	x	1.00	=	2.2	*1.1*
wall 1	0.641	Add	125	0.025	100%	0.15	x	96.6	x	1.00	=	14.7	*7.5*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	0.641	Add	125	0.025	100%	0.15	x	66.0	x	0.50	=	5.0	*2.6*
floor 2			0				x		x		=		
window 1	5.200	Replace			100%	1.00	x	3.4	x	1.00	=	3.4	*1.8*
window 2	2.900	Replace			100%	1.00	x	23.0	x	1.00	=	23.0	*11.7*
door 1	3.500	Replace			100%	1.40	x	1.9	x	1.00	=	2.7	*1.4*
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	281.2	x	1.00	=		*0.0*

	related to: envelope area	reference area			
Heat transfer coefficient by transmission H_{tr}	0.22	0.45	$\frac{W}{m^2K}$	sum **61**	*30.9*

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		h_{room} m (room height (standard value))		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.10	) x	135.3	x	2.50	=	**58**	*29.3*

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a			
accumulated differences between internal and external temperature	(	20.0	-	6.6	) x	212	=	2841			
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
Total heat transfer Q_{ht}	(	61	+	58	) x	1.01	x	68.2	=	**8145**	*60.2*

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	324	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.2	x	225	=	674	*5.0*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	402	=		*0.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.2	x	221	=	662	*4.9*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	115	=		*0.0*
Solar heat load during heating season Q_{sol}												sum	**1335**	*9.9*

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	212	x	135.3	=	**2065**	*15.3*

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 51

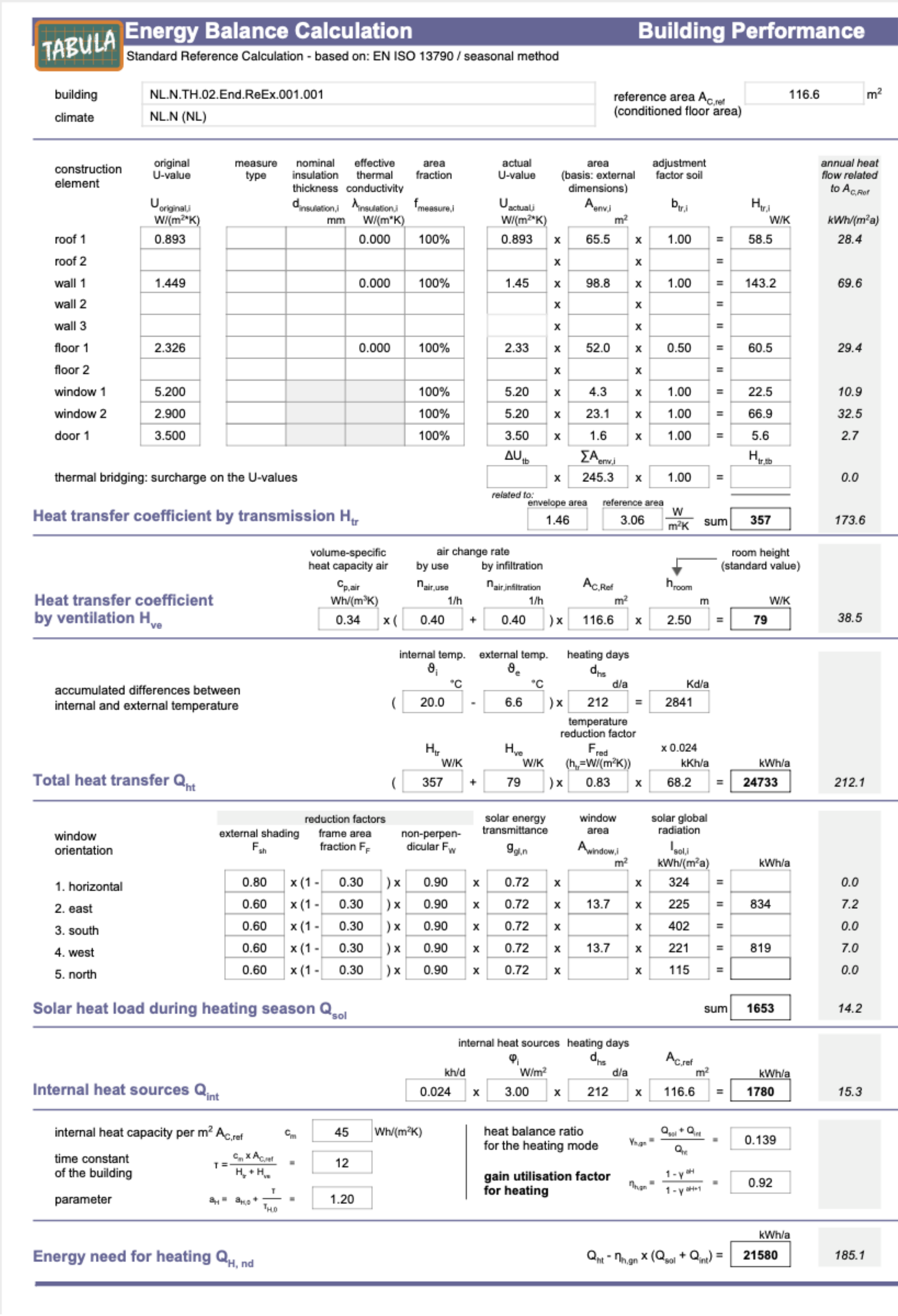
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 2.52

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.417

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.93

Energy need for heating $Q_{H,nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **4975** kWh/a *36.8*

Figure B.6: Home characteristics semi-detached home with a thorough renovation



TABULA

Energy Balance Calculation — Building Performance

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.TH.02.End.ReEx.001.001	reference area $A_{C,ref}$ (conditioned floor area)	116.6 m²
climate	NL.N (NL)		

construction element	original U-value $U_{original,i}$ W/(m²K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$ kWh/(m²a)*
roof 1	0.893			0.000	100%	0.893	x	65.5	x	1.00	=	58.5	*28.4*
roof 2							x		x		=		
wall 1	1.449			0.000	100%	1.45	x	98.8	x	1.00	=	143.2	*69.6*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	2.326			0.000	100%	2.33	x	52.0	x	0.50	=	60.5	*29.4*
floor 2							x		x		=		
window 1	5.200				100%	5.20	x	4.3	x	1.00	=	22.5	*10.9*
window 2	2.900				100%	5.20	x	23.1	x	1.00	=	66.9	*32.5*
door 1	3.500				100%	3.50	x	1.6	x	1.00	=	5.6	*2.7*
						ΔU_{tb}		$\Sigma A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	245.3	x	1.00	=		*0.0*

related to: envelope area 1.46 reference area 3.06 W/(m²K) sum **357** *173.6*

Heat transfer coefficient by transmission H_{tr}

Heat transfer coefficient by ventilation H_{ve}

volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
0.34	x (	0.40	+	0.40	) x	116.6	x	2.50	=	**79**	*38.5*

accumulated differences between internal and external temperature

	internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a
(	20.0	-	6.6	) x	212	=	2841

Total heat transfer Q_{ht}

	H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
(	357	+	79	) x	0.83	x	68.2	=	**24733**	*212.1*

Solar heat load during heating season Q_{sol}

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.72	x		x	324	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.72	x	13.7	x	225	=	834	*7.2*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.72	x		x	402	=		*0.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.72	x	13.7	x	221	=	819	*7.0*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.72	x		x	115	=		*0.0*

sum **1653** *14.2*

Internal heat sources Q_{int}

kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
0.024	x	3.00	x	212	x	116.6	=	**1780**	*15.3*

internal heat capacity per m² $A_{C,ref}$ c_m = 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 12

parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.20

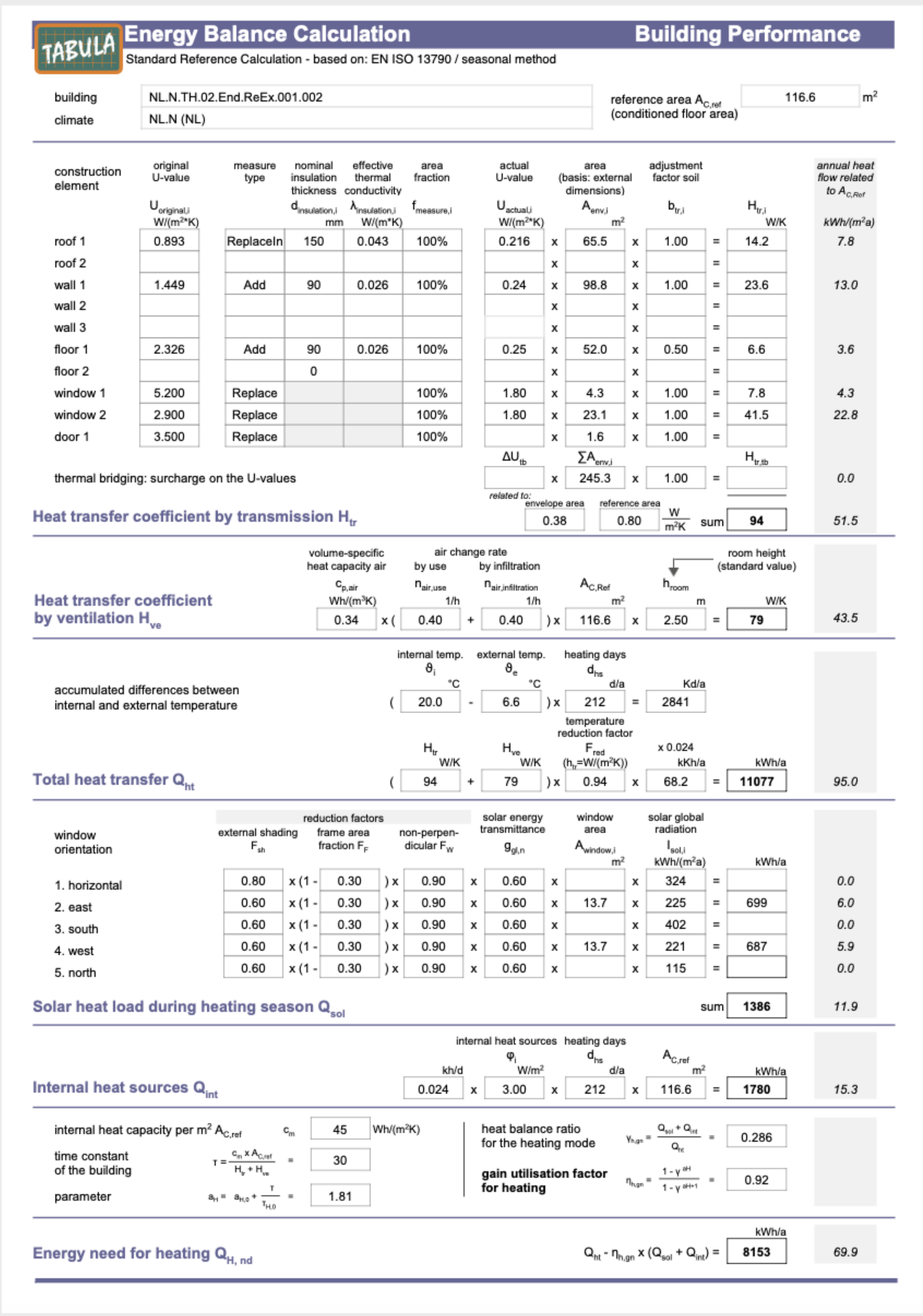
heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.139

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{a_H}}{1 - \gamma^{a_H+1}}$ = 0.92

Energy need for heating $Q_{H,nd}$

$Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **21580** kWh/a *185.1*

Figure B.7: Home characteristics terraced home with a no renovation



TABULA **Energy Balance Calculation** **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.TH.02.End.ReEx.001.002	reference area $A_{C,ref}$ (conditioned floor area)	116.6	m²
climate	NL.N (NL)			

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	*annual heat flow related to $A_{C,Ref}$ kWh/(m²a)*
roof 1	0.893	ReplaceIn	150	0.043	100%	0.216	x	65.5	x	1.00	=	14.2	*7.8*
roof 2							x		x		=		
wall 1	1.449	Add	90	0.026	100%	0.24	x	98.8	x	1.00	=	23.6	*13.0*
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	2.326	Add	90	0.026	100%	0.25	x	52.0	x	0.50	=	6.6	*3.6*
floor 2			0				x		x		=		
window 1	5.200	Replace			100%	1.80	x	4.3	x	1.00	=	7.8	*4.3*
window 2	2.900	Replace			100%	1.80	x	23.1	x	1.00	=	41.5	*22.8*
door 1	3.500	Replace			100%		x	1.6	x	1.00	=		
						ΔU_{tb}		$\sum A_{env,i}$				$H_{tr,tb}$	
thermal bridging: surcharge on the U-values							x	245.3	x	1.00	=		*0.0*

related to: envelope area 0.38 reference area 0.80 $\frac{W}{m^2K}$ sum **94** *51.5*

Heat transfer coefficient by transmission H_{tr}

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.40	) x	116.6	x	2.50	=	**79**	*43.5*

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a
accumulated differences between internal and external temperature	(	20.0	-	6.6	) x	212	=	2841

		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a	
Total heat transfer Q_{ht}	(	94	+	79	) x	0.94	x	68.2	=	**11077**	*95.0*

window orientation	reduction factors: external shading F_{sh}		reduction factors: frame area fraction F_F		reduction factors: non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	324	=		*0.0*
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.7	x	225	=	699	*6.0*
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	402	=		*0.0*
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.7	x	221	=	687	*5.9*
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	115	=		*0.0*

Solar heat load during heating season Q_{sol} sum **1386** *11.9*

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	212	x	116.6	=	**1780**	*15.3*

internal heat capacity per m² $A_{C,ref}$ c_m 45 Wh/(m²K)

time constant of the building $\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ = 30

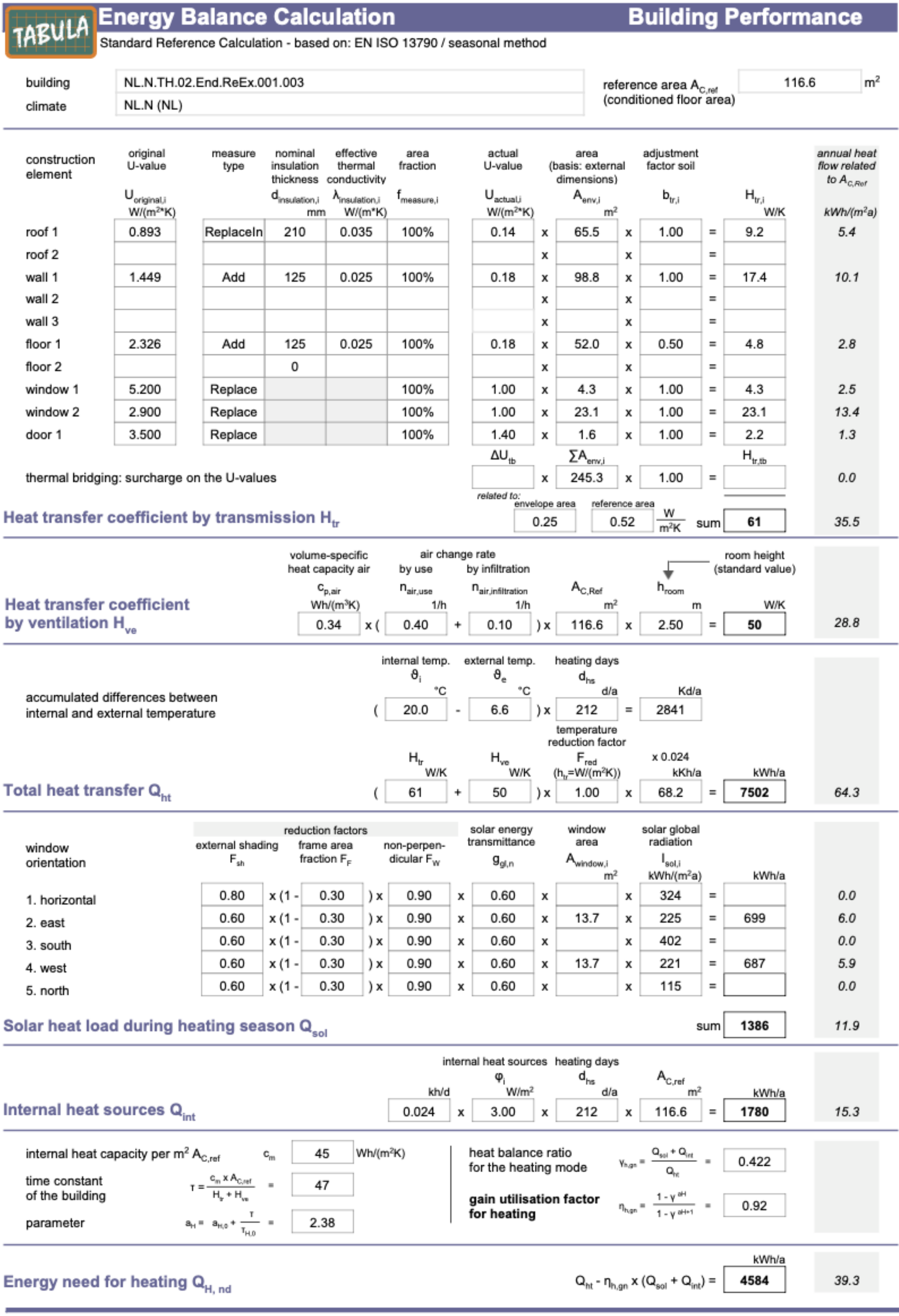
parameter $a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ = 1.81

heat balance ratio for the heating mode $\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$ = 0.286

gain utilisation factor for heating $\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$ = 0.92

Energy need for heating $Q_{H,nd}$ $Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **8153** kWh/a *69.9*

Figure B.8: Home characteristics terraced home with a medium renovation



TABULA **Energy Balance Calculation** **Building Performance**

Standard Reference Calculation - based on: EN ISO 13790 / seasonal method

building	NL.N.TH.02.End.ReEx.001.003	reference area $A_{C,ref}$ (conditioned floor area)	116.6 m^2
climate	NL.N (NL)		

construction element	original U-value $U_{original,i}$ W/(m²*K)	measure type	nominal insulation thickness $d_{insulation,i}$ mm	effective thermal conductivity $\lambda_{insulation,i}$ W/(m*K)	area fraction $f_{measure,i}$	actual U-value $U_{actual,i}$ W/(m²*K)		area (basis: external dimensions) $A_{env,i}$ m²		adjustment factor soil $b_{tr,i}$		$H_{tr,i}$ W/K	annual heat flow related to $A_{C,Ref}$ kWh/(m²a)
roof 1	0.893	ReplaceIn	210	0.035	100%	0.14	x	65.5	x	1.00	=	9.2	5.4
roof 2							x		x		=		
wall 1	1.449	Add	125	0.025	100%	0.18	x	98.8	x	1.00	=	17.4	10.1
wall 2							x		x		=		
wall 3							x		x		=		
floor 1	2.326	Add	125	0.025	100%	0.18	x	52.0	x	0.50	=	4.8	2.8
floor 2			0				x		x		=		
window 1	5.200	Replace			100%	1.00	x	4.3	x	1.00	=	4.3	2.5
window 2	2.900	Replace			100%	1.00	x	23.1	x	1.00	=	23.1	13.4
door 1	3.500	Replace			100%	1.40	x	1.6	x	1.00	=	2.2	1.3
thermal bridging: surcharge on the U-values						ΔU_{tb}	x	$\Sigma A_{env,i}$ 245.3	x	1.00	=	$H_{tr,tb}$	0.0

related to: envelope area 0.25 reference area 0.52 $\frac{W}{m^2K}$ sum **61** 35.5

Heat transfer coefficient by transmission H_{tr}

	volume-specific heat capacity air $c_{p,air}$ Wh/(m³K)		air change rate by use $n_{air,use}$ 1/h		air change rate by infiltration $n_{air,infiltration}$ 1/h		$A_{C,Ref}$ m²		room height (standard value) h_{room} m		W/K	
Heat transfer coefficient by ventilation H_{ve}	0.34	x (	0.40	+	0.10	) x	116.6	x	2.50	=	**50**	28.8

		internal temp. ϑ_i °C		external temp. ϑ_e °C		heating days d_{hs} d/a		Kd/a		
accumulated differences between internal and external temperature	(	20.0	-	6.6	) x	212	=	2841		
		H_{tr} W/K		H_{ve} W/K		temperature reduction factor F_{red} (h_{tr}=W/(m²K))		x 0.024 kKh/a		kWh/a
Total heat transfer Q_{ht}	(	61	+	50	) x	1.00	x	68.2	=	**7502**

Total heat transfer: 64.3

window orientation	reduction factors: external shading F_{sh}		frame area fraction F_F		non-perpendicular F_W		solar energy transmittance $g_{gl,n}$		window area $A_{window,i}$ m²		solar global radiation $I_{sol,i}$ kWh/(m²a)		kWh/a	
1. horizontal	0.80	x (1 -	0.30	) x	0.90	x	0.60	x		x	324	=		0.0
2. east	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.7	x	225	=	699	6.0
3. south	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	402	=		0.0
4. west	0.60	x (1 -	0.30	) x	0.90	x	0.60	x	13.7	x	221	=	687	5.9
5. north	0.60	x (1 -	0.30	) x	0.90	x	0.60	x		x	115	=		0.0

Solar heat load during heating season Q_{sol}

sum **1386** 11.9

	kh/d		internal heat sources φ_i W/m²		heating days d_{hs} d/a		$A_{C,ref}$ m²		kWh/a	
Internal heat sources Q_{int}	0.024	x	3.00	x	212	x	116.6	=	**1780**	15.3

internal heat capacity per m² $A_{C,ref}$	c_m	45 Wh/(m²K)	heat balance ratio for the heating mode	$\gamma_{h,gn} = \frac{Q_{sol} + Q_{int}}{Q_{ht}}$	=	0.422
time constant of the building	$\tau = \frac{c_m \times A_{C,ref}}{H_{tr} + H_{ve}}$ =	47	**gain utilisation factor for heating**	$\eta_{h,gn} = \frac{1 - \gamma^{aH}}{1 - \gamma^{aH+1}}$	=	0.92
parameter	$a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}}$ =	2.38				

Energy need for heating $Q_{H, nd}$

$Q_{ht} - \eta_{h,gn} \times (Q_{sol} + Q_{int})$ = **4584** kWh/a 39.3

Figure B.9: Home characteristics terraced home with a thorough renovation

C

APPENDIX MODELLING RESULTS

The appendix presents the raw output data as derived from the linear optimization model.

House/Consumer Type	Total power consumed flexible profile (kWh)	Total power consumed static profile (kWh)
D1C1	12127.897	13780.9537
D1C2	12214.9202	13307.3017
D1C3	14303.8054	14994.0225
D1C4	11951.1613	14625.4309
D1C5	9390.39035	12610.9664
D2C1	3959.50747	4552.81877
D2C2	3992.22827	4396.33816
D2C3	4721.84528	4953.58075
D2C4	3867.35946	4831.809
D2C5	3006.28487	4166.2896
D3C1	2542.11117	2960.35301
D3C2	2574.01198	2858.60553
D3C3	3056.72617	3220.93816
D3C4	2479.55391	3141.75921
D3C5	1922.35265	2709.0224
SD1C1	5808.38364	6614.85778
SD1C2	5834.13787	6387.50478
SD1C3	6869.29901	7197.1308
SD1C4	5701.98626	7020.20681
SD1C5	4438.10118	6053.26384
SD2C1	3236.7409	3736.16966
SD2C2	3267.68431	3607.75733
SD2C3	3870.84949	4065.04608
SD2C4	3160.33015	3965.1168
SD2C5	2454.05268	3418.97309
SD3C1	2078.30142	2429.5311
SD3C2	2106.10905	2346.02799
SD3C3	2503.60518	2643.39063
SD3C4	2025.42061	2578.40929
SD3C5	1569.92186	2223.26665
T1C1	7864.00333	8901.47529
T1C2	7881.72821	8595.53114
T1C3	9250.61559	9685.02787
T1C4	7768.08602	9446.94497
T1C5	6061.86724	8145.7501
T2C1	3176.73215	3654.50475
T2C2	3203.4758	3528.89924
T2C3	3789.86433	3976.19262
T2C4	3102.63022	3878.44758
T2C5	2411.52749	3344.24141
T3C1	1942.90259	2266.20127
T3C2	1968.01863	2188.31182
T3C3	2338.22198	2465.6837
T3C4	1894.38814	2405.07085
T3C5	1468.67434	2073.80335

House/Consumer Type	Average temperature flexible profile	Average temperature static profile
D1C1	19.1368472	20
D1C2	19.027055	19.6
D1C3	20.6833907	21
D1C4	19.1012936	20.7
D1C5	17.1082616	19
D2C1	19.0974574	20
D2C2	19.1094461	19.6
D2C3	20.7658776	21
D2C4	18.9469557	20.7
D2C5	17.0213309	19
D3C1	19.0082895	20
D3C2	19.0601255	19.6
D3C3	20.7258471	21
D3C4	18.8488839	20.7
D3C5	16.9380945	19
SD1C1	19.1735753	20
SD1C2	19.1152361	19.6
SD1C3	20.7642866	21
SD1C4	19.0545769	20.7
SD1C5	17.1051858	19
SD2C1	19.0695686	20
SD2C2	19.0997765	19.6
SD2C3	20.7565115	21
SD2C4	18.9185609	20.7
SD2C5	16.994308	19
SD3C1	18.9827926	20
SD3C2	19.0402548	19.6
SD3C3	20.708208	21
SD3C4	18.8189826	20.7
SD3C5	16.9168298	19
T1C1	19.2107313	20
T1C2	19.0869723	19.6
T1C3	20.7404055	21
T1C4	19.1518883	20.7
T1C5	17.1590652	19
T2C1	19.0939881	20
T2C2	19.1082943	19.6
T2C3	20.7651989	21
T2C4	18.9432058	20.7
T2C5	17.0179153	19
T3C1	18.9975489	20
T3C2	19.0521601	19.6
T3C3	20.7192571	21
T3C4	18.8363174	20.7
T3C5	16.9290285	19

House/Consumer Type	Hours of flexibility provision upward regulation	Hours of flexibility provision downward regulation
D1C1	705	1142
D1C2	525	765
D1C3	625	671
D1C4	698	3236
D1C5	477	5639
D2C1	615	949
D2C2	561	793
D2C3	695	883
D2C4	500	1085
D2C5	314	928
D3C1	291	651
D3C2	306	559
D3C3	400	658
D3C4	233	723
D3C5	135	566
SD1C1	884	1110
SD1C2	703	854
SD1C3	807	873
SD1C4	754	1315
SD1C5	476	1237
SD2C1	457	823
SD2C2	438	687
SD2C3	520	755
SD2C4	340	909
SD2C5	224	755
SD3C1	201	447
SD3C2	210	385
SD3C3	251	493
SD3C4	157	519
SD3C5	85	381
T1C1	912	1132
T1C2	636	790
T1C3	743	760
T1C4	849	1427
T1C5	581	1497
T2C1	435	749
T2C2	377	602
T2C3	445	670
T2C4	331	834
T2C5	214	691
T3C1	174	366
T3C2	167	308
T3C3	200	376
T3C4	132	424
T3C5	72	294

House/Consumer Type	Total flexibility provided upward regulation (kWh)	Total flexibility provided downward regulation (kWh)
D1C1	608.086091	1010.32015
D1C2	420.253265	652.503621
D1C3	503.751674	619.471674
D1C4	675.391376	2160.80317
D1C5	424.72433	3273.1001
D2C1	427.708364	668.103408
D2C2	326.270805	530.108455
D2C3	393.36649	598.798048
D2C4	373.249455	778.268516
D2C5	234.942083	632.001089
D3C1	189.973669	369.618368
D3C2	171.828213	310.975217
D3C3	220.325761	376.617971
D3C4	164.867507	420.698346
D3C5	99.0721928	316.136532
SD1C1	635.711637	899.377511
SD1C2	429.28284	648.28207
SD1C3	492.860382	684.605926
SD1C4	618.016959	1107.42858
SD1C5	380.995383	961.380814
SD2C1	303.380736	521.099783
SD2C2	243.427048	419.4505
SD2C3	285.020829	474.515366
SD2C4	252.938089	592.891887
SD2C5	164.858493	468.769983
SD3C1	126.589099	235.792576
SD3C2	116.189242	200.438708
SD3C3	139.957927	259.930662
SD3C4	106.408194	276.990763
SD3C5	62.2162881	197.188284
T1C1	684.92941	972.171647
T1C2	418.829281	636.981841
T1C3	486.516877	642.331379
T1C4	757.600485	1286.15167
T1C5	460.978848	1193.03348
T2C1	280.153923	467.251005
T2C2	198.611758	359.842939
T2C3	230.271249	407.565011
T2C4	239.28353	537.574588
T2C5	154.136958	423.973736
T3C1	107.209467	187.137553
T3C2	88.2155838	154.893467
T3C3	105.809359	193.519114
T3C4	91.0484748	220.246293
T3C5	53.9099882	149.199568

House/Consumer Type	Average flexibility provided upward regulation (kW)	Average flexibility provided downward regulation (kW)
D1C1	0.86253346	0.88469365
D1C2	0.80048241	0.85294591
D1C3	0.80600268	0.92320667
D1C4	0.96760942	0.66773893
D1C5	0.8904074	0.58043981
D2C1	0.69546075	0.70400781
D2C2	0.58158789	0.66848481
D2C3	0.56599495	0.67814049
D2C4	0.74649891	0.71729817
D2C5	0.7482232	0.68103566
D3C1	0.65283048	0.56777015
D3C2	0.56153011	0.55630629
D3C3	0.5508144	0.57236774
D3C4	0.70758587	0.58187876
D3C5	0.73386809	0.55854511
SD1C1	0.71913081	0.81025001
SD1C2	0.61064415	0.75911249
SD1C3	0.61073158	0.78419923
SD1C4	0.81965114	0.84215101
SD1C5	0.80041047	0.7771874
SD2C1	0.66385281	0.63317106
SD2C2	0.55576952	0.61055386
SD2C3	0.54811698	0.62849717
SD2C4	0.74393556	0.6522463
SD2C5	0.73597542	0.62088739
SD3C1	0.62979651	0.52750017
SD3C2	0.55328211	0.52062002
SD3C3	0.5576013	0.52724272
SD3C4	0.67775919	0.53370089
SD3C5	0.73195633	0.51755455
T1C1	0.75101909	0.85880888
T1C2	0.65853661	0.80630613
T1C3	0.65480064	0.84517287
T1C4	0.89234451	0.9012976
T1C5	0.79342315	0.79694955
T2C1	0.64403201	0.62383312
T2C2	0.52682164	0.59774575
T2C3	0.51746348	0.60830599
T2C4	0.72291097	0.64457385
T2C5	0.72026616	0.61356546
T3C1	0.61614636	0.51130479
T3C2	0.52823703	0.50290087
T3C3	0.52904679	0.51467849
T3C4	0.68976117	0.51944881
T3C5	0.74874984	0.50748152

D

APPENDIX MODEL SETUP

This appendix presents how the model variables have been configured for the main run of the linear optimization model. The exact configurations regarding dwelling type, insulation level and consumer temperature preferences can be found in table D.1.

Table D.1: Overview of User Types and Residential Dwellings

HouseConsumer Type	House	Insulation	Lower Temperature Bound	Upper Temperature Bound	Reference
D1C1	Detached	Poor	18.6	22.1	20
D1C2	Detached	Poor	18.7	20.6	19.6
D1C3	Detached	Poor	20.4	22.2	21
D1C4	Detached	Poor	18.4	24.2	20.7
D1C5	Detached	Poor	16.3	21.1	19
D2C1	Detached	Medium	18.6	22.1	20
D2C2	Detached	Medium	18.7	20.6	19.6
D2C3	Detached	Medium	20.4	22.2	21
D2C4	Detached	Medium	18.4	24.2	20.7
D2C5	Detached	Medium	16.3	21.1	19
D3C1	Detached	Good	18.6	22.1	20
D3C2	Detached	Good	18.7	20.6	19.6
D3C3	Detached	Good	20.4	22.2	21
D3C4	Detached	Good	18.4	24.2	20.7
D3C5	Detached	Good	16.3	21.1	19
SD1C1	Semi-detached	Poor	18.6	22.1	20
SD1C2	Semi-detached	Poor	18.7	20.6	19.6
SD1C3	Semi-detached	Poor	20.4	22.2	21
SD1C4	Semi-detached	Poor	18.4	24.2	20.7
SD1C5	Semi-detached	Poor	16.3	21.1	19
SD2C1	Semi-detached	Medium	18.6	22.1	20
SD2C2	Semi-detached	Medium	18.7	20.6	19.6
SD2C3	Semi-detached	Medium	20.4	22.2	21
SD2C4	Semi-detached	Medium	18.4	24.2	20.7
SD2C5	Semi-detached	Medium	16.3	21.1	19
SD3C1	Semi-detached	Good	18.6	22.1	20
SD3C2	Semi-detached	Good	18.7	20.6	19.6
SD3C3	Semi-detached	Good	20.4	22.2	21
SD3C4	Semi-detached	Good	18.4	24.2	20.7
SD3C5	Semi-detached	Good	16.3	21.1	19
T1C1	Terraced	Poor	18.6	22.1	20
T1C2	Terraced	Poor	18.7	20.6	19.6
T1C3	Terraced	Poor	20.4	22.2	21
T1C4	Terraced	Poor	18.4	24.2	20.7
T1C5	Terraced	Poor	16.3	21.1	19
T2C1	Terraced	Medium	18.6	22.1	20
T2C2	Terraced	Medium	18.7	20.6	19.6
T2C3	Terraced	Medium	20.4	22.2	21
T2C4	Terraced	Medium	18.4	24.2	20.7
T2C5	Terraced	Medium	16.3	21.1	19
T3C1	Terraced	Good	18.6	22.1	20
T3C2	Terraced	Good	18.7	20.6	19.6
T3C3	Terraced	Good	20.4	22.2	21
T3C4	Terraced	Good	18.4	24.2	20.7
T3C5	Terraced	Good	16.3	21.1	19

E

APPENDIX MODEL STRUCTURE

This appendix presents the code as was implemented in python in order to obtain the results which have been analysed in chapter 7.

```python
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
This model optimizes the dispatch of a HVAC unit considering
different residential building and consumer user configurations.

Consumer user profiles are defined in the file RealConsumers.csv
Residential characteriatics are defined in the file RealHouses.csv
"""

#import modules
import os
from os.path import normpath, join
import copy
import itertools
import pandas as pd
import pandapower as pp
import pandapower.networks as pn
import numpy as np
from joblib import Parallel, delayed
import picos as pic
import matplotlib.pyplot as plt
from datetime import date, timedelta
from varname import nameof
from random import *

import System.Assets as AS
import System.Markets as MK
import System.EnergySystem as ES

import sys

print('Code started.')
#plt.close('all')

############## VERSION ##############


__version__ = "1.1.0"

#######################################
###
### Case Study: Building HVAC flexibility
###
#######################################

path_string = normpath('Results/Building_Case_Study/')
if not os.path.isdir(path_string):
    os.makedirs(path_string)

#######################################
### STEP 0: Load Data applicable to all runs
#######################################


#Load Temperature Data, using 2010 time series
Weather_data_path = os.path.join("Data/Weather/air_temperature_2010.csv")
W_data = pd.read_csv(Weather_data_path,index_col="datetime", sep = "," , parse_dates=True)
wdf = pd.DataFrame(data=W_data, index=None, columns=None, dtype=None, copy=False)
wdf1 = wdf["Default"]
pd.to_datetime(wdf1)

#Load House Data of identified house types
Houses_data_path = os.path.join("Data/Building/RealHouses.csv")
H_data = pd.read_csv(Houses_data_path, index_col=0)
print(H_data.head() )
Houses = H_data.to_dict(orient='index')
print(Houses)
```

```
House_label_list = list(H_data)
#Load Consumer data of consumer profiles
Consumers_data_path = os.path.join("Data/Building/RealConsumers.csv")
C_data = pd.read_csv(Consumers_data_path, index_col=0)
print(C_data.head() )
Consumers = C_data.to_dict(orient='index')
Consumer_label_list = list(C_data)



#Load Price Data using Eneco existing policy in 2030
Scenario = "existing" #Indicate which price scenario to run, choose from ["circles", "tides", "accelerated", "existing"]
Year = "2030" #Indicate which year to run, choose between ["2020" until "2060"]
Prices_data_path = os.path.join("Data/Prices/", "epsi_output_nominal_smp_nl_" + Scenario + ".csv")
Prices_data = pd.read_csv(Prices_data_path, index_col="datetime", sep = "," , parse_dates=True)
df = pd.DataFrame(data=Prices_data, index=None, columns=None, dtype=None, copy=False)
df1 = df["smp_nl_" + Scenario]
pd.to_datetime(df1)

#Define which house and consumer types to consider
Types = ['D1','D3','SD1','SD2','SD3','T1','T2','T3']
Consumer = ['C1','C2','C3','C4','C5','C6','C7','C8','C9','C10'] # Choose from ['C1','C2','C3']
#Create combinations of house and consumer types
Typesall1 = list(itertools.chain.from_iterable(itertools.repeat(x, 10) for x in Types))
Consumerall1 = Consumer * 10

#######################################
### STEP 1: setup parameters and dunctions
#######################################

#Definition function indicating how to unpack the data gathered from the model
def unpackarray(array):
    newarray = np.concatenate(array)
    lastarray = np.hstack(newarray)
    plt.plot(lastarray)
    plt.show()
    list1 = lastarray.tolist()
    return(list1)

#Definition function running the linear optimization model
def runcode(col,col1): #col indicates the home type and col1 indicates the consumer type
    dt = 15/60 #1 minute time intervals
    T = int(24/dt) #Number of intervals
    dt_ems = 60/60 #15 minute EMS time intervals
    T_ems = int(T*dt/dt_ems) #Number of EMS intervals
    T_market = T_ems #market and EMS have same length
    powerhp = [] #create empty list of heat pump consumption power
    temphome= [] #create empty list of home indoor temperature
    pricelist = [] #create empty list of electricity prices
    outsidetemp = [] #create empty list of outdoor temperature


    T0_cons = Consumers['T0'][col1] #set the initial temperature to the average temperature indicated by each consumer type

    count = 0
    #Set up the amount of days corresponding to each month, run the model for a full year
    for Month in range(1,13):
        if Month == 1:
            dayrange = 32
        if Month == 2:
            dayrange = 29
        if Month == 3:
            dayrange = 32
        if Month == 4:
            dayrange = 31
        if Month == 5:
            dayrange = 32
        if Month == 6:
            dayrange = 31
```

```
            dayrange = 31
        if Month == 7:
            dayrange = 32
        if Month == 8:
            dayrange = 32
        if Month == 9:
            dayrange = 31
        if Month == 10:
            dayrange = 32
        if Month == 11:
            dayrange = 31
        if Month == 12:
            dayrange = 32
        for day in range(1,dayrange):
            #For the defined day, read the corresponding price data
            Make_wdate = "2020" + "-"+ str(Month) +"-" + str(day) #The number 2020 is used due to the time series format but the mo
            Hourly_temp = wdf1.loc[Make_wdate]
            Make_date = Year + "-"+ str(Month) +"-" + str(day)
            hourlyprices = df1.loc[Make_date]/1000
            MWhPrices = df1.loc[Make_date]

            #Load Price Data
            pricesf = pd.DataFrame(np.repeat(hourlyprices.values,T_market/24,axis=0)) #Transform hourly prices to 15 min intervals
            pricesmwh = pd.DataFrame(np.repeat(MWhPrices.values,T_market/24,axis=0)) #Transform hourly prices to 15 min interv
            stacked_prices = np.hstack(pricesf.to_numpy()) # Make prices readable for program

            #Market parameters
            dt_market = dt_ems #market and EMS have the same time-series
            T_market = T_ems #market and EMS have same length
            prices_import = stacked_prices #Indicate import price of power

            #Defined parameters which are not used but could be defined in future versions
            prices_export = 0.04*np.ones(T_market) #money received of net exports
            demand_charge = 0.10 #price per kW for the maximum demand
            Pmax_market = 500*np.ones(T_market) #maximum import power
            Pmin_market = -5*np.ones(T_market) #maximum export power

            #######################################
            ### STEP 2: setup the network, for this version of the model network capacity is not considered
            #######################################

            #(from https://github.com/e2nIEE/pandapower/blob/master/tutorials/minimal_example.ipynb)
            network = pp.create_empty_network()
            #create buses
            bus1 = pp.create_bus(network, vn_kv=20., name="bus 1")
            bus2 = pp.create_bus(network, vn_kv=0.4, name="bus 2")
            bus3 = pp.create_bus(network, vn_kv=0.4, name="bus 3")
            #create bus elements
            pp.create_ext_grid(network, bus=bus1, vm_pu=1.0, name="Grid Connection")
            #create branch elements
            trafo = pp.create_transformer(network, hv_bus=bus1, lv_bus=bus2, std_type="0.4 MVA 20/0.4 kV", name="Trafo")
            line = pp.create_line(network, from_bus=bus2, to_bus=bus3, length_km=0.1, std_type="NAYY 4x50 SE", name="Line")
            N_buses = network.bus['name'].size

            #######################################
            ### STEP 3: setup the assets
            #######################################

            #initiate empty lists for different types of assets, in this model only building assets are implemented
            storage_assets = []
            building_assets = []
            nondispatch_assets = []


            #Load at bus 3, not used in this version of the model
            Pnet = 0.01*np.ones(T)
            Qnet = np.zeros(T)
            load_bus3 = AS.NondispatchableAsset(Pnet, Qnet, bus3, dt, T)
            nondispatch_assets.append(load_bus3)
```

```
        #Building asset at bus 3
        hourlytemps = pd.DataFrame(np.repeat(Hourly_temp.values,T_market/24,axis=0)) #Transform hourly prices to 15 min inte
        Hourtemp = np.hstack(hourlytemps.to_numpy()) # Make prices readable for program
        Ta_i = Hourtemp #Read outdoor ambient temperature

        Tmax_bldg_j = Consumers['Tmax'][col1]*np.ones(T_ems) #Set up maximum acceptable temperature of consumer type
        Tmin_bldg_j = Consumers['Tmin'][col1]*np.ones(T_ems) # Set up mimimum acceptable temperature of consumer type
        heatmax_j = Houses['heatmax'][col] #Set up maximum heating capacity of installed heat pump in dwelling
        coolmax_j = Houses['heatmax'][col] #Set up maximum cooling capacity of installed heat pump in dwelling
        CoP_heating_j = 3.25 + 0.0875 * hourlytemps.values.mean() #Make heating COP dependent on outdoor temperature
        CoP_cooling_j = 3.25 + 0.0875 * hourlytemps.values.mean() #Make cooling COP dependent on outdoor temperature
        #Parameters from MultiSAVES
        C_j= Houses['C'][col] #Define building thermal capacity
        R_j = Houses['R'][col] #Define building heat transfer coefficient
        Hourtemp = np.hstack(hourlytemps.to_numpy()) # Make hours readable for program
        Ta_i = Hourtemp # Read outfoor temperature
        T0_j = T0_cons #Set up initial temperature at interval time
        bus_id_bldg_i = bus3
        i = AS.BuildingAsset(Tmax_bldg_j, Tmin_bldg_j, heatmax_j, coolmax_j, T0_j, C_j, R_j, CoP_heating_j, CoP_cooling_j, Ta
        building_assets.append(i)
        N_BLDGs = len(building_assets)

        ########################################
        ### STEP 4: setup the market
        ########################################

        bus_id_market = bus1
        market = MK.Market(bus_id_market, prices_export, prices_import, demand_charge, Pmax_market, Pmin_market, dt_mar

        ########################################
        #STEP 5: setup the energy system
        ########################################

        energy_system = ES.EnergySystem(storage_assets, nondispatch_assets, network, market, dt, T, dt_ems, T_ems, buildin

        ########################################
        ### STEP 6: simulate the energy system:
        ########################################

        output = energy_system.simulate_network()

        #Set up output variables from running the simulations
        buses_Vpu = output['buses_Vpu']
        buses_Vang = output['buses_Vang']
        buses_Pnet = output['buses_Pnet']
        buses_Qnet = output['buses_Qnet']
        Pnet_market = output['Pnet_market']
        Qnet_market = output['Qnet_market']
        buses_Vpu = output['buses_Vpu']
        P_import_ems = output['P_import_ems']
        P_export_ems = output['P_export_ems']
        P_BLDG_ems = output['P_BLDG_ems']
        P_demand_ems = output['P_demand_ems']
        P_demand_base = np.zeros(T)
        for i in range(len(nondispatch_assets)):
            bus_id = nondispatch_assets[i].bus_id
            P_demand_base += nondispatch_assets[i].Pnet

        #Update counter necessary for saving the temperature for the next simulation day
        count+= 1
        ########################################
        ### STEP 7: save results
        ########################################
        print(Month,day) #Indicate which date is simulated
        print(col,col1) #Indicate which house and consumer type is simulated
       #Save the power consumed by heat pump and home indoor temperature in a list
        for i in range(N_BLDGs):
```

```
                powerhp.append(building_assets[i].Pnet)
                temphome.append(building_assets[i].T_int)

            T0_cons = temphome[count-1][23] #Update the initial temperature for the next day with the last indoor temperature registe
            pricelist.append(pricesmwh) #Save the electricity price
            outsidetemp.append(Hourtemp) #Save the outside temperature


    #Convert the lists to dataframes
    outtemperature = unpackarray(outsidetemp) #Outdoor temperature df
    eprices = unpackarray(pricelist) #Electricity price df
    intemperature = unpackarray(temphome) #Infoor temperature df
    hppower = unpackarray(powerhp) #Power consumer by heat pump df

    #Store all dfs in one frame
    data = {'Outside temperature': outtemperature, 'Electricity Prices': eprices, 'Indoor temperature': intemperature, 'Power heat pur
    sd = pd.DataFrame.from_dict(data, orient = 'index')
    ssd = sd.transpose()
    ssd.to_csv(col + col1 + 'output.csv') #Save file  with all data as csv
    return(ssd)

#Simulate multiple runs at the same time
results = Parallel(n_jobs=1, backend="threading")(delayed(runcode)(i,j) for i,j in zip(Typesall1, Consumerall1))

#Check if combinations of consumers and homes are created correctly
for i,j in zip(Typesall1, Consumerall1):
    print(i,j)
```