The heat is on:

Examining the weights of factors influencing the choice between residential heating systems and their differences across the Netherlands

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by

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Abstract

In this master thesis, I investigated which factors influence the preference between several heating technologies relevant to the heat transition and how that preference is influenced by local context. Here both economic, cultural and technical aspects are taken into account.

The Netherlands is working on emitting no more carbon emissions in the built environment by 2050. As a result, many buildings require a new heating system. First, I looked at which heating technologies are most relevant for the Dutch heat transition. Indeed, there are plenty of beautiful innovations, however, they may be too new, complex or expensive to be a realistic option for goals set for 2050. Thus, I looked into Dutch policy notes, municipality and real-estate plans to see which technologies are serious candidates for mass implementation. It became clear that most actors see (hybrid) heat pumps and district heating systems as the most realistic, where heat pumps are powered by electricity and district heating systems use energy sources such as waste-heat, geothermal-, aqua thermal-, or ground heat. Hybrid heat pumps are planned to be used as a temporary solution when they can be supplied with natural gas in the meantime. Though many municipalities also hope to use hybrid heat pumps, which are easier to implement than full-electric heat pumps, with sustainable gasses in the future, there are many doubts about how realistic that will be due to the limited availability of sustainable gas. Therefore this research will focus on comparing heat pumps and district heating.

Next, through a literature study and exploratory interviews with two experts, a list of sixteen factors perceived as relevant for deciding between installing a heat pump or a district heating was conducted. Three types of local context are determined, representing a significant portion of Dutch neighbourhoods. These are rural, such as small towns further from cities, suburban (neighbourhoods close to cities with medium population density), and social living (buildings where residents share certain spaces, such as a central entrance). Through the best-worst method, a multi-criteria decision method, the factors were assigned weights varying per local context. To this end, seven expert interviews are conducted to determine the factors' global weights. Another eight interviews were held to determine the weights for the local contexts.

In general, *capital investments*, *building characteristics* and *market facilitation* were rated as most important by the experts. These results coincide with the literature. Financial factors increase the feasibility of a project. Building characteristics are often a starting point for determining which technology will be applied. Market facilitation also has a positive symbolic effect, as subsidies increase technology acceptance. In rural context, *capital investments*, *pay-back period* and *consumer willingness* are most important. People act more independently and base their decision on what it brings to them. In social living, *market facilitation*, *coercive pressures* and *building characteristics* are most important. This is due to the effect that often an external actor is involved with the decision making opposed to the residents. In suburban neighbourhoods, *human resources available for implementing* and *capital investments* are most important. This is because it is the largest group, and by focusing on making those more sustainable, you get the most gain in reaching your climate

goals.
For further research, it is recommended to assess the scores of each factor in each context, so as to gain more knowledge on which technology is most likely where. Additionally, one could dive deeper into how the local contexts relate to the Netherlands.

Preface

To all students working on their thesis: last year, over 3,700 students handed in their master thesis (TU Delft, 2021). And now I am one of them, as will you later. Though the whole experience can sometimes be daunting and exhausting, as I understood my topic better, I enjoyed it more and more. Keep on learning; it is only temporary after all.

I am content with how it all turned out. Looking back on my student trajectory, I liked how I always chose to broaden my horizon. From studying hardcore theoretical physics (determining the orientation of silicon crystals using electron microscopy diffraction patterns), to medical engineering (quantifying the distortion dental braces cause in MRI imaging), to socio-technical research on the heat transition. Yeah I like learning new perspectives on a problem. I am glad I got all the space I needed to discover different topics and methods. And well, I look forward to the next puzzle.

I want to thank most of all the experts that I got to talk to during this research. Whether it be a lengthy phone call with good leads, bits of advice on who to approach, or those who participated in one of the interviews. I learned so much from talking to you all; you made the heat transition come to life with all your stories. Next, the supervisors and the other members of the thesis circle for their honest feedback and helpful input. And many thanks to all the friends and study mates with whom I spent many, many hours in Echo, TN and 2wi, you know who you are ;)

Delft, November 2022

Abbreviations

BWM	-	Best-worst method
COP	-	Coefficient of performance
DH	-	District heating
DOI	-	Diffusion of innovation
GIS	-	Geographic information system
HP	-	Heat pump
HT	-	High-temperature
LT	-	Low-temperature
MCDM	-	Multi-criteria decision method
MT	-	Medium-temperature
NPE	-	Nationaal Plan Energiesysteem 2050
PBL	-	Planbureau voor de Leefomgeving
RVO	-	Rijksdienst voor Ondernemend Nederland
TVW	-	Transitievisie Warmte

Contents

Chapter 1

Introduction

There is no denying of the dangers and the effects of climate change, looking for instance at the impact on vegetation, weather patterns, and changes in nature such as coral reefs (Sykes, 2009; D'Agostino and Schlenker, 2016; Hoey et al., 2016). Climate change occurs due to the increased amount of carbon-based greenhouse gases. The Netherlands, in compliance with global agreements such as the Paris agreement, set goals for reducing its carbon emissions to limit the effects of climate change. To achieve this, the Dutch need to decarbonise their energy system.

To decarbonise, the government needs to phase out fossil fuel sources. However, the country is greatly dependent on the usage of fossil fuels. For instance, the average building uses approximately 71% of its for heating, which for all buildings encompasses 20% of the total yearly energy usage in the Netherlands (CBS, 2019). Currently, 85% of all buildings are heated by natural gas (CBS, 2019), as seen in figure 1.1. As natural gas is carbon-emitting, the Rijksoverheid decided to phase out natural gas and that by 2050 no more houses may be heated using natural gas (Ministerie van Economische Zaken, 2016). Thus, many buildings will need a new energy source for heating.

This research aims to clarify which heating systems are suspected to thrive in different types of local context, by examining which factors, in general, are perceived as important. There are several sustainable alternatives for heat generation, for instance, using heat pumps, district heating, geothermal heat, sustainable gasses or other electric solutions. What heating technology to use where is a complicated question due to the many variables involved. The results will increase the knowledge of which heating technology are more likely to be allocated among different locations and why. The results may give policymakers, municipalities, and the national government exciting insights. The research adds to the scientific literature as the results can be used for further studies on energy source allocation and give insights into which factors are perceived as important.

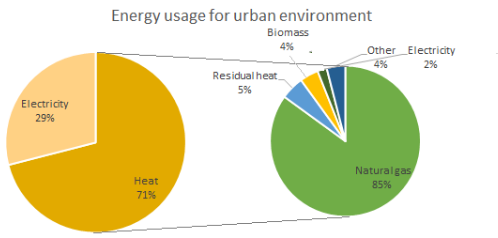

Figure 1.1: Energy usage in the urban environment. The left pie chart shows that most consumed energy goes into heat, generated by the sources mentioned in the pie chart on the right (statistics from CBS, 2019).

1.1 On the problem and heating systems

Let us briefly examine some heating alternatives: heat pumps, district heating, and geothermal heat. Heat pumps use electric energy to transfer heat from one space to another, which usually comes down to the transfer of heat between the outside and the inside of a house. These devices have the advantage of having high efficiency and, when used with low-carbon electricity, have a low carbon footprint (Fischer and Madani, 2017). District heating comprises a centralised plant or distributed heat-producing units, which connect through a network of pipes to multiple buildings in a neighbourhood or even a whole city. The heat source is flexible; it can be waste heat from an industrial plant, renewable, biomass, or fossil-fuel boilers. (Lund et al., 2014) Very innovative district heating systems, such as 5th generation district heating systems which are bi-directional and incorporate renewable energy sources and heating storage, lead to a reduction in heating demand, as less heat is wasted (Boesten et al., 2019). Geothermal heat is sustainable heat gained by pumping water to deep depths, ranging from 2-6km, where the earth heats it. The heat is then extracted from the water and gets distributed, for instance, to heat buildings or industry processes (Mijnlieff, 2020).

Previous studies expect district heating, geothermal, and heat pumps to play a central role in future energy systems, even for residential consumers, for they can be cost-competitive alternatives to biomass boilers (Petrović and Karlsson, 2016; Boesten et al., 2019). Allocating these promising technologies is challenging. For one, you cannot install heat pumps in every house due to the increased electricity demand that would cause. The fossil fuel demand would shift from the building side to the central electricity production side, making lowering carbon emissions futile (Walker et al., 2019). It is also unlikely to have every house on a district heating network. These networks become more ineffective for areas with a low energy consumption density, and there need to be sufficient usable heat sources (Zach et al., 2019).

Thus, it is expected that the Netherlands will have a mix of different heating technologies in the future. What will that mix look like? Is that dependent on the building density, the grid, finances, energy production facilities, or consumer preference? And what will that mix look like across the Netherlands? Will we see a different energy system for urban and rural? These are questions that I wish to investigate through this research.

There are bodies of literature that research technology adoption and dominance. For instance, diffusion of innovation, which examines the adoption of an innovation. By analysing a set of factors, researchers can attain information on the rate of adoption. These factors (relative advantage, complexity; compatibility; trialability; observability) concern themselves with the adopter's perception of the innovation. Thus, analysing the factors gives us information about their possible adoption rate. Besides looking at the aspects of the innovation itself, network externalities can also significantly impact the adoption of technology Katz and Shapiro, 1986. Network externalities are external consumption benefits, such as compatibility with other products or a large user base. Another body of literature concerns itself with institutionalisation, where obligations or social processes influence the behaviours of organisations, for instance by making themselves similar to other organisations in the same environment.

It is important to note that typically no single factor tips the balance between two different technologies; it is the interplay between several factors that determine the more dominant technology (Suarez, 2004). However, tweaking factors could enhance the feasibility of a technology. For instance, in a paper from 2019, the integration of district heating using factors related to energy and spatial planning was examined. The research found that tweaking the attribution of certain factors, such as using policies, could enhance the district heating systems' feasibility and advantages. (Zach et al., 2019)

The effect of location is seen in more research There has also been some research on the preference between heating systems using geographical factors, such as altitude and population size (Franceschinis et al., 2016). Franceschini found that these factors, including the location of the surveyed participants, influenced the residents' preference for specific features in heating systems. The research suggests that the location could influence the adoption of specific technologies. Spatial distribution is essential, as is seen with wind and solar renewable energy technologies. These yield more energy in the peripheral of Europe rather than the centre, and that affects their implementation when creating an energy supply system on different scales (continental, national and regional) (Tröndle et al., 2020).

Different locations can give rise to different weights given to local and regional factors, such as land availability, technological needs, and replicability, as seen in (Kalbar et al., 2012). Here Kalbar compared a few different water cleaning systems amongst different scenarios, including technical and spatial changes. Redistributing the weights for different scenarios and locations yielded different results for the preferable technology. A fairly new study did something quite comparable. Here several renewable energy sources were compared and a ranking for different regions was determined (Alkan and Albayrak, 2020). This shows that you can use multi-criteria decision methods to determine the best technology for a location. So, it could be useful to assess their dominance using factors and to look at locations for heating technologies.

1.2 Knowledge gap & research questions

The studies above differ because the factors used were majorly technology or location-focused. However, to answer the question of how to use the different heating technologies, we need to consider their economic and technological aspects. Using both research fields, economic and non-economics technology adoption, we may derive interesting conclusions on how two heating technologies, district heating and heat pumps, are expected to contribute to society.

What has been seen little before is the influence of location on the adoption of new technologies. Location likely plays a role, looking for instance in previous research (Minaei et al., 2021; Tercan, 2021; Alkan and Albayrak, 2020; Kalbar et al., 2012), however *how* and *why* location plays a role, is relatively unknown, specifically for heating technologies. These questions can be answered by analysing factors using multi-criteria decision-making (MCDM) tools. This leads to a knowledge gap; there is little knowledge on which heating technology shall be dominant and how that depends on location due to a lack of research on how location plays a role in technology dominance battles.

The main research question is as follows: *"What factors influence the preference between different heating systems for real estate and how are they affected across different areas in the Netherlands according to experts?"*

The main research question is answered through the following sub-questions:

1. *Which heating systems are seen as relevant for the Dutch energy transition?*
2. *What factors, according to literature and experts, influence the choice between the relevant heating systems?*
3. *What is the weight of these factors according to experts?*
4. *How are the weights of the factors dependent on local context?*

1.3 Research approach

The research aims to provide knowledge on the factors concerning decision-making on heating system choices and how they may differ within the Netherlands. This research will have a practical perspective. The research's scope is narrowed to relevant technologies, as the energy transition is already happening. Some technologies are too new or complex to be expected to have a (significant) role in the heat transition. Here field experts provide a benefit, as their knowledge can be used to see which factors are important in practice.

First, it will be determined which technologies are most likely to play a role in the Dutch heat transition. It is useful to narrow all the different heating system options down to the most relevant ones. This will make the exploratory interviews and the topic of the BWM more focused. After all, comparing heating systems that are not feasible to be implemented in the near future is irrelevant and does not fit the research goal. I will look at secondary data to find out which technologies are relevant. Looking up secondary data has the advantage that it is readily available and is often used to support further research (Guerin et al., 2018; Sekaran and Bougie, 2016).

The second sub-question aims to gather information on what factors have a role in the decision-making of different heating technologies. The second sub-question will be answered in three parts. Firstly, some theories on innovation adoption are investigated through a literature study to provide a deeper understanding of technology adoption. The adoption of heating technologies is not unique, and there are aspects of general adoption theories that can be applied. Secondly, a literature study specifically on heating system adoption is performed. There can be factors specific to heating systems, and by looking into past papers, a better understanding of the specific case is achieved (Snyder, 2019). Lastly, exploratory interviews with experts are used to find factors that may have been overlooked or are specific to the Dutch heat transition. The interviews can be held with academics, consultants, or government officials. The interviews will give a better insight into the real-life situation of the problems, as they have experienced in the field of heating system integration. (Alshenqeeti, 2014).

The best-worst method (BWM) is used for the third sub-question. This method lets us gain insight into the influence of the factors in decision-making (Rezaei, 2015). The best-worst method compares a set of alternatives (the different heating system configurations) among several criteria (the factors). The method determines the optimal weights for the criteria. It has the advantage that it is robust and requires fewer comparisons than other multi-criteria decision-making methods, which increases its simplicity while remaining accurate (Rezaei, 2015).

Lastly, during an additional expert interview, experts will be asked to weigh the factors in different local contexts through another BWM. As a result, we will have the general weights and the weights per local context. Together, these give information on which factors are essential in which local context.

Using all this information, the main question can be answered. The research is summarised in the flow diagram in figure 1.2.

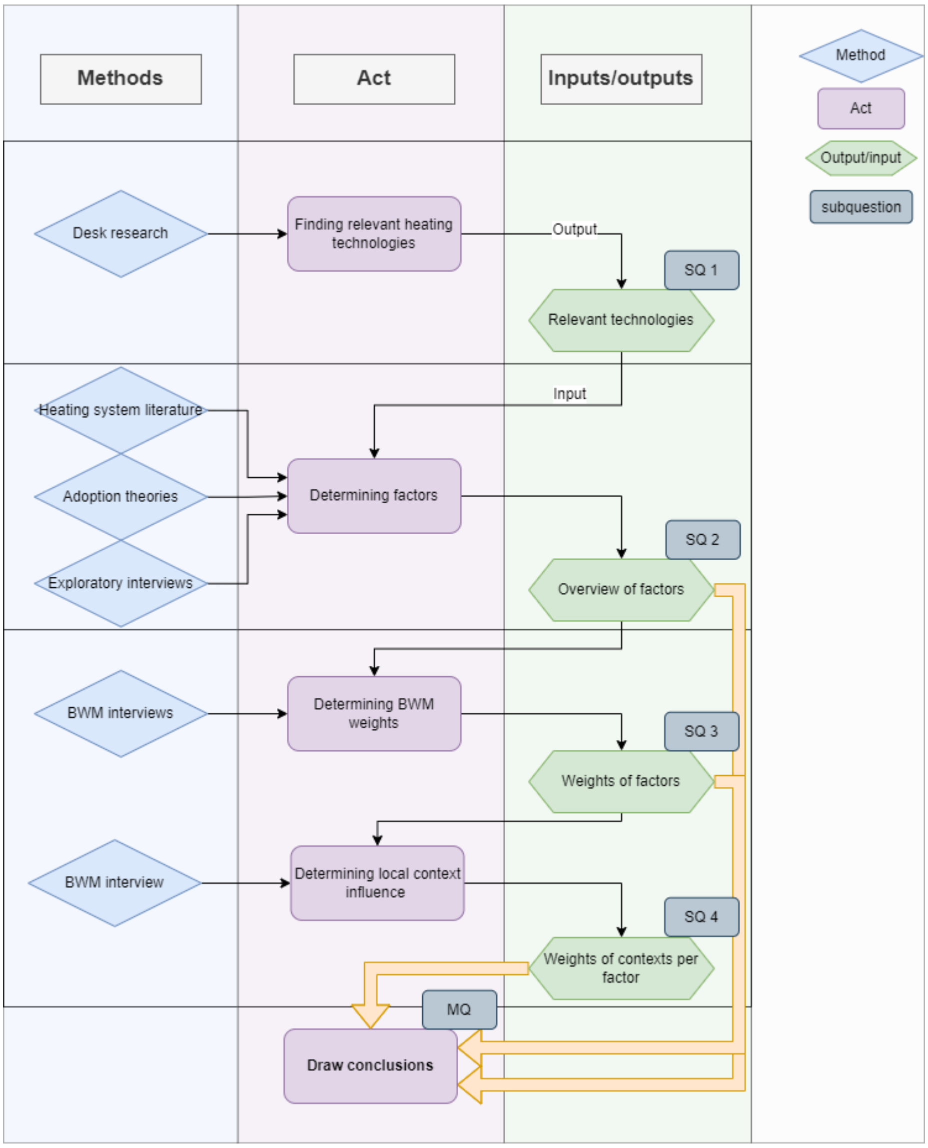

Figure 1.2: Research flow diagram

1.4 Relevance

1.4.1 Societal relevance

This research is easily linked to society, as the energy transition is a major challenge during the coming decades. As the Netherlands is phasing out natural gas, a need arises for sustainable energy sources, such as heat pumps and modern district heating systems. This research aims to clarify how to effectively use the different heating methods and increase the knowledge on which heating technology to allocate among different regions and why. This will give policymakers, municipalities, and the national government interesting insights. By knowing the predicted dominance of technologies, one can more effectively use governing tools to accelerate the transition to a sustainable heating system.

1.4.2 Academic relevance

This research adds to the scientific literature because the combination of technology adoption with variations in location is little researched, specifically for heating technologies. By investigating the role of location on adoption, one can learn more about the implementation of technology. This has been researched little with multi-criteria decision-making tools.

Incorporating spatial context in research that uses modelling methods (for instance, by incorporating GIS, Geographic Information System) is difficult due to a lack of geospatial data and the massive amount of computer processing required to analyse individual housing units. Thus far, the spatial context has received limited research attention (Rafiee et al., 2019). By incorporating spatial context in the criteria used for MCDMs, there is a more straightforward method of researching the effects of location on research problems.

Furthermore, there have been very few papers that use BWM to compare heating systems. Using Scopus, only one paper was found that used a BWM framework to compare heating systems, namely heat pumps, solar heating, and wood pellet boilers Balezentis et al., 2021. No papers were found that compared the potential use of heat pumps and district heating using BWM.

1.4.3 Link to SET

This research project will be performed as a thesis for the master of Sustainable Energy Technology (SET). The program teaches about renewable energy sources and related technologies. The program also looks at the economic and social systems involved in energy production, distribution, and transition. Notably, a research project of SET contains system integration. This research will merge knowledge of energy systems with social and economic systems.

The topic will focus mainly on system integration within the Economics & Society profile. As told by the objectives of a SET thesis, the research will include a literature study, theoretical work with interpretation, and evaluation of the results. This aligns with the research objective of the SET program.

1.5 Structure

The thesis is structured as follows. First, in chapter 2, the methodology will be presented. Chapter 3 will review adoption theories and present literature on heating system adoption. Here a list of preliminary factors found in literature and theory is presented. Afterwards, chapter 4 will discuss which technologies are seen as relevant for the Dutch heat transition. Chapter 5 presents the results, which include the results of exploratory interviews, the final list of factors, their weights, and their local dependency. Chapter 6 provides the discussion and future recommendations, followed by the conclusions in chapter 7.

Chapter 2

Methodology

To answer the main question *'What factors influence the preference between different heating systems for real estate and how are they affected across different areas in the Netherlands according to experts?'* first the four sub-questions need to be answered. They will be answered using the methodology described in this chapter. Each section will discuss a method and explain how that will fit a corresponding sub-question.

2.1 Exploring relevant heating systems: desk research

To start, desk research will be used to answer the first sub-question; "*Which heating systems are seen as relevant for the Dutch energy transition?*". Desk research is a method for collecting secondary data, which already exists and was initially obtained for other purposes (Sekaran and Bougie, 2016). As there are already (rough) plans and visions for the heat transition, I want to look at the heat technologies expected to be used in the coming decade(s). This results in a more practical outcome and more focused results.

The process is divided into three steps:

1. Define topic: 'What are likely technologies to be implemented for the heat transition, according to the parties involved with implementing the technologies.' The question is narrowed down to '..,*according to the parties involved..*'' as these are more likely to match reality.
2. Identify select and review sources: the sources are found using inclusion- and exclusion criteria and search terms. The Klimaatakkoord (climate agreement) will be used as a starting point. The Klimaatakkoord is the Dutch response to the Paris Agreement, containing agreements on measures to meet climate goals (Klimaatakkoord.nl, 2018).

Inclusions criteria: Preferable use reports published later than 2016, when the predecessor of the Kimaatakkoord, the 'Energieagenda', was published. These contain the latest policy, technological and economic developments. I will focus on government reports, municipalities and regional reports, as they are critical in determining the heat transition (Jetten, 2022). Furthermore, government reports would contain steps that the industry and other actors will take. There will also be a focus on guidelines given to and by the built environment sector as these are close to feasibility. Scenario studies are included, as they provide several perspectives and possibilities.

Exclusion criteria: reports on the newest technology innovations are excluded, as they are less likely to be implemented for the 2030 and 2050 heat goals. Furthermore, files from before December

2015, when the Paris Agreement was released, are excluded.

Search terms: the Klimaatakkoord and its predecessor, the Energieagenda, are used as starting documents. These search terms are derived from keywords that are used in these two documents. Google is used as the search engine. The search terms are translated to Dutch during the analysis. Furthermore, backward reference searching is applied. The following search terms will be used:

Table 2.1: Search terms used for desk research on relevant heating systems

Long-term strategy OR vision AND climate AND Netherlands
Vision OR strategy AND heat AND transition AND extern* advice
Energy AND heat AND scenarios
Report AND transition AND government AND heat OR natural gas

3. Combine and compare: lastly the findings need to be put together to a cohesive whole. This is next followed by a short discussion to interpret the findings. The results of the desk research are in chapter *4. Heating systems across the Netherlands*.

Furthermore, I will look at different multiple Transitievisies Warmte (TVW, 'transition vision on heat'). At a municipality level, each municipality is obliged to make a TVW, which is meant as a guideline for their approach to heat transition. Here municipalities will provide timelines and solutions to make different neighbourhoods natural gas-free. These will give a concrete indication of which technologies municipalities envision for their neighbourhoods.

Careful attention is paid to reading both visions of small, big, dense, urban and rural municipalities. Every time the municipalities population and density are checked to confirm this. This ensures that a complete vision is from a broad perspective. In total, 24 TVWs are read, two for each province. Each municipality notes down which technologies they expect to include and exclude.

2.2 Exploring heating system adoption factors

The second sub-question, '*What factors, according to literature and experts, influence the choice between the relevant heating systems?*, is split into three parts: factors according to general literature on innovation adoption, according to literature on heating system adoption and factors according to experts.

In section 2.2.1, the method for finding factors according to literature is described. The method for determining the factors according to field experts is described in the next section 2.2.2.

The results of both analyses are merged to form a final list of factors.

2.2.1 Literature review

The factors according to theory and literature are found using a literature review.

First existing theories on innovation adoption and format selection are studied. From this, a list will be made with factors that are relevant for innovation adoption. Here Van de Kaa et al., 2011 is used as a starting point. This paper proposes a framework where several literature streams on interface format selection are merged. Though this paper is not specifically about adoption, it does provide a good overview of relevant literature streams, which can then separately be further investigated for their relevance to this specific problem. Here it is determined that *diffusion of innovation*, *neo-institutional theory*, and *network economics* are further investigated. These three literature streams each tell us something about the adopter perspective, the institutional aspects, and market mechanisms.

Next, literature on heating system adoption is examined to find factors which are not already mentioned in one of the adoption theories. The review is based on two sets of search terms, which are found through trial and error. The systematic literature review is presented in figures 2.1 and 2.2 below, illustrating a Prisma diagram. All results are found through Scopus. Backward referencing is applied to find more details on specific factors. New factors are then added to a list. Factors that overlap in definition or are closely related are reworked or removed to make a shorter list with unique factors.

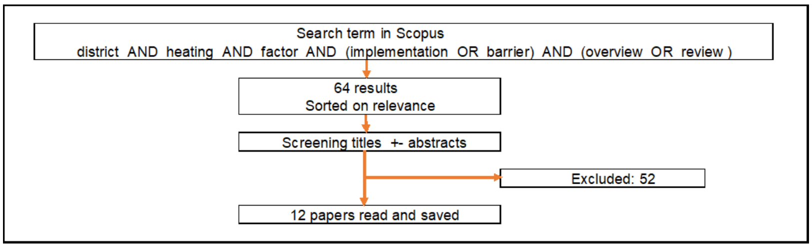

Figure 2.1: Prisma diagram for literature review on district heating adoption

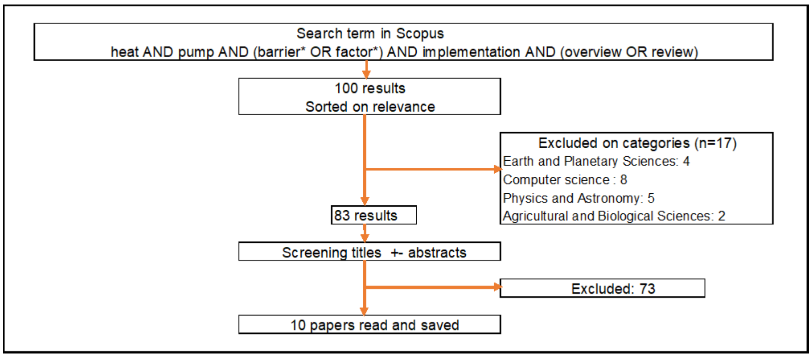

Figure 2.2: Prisma diagram for literature on heat pump adoption

2.2.2 Exploratory interviews

Interviews are used as a method to answer the second part of the second sub-question; "*What factors, according to literature and experts, influence the choice between the relevant heating systems?*".

Here the goal is to find any factors which are not discovered during the literature review. These may be factors which are specific to Dutch context. A final list with relevant factors can be constructed using the results of the exploratory interviews and the literature study.

The interviews will be conducted in a semi-structured way due to their exploratory nature. So there will be no fixed set of questions, however, there will be preparations. Firstly, the interviewer will introduce herself and explain the purpose of the interview. Next, the confidentiality of the data will be assured, and permission will be asked to record the interview. Following this, the interviewer will ask broad, open-ended questions to start the interview and ensure that the interview stays on topic. Example questions are listed in the table 2.2. This table is used as a rough guideline during the interviews. The interviews are about an hour long.

The questions and topics mentioned in table 2.2 are used as a guideline for the exploratory interviews.

Data processing

Afterwards, the interviews will be transcribed intelligently verbatim, where filler words and grammatical errors are removed, but otherwise the wording is authentic. The transcript can therefore be accurately used for quotes. As all interviews are in Dutch, the quotes will be translated into English using DeepL, an online neural machine translation service. Factors are determined by careful reading and underlining interesting statements and all statements which refer to possible factors.

Table 2.2: Questions that are asked during the exploratory interviews.

Introduction
·Introduction of interviewer ·Explain purpose of interview ·Discussing confidentiality ·Asking permission to record
General questions
· *Tell me something about how* [municipality/company/etc] *go about determining which heating system to use* · *Compared to* [technology A], *what are the strengths and weaknesses of* [technology B] · *How do these strengths and weaknesses impact the decision process?* · *What problems do you face when opting for one technology?*
Probing tactics
· *So you are saying that* (...)? · *Would you give an example?* · *Could you tell me more about* (...) ? · *Could you go over that again?* · Repeating the answer
Final questions
· *Is there anything more you'd like to share on (...)?* · *Do you have a colleague in mind who I should also interview on this topic?*

Experts: whom to interview

There is no 'golden rule' on determining whether one is an expert (Shanteau et al., 2002). The definition of 'expert' varies per research goal. Therefore one determines their own requirements that an expert needs to fulfil. The criteria that are used for this research are listed below. These criteria account for all performed interviews.

- The expert should know about both heat pumps and sustainable district heating so that the expert can perform good comparisons.
- The expert should be familiar with the implementation or the regulation of the technologies. The research concerns the adoption of the technologies within real estate and how consumers choose between one or the other technology. Therefore the expert cannot just be familiar with the technical aspects behind the technology.
- The expert needs to have verifiable experience in planning heating system technologies.

The interviewed experts are shown in figure 2.3. The aim is to have various backgrounds to provide a broad perspective on the problem. The experts can be found, among others, in consultancy, government, academics, and industry. Mainly experts with a consultancy role are interviewed, as they have a good overview of all the different stakeholder perspectives, which makes them able to give more general viewpoints.

		BWM							
	Exploratory								Local context
	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9
Role	Academic, industry	Academic	Consultant	Consultant	Consultant	Consultant	Director, consultant	Consultant, installation	Consultant
Domain	Engineering	Policy	Architectural	Engineering	Social urban	Engineering	Management	Engineering, Management	Managemen t

Figure 2.3: Backgrounds and roles of the interviewed experts. Expert 1 and 2 were spoken for the exploratory interviews. Expert 2-8 were spoken for the global weights BWM, and expert 9 was interviewed for the local context BWM

2.3 Determining weights: secondary interviews using best-worst method

This section will discuss the methods for answering the third sub-question; *'What is the weight of these factors according to experts?'* This will be done through the best-worst method, where the data is acquired using a second round of interviews. Here first the steps and corresponding maths behind BWM are explained, followed by a comparison between BWM and other similar methods. Next, I will go into more detail on how the interviews are performed—followed by how the consistency is determined and how the sensitivity analysis will be performed.

2.3.1 Best-worst method: determining factor weights

The best-worst method, or BWM, is a multi-criteria decision-making (MCDM[1]) tool.

MCDM tools are used when analysing a problem with a discrete decision space, meaning there is a fixed set of alternatives to choose from. MCDM tools let one determine the best alternative using several (weighted) criteria. MCDM is frequently applied in technology or site selection (Khanlari et al., 2022).

[1] Generally, multi-criteria decision-making is split up into two branches; multi-objective decision-making (MODM), which handles continuous problems, and multi-attribute decision-making (MADM), which solves discrete problems. However, literature often means MADM tools when discussing MCDM (Rezaei, 2015). Therefore, for the remainder of this thesis when talking about MCDM, I will mean discrete MCDM (so MADM) tools.

An MCDM problem can briefly be written down as

$$V_i = \sum_{j-1}^{n} w_j p_{ij} \tag{2.1}$$

where n is the amount of alternatives, w_j the weights of criterion j, and p_{ij} the score of alternative i with respect to criterion j. V_i then signifies the value of alternative i. By analysing all alternatives like this, the one with the highest value V is selected as the most desirable alternative. This research only determines the w_j's. BWM uses pairwise comparisons. Here we can determine the criteria weights by only using best-to-others and worst-to-others comparisons. Now, the BWM procedure is explained.

BWM steps

The best-worst method is performed as follows. Firstly a set of decision criteria $c_1, c_2, ..., c_n$ is determined. During the research, these decision criteria are referred to as 'factors'. Next, the most important (e.g. best) and the least important (e.g. worst) decision criteria are determined. Now the comparisons are made. The preference of the best criterion over all other criteria is stated in the following best-to-others vector A_B:

$$A_B = (a_{B1}, a_{B2}, ..., a_{Bn}) \tag{2.2}$$

where a_{Bj} signifies the preference of the best criterion to criterion j, with $a_{BB} = 1$. Next, the same is done for the worst criterion, resulting in the worst-to-others vector A_W:

$$A_W = (a_{1W}, a_{2W}, ..., a_{nW})^T \tag{2.3}$$

Note that the subtext is flipped (jw instead of wj), so the preference of criterion j over the worst criterion is determined.

The next step is to determine the weights of the criteria. The ideal weight of criterion j, w_j, would be the one where $w_B/w_j = a_{Bj}$ and $w_j/w_W = a_{jW}$. So to find that, we need to want to minimise $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ Then the following optimisation problem is solved to find the optimal weights $(w_1^*, w_2^*, ..., w_n^*)$:

$$\begin{aligned}
&\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \quad \text{for all } j \\
&\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \quad \text{for all } j \\
&\sum_j w_j = 1 \\
&w_j \geq 0, \quad \text{for all } j
\end{aligned} \tag{2.4}$$

The problem can easily be solved using an Excel model published by Rezaei (Rezaei, 2022).

2.3.2 Comparison with other Multi-Criteria-Decision-Making methods

A significant difference between different MCDM methods is how the weights are obtained. Inconsistency is a problem with pairwise comparison matrices. Rezaei argues that the inconsistencies arise from the unstructured way the comparisons are executed. Then, for instance, inconsistencies come into play due to a lack of concentration of the participants, making the final weights more unreliable. Here, BWM comes in. BWM uses fewer comparison data compared to other MCDM methods. This is especially the case for AHP (analytic hierarchy process), a well-used method very similar to BWM, which also uses pairwise comparisons (Şahin, 2021). The main difference with AHP is that AHP requires $n(n-1)/2$ comparisons, while BWM requires $2n-3$ comparisons, with n being the number of criteria. For $n = 9$ this gives the difference between making fifteen or thirty-six comparisons. This makes BWM take less time while retaining consistency. It is found that BWM and AHP give similar results when using the same expert knowledge (Şahin, 2021).

BWM, as is AHP, is a subjective method, as opposed to objective methods that use mathematical models and data. A subjective method is chosen for this research, as it allows the input of field experts, thus providing very down-to-earth results which closely match reality.

2.3.3 Best-worst method interviews

The BWM data is gathered using structured interviews, where the researcher guides the interviewee through constructing the best-to-others and others-to-worst vectors. By performing the best-worst method as an interview rather than an online survey, valuable information from the participants' comments is gained. This is done by asking the participants why they rate specific criteria the way they do. This additional knowledge from experts in the field helps to get a better picture of what is happening.

The structure of the interview is displayed in table 2.3. The interviewees will determine the most and least important decision criteria. After that, they will construct the best-to-others and worst-to-others vectors, noted in equations 2.2 and 2.3. They will fill in the information in a fillable Excel sheet, which clearly outlines the information they need to fill in. The Excel sheet is used from Rezaei, 2022.

It is vital to ensure the interviewees understand what the comparisons mean. The interviewer helps the participants by repeating their answers in written form. Thus if a participant scores the comparison of A to B with 5, the interviewer will repeat, "so you say criteria A is strongly more important than criteria B?". An example is provided in case the participants do not grasp the method.

Table 2.3: Proceedings for the best-worst-method interviews.

Introduction
·Introduction of interviewer ·Explain purpose of interview ·Discussing confidentiality ·Asking permission to record
Explanation of BWM
· Determine the most and least important factor · Compare them using a 1-9 scale · *Feel free to assign the same number multiple times* ·*If you think a factor is completely irrelevant, you can leave it empty* ·*Feel free to make comments on your reasoning*
Proceed to first category
· Explanation of the factors ·*Which factor is most important, and which one is least important when deciding between a hybrid heat pump, electric heat pump, or district heating?* ·Best-to-others: *how much more important is the best factor compared to factor X?* ·Others-to-worst: *now compare how much more important factor Y is compared to the worst.*
Repeat for all four categories
Repeat for category-comparison

2.3.4 Checking consistency & sensitivity

Once the results are obtained, the data needs to be checked on whether it is reliable. For that, the consistency is checked. The comparison matrix is said to be inconsistent when the comparisons do not align with each other. The data is inconsistent, and therefore the results also become more unreliable. This happens when $a_{Bj} \times a_{jW} \neq a_{BW}$. It is a recurring problem (Rezaei, 2015; Liang et al., 2020), and therefore it is important to check the comparison data. Some inconsistency is allowed, as achieving perfect, consistent data is unrealistic.

This section explains the consistency ratio, a method for quantifying the consistency of the comparison data. Also, a sensitivity analysis will be performed, which is explained here as well.

Output consistency ratio

ξ, as used in equation 2.4, can help us determine the consistency of the data. One method for testing the consistency of the data is by looking at the output consistency ratio, CR^O, as noted in equation 2.5. The ratio gives us information about the inconsistency, as it reflects the value of ξ^* compared to its maximum value. The closer the ratio is to zero, the more consistent the data is.

$$CR^O = \frac{\xi^*}{\max \xi} = \frac{\xi^*}{\text{Consistency Index}} \tag{2.5}$$

Now a brief explanation of how equation 2.5 is derived and subsequently used. The data is defined as inconsistent when $a_{Bj} \times a_{jW} \neq a_{BW}$. In the BWM procedure, this is 'fixed' with ξ, as seen in:

$$(a_{Bj} - \xi) \times (a_{jW} - \xi) = (a_{BW} + \xi) \tag{2.6}$$

By solving equation 2.6 for a_{BW}, we can find the maximum possible ξ as a function of $a_{BW} \in \{1, 2, ..., 9\}$. The maximum ξ is called the *consistency index*. As the values of the consistency index are solely a function of $a_{BW} \in 1, 2, ..., 9$, they are calculated in advance. Thus, using the obtained ξ^* from the solution of equation 2.4 and the consistency index, we can check the consistency of the data.

Sensitivity analysis

A one-at-a-time sensitivity analysis is performed. One expert-data-set at a time is removed from the whole set. For every removal, the average change in global weight (avg(dGW))is noted down, which is calculated using the equation below

$$avg(dGW) = \frac{\sum_i^N |GW_i - GW_{i0}|}{N} \tag{2.7}$$

with N being the number of factors, which is sixteen for this case. GW is the global weight, with GW_{i0} being the global weight of derived from the full data set.

2.4 Role of local context

For this research, we also want to extend the knowledge of how the adoption of technology is affected by location and thus the local context. The goal is therefore to determine whether the weights are dependent on local context. So not whether the final score is would vary per context, but really just the weights. For example, does a municipality look at capital investments differently when we are talking to a rural municipality versus an urban municipality?

Three types of local contexts are determined. They each differ in their characteristics, which include physical, (location, facilities, characteristics), social, (stakeholders, demographic, politics), economic (resources, supply and demand) and cultural characteristics (trust, openness to change) (Gordon, 2022).

- Local context 1: rural
  Small towns and larger farms. Some distance to cities. Independent way of thinking. Low population size, low population density. Few stakeholders involved. More possibilities for renewable energy.
- Local context 2: social living
  Social housing, city. Flats. Buildings where people live separately, but share certain attributes such as a central entrance or ventilation system. Openness to change, if little negative effects. High population size, high population density. Many different stakeholders involved.
- Local context 3: suburban
  Nearby cities. medium population size. medium population density. Close to industry. Many similar stakeholders involved.

The three contexts are then presented to the interviewee. The interviewee will perform a BWM on the three contexts for each factor. This will result in three weights, one for each context, for every factor.

The best-worst methodology is applied at three levels. The hierarchy of the levels is shown in figure 2.4. The 'Category' and 'Factors' levels are determined in the BWM interviews. 'Local context' is added in the local-context interview.

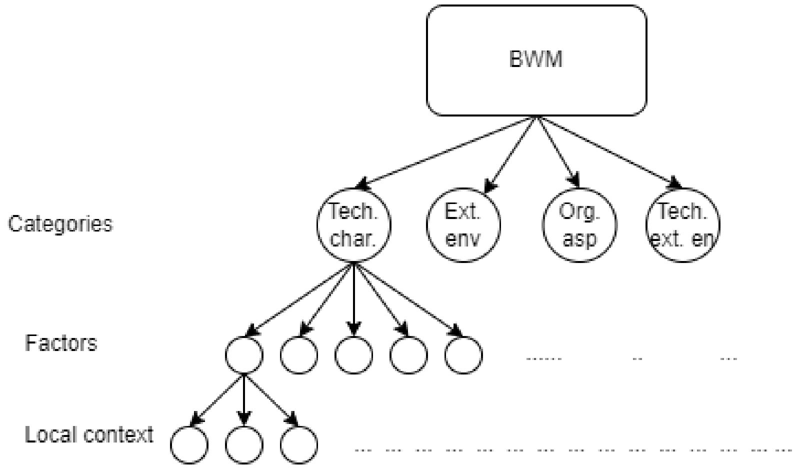

Figure 2.4: Hierarchy of all the weights acquired through the best worst method.

Chapter 3

Theory

There are multiple bodies of literature that research technology adoption, for instance, *evolutionary economics*, *network economics*, *neo-institutional economics*, *diffusion of innovation*, and *technology management*. These literature frameworks present researchers with theories to explain why which technologies, also often referred to as innovations, are more likely to become widely accepted for a longer period. Each theory has a different focus. Some look more at the company, others at the institutions surrounding it, or they focus on the consumers or the product. Each of these theories mentions several factors which influence the adoption, and thus for every theory, the factors relate to different aspects of the entire adoption process. Therefore, combining the literature streams gives a more complete overview of the different factors involved in the selection process. However not all literature streams may be relevant to this specific research problem. This has several causes, which are discussed later in this chapter. Likewise, not all factors from a literature stream may be relevant to the case. In previous research, it is also frequently seen that a selection is made of relevant factors, and these are then further examined (for example van de Kaa et al., 2019; Balezentis et al., 2021).

The theories mentioned shed light on the adoption of *an* innovation and are not heating technology specific. There may be factors involved that are specifically applicable to heating systems. I will investigate those by diving into the literature on the adoption of heating technologies. Together with the theories, a quite complete image of relevant factors is determined.

In the following chapter, I will first discuss relevant theories on technology adoption. Box 3.1 notes explicitly the (ir)relevance of several theories and why it was (not) chosen for this topic. Next, the literature on heating systems is discussed in section 3.2. Combining the two a list of factors is attained. Modifications however are necessary, and those are presented in section 3.3. The last section presents literature on the local context within energy systems.

3.1 Theories on technology adoption

3.1.1 Network economics

Here the technology adoption is studied in industries where network externalities are important. Network economists such as Katz & Shapiro and Farrell & Saloner argue that technology adoption is influenced by market mechanisms, which firms cannot influence. An oligopoly model Katz and Shapiro, 1985 showed that the choice of adoption was influenced by whether the innovation was compatible with other products. These positive external consumption, called network externalities, are benefits that the consumer has when using a product, for instance by having compatible products or services in the landscape. For example, a social media platform has more positive consumption benefits if many of your friends use the platform as well. Or energy-related, the adoption of electronic vehicles gets more attractive if there is sufficient charging infrastructure. An additional source of positive network externalities is the quality and availability of additional services post-purchase, which may depend on the experience and size of the service network (Katz and Shapiro, 1986). Farrell and Saloner, 1985 adds that due to certain market characteristics an inferior product can remain dominant over a better alternative. The market can experience a bandwagon effect, where adopters copy the choice of early adopters. Thus technologies that have an initial advantage tend to increase their advantage. That is further enhanced by having a large installed base.

- *Network externalities*: Network externalities are the added benefit of using a technology provided by the existence of complementary goods and/or by the number of other users that the technology has.
- *Bandwagon effect*: users tend to use the same technology that other users are already using. The barrier to transitioning is lowered by others that have already switched.

Network economics is frequently used in books on climate change economics and regulation (Mitchell and Woodman, 2010; Maréchal, 2013). Fuentes and Ozuna, 2021 argued that network externalities play a role when introducing digitalization in an decentralized power grid business model. By approaching the district heating business model as a network, one can see through network economics that adding members to the network affects the value of the service to existing members (Sandoff and Williamsson, 2015). Furthermore network economics come into play when analyzing scale effects in the bioenergy industry (Roos et al., 1999). Network economics however is little used in research specific on the adoption of heat technologies.

3.1.2 Neo-institutional theory

Institutional theories see firms as adaptive, social constructions that are shaped in reaction to their external environment. Institutional rules are not strict rules, but function rather more as myths that organizations adopt to gain legitimacy, resource stability, and overall enhance their prospects (Meyer and Rowan, 1977). Neo-institutional theory dives deeper into the effects of formal and informal rules on the behavior of individuals, groups, or organizations (P. Dimaggio, 1998). Meyer and Rowan and P. J. Dimaggio and Powell, 1983 argue that organizations change by their institutional environment and slowly start to resemble each other. This happens through institutionalization, a process where formal institutions get widely accepted and incorporated (Meyer and Rowan, 1977). This leads to isomorphism, where new units are forced to resemble the other units within the same environment to survive. Isomorphism happens through three types of mechanisms.

The following three mechanisms or factors are described:

- *Coercive isomorphism*: formal and informal pressures of another actor that the actor may be dependent on. This can be by rules and practices, but also by social pressures and cultural expectations of society. Larger organizations can put pressure on smaller firms that are dependent on them and shape them.
- *Mimetic isomorphism*: organizations imitating other organizations within the same environment. Done for instance to reduce risks and overall costs, as each organization is then faced with the same difficulties.

- *Normative isomorphism*: imitation process of actors within different firms, because organizations tend to model themselves after organizations they find successful. This happens through professionalization within firms, they copy their activities, for instance by hiring people with similar backgrounds.

There has been surprisingly little research that used institutional theory on the heat transition. Papers that refer to Dimaggio and Meyer concern themselves mainly with management, entrepreneurship, and business development. There are some energy-related researches, such as the impact of mentioned mechanisms on green innovation (Li et al., 2017; Borsatto and Amui, 2019)and carbon management (Liu et al., 2018). Though many papers (Lygnerud, 2018) mention institutional factors that play a role, such as policies and (price) regulations, they do not apply institutional theories concerning isomorphism.

3.1.3 Diffusion of Innovation

Rogers' *Diffusion of Innovation*, DOI, focuses on the value of the adoption to the user by looking at the general attitude that consumers have towards an innovation. Here *diffusion* is the process by which an innovation is communicated over time throughout a social system. *Innovation* can be new technologies or ideas and practices that are *perceived* as new (Rogers, 1962). That signifies that the innovation does not need to be new upon itself, it can be that adopters have already long heard of it but never truly considered adopting it, giving it a 'newness' in the present moment. This is the case for many heating systems. Heat pumps, district heating, geothermal, and biofuels are mature technologies, however, the energy transition gives newness to them and adopters now determine their opinions on them.

How an innovation moves through an innovation-decision process is determined by the attributes of the innovation (Rogers, 1962). These are:

- *Relative advantage*: the degree to which a new idea is perceived as superior to the existing practice that it replaces. Thus whether the technology itself is superior to the one it supersedes or competes with. This is often seen as an important characteristic.

- *Compatibility*: the degree to which an innovation can co-exist with the existing innovations. Compatibility focuses on if the innovation is "consistent with the existing values, past experiences, and needs of potential adopters", Rogers, 1962. Rogers gives an example where soil-conservation innovations, which have generally been adopted slowly, conflict with American farmers' values on increasing farm production. There may also be negative compatibility with past ideas. Where if there is a negative experience with an innovation, potential adopters will also reject similar future innovations. Compatibility also concerns itself with the needs felt by clients, whether they recognize it or not.

- *Complexity*: the degree to which a new idea is perceived as relatively difficult to understand. Less complex innovation relates to a higher adoption rate.

- *Trialability*: the degree to which an innovation can be experimented with. Relevant when the idea is new and the adopter can adjust it to its own needs.

- *Observability*: the degree to which the innovation is easily visible to others. Some innovations are easier to communicate to others, which positively impacts the adoption rate.

DOI looks at the perceived attributes of an innovation. It has been shown that these are good predictors of consumer adoption (Guagnano et al., 1986; Labay and Kinnear, 1981). The usage of DOI is seen a lot in renewable energy problems, such as distributed energy resources (Outcault et al., 2022), renewable energy transition (Vögele et al., 2022; Elmustapha et al., 2018), and energy efficiency measures. Though not the same as heating systems, they operate in a similar environment with similar adopters. Concerning heat pumps and district heating, the results are still prominent. DOI fits with adopter-centred approaches and is thus for instance used to examine residential heating systems (Mahapatra and Gustavsson, 2008). DOI is often used in agent-based modeling, for example, Sopha et al., 2013 determined variables for ABM using DOI to investigate the diffusion of heating systems.

Box 3.1 ***Relevance of theories on technology adoption***

Network economists take the effect of network externalities on the adoption of a technology into account. As the technologies will replace existing heating methods, network effects may be in place. Furthermore, as many municipalities are transitioning on the same timeline, a bandwagon effect may arise.

Neo-institutional theory looks at the effects of the external environment on firms. The energy transition happens in a big social system, with many organisations involved, and is partly possible through societal changes. These movements are also subject to institutionalisation, and new rules and systems are put into place. I find it therefore interesting to look also at this socio-technical system through the eyes of institutional theory.

Diffusion of innovation focuses on the value of the adoption to the user. It is shown that social acceptance can influence the implementation of RES and heat pumps (Peñaloza et al., 2022). Therefore it is useful to take the user perspective into account. This is where DOI comes into play.

Technology management I found less relevant. This body of literature concerns itself with technology battles, which investigate the emergence of a dominant technology among competing technologies (Suarez, 2004). Suarez proposes a framework for determining how a technology achieves 'dominance', meaning that one technology emerges as dominant among several competing ones. Suarez's framework uses both firm-level and environmental factors, integrating institutional and network economics (Van de Kaa et al., 2011). The difference is that the framework has the firm's technological design and strategy as a focal point. However, this research looks more at the role of technology within the energy transition, where government and adopter play a big role and where firms act more as a supplier.

Evolutionary economy is excluded from the research as well. Here the survival of a firm is similar to the process of natural selection, where uncertainty and periods of change can lead to a breakthrough where new markets and applications arise. After the breakthrough comes an era with technological variation from which a dominant design will occur (Anderson and Tushman, 1990). The theory focuses more on the speed, and the likelihood of dominance, which does not align with the main question on *how* technology choices are made. Therefore this theory is left out.

3.2 Literature on heating system adoption

The following section will go over the factors in literature on heating system adoption, found through the method mentioned in 2.2.1. Figure 3.1 shows all factors with their definition. Though undoubtedly more authors than in this text and the figure have mentioned the factors, only a maximum of three authors are mentioned.

One factor typical for heating systems are *building characteristics*. Aspects like insulation influence the efficiency of the technology (Abbasi et al., 2021). Furthermore it is seen that for different types of buildings (such as flat building or a row house) other types of heat renovation are more fit (Kieft et al., 2021).

A local *match supply and demand* is important as transporting heat over large distances to end-users can become too costly or unfeasible. There needs to be a match between heat availability and the local heat demand when re-using waste heat from industry (Walsh and Thornley, 2012). Without clients or a supplier it will be ineffective to construct a heating network (Päivärinne et al., 2015).

The *technical infrastructure*, such as the (non) existence and quality of heat transportation piping, or the infrastructure of the local electricity grid can have a large influence on the improving heat utilisation (Walsh and Thornley, 2012). For instance, heat pumps change the electricity demand which needs to be accounted for through additional electricity grid infrastructure investments (Gaur et al., 2021).

Changing heating system impacts the *consumer experience*. Switching of a heating system can cause disruptions. There needs to be a change in gap appliances, heating distribution systems. And during the installation process there are noise levels and interrupted supply of hot water (Abbasi et al., 2021). This all contributes to the amount of hassle involved with installing, which negatively contribute to the adoption rate of consumers (Snape et al., 2015).

The installation of new heating systems is highly reliant on *capital investments*, however investment funds are limited and that has been shown to be a barrier (Broberg Viklund, 2015; Rohdin et al., 2007). The capacity factor (CAPEX per kW of electricity factor) for heat pumps is high compared to market competitors (Abbasi et al., 2021).

Regulatory infrastructure play a role. Due to regulatory gaps and constraints, there will be conflicts over strategy, ownership, and lack of standardisation (Abbasi et al., 2021). Proper regulatory infrastructure will increase the potential of these technologies. External control through, for instance the EU emission trading scheme or municipality interference, resulted in more attention to heat possibilities (Völlink et al., 2002).

Market facilitation is often mentioned as a factor. The operating costs are dependent on electricity pricing and carbon taxing and the costs form a large share of the costs of ownership. Therefore financial triggers facilitate the update of HP and DH (Abbasi et al., 2021). Examples of market facilitation are electricity tariff revision, tax incentives and subsidies, or higher mortgage loans for sustainable renovations (Kieft et al., 2021).

Risk aversion is often seen in projects with large collaborations among both parties, the industry providing heat and the receiving party (municipalities, private organizations...) (Thollander et al., 2010). There are several types of risks, such as risks regarding energy pricing, business strategy risks, or risk of shifts in ownership or closure of business. Furthermore, homeowners may also show risk aversion to new technologies (Michelsen and Madlener, 2012).

Knowledge development is often mentioned as an important step. Lack of knowledge on how the technology performs in practice sometimes lacks (Kieft et al., 2021). Thollander et al., 2010 noted that new ideas and technologies are more likely to break through when they are introduced by an external actor. Lack of awareness has been shown to be a barrier Benchmarking and networking is often noted as driving forces to improving energy methods, as lack of awareness is perceived as a barrier (Palm and Thollander, 2010; Broberg Viklund, 2015).

3.3 Modifications and preliminary list of factors

Thus far, we found the following factors, as shown in figure 3.1. The factors noted with a colour need adjusting based on the heating system context. This section will go into detail on these modifications. First, irrelevant factors to the context may be removed, noted in grey. Next, some factors (partly) overlap, noted with a colour, will be discussed after that. This section's end will be an updated list of preliminary factors.

Source	Author	Factor	Description
Neo-institutional theory	(Dimaggio & Powell, 1983)	Coercive isomorphism	Formal and informal pressures of another actor that the actor may be dependent on. Can be by rules and practices by a governing organization, but also by social pressures and cultural expectations of society. For example dependence of utility managers, government policies, and customer opinions
	(Dimaggio & Powell, 1983)	Mimetic isomorphism	Organizations imitating other organizations within the same environment. Done for instance to reduce risks and overall costs, as each organization is then faced with the same difficulties.
	(Dimaggio & Powell, 1983)	Normative isomorphism	Imitation process of actors within a firm, due to similar backgrounds
Network economics	(Katz & Shapiro, 1985)	Network externalities	Network externalities are the added benefit of using a technology provided by the existence of complementary goods. For example, already producing your own electricity or having energy storage facilities.
	(Katz & Shapiro, 1985), (Farrell & Saloner, 1985)	Installed base	The amount of users that a technology has.
	(Farrell & Saloner, 1985)	Bandwagon effect	Users tend to use the same technology that other users are already using. For instance, due to uncertainty, a party is not sure whether switching to a new technology is a good choice.
Diffusion of innovation	(Rogers, 1962)	Relative advantage	The degree to which the new technology is superior to the existing practice, e.g. a CV or HR boiler. Superiority can be expressed in comfort, increased status or climate impact
	(Rogers, 1962)	Compatibility	The degree to which an innovation can co-exist with the existing innovations
	(Rogers, 1962)	Complexity	Degree to which a new idea is perceived by the adopters as relatively difficult to understand and use
	(Rogers, 1962)	Triability	Degree to which an innovation can be experimented with
	(Rogers, 1962)	Observability	Degree to which the innovation is easily visible to others
Literature	(Abbasi et al., 2021)	Market facilitation	Effectiveness and availability of grants and financial programs, availability of investment grants
	(Abbasi et al, 2021), (Viklund, 2015)	Capital investments	Having the capita to make the required investments
	(Abbasi et al, 2021), (Kieft et al., 2021)	Building characteristics	How suitable the building is for the technology; e.g. different energy labels, space, housing density
	(Walsh & Thronley, 2012), (Päivärinne & Hjelm, 2015)	Match supply and demand	If the possible energy supply matches the local heat demand. For example, if there is enough waste-heat from industry to match demand for a heating network.
	(Walsh & Thronley, 2012), (Abbasi et al, 2021)	Availability of technical infrastructure	Existence of technological infrastructure, for example existance and quality of piping for heat transportation, availability of equipment, availability on electricity grid.
	(Thollander, 2010)	Risk aversion	Wanting to limit the amount of risks involved, such as the risk of closure of the industry that provides heat
	(Abbasi et al, 2021), (Thollander, 2010)	Regulatory infrastructure	Whether regulatory barriers such as conflicts over strategies, ownership, and lack of standardization have been resolved. If that is not the case then there may be additional risks that slow or limit the transition.
	(Viklund, 2015)	Knowledge development	Availability of information or education regarding implementing heat technologies. Having good examples. Can be relevant for both larger organisations or individual consumers
	(Thollander, 2010), (Karytsas, 2014)	Energy costs & efficiency	Costs of energy when the installation is in operation. The more efficient a technology is, the lower will be its consumption and operating costs.

Figure 3.1: Intermediate list of factors found from the literature review. Greyed factors are later removed. Coloured pairs need to be adjusted or merged to fit the heating system context. Their changes are mentioned in section 3.3.1.

Irrelevant factors

Some factors noted in theory are not relevant to heating systems, as some of these are aimed towards innovations in consumer products such as software and hardware and not complex systems where stakeholders such as municipalities and housing associations are more prominent. Two factors are seen as irrelevant to this case

One is *normative pressures*, which concerns itself with changes that happen due to actors within different firms starting to imitate other firms they perceive as successful. For instance, by hiring people from the same background. One could imagine a scenario where municipalities imitate municipalities with a successful transition. However, both experts indicated during the exploratory interview that this is not the case. Therefore *normative pressures* is not included in the final list of factors.

A similar argument goes for *triability*, a factor from diffusion of innovation. There has been no sign of it being relevant to heating system adoption literature or the experts. Furthermore, the technologies have reached maturity. They are rather complex. Experimenting and improving the technology seems like an expensive endeavour with little added value. The final users, residents, are unlikely to want to experiment with the technology (Elmustapha et al., 2018). So, this factor can be removed as well.

Rogers states in his works on diffusion of innovation that *observability*, the degree to which an innovation is easily visible to others, is a factor which could be significant. For example: why hardware sometimes gets adopted more quickly than software (Rogers, 1962). It is debatable whether this applies to heating systems. First, both technologies are not or are limited visible once installed. DH pipes are underground. And although heat pumps do have an outside unit, these are usually installed on the roof, in the garden or on the (rear)facade of a house, and their visibility is limited. The installations within ones house are often more prominent as opposed to common cv-boilers for heat pumps. Secondly, in the literature, there is no indication that observability plays a role in heating systems. Observability is not found in other heating system adoption literature, nor mentioned by experts. However, literature on other clean energy technologies, such as solar systems or electric vehicles, has shown that observability positively influenced the adoption (Guagnano et al., 1986). Therefore, it is decided to keep observability on the list. If the factor is irrelevant for heating systems, then it will show up in the BWM results.

3.3.1 Overlap between factors

There is some overlap between certain factors within different theories and studies.

Mimetic isomorphism & bandwagon effect

Firstly, *mimetic isomorphism* from neo-institutional theory strongly overlaps with the *bandwagon effect* as seen in network economics. Here the parties change their behaviour due to changes done by early adopters. As this is so similar, mimetic isomorphism is removed from the final list of factors.

Risk aversion & regulatory infrastructure

Risk aversion and *regulatory infrastructure* in the literature-found factors also overlap. Here *risk aversion* can be seen as an element of *regulatory infrastructure.* If there is a good regulatory infrastructure, e.g. regulations concerning ownership, responsibility and clarity on the content of contracts, then there would be fewer risks. Therefore *risk aversion* can be removed from the list.

Installed base & network externalities

The definition of *network externalities* is slightly adjusted. As described in section 3.1.1, network externalities have two sources. One source of network externalities is added benefit provided by the existence of complementary goods which may be relevant for some products. Examples of this might be that houses are already equipped with their own RE source or energy storage. Here adding a heat pump may be extra beneficial. The other is the number of users. A classic example is social media, which has increased value the more people are on it. For energy, the benefits of already having a large amount of users are different. It can have effects on infrastructure (there can be more piping nearby, which "can have advantages, it can also have disadvantages"- (expert #2)), observability, and knowledge development. But these potential benefits are already encapsulated in other factors in the list. Thus the definition will be adjusted from *"Network externalities are the added benefit of using a technology provided by the existence of complementary goods and/or by the number of other users that the technology has."* to *"Network externalities are the added benefit of using a technology provided by the existence of complementary goods."*

Installed base as mentioned in literature, is inherently a part of *Network externalities.* Network externalities can arise by having a large(r) installed base. An increased installed base may not always lead to network externalities. Then however, the factor *installed base* is irrelevant. So it can safely be removed from the list.

3.3.2 Preliminary list of factors

Adjusting all this into figure 3.2, the following list of factors arises. Note that this is still a preliminary factor list. Factors arising from the exploratory interviews will be added later in chapter *5. results*, see figure 5.2 if you are too curious.

3.4 Local context in literature

Previous research suggest that there can be geographical indicator for technology dominance. This was for instance asserted when investigating the choice for smart grid power line communication systems. Though there is one dominant technology predicted, the authors argue that 'multiple technologies may co-exist depending on geographical indicators' (van de Kaa et al., 2019). There are factors that are closely linked to geographical indicators, such as installed base and the local regulator (the distribution system operator (DSO) in this paper's case, which regulates and manages the distribution of energy from source to final consumer). Installed base and regulator are factors mentioned in Van de Kaa et al., 2011's framework, thus geographical influences can be taken into account using factors from the framework.

There has been research on determining the optimal location for certain technologies, using MCDMs. It was for instance found that land use, wind velocity, and proximity to urban settlements and conservation zones are important criteria when determining suitable wind farm locations (Tercan, 2021). Though these factors are specifically important for wind farms, it does show that non-technical aspects, such as distance to urban settlements, play a role when determining sustainable energy land uses.

There are also social and cultural differences between regions. So do regions near large cities (>250.000) have a larger GDP and bigger population growth compared to regions near a city (>250.000) and regions with/near a small city (<250.000) (OECD, 2020). Taking this into account it could be that these traits also affect the views on certain technologies among different regions, as they have different jobs opportunities and lifestyles.

Source	Author	Factor	Description
Neo-institutional theory	(Dimaggio & Powell, 1983)	Coercive isomorphism	Formal and informal pressures of another actor that the actor may be dependent on. Can be by rules and practices by a governing organization, but also by social pressures and cultural expectations of society. For example dependence of utility managers, government policies, and customer opinions
Network economics	(Katz & Shapiro, 1985), (Farrell & Saloner, 1985)	Network externalities	Network externalities are the added benefit of using a technology provided by the existence of complementary goods. For example, already producing your own electricity or having energy storage facilities.
	(Farrell & Saloner, 1985), (Dimaggio & Powell, 1983)	Bandwagon effect	Users tend to use the same technology that other users are already using. For instance, due to uncertainty, a party is not sure whether switching to a new technology is a good choice.
Diffusion of innovation	(Rogers, 1962)	Relative advantage	The degree to which the new technology is superior to the existing practice, e.g. a CV or HR boiler. Superiority can be expressed in comfort, increased status or climate impact
	(Rogers, 1962)	Compatibility	The degree to which an innovation can co-exist with the existing innovations
	(Rogers, 1962)	Complexity	Degree to which a new idea is perceived by the adopters as relatively difficult to understand and use
	(Rogers, 1962)	Observability	Degree to which the innovation is easily visible to others
Literature	(Abbasi et al., 2021)	Market facilitation	Effectiveness and availability of grants and financial programs, availability of investment grants
	(Abbasi et al, 2021), (Viklund, 2015)	Capital investments	Having the capita to make the required investments
	(Abbasi et al, 2021), (Kieft et al., 2021)	Building characteristics	How suitable the building is for the technology; e.g. different energy labels, space, housing density
	(Walsh & Thronley, 2012), (Päivärinne & Hjelm, 2015)	Match supply and demand	If the possible energy supply matches the local heat demand. For example, if there is enough waste-heat from industry to match demand for a heating network.
	(Walsh & Thronley, 2012), (Abbasi et al, 2021)	Availability of technical infrastructure	Existence of technological infrastructure, for example existance and quality of piping for heat transportation, availability of equipment, availability on electricity grid.
	(Abbasi et al, 2021), (Thollander, 2010)	Regulatory infrastructure	Whether regulatory barriers such as conflicts over strategies, ownership, and lack of standardization have been resolved. If that is not the case then there may be additional risks that slow or limit the transition.
	(Viklund, 2015), (Thollander, 2010), (Palm, 2010)	Knowledge development	Availability of information or education regarding implementing heat technologies. Having good examples. Can be relevant for both larger organisations or individual consumers
	(Thollander, 2010), (Karytsas, 2014)	Energy costs & efficiency	Costs of energy when the installation is in operation. The more efficient a technology is, the lower will be its consumption and operating costs.

Figure 3.2: Preliminary list of factors relevant to heating system context, based on a literature review. In a later chapter, factors brought by experts will be added to the list.

Chapter 4

Heating systems across the Netherlands

This chapter aims to identify which heating systems are expected to play a role in the Dutch energy transition. There are many alternatives for heating systems, such as district heating, heat pumps, hybrid systems, green gas and infrared panels. As here it is specifically asked which are likely to play a role in the coming few decades, it is not sufficient to only search in literature to find which technologies are likely to be used for a heat transition. Within the literature, it isn't easy to decipher whether innovations are close to being executable. As the Dutch ministry operates on the deadlines set by the Klimaatakkoord and Paris agreement, innovations must be feasible within this time frame. Therefore this chapter serves as a check that we are analysing relevant technologies.

This chapter will answer the first sub-question *'Which heating systems are seen as relevant for the Dutch energy transition?'*, using the methodology described in section 2.1. The first section will look at the role of government and several policies regarding the heat transition. This will be followed by a short section on advices that several independent organisations have given. Next, the role of municipalities and their perspectives are further analysed. With this information, a conclusion is drawn upon which technologies are seen as relevant to the Dutch heat transition. The relevant technologies are then explained in more detail in the last section.

4.1 Dutch policy on heat transition

In this section, we will look at the role the government is playing. A national goal is to have no more carbon emissions through the built environment in 2050. To guide this process, the government constructed policy frameworks. Here, we will briefly go over some of the policy frameworks surrounding the built environment and heat transition to determine which heat system technologies are prominent.

The ministry of economic affairs and Climate is currently constructing a long-term vision on energy and the complementary approach, the 'Nationaal Plan Energiesysteem 2050 (NPE, national plan energy system). Though the plan still needs to be finished, the minister of Energy published the outlines. These state that the future system will need both district heating, hybrid heat pumps with sustainable gasses and all-electric solutions (Jetten, 2022). This is confirmed as well by the predecessor of the Climate Agreements (Ministerie van Economische Zaken, 2016).

The 2019 Climate Agreement states that the government still makes efforts to use sustainable gasses, whether biogas, green gas or hydrogen. It would be helpful to have sustainable gas, as gas is currently used as a base fuel for many applications. Sustainable gas could play a role in real estate; for instance with hybrid heat pumps, but the supply is limited. It is more prudent to commit sustainable gas towards an industry with fewer alternatives for heat (Ministerie van Economische Zaken, 2016). The green gas sector is expected to grow to better meet future demand (Klimaatakkoord, 2019)

One of the other policy frameworks is the Nationale Prestatieafspraken ('national performance agreements'). Among other agreements, it is decided that housing associations are mandated to make 450.000 houses natural-gas free and to improve the energy labels of 675.000 houses by 2030 through insulation (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). Here the housing associations are expected to cooperate with the local municipalities, where the Transitievisie Warmte (TVW, transition vision on heat) will be used as a guideline. Furthermore, the cabinet is working on a mandate that a cv boiler must be replaced with a hybrid heat pump or another sustainable alternative. There is an exemption when a house is planned to be put on a district heating network within ten years after the replacement (*Nationale Prestatieafspraken*, 2022). These agreements are made through cooperation between Aedes (association of housing associations), Woonbond (association for renters), VNG (association of municipalities) and the government. Thus the heat system technology choice is made locally with housing associations and municipalities.

4.2 Independent advice reports

In this section two independent advisors are discussed with the goal of seeing what independent organisations see as achievable. Independent organisations give advice and reports on the energy transition process, often in cooperation with other parties such as cities, grid operators, or real estate associations.

Stroomversnelling, formally known as 'Energiesprong', is a non-profit initiative which promotes affordable, comfortable and sustainable framework conditions in laws and regulations through solid lobbying. Stroomversnelling actively contributed to the market formation of sustainable home renovations (Kieft et al., 2021). Additionally, Stroomversnelling contributed a standardised renovation guideline which focuses on installing individual solutions (e.g. decentralised heat pumps and other electric solutions). Here they focused on proven technologies, which are suppliable and affordable. Berenschot is an independent advisory group, a consultancy organisation which, among other areas, provides advice on the energy transition. They also provide their services to government agencies. They conducted a scenario study with four climate-neutral scenarios. These are investigated to gain more knowledge on the possible pathways. This was done as an update to a similar study by the grid operators. Here they used the Climate Agreement as a starting point for the developments till 2030.

Berenschot mentions high-temperature district heating as ideal because no direct adjustments are required for the houses, which results in a high social acceptance of the technology, making it easier to implement. Berenschot indicates heat pumps as a reasonable and realistic heating method. Many civilians are prepared to invest in isolation, solar panels and batteries. In all scenarios, at least 25% of the households would switch towards all-electric heat pumps. Stroomversnelling sees all-electric or hybrid solutions for all houses that are not connected to a collective heating system such as district heating. All-electric is most fit for well-insulated houses so that the system can run at low temperatures. Stroomversnelling sees possibilities for installing hybrid heat pumps using natural gas as a temporary solution till the house is suitable for an all-electric heat pump. These are best fit for medium-insulated houses. Once the house is better insulated, the owner should switch towards an all-electric heat pump. Berenschot does see possibilities for hybrid heat pumps with hydrogen or green gas, though which gas depends on the transition path.

The opinions on sustainable gas are conflicting. On one hand, national policy frameworks expect that hybrid heat pumps, using either natural gas or sustainable gas, will play a role (Klimaatakkoord, 2019). There are arguments that green gas can be used in the current natural gas infrastructure, making it more accessible. On the other hand, one still faces the problem that the current gas infrastructure is outdated and would require significant investments to make it work (Stroomversnelling, 2022). The government acknowledge that there is a limited supply and that real estate is one of many sectors that want to use gas. The Dutch market is sceptical about implementing green gas due to its limited availability (Stroomversnelling, 2022, p. 43). Monumental buildings, which are very difficult to renovate, can be supplied with green gas.

Two other technologies that are sometimes mentioned are infrared panels, a type of electrical heating, or using hydrogen. Firstly, infrared panels are only advised as additional heating, as costs are relatively high. (Stroomversnelling, 2022). It could be used as a solution for specific rooms that are more expensive to supply with electric heat pumps (for instance, an attic or garage). Next, there are a few objections to hydrogen. So far, hydrogen has only been used on a pilot basis as a heating method. There is too little insight and certainty on the price and availability of hydrogen (Stroomversnelling, 2022, p. 43). Due to its process, hydrogen is inherently expected to remain more expensive than direct heating using electricity.

4.3 Municipality role and actions

The national government gives municipalities a prominent role in making their neighbourhoods natural-gas-free (Klimaatakkoord, 2019;Jetten, 2022). This section will go over the

At a municipality level, each municipality is obliged to make a Transitievisie Warmte (TVW, 'transition vision on heat'), which is meant as a guideline to their approach of the heat transition. Here municipalities will provide timelines and solutions to make their different neighbourhoods natural gas-free. The TVWs indicate the first steps. It does not (yet) show definitive choices and will be updated every five years (PAW, 2019). With all municipalities and their transition visions combined, the Climate Agreement's goal of making 1.5 million homes more sustainable will be met (RVO, 2022). The TVWs give a concrete indication of what municipalities envision implementing in their neighbourhoods. It thus also gives a direct link to what they see as feasible heating alternatives.

Box 4.1 ***Constructing a transition vision on heat: tools and possibilities***

The government provides several tools to support the municipalities in producing the Transitievisie Warmte, one of them being *De Leidraad*. These tools are used by the municipalities (among others, Sud-west Frysland, Etten-Leur and Heerlen stated to have used these tools) As a part of De Leidraad, the costs and CO_2 reductions for five different heating strategies are calculated. These calculations are performed by the Planbureau voor de Leefomgeving (PBL, Netherlands Environmental Assessment Agency), the Expertisecentrum voor Warmte (ECW, expertise centre for heat) then helps to add local data of a municipality into the model. (RVO, 2022)
The ECW provides five strategies.

1. **Strategy 1: Individual electric heat pump**: Either ground or air source heat pump. House is isolated to shell B. Individual all-electric solution
2. **Strategy 2: district heating with mid- to high temperature source**: Temperature around 70^o C. Heated water can be used directly.
3. **Strategy 3: district heating with low-temperature soure**: Lower temperature. Heat needs to be raised to a higher temperature using either a collective heat pump or an individual heat pump.
4. **Strategy 4: green gas**: Use either a hybrid heat pump or cv-boiler.
5. **Strategy 5: hydrogen**: Hybrid heat pump with hydrogen.

The district heating networks' possible energy sources (such as geothermal, waste or aqua-thermal heat) are left out, as these are less relevant to the research question. Some municipalities are explicit about the types of temperature scale for district heating, as this is partially determined by the heat source and affects the required insulation level and thus costs (LT requires a high standard of insulation (Stroomversnelling, 2022). Most, however, are not explicit or use a combination of LT, MT and HT heat networks. Most municipalities refer to all-electric solutions. These contain stand-alone heat pumps, only powered by electricity, possibly combined with infrared panels or electrical heaters. 'Heat pump' is noted if a municipality is not explicitly referring to a stand-alone electric heat pump or a hybrid heat pump.

4.3.1 Analysing multiple municipalities' transition visions

Provincie	Municipality	Will include	Will exclude
Groningen	Groningen	Heat pump, district heating, hybrid heat pump with green gas for buildings with no other solution available	Collective heatpump, hydrogen, pellet stove
	Midden-Groningen	Hybrid heat pumps, district heating	Hydrogen and greengas excluded till at least 2030
Friesland	Sudwest-Frysland	Heat pump, district heating, hybrid heat pump	Green gas and hydrogen
	Waadhoeke	All-electric, district heating, hybrid heat pump with green gas	
Drenthe	Assen	Heat pump, HT district heating	
	Aa en Hunze	Heat pump, district heating, green gas	Hydrogen
Flevoland	Lelystad	Heat pump, district heating	Green gas and hydrogen
	Dronten	All-electric, LT district heating, hybrid heat pump as temporary solution	MT and HT district heating, green gas and hydrogen.
Gelderland	Maasdriel	All-electric, plausible hybrid solution with green gas	District heating with waste-heat or geothermal heat
	Apeldoorn	Heat pump, district heating, temporary hybrid heat pump, green gas	
Overijssel	Hof van Twente	All-electric, temporary hybrid heat pump, small-scale district heating	Green gas and hydrogen
	Harderwijk	Heat pump, district heating	Green gas and hydrogen untill 2030
Utrecht	Utrecht	District heating, possibly heat pump or sustainable gassess	
	Utrechtse Heuvelrug	All-electric, district heating	Green gas and hydrogen
Brabant	s-Hertogenbosch	All-electric, district heating	Green gas and hydrogen
	Etten-Leur	All-electric, district heating, temporary hybrid heatpump with green gas or hydrogen	
Zuid-Holland	Delft	All-electric, district heating, hybrid heat pump with green gas or hydrogen	
	Zuidplas	All-electric, (small-scale) district heating	
Noord-Holland	Bergen	All-electric, (small-scale) district heating	
	Alkmaar	All-electric, district heating	
Limburg	Heerlen	Heat pump, district heating, green gas	Hydrogen
	Venlo	All-electric, district heating, hybrid heat pump with green gas	Hydrogen
Zeeland	Goeree-Overflakkee	All-electric, district heating, green gas, hydrogen	
	Terneuzen	All-electric, district heating, hybrid heat pump with green gas	

Figure 4.1: Results from going through transition visions on heat of twenty-four municipalities.

Figure 4.1 shows the chosen municipalities and their corresponding technology choices.

Quite some municipalities indicated that they have neighbourhoods where they do not see a straightforward solution yet. Often in these cases, they leave it as a blank or ascribe a hybrid heat pump with natural gas as a temporary solution, as Assen, Etten-Leur and The Hague (see figure 4.2) (RVO and PAW, 2021)[1].

[1] All TVWs are collected through a digital map made by RVO, a government agency, and are cited through this singular citation

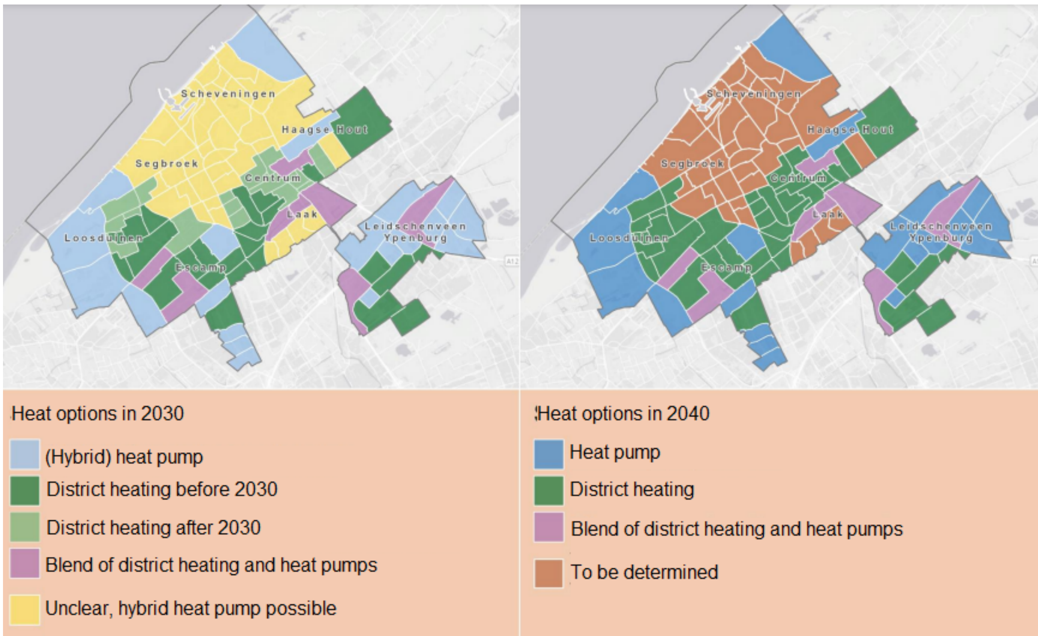

Figure 4.2: Map shows the ambitions of heat systems in 2030 and 2040 in The Hague. (Adapted from RVO and PAW, 2021, Den Haag p.3)

4.4 Conclusion: which are the relevant heating technologies

The following conclusions are drawn from the previous sections.

First, we see that in all sources, the main focus is on heat pumps, hybrid heat pumps (with sustainable gasses or natural gas), and district heating. Most municipalities first consider whether an all-electric heat pump or DH is an option, and if that is not the case, they commit to a hybrid solution. Secondly, there is only a small role for other heating methods, such as solar collectors, infrared panels and electric heaters. Generally, they will be used as additional heaters. Thirdly, heat sources such as geothermal energy and ground-coupled heat exchanger are generally only used in combination with a district heating network and/or a heat pump. So we can conclude that when these heat sources are chosen, there will also be a DH or HP.

Lastly, there are varying opinions on sustainable gas. Some municipalities do not see it as an option until at least 2030, but they hope to use sustainable gasses post-2030 for previously installed hybrid heat pumps. Some are sceptical, such as Sudwest-Frysland, who refers to a government letter where a minister says, "...hydrogen and green gas will not be able to play a significant role in the built environment till 2030. The price and availability of hydrogen and green gas are highly uncertain, as a result of which hydrogen and green gas, even after 2030, are only expected to be a logical option for the built environment if no other realistic heat alternatives are available", Ollongren, 2021. Hybrid heat pumps with natural gas can be a solution for the coming decades. However, I expect that in 2050 only some of them can be used with sustainable gas. Most will eventually switch to an all-electric solution or a heating network.

In this stage, there are few distinctions made on the temperature level of the district heating systems or the specific type of heat pump. It is concluded that first decisions are made on whether a hybrid heat pump, all-electric heat pump or district heating is the main source, and only thereafter do decisions follow on the specifics. It is therefore decided that it is better to keep the technologies at a broad distinction. The first step is deciding between the categories (heat pump, district heating, hybrid, gas), and only after that distinction has been made do people look at exactly which type of heat source (air-source, water-source, geothermal or waste heat...) is going to be used. In this research, sustainable gas solutions will be excluded, as there are too many uncertainties surrounding them and it is likely that only a small portion of homes will be supplied with sustainable gas. During the interviews that will follow the expert will be told to focus on decisions between a hybrid heat pump, an all-electric heat pump and district heating.

4.5 On the relevant heating technologies - technical aspects and actors

As mentioned in the previous section, this research will focus on hybrid heat pumps, all-electric heat pumps and district heating. In this section, more details on the three technologies are given, including basic technical aspects and which actors are involved when installing one of the technologies. Box 4.2 goes into more detail on the temperature levels involved with heating systems.

4.5.1 District heating

District heating supplies heat through a network of pipes, which transport hot water or steam to the end users. District heating networks vary in scale, from several houses to entire cities (Boesten et al., 2019). Note that the district heating network is in essence a way for *transporting* heat from a source to an end-user. The heat sources differ among networks and are dependent on local availability. Heat can be produced in different ways. The most classic one is where the heat is produced at a central facility using a combined heat and power (CHP) plant, which is in general based on fossil fuels. There are more sustainable methods for heat production. One is using geothermal energy. Geothermal heat is sustainable heat gained by pumping water to deep depths in the earth, ranging from 2-6km, where the earth heats it. The water is pumped back to the surface, extracted from the water and gets distributed, for instance, to heat buildings or industrial processes. Unfortunately, not all land is suitable for geothermal heat extraction (Mijnlieff, 2020). Other sustainable heat sources are biomass incineration or industrial waste heat.

Installing a district heating network is a complex process, with multiple actors involved. Grid operators, heat suppliers, municipalities and property owners (such as housing cooperations and rental organisations) and sometimes energy cooperations are involved. End-users are involved through a participation process. The heat suppliers could come from industry or other companies that are capable of supplying heat. Sometimes the municipality takes on that role.

End-users participation is required to complete the balance sheet and get a clear picture of the heat demand which needs to align with the heat supply. Housing corporations are responsible for the heat supply of renters. Housing corporations can make plans to change the heating system which can only be executed if 70% of the renters agree to the plan (Milieu centraal, 2022). Building owners can decide by themselves whether they want to connect to a district heating system. There are (currently) no mandates.

Box 4.2 ***Temperature levels in heating systems***

Heating systems can operate on different temperature levels. Most heating systems use water to transport the heat. The water can transport the heat using different temperatures (Milieu centraal, 2022).
Insulation levels and heat sources influence which temperature level is best suited for the heating system. There are four temperature categories.

- **HT: high temperature -** $+75^o$

  High temperature is suitable for every type of building, including poorly insulated ones. However, a lot of heat goes to waste in poorly insulated houses. Waste, incineration or geothermal heat can supply this temperature level.

- **MT: medium temperature -** $55 - 75^o$

  As the temperature is lower, there is less heat loss. This is fit for moderately insulated buildings.

- **LT: low temperature -** $30 - 55^o$ **& VLT: very low temperature -** $10 - 30^o$

  This level is mostly used for very new or renovated buildings with a high standard of insulation. Due to the insulation level, there is very little heat loss, and therefore the low temperatures suffice for heating the building. You do need an additional electric component to boost the temperature level for the water tap, as that water needs to be at least 55^o to be safe from contamination.

  A low-temperature heating system provides more comfort to the building's occupants, as the heat is distributed more evenly.

  A house with poorer insulation can be connected to a low-temperature heat source, but the building would need an additional heat pump to boost the temperature to a higher level. Examples of low-temperature heat sources are aqua thermal heat, ground-source heat or low-temperature waste heat (Milieu centraal, 2022).

4.5.2 Heat pumps

A heat pump is a mechanical system which allows the transfer of heat from a lower-temperature source to a higher-temperature sink. If one wants to heat a building, then the heat pump would extract heat from the colder outside and transfer it to the inside of a building. The heat is converted to a higher temperature, which can be used to heat water. The heat source is usually ground or air. An air heat requires fewer capital investments than a ground-source heat pump. A ground-source heat pump can be used to cool in summer as well and overall uses less energy, as the ground is at a more stable temperature. The heat sink is generally water and sometimes air. Water is straightforward as most houses already use water as their heat conductor (Kieft et al., 2021). Air sinks are fit when homes are equipped with mechanical ventilation (Milieu Centraal, 2021). Stroomversnelling indicated that both air-water heat pumps (where are is the heat source, and water the heat sink through which the heat is supplied throughout the building), water-water heat pumps and air-air heat pumps are good alternatives.

Heat does not naturally flow from a cold place to a warm place, as described by the second law of thermodynamics. Work is required to achieve this heat transfer. With heat pumps, the work is attained using electricity. As heat is *transmitted* as opposed to being *generated*, heat pumps have a very high coefficient of performance, COP. The COP denotes the ratio between delivered heat and input work. A heat pump with a COP of 4.0, a value within the typical range (Abbasi et al., 2021), provides 4 kWh of heat for every 1 kWh of electricity provided.

A heat pump is as sustainable as the used electricity. Though electricity is not yet produced fully sustainably, one still makes considerable cuts on their carbon emissions by up to 55% (Milieu Centraal, 2021).

All-electric heat pump - A full-electric heat pump produces heat at low temperatures. To function properly the building needs moderate to good insulation levels, as poorly isolated buildings can not get warm enough on a low-temperature heat (Milieu Centraal, 2021).

Hybrid heat pump - A hybrid heat pump uses electricity as well and is often air-source. The hybrid heat pump is connected to an (existing) gas-using boiler. The hybrid heat pump is better suited for buildings that do not have the proper insulation levels required for a full-electric heat pump. On colder days the boiler jumps in to provide additional heat. The hybrid heat pump is therefore not a fully sustainable solution, as it is still reliant on natural gas. Green gas could also be used, however that is not often done (Stroomversnelling, 2022).

The process from having a vision for heat pumps in the TVW to installing heat pumps in buildings is still in its infancy. Currently, there are no mandates upon which municipalities can rely. It is up to housing corporations for renters or individual homeowners to choose to install a heat pump. A housing corporation can install heat pumps at its own pace. The municipalities can stimulate the installation of heat pumps. The main adopter is therefore the end-user, which can be stimulated by municipalities.

Chapter 5

Results

This chapter presents the results of the performed methods as mentioned in chapter *2. Methodology*. The methods have been executed, which lead to the answers of the three sub-questions. This chapter is divided into three sections.

The first section, section 5.1, answers the second sub-question *"What factors, according to literature and field experts, influence the choice between the relevant heating systems?"*. Section 5.2 will go over the results of the best-worst method and thus answer sub-question 3. The last sub-question, *"Which factors are dependent on local context?"*, is answered in section 5.3. Afterwards, in section 5.4 and 5.5 the results are briefly described and discussed.

5.1 Identified factors

This section presents the literature review results and the exploratory interviews, where they are merged to form a final list of the relevant factors. This will answer the second sub-question. Chapter *3. Theory* already provided a preliminary list of factors found in literature and theory. First, the results of the exploratory interviews are presented. These provide three new factors. These are then merged with the preliminary list in section 3.3.1, where arguments are put forth for the overlap and explain how they will be resolved.

5.1.1 Exploratory interviews

There were two exploratory interviews held with experts in the field. Expert 1 had a mixed background in academia and industry, and expert 2 has an academic background and gives advice to public and private organisations on energy. Most of the factors they mentioned were also seen in literature and some in the adoption theory.

The experts noted three new factors. Firstly, both mentioned that the pay-back period is an important indicator, especially when an industry becomes involved, for instance, when investors are involved in the construction of heating networks. Secondly, expert 2 mentioned that human resources within municipalities have difficulties executing larger or more complex projects due to a lack of people. Furthermore, there are also practical limitations concerning labour shortages. Thus these two factors are added to the list.

Lastly, both experts noted that the consumers' opinion mattered, "[the municipalities need] to convince residents [...] the need to switch to a new heating system" (Expert #2). This opinion is influenced by their needs and wants, and if it matches their values, among others on pricing.

The three factors are shown in figure 5.1.

Source	Factor	Description
Experts	Consumer willingness	Whether the consumers are convinced they need the technology. Influenced by up-front costs
	Human resources available for implementing	More complex projects require more people to work on them within municipalities or other organizations.
	Pay-back period	The time it takes for the initial investment to be earned back.

Figure 5.1: Factors mentioned by experts that were not already found in literature or adoption theory

5.1.2 Modifications to the factors

Some factors overlapped partly or need to be clearer. By making a slight adjustment to the definition the overlap can be mitigated while keeping the list complete.

Compatibility & consumer willingness

One can see an overlap between Roger's *Compatibility* and *Consumer willingness* as stated by the experts. Consumer willingness comes from the opinion that adopters form on technologies. Compatibility discusses similar topics. Thus, for the final list, '*compatibility*' is rephrased to '*consumer willingness*' to make it more straightforward for the experts during the BWM interviews about what the factor means. The financial influences on consumer willingness are accordingly left out, as those are also described with *pay-back period* and *capital investments*.

Energy costs & efficiency & capital investments & pay-back period

These three factors are all related to the monetary aspects. *Capital investments* is important before the purchase, and *energy costs & efficiency* tells us something about the operating costs after installation. Combining these one can roughly calculate the pay-back period. In other words, once you know two of these you have an indication of what the third will be like. One of these three can therefore be removed from the list. As the pay-back period is put forward by the experts, that one stays. The operating costs are highly volatile, as they depend among others on gas prices. Capital investments are a more reliable parameter, as it remains somewhat constant. Therefore, energy costs & efficiency is removed from the list.

5.1.3 Final list of factors

Category	Source	Author	Factor	Description
Technology characteristics	Diffusion of innovation	(Rogers, 1962)	**Relative advantage**	The degree to which the new technology is superior to the existing practice, e.g. a CV or HR boiler. Superiority can be expressed in economic profitability, giving status, or in other ways (Rogers, 1962)
Technology characteristics	Diffusion of innovation	(Rogers, 1962)	**Complexity**	Degree to which a new idea is perceived by the adopters as relatively difficult to understand and use
Technology characteristics	Diffusion of innovation	(Rogers, 1962)	**Observability**	Degree to which the innovation is easily visible to others
Technology characteristics	Experts		**Pay-back period**	The time it takes for the initial investment to be earned back.
Technology characteristics	Literature	(Viklund, 2015)	**Knowledge development**	Availability of information or education regarding implementing heat technologies. Having good examples. Can be relevant for both larger organisations or individual consumers
External environment	Experts, Diffusion of Innovation	(Rogers, 1962)	**Consumer willingness**	Consumer opinion on technologies and whether they are convinced that they need the new technology. This is influenced by the values that consumers have and possible past experiences. Includes intrinsic motivation such as climate and political opinions.
External environment	Literature	(Abbasi et al, 2021), (Thollander, 2010)	**Regulatory infrastructure**	Whether regulatory barriers such as conflicts over strategies, ownership, and lack of standardization have been resolved. If that is not the case then there may be additional risks that slow or limit the transition.
External environment	Literature	(Abbasi et al., 2021)	**Market facilitation**	Effectiveness and availability of grants and financial programs, availability of investment grants
External environment	Neo-institutional theory	(Dimaggio & Powell, 1983)	**Coercive pressures**	Formal and informal pressures of another actor that the actor may be dependent on. Can be by rules and practices by a governing organization, but also by social pressures and cultural expectations of society. For example dependence of utility managers, government policies, and customer opinions
External environment	Network economics	(Katz & Shapiro, 1985), (Farrell & Saloner, 1985)	**Network externalities**	Network externalities are the added benefit of using a technology provided by the existence of complementary goods. For example, already producing your own electricity or having energy storage facilities.
External environment	Network economics, Neo-institutional theory	(Farrell & Saloner, 1985), (Dimaggio & Powell, 1983)	**Bandwagon effect**	Organisations or users tend to use the same technology that others are already using. For instance, due to uncertainty, a party is not sure whether switching to a new technology is a good choice.
Organisation aspects	Experts		**Human resources available for implementing**	More complex projects require more people to work on them within municipalities or other organizations.
Organisation aspects	Literature	(Abbasi et al, 2021), (Viklund, 2015)	**Capital investments**	Having the capita to make the required investments
Technical external environment	Literature	(Abbasi et al, 2021), (Kieft et al., 2021)	**Building characteristics**	How suitable the building is for the technology; e.g. different energy labels, space, housing density
Technical external environment	Literature	(Walsh & Thronley, 2012), (Päivärinne & Hjelm, 2015)	**Match supply and demand**	If the possible energy supply matches the local heat demand. For example, if there is enough waste-heat from industry to match demand for a heating network.
Technical external environment	Literature	(Walsh & Thronley, 2012), (Abbasi et al, 2021)	**Availability of technical infrastructure**	The existence of technological infrastructure, for example, existence and qualilty of piping for heat transportation, availability of equipment, availability on electricity grid.

Figure 5.2: Complete list of factors that are to be used in the best-worst analysis interviews

Factors found in theory for which there are compelling arguments that are irrelevant may be removed. Figure 5.2 shows the complete list of factors. They are categorised into four categories. The definitions of the categories are mentioned in figure 5.3.

Technology characteristics	Aspects which are specific for different for either heat pumps and district heating. Concern the technologies' costs and capabilities. And whether it is percieved as complicated.
External environment	Aspects belonging to the environment outside the control of the implementing organisation or technology manufacturers. Mostly concerns social and governmental pressures, regulatory infrastructure and market facilitation, consumer opinion and whether users possess complementary products.
Organisation aspects	Practical aspects of the organisation. Their capacity in terms of human resources and capita.
Technical external environment	Technical concerns which influence the executionability of the technology. Such as building environment, electrical grid capabilities and match supply and demand

Figure 5.3: Definitions of the categories which are used in the final list of factors.

5.2 Best-worst method analysis

Here the results of the best-worst analysis shall be described.

5.2.1 Weights

The weights of the factors are shown in figure 5.4. The global weight of a factor is found by multiplying the average local weight with the average corresponding category weight. The factors are ranked on global weight score. The category weights are ranked on a scale of A to D, A being the most important category.

	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8			
	Local & category weight							Average weight	Global weight*100	Ranking
Technology characteristics	**0,10**	**0,05**	**0,47**	**0,07**	**0,41**	**0,14**	**0,49**	**0,25**	**-**	**B**
Pay-back period	0,10	0,54	0,54	0,19	0,06	0,18	0,45	0,29	7,28	6
Relative advantage	0,25	0,11	0,16	0,50	0,08	0,10	0,28	0,21	5,22	12
Complexity	0,05	0,13	0,11	0,11	0,24	0,10	0,11	0,12	3,04	14
Knowledge development	0,43	0,17	0,13	0,14	0,43	0,57	0,04	0,27	6,73	8
Observability	0,17	0,05	0,06	0,06	0,18	0,05	0,11	0,10	2,42	15
External environment	**0,47**	**0,51**	**0,26**	**0,57**	**0,13**	**0,57**	**0,05**	**0,36**	**-**	**A**
Consumer willingness	0,13	0,03	0,29	0,37	0,07	0,13	0,22	0,18	6,45	9
Coercive pressures	0,20	0,43	0,11	0,22	0,25	0,08	0,05	0,19	6,99	7
Network externalities	0,10	0,11	0,04	0,11	0,15	0,04	0,15	0,10	3,63	13
Bandwagon effect	0,34	0,06	0,11	0,04	0,25	0,19	0,09	0,15	5,61	11
Regulatory infrastructure	0,03	0,18	0,17	0,11	0,15	0,13	0,33	0,16	5,72	10
Market facilitation	0,20	0,18	0,29	0,15	0,15	0,43	0,15	0,22	8,05	3
Organisation aspects	**0,26**	**0,22**	**0,10**	**0,14**	**0,41**	**0,14**	**0,15**	**0,20**	**-**	**C**
Human resources available for implementing	0,86	0,13	0,17	0,14	0,17	0,90	0,17	0,36	7,31	5
Capital investments	0,14	0,88	0,83	0,86	0,83	0,10	0,83	0,64	12,96	1
Technical external environment	**0,17**	**0,22**	**0,17**	**0,23**	**0,06**	**0,14**	**0,31**	**0,19**	**-**	**D**
Building characteristics	0,45	0,67	0,43	0,44	0,11	0,70	0,66	0,50	9,19	2
Match supply and demand	0,45	0,25	0,43	0,44	0,89	0,07	0,24	0,40	7,35	4
Availability of technical infrastructure	0,09	0,08	0,14	0,11	0,00	0,23	0,10	0,11	2,02	16

Figure 5.4: The weights found through the best-worst method analysis. The factors are sorted per category. The categories and their corresponding scores are shown in **bold**. The local and global weights are determined, as well as the relative standard deviation.

It is seen that *capital investments* has the highest weight, followed by *building characteristics*, *coercive pressures*, and *market facilitation*. *External environment* is the most important category.

The experts found *availability of technical infrastructure* the least important factor, followed by *observability* and *complexity*

5.2.2 Consistency

Figure 5.5 shows the output consistency ratios per category. All consistency ratios are close to zero and therefore consistent Due to *Organisation aspects* having only two factors, the ratio will be per definition zero. So also no threshold can be assigned. Similarly *Technical external environment* has only three factors, making it also relatively easy to have a consistent result, resulting in the many zeros. The individual results are consistent, therefore no interview needs to be removed from the data-set.

	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8
	Consistency ratio						
Technology characteristics	0,016	0,023	0,032	0,038	0,016	0,032	0,024
External environment	0,011	0,024	0,042	0,017	0,049	0,014	0,051
Organisation aspects	0	0	0	0	0	0	0
Technical external environment	0	0,022	0	0	0	0,045	0,020
Categories	0,032	0,039	0,032	0,029	0,047	0,000	0,028

Figure 5.5: Consistency ratios. All data is consistent.

5.2.3 Sensitivity

The results of the sensitivity analysis are shown in figure 5.6. It is seen that removing one expert can alter the global weight by an average of 2,15.

	avg(dGW)	max(dGW)
Expert 2	0,54	1,93
Expert 3	0,59	1,65
Expert 4	0,57	1,94
Expert 5	0,62	1,75
Expert 6	0,88	2,71
Expert 7	0,81	2,55
Expert 8	0,83	2,53
Averaged	0,69	2,15

Figure 5.6: Results of the sensitivity analysis. dGW signifies the change in global weight.

5.3 Local context

Expert 9 performed a local context BWM on all sixteen factors. The results are shown in figure 5.7. Here the three local contexts are weighted against each other for each factor.

Figure 5.8 shows the final weights on which factors are important in which local contexts. Here the local context weights are multiplied with the global weights of figure 5.4, and normalised so each column sums to 100.

		1. Rural	2. Social living	3. Suburban	Consistency ratio
Technology characteristics	Pay-back period	0,72	0,07	0,21	0,02
	Relative advantage	0,47	0,05	0,47	0,00
	Complexity	0,29	0,17	0,54	0,01
	Knowledge development	0,10	0,76	0,14	0,01
	Observability	0,07	0,21	0,72	0,02
External environment	Consumer willingness	0,67	0,06	0,27	0,03
	Coercive pressures	0,07	0,71	0,21	0,03
	Network externalities	0,67	0,06	0,27	0,03
	Bandwagon effect	0,14	0,67	0,18	0,05
	Regulatory infrastructure	0,26	0,66	0,08	0,02
	Market facilitation	0,06	0,66	0,28	0,03
Organisation aspects	Human resources available for implementing	0,24	0,11	0,64	0,02
	Capital investments	0,60	0,06	0,35	0,02
Technical external environment	Building characteristics	0,21	0,71	0,07	0,03
	Match supply and demand	0,33	0,33	0,33	0,00
	Availability of technical infrastructure	0,06	0,47	0,47	0,00

Figure 5.7: Weights assigned to factors based on local context.

5.4 Results of global BWM

We'll first look at the general results. From figure 5.8, it is seen that the most critical factor is *capital investments*, followed by *building characteristics* and *market facilitation*. I will first go into more detail about these three factors. Why did the experts say those are important, and how does that align with the exploratory interviews and the literature? Next, I'll briefly discuss the least important factors.

Firstly, *capital investments*. Almost all experts said in some phrasing that ”eventually, money is everything” and ”after all, we're Dutch”. It is not as surprising if you cannot afford an investment, it is less likely to be executed. The results that *capital investments* is most important is supported by other studies (Stavins and Jaffe, 1994). In modelling, it is shown that investment costs can significantly influence the uptake of heat pumps (Petrović and Karlsson, 2016). Though there is also some disagreeing. Interviews performed during Thollander et al., 2010 valued *access to capital* not as high as in other research. Here, market facilitation and decreased operating costs were more valued. The difference between Thollander's study and this research is that Thollander focused on the collaboration between industries and energy utilities, whereas here, the experts also took other stakeholders into account. This could suggest that *capital investments*'s importance share is from municipalities and the end-users. This line of reasoning does contrast with Karytsas and Theodoropoulou, 2014, where end-users were asked which factors they took into account when selecting a heating system.

It makes sense that *building characteristics* is perceived as significant. Expert 2 said that mu-

	1. Rural	2. Social living	3. Suburban	Global weight
Pay-back period	**15,66**	1,32	5,21	7,28
Relative advantage	7,36	0,74	8,37	5,22
Complexity	2,64	1,37	5,58	3,04
Knowledge development	2,00	13,90	3,13	6,73
Observability	0,48	1,39	5,93	2,42
Consumer willingness	12,88	1,03	5,92	6,45
Coercive pressures	1,49	13,54	5,08	6,99
Network externalities	7,26	0,58	3,33	3,63
Bandwagon effect	2,39	10,25	3,49	5,61
Regulatory infrastructure	4,46	10,26	1,49	5,72
Market facilitation	1,50	**14,45**	7,50	8,05
Human resources available for implementing	5,32	2,20	**15,97**	7,31
Capital investments	**23,05**	1,95	**15,25**	**12,96**
Building characteristics	5,86	**17,79**	2,22	9,19
Match supply and demand	7,30	6,64	8,31	7,35
Availability of technical infrastructure	0,35	2,58	3,22	2,02
+	100,00	100,00	100,00	100,00

Figure 5.8: Final results. Weights on the importance of factors in certain local contexts.

nicipalities initially look at the buildings in a neighbourhood, their types, insulation levels, and densities. From there, the first plans are drawn to see which technology fits. Confirming this, it has been shown that uptake of HP has been higher for more suitable buildings (Abbasi et al., 2021;Zach et al., 2019). Most transition visions and the renovation guide of Stroomversnelling are built up this way (Stroomversnelling, 2022; RVO and PAW, 2021).

Market facilitation also plays a largely symbolic role, according to the experts. According to expert 1: "If the government says 'this is a standard technique, you can choose from it', then the acceptance increases". Similar was said by expert 4: "if there is no subsidy on a technology, we can hardly sell it. Even if [the finances are favourable], customers find the technology hard to accept [as there is no subsidy on it]." Market facilitation is also heavily supported by literature (Abbasi et al., 2021; Werner, 2017; Palm and Thollander, 2010; Mitchell and Woodman, 2010).

Availability of technical infrastructure, was by almost all experts rated as the least important factor in the technical external environment category. They all had similar opinions; 'Infrastructure just has to fit in. It's the closing post' - Expert 6. "Infrastructure can be built"- Expert 3. The literature on the availability of technical infrastructure was already mixed to start with. Abbasi urged that the lack of infrastructure was a significant barrier to heat pump rollout. In Walsh and Thornley, 2012, it also showed up as a barrier, though it received low rankings from the research's participants. Thollander, however noted that technical factors such as correct piping are not necessary. Even in countries where the infrastructure does exist, other factors inhibit the rollout of district heating (Thollander et al., 2010). Thus I agree that aspects surrounding the technical infrastructure, such as lack of clarity on cost and project ownership matter, the actual presence or lack thereof does not play a role in the preference for a heating system.

Another irrelevant factor is *observability*. Rogers state that observability, the degree to which an innovation is visible to others, is positively related to the rate of adoption (Rogers, 1962, p. 240). However, most experts noted that end-users see observability as a negative thing. With heat pumps, they do not like to have a visible outside unit or large units inside their house. Here comes a significant difference into play with heat systems and innovations to which Rogers generally applies. Consumers do not choose between having or not having a heating system. Every house will have *some* type of heating system. It is a necessity. Users want the service, which is heat, and as long as the heat is well supplied, they do not want to be further bothered by the system and technology surrounding it. And when it was seen as somewhat important, the experts argued that it would have a negative effect, as end-users prefer the technologies they do not see. Here is a difference between heating systems and the technologies commonly ascribed with DOI: a heating system is a service, it provides heat. The technology and machines surrounding it are only distracting.

5.5 Results local context BWM

Here I will discuss the findings for the different contexts. Here I take the interview with expert 9 and the literature on spatial energy planning into account.

The most critical factors for rural are *pay-back period* and *capital investments.* These are both financial factors.

For social living, the choice is mainly determined by *building characteristics* and *coercive pressures.*

In suburban areas, *capital investments* and *human resources available for implementing* are most important.

The interviewee made a few distinctions. In their experience, people who live in more rural think and act more independently. They let themselves be less persuaded by coercive pressures. When asked about capital investments, ”... someone in the countryside decides for themselves whether they are going to do it, and will care the least about the people around him, and will care the most about the money and whether it makes enough money.” This independent way affects their priorities. For one, money is leading. But the second most factor after money is consumer willingness. They have to want it. And then they will take action.

For social living, capita is less important as ”it’s often communal money or money you don’t decide on on your own”. But then still, why are monetary factors weighed less? That is because other factors are more critical for social living: ”Even though all decisions are often made on financial grounds, if another trigger causes something, then it no longer matters. The money just has to get there.” This trigger is often technical feasibility or outside pressures.

Social living is more prone to coercive pressures, as they are easiest to steer; ”if you have someone from above saying ’this has to be it,’ either a heat pump or a heat grid, then a flat just does that”. The expert says that social living is the most influenceable. Therefore consumer willingness is not as important, as their *own* opinion is not decisive. Looking back at the regular BWMs, this could explain the variance in consumer willingness weights. Some experts viewed it from a real estate perspective, where consumer willingness is less critical (expert 3, architectural background). In contrast, others more often provide services to private suburban clients (such as expert 4).

Suburban is somewhat in between. The most important factor rated is *Human resources available for implementing.* The expert explained that most attention is paid to suburban areas, as to make a large group move forward with a solution here. Furthermore, with most factors, suburban is somewhat in between. Interestingly, building characteristics turned out to be the least important factor. When asked, the expert said that most solutions are feasible for suburban areas, so the building characteristics are less of a bottleneck.

Chapter 6

Discussion

In this chapter, we will dive deeper into the process. First, in section 6.1, I will go back to the underlining theories to see how they were relevant. Next, some limitations encountered are described in section 6.2. This is followed by a discussion on the methodology behind the local context in section 6.3. Ideas for further research are presented in section 6.4. In section 6.5, I will reflect on the research process, on what went well and what could have gone better.

6.1 Relevance of the theories

Here the three theoretical literature streams are reflected upon. While diffusion of innovation was already applied to heating system problems, the other two, neo-institutional theory and network economics, were applied little to sustainable heat problems. Here I look back on whether the theories turned out to be relevant, which parts were important, and why they turned out to be or not be relevant.

We initially started with five factors originating from DOI, of which *triability* was scrapped due to the maturity of the technologies. That left us with relative advantage, compatibility, complexity, and observability. Compatibility is rephrased as consumer willingness. Both experts and literature stated that adopters are essential in the heat transition. Mahapatra and Gustavsson, 2008 opted that it is crucial to look at factors influencing the adopter as they decide to adopt a heating system and therefore influence the adoption rate (Rogers, 1995). Expert 5 opted that a participative process with the residents is essential; "Ultimately, it's about whether the end user wants something or not".

However, we see that most of Rogers's factors are unimportant. I found this quite surprising, as the adopters are central to Rogers' diffusion of innovation. The low rating of *consumer willingness* stands out. The experts noted that some consumers act more out of intrinsic motivation, as they want to reduce their environmental emissions or not be reliant on foreign gas. For some customers, *consumer willingness* would be important. However, that fraction is smaller, and thus consumer willingness got a relatively low score.

So what happened to the adopters? Well, that the adopters are influential remains true. However, as noted by Stroomversnelling, "...the step to upscaling [...] is mainly about the participation process that you enter with the residents; what will it bring them? How do you communicate that? Good customer-oriented communication is essential." (Stroomversnelling, 2022, p.44). This participative process involves the technology's effect on their daily lives, where clear communication is most important. And these questions fall under other factors, such as monetary factors, knowledge development and relative advantage. We see these factors are more important than the other factors from DOI. This is confirmed in other heating system adoption literature. Complexity is found to not be of much importance. Ease of use and ease of installation are considered relatively unimportant (Karytsas and Theodoropoulou, 2014). The adopters are essential. However, they make their choices mainly based on factors outside of DOI.

Neo-institutional theory plays a role to some extent. The heat transition is a complex process due to the many stakeholders involved. In the results, we see that *coercive pressures* play a significant role. There are several examples of why this is so important. Expert 4 found that elderly customers experience a considerable dependence on their children, and they follow their advice on housing renovations. Expert 4 also noted that end-users experience pressure from the government to act more sustainably. And regulations; from 2026 onward, houses need to replace their cv-boiler with a hybrid heat pump or another sustainable alternative (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). Coercive pressures play a large role on multiple levels, it thus only makes sense that the final score turned out quite high. This is confirmed by the literature (Sandoff and Williamsson, 2015, p.311; Lake et al., 2017, p.423) Coercive pressures are noted in the literature as well. In the Swedish DH industry, municipalities and the government were the main catalysts for implementing district heating systems (Sandoff and Williamsson, 2015, p.311).

Imitation and bandwagon effect are less critical. When asked about it during the exploratory interview, expert 2 noted during the exploratory interviews that copy-cat effects were not seen for municipalities or real-estate holders. However, it does hold for end-users. There is a certain social aspect that adopters think more about the technology when their neighbours have already adopted it (Snape et al., 2015). Though the extent of it is not as significant, as seen in the BWM results.

To conclude, institutional effects are mainly relevant when they take the form of group pressures, as there is a close interplay between the different actors. Formal and informal pressures of actors upon which you are reliant thus have a larger effect.

Network economics seems only to contribute little in the case of heating systems, as is seen in the results. *Network externalities* got a low score. Though consultants like to look for synergies, it is only a nice bonus and not an essential part. Furthermore, the synergy options can be added later on. Network effects like externalities and the bandwagon effect are little seen in the literature. Though some modelling studies take neighbour effects into account, it remains limited.

6.2 Limitations with the execution and methodology

Here, I will take another look at the methodology. First, I will address two aspects of the best-worst method that could have affected the results. One is how the category sizes might influence the weight outcomes. The other is about how experts approach filling in the best-worst analysis. Next, the number of experts and the expert's backgrounds are discussed. Lastly, I will dive deeper in the role of the different actors and adopters on the problem.

Influence of category sizes

In the best-worst method, the global weights are determined by multiplying the local weight with its corresponding category weight. The results show that the weight distribution in the categories with few factors is larger. This makes sense as the weights within a category must all add up to 1. Therefore the general weight per factor will be lower within categories with a larger number of factors. This could lead to factors within large categories becoming less important than they might be. The categories are weighted by the experts, which would account for this. However, the experts compare the category definitions and do not explicitly consider how many factors they contain. That may affect the resulting weights. I think you can get more reliable results if all the categories were roughly the same size. Or the experts need to be more explicitly made aware of the category sizes, although I suspect that that may lead to more confusion. Improving this might have led to better comparisons between the categories and thus more reliable global weights.

BWM: Others-to-worst vectors

Most experts found it confusing to fill in the worst-to-others vectors. The experts can roughly be divided into two groups. First, quite some experts determined the worst-to-other score by looking back at their best-to-others score.

For instance, in figure 6.1, where the best-to-worst ratio is 7, and the best-to-other is 3. Some experts would determine the comparison by subtracting the two, saying that the other-to-worst BC comparison equals 4 or 5. This results in a low consistency ratio, which is by itself a positive thing; however, it is the question of whether that is desired—these experts then do not actively think again about how the factors relate to each other. The second group, who did not see this connection, struggled more with determining others-to-worst vectors. It takes a mental switch, as you now assign the scores effectively inverse. This would confuse the experts, resulting in a higher consistency ratio. It remains challenging to conduct the BWM interviews. More practice or time with the interviewees could alter how the interviews went.

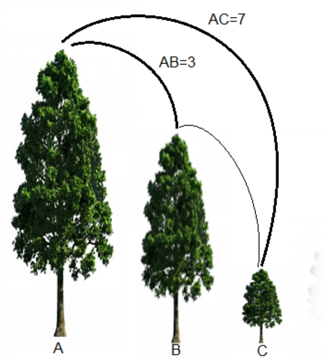

Figure 6.1: Example of pairwise comparison. Here the left tree A is the most important criterion and tree C is the least important criterion.

Variety of expert backgrounds

The vast majority of the experts (seven out of eight) who participated in the BWM interviews had a current job within the consultancy field. This was partially intended, as consultants can offer insights on multiple actors, they have had contact with a variety of problems and stakeholders. That would contribute to a more general BWM outcome. However, it would have also been interesting to include experts within real estate or municipalities. The research's goal is to identify the factors and weights according to experts. Though now there may be a too limited set of expert opinions. This could be a limitation as including stakeholders may alter the results.

Number of interviews

One other limitation is the number of interviews, which is especially prevalent with the local context interview. Here, only one expert was interviewed to fill out the BWM analysis. Of course this leads to great uncertainty and the results will be much more reliable with more expert opinions.

For the regular BWM interviews, with seven interviews being significantly more than one interview, there still lies the question of when one has done 'enough' interviews. The sensitivity analysis (figure 5.6) showed that removing an expert from the data set alters the global weights by an average of ± 0.7, with a maximum of ± 2. Though this is relatively little, it does alter the ranking. The results are reliable enough, but when interpreting the results one should keep the uncertainty in mind and take the ranking with a grain of salt. Only when there are larger differences, such as the difference between *capital investments* (weight of 13) and *building characteristics* (weight of 9), the ranking is reliable.

On the actors and adopters

As noted in section 4.5, the different technologies involve different actors. In essence, two decision steps are made. One, there is the moment when a decision is made whether there comes a district heating network or individual solutions such as heat pumps are preferred. And secondly, whether an end-user is going to connect to said district heating network or choose to install a heat pump. During this research the experts were asked to perform their BWMs *in general*, so determining the weights taking the multiple actors into account. This has some advantages as one can get a general, broad view. However, it also makes sense to determine the weights for the different actors in further research. That way one can more precisely identify the stakes and concerns of each actor.

To continue on the topic of actors, the generalization of the adopter can also clarify some results. As discussed earlier in section 6.1, Rogers' factors, which have the adopter central, were not the most relevant. This can be explained by the fact that the adopter is taken partially as municipalities, housing cooperations and rental corporations, which may have different stakes than regular individual end-users.

This line of reasoning can be extended to the factor relevance, taking for instance *availability of technical infrastructure*. Most actors take the infrastructure as it is. For the larger, executive parties, the infrastructure can be laid down if it is not already there and it is a closing post, as mentioned by multiple experts.

When one views the end-user as the main adopter, district heating is simply a very, very unlikely option if there is, or will be, no heating network set in place. *Availability of technical infrastructure* is then a huge deal-breaker. However, in this research the experts were asked to take a hypothetical case where both district heating and heat pumps were an option. After all, one cannot have a preference for something that is not executable. And in that case, the availability of technical infrastructure is not important anymore.

The way this research is set up does limit how much information the factors' weights give us on how important it is to the different actors and adopters. That is okay as the goal of this research is to also look at the effect of local context. It is a limitation in the way that the final weights may not be representative to each actor.

6.3 Discussion on local context

In this research, I introduced the effect of local context on preferences. In this section, three limitations are discussed. First, the local context may or may not represent the country well. Secondly, I discuss one category of buildings that is excluded from the research. And lastly, I discuss the calculations concerning local context.

The types of local context

Three types of local contexts were chosen. These were chosen so that they all differed and that there was little to no overlap between them. This ensures that the expert can clearly distinguish them and thus provide more accurate ratings. The three types may be a partial representation of the Netherlands. Not every neighbourhood may be accurately classified within those three categories.

Thus, one can hardly say that these ratings entirely relate to the whole country. Classifying the majority of the country within a handful of context types can be a new study in itself and thus not done in this research. I recommend looking more in detail into the different types of local contexts in the Netherlands.

Monumental buildings are left out

The local context surrounding old buildings, old city centres or monumental buildings is left out. This is done for two reasons. Firstly, many TVWs consider using sustainable gas with a hybrid heat pump for their monumental buildings, as they might be one of the only options (RVO and PAW, 2021, Delft, Groningen, Apeldoorn). As sustainable gasses are excluded from this research, as they are not available for the vast majority of the buildings, it is only fitting to exclude the context of old buildings as well. Secondly, making monumental buildings more sustainable likely requires permits, where the rules differ per building and municipality (van Rooij, 2019). A case-by-case approach is better suitable.

Taking local context into account

This research determined the final weight by multiplying the global weight with the local weight and normalising. As a result, the local weight greatly affects the final weight, as is seen in figure 5.8. It makes one wonder if there are more suitable ways of considering the local context. And how representative is this? Of course, if you get a situation where in general factor X is said to be of some importance, but if it appears that the factor is less relevant in setting A, it only makes sense that the overall weight should thus be lower. It could be interesting to look into different methods. There may be a bias during the interviews. The factors were presented one by one during the BWM local context interview. This gave the interviewee with each factor a chance to rethink whether the local context was of influence. However, this presentation possibly made the interviewee more inclined to assign a local context variation for each factor. To counteract that I reminded the interviewee that it was allowed to assign 'equal' or other values multiple times.

6.4 Further research

Actors and experts in BWM

Most of the experts who participated have a job in consultancy. The advantage of experts in consultancy is that these people have interacted with homeowners, real estate owners and municipalities. Thus they have a good overview of the different stakeholder views. Though attention was paid to the speciality and backgrounds of the consultants, it is also likely that exciting insights can be gained by interviewing employees of municipalities or energy cooperations. They provide another new perspective and still play an essential role.

Furthermore, in this research, the *general* preference of factors was asked of the experts. Many experts noted that the preference also depends on *who* you ask it to. Different stakeholders, such as real-estate holders, municipalities and residents, will have different preferences and priorities. It is interesting to look at the differences among these actors.

Scoring

A logical next step would be determining the scores for each factor in each local context. This will indicate how the technologies are performing and where there is room for improvement. There are several approaches to scoring. First, one could ask several experts for their opinion, letting them give scores between 1 and 5 for each factor. It can also be approached quantitatively. For each factor, a measurable quantity needs to be sought out. For some factors that might be less obvious, such as regulatory infrastructure. The list of factors may need to be adjusted accordingly. One could also approach it with mixed methods, where the factors which can be quantified (f.e. pay-back period and building characteristics) are quantified and normalised between a score of 1 to 5, and experts rate the remaining factors.

Technologies in detail

In this research, I chose to keep the technical aspects quite general. I did not go into detail on the exact types of heat pumps or the exact sources and temperature levels of a district heating system for a few reasons. Firstly, I was more interested in the difference between heat pumps and district heating. Deciding between those two is the first step in determining what the new heat system will be like (RVO and PAW, 2021). The two are very different as one is an individual system and the other is collective, which affects many aspects. In further research, one could look into the preference between specific heating systems. If you were to look into more details on the heat systems, such as choosing between air-source and water-source heat pumps, or geothermal-based district heating and waste heat district heating, it would be better to re-look the factors to see which remain essential once you have decided the general direction of your system.

6.5 Reflection

One thing I would change is how I approached chapter 4 on heating systems. When answering that research question, I mainly focused on government documents. However, I believe that part of the research would have been better if I first had a few conversations with consultants, municipalities and real-estate owners to find out how they choose a heating system. With that information, I could do the desk research in more detail, allowing me probably to achieve a higher-quality analysis in less time.

It was my first time conducting interviews during my studies. I noticed that I got better at getting my message across as I did more interviews. Even though I prepared well and practised with a friend beforehand, it would sometimes be tricky to clearly convey the scope of the research to the interviewees or explain well what the factors did and did not entail. My lack of experience could impose a bias, as due to a lack of trust and credibility the interviewees do not come out with their true opinions and provide information that they think the interviewer wants to hear (Sekaran and Bougie, 2016). I highly doubt this is the case with all interviewees, but it is possible with some of the first interviews. Overall, I enjoyed the interviews and I am glad I got to do them as a part of my studies. I would recommend it to other students, just for the experience and to get out of the university bubble.

Chapter 7

Conclusion

This chapter contains the conclusion to the main question and the theoretical contribution. I will briefly go through the four sub-questions to answer the main question. In the next section the theoretical contribution is presented.

1. Which heating systems are seen as relevant for the Dutch energy transition? The research found that the government promotes the usage of heat pumps, district heating and sustainable gasses such as hydrogen gas and biogas. The national government admitted that local actors should be in charge of the decision-making for a heating system, as these affect the actors on a local scale and can be pretty specific. The municipalities will take on a prominent role. Real estate companies are expected to work together with municipalities, using the transition vision on heat (TVW) that every municipality has produced. In the TVWs, it is seen that first, a general decision is made between all-electric heat pumps, hybrid heat pumps or a district heating network. Only after that are decisions made on the exact types of heat pumps and district heating. These decisions would include the temperature scale and heat sink or energy source. Therefore, these three broad technologies, all-electric heat pumps, hybrid heat pumps and district heating, are used for the remainder of the research.

2. What factors, according to literature and experts, influence the choice between the relevant heating systems? Sixteen factors were identified. Of these, seven originated from literature streams on innovation adoption. Another seven were found in heating system literature. Three additional factors were provided by experts, of which one factor partly overlapped with literature. This shows that checking different types of sources for factors is helpful.

3. What is the weight of these factors according to experts? Of the sixteen factors, *capital investments*, *building characteristics*, and *market facilitation* were weight as most important by seven experts who performed a best-worst analysis. The external environment was rated as the most important category, which includes factors on social and governmental pressures, regulatory infrastructure and market facilitation. These all belong outside the control of the implementing organisations.

4. How are the weights of the factors dependent on local context? All weights, except one, match supply and demand, are dependent on local context. For this research, three types of local contexts were identified. One is rural living, including small towns, which have a more independent way of thinking and are further from the cities. Second is social living, including homes that share certain attributes of their building. Third, suburban neighbourhoods nearby cities. For rural living, pay-back period capital investments, consumer willingness and network externalities are weighted highest compared to the other contexts. This can be explained as residents in rural living tend to act more independently. Therefore their own money and willingness are critical. Network externalities got a high rating as rural living requires more tailor-made solutions, which allow for more opportunities to create synergies with network externalities. Knowledge development, coercive pressures, and building characteristics are weighted highest for social living, compared to the other contexts. This can be explained as social living decisions need to be communally made by an organisation standing beside the residents. These decisions are based on building characteristics and coercive pressures. Knowledge development is critical as more education is required for communal buildings. For suburban living, observability and human resources available for implementing and weighted highest compared to the other contexts. Here observability is rated highest as residents care most about the visibility of their system. Human resources are more important as the suburban context contains the largest group of clients.

What factors influence the preference between different heating systems for real estate and how are they affected across different areas in the Netherlands according to experts? The research found that the monetary factors are most important for rural living, followed by consumer willingness. The rural context is less prone to coercive pressures. Factors like building characteristics and market facilitation are less critical as more tailor-made solutions are required. For social living, building characteristics and market facilitation are the most important. Consumer willingness and capital investments are more irrelevant, as an outside leading party often makes decisions based on the building characteristics with communal money. For suburban neighbourhoods, capital investments and Human resources available for implementing are most important, as people are spending their own money. Human resources are important as the suburban context contains the largest group of clients.

Theoretical contribution

In this research, several literature streams on adoption were applied towards a new topic, heating systems. Though some theories have been individually applied to the heat transition topic (such as Mahapatra and Gustavsson, 2008, Sopha et al., 2013 and Lygnerud, 2018), combining multiple literature streams was thus far paid no attention to.

There have been previous studies which combine several literature streams on innovation adoption, however, it has yet to be applied to heating systems. Heating systems are generally approached through modelling, policy analysis or end-users barriers, and not yet through a combined set of adoption literature streams. By combining, I expanded the literature on heating system adoption. Factors from multiple streams were relevant; if the streams were not combined, factors could have been missed.

This research combines multiple perspectives on heat transition. Here I looked at heating systems from not just the end-user or the industry's perspective but all combined. Usually, a paper focuses on the end-user, the industry, or the government level, where recommendations follow. This research combines them all. I do not look at the perspectives separately but ask for the *general* vision. The research can therefore give insights to a broad range of interested parties.

I proposed a method to take local context into account. Taking local context into account is not new. Generally, this is assessed through modelling, such as GIS, where one can model with all kinds of geographical indicators, or by interviewing actors within such as context (for instance, Tercan, 2021; Zach et al., 2019; Franceschinis et al., 2016). Investigating the effect of local context through a BWM study is accessible and requires much less work and data. By asking experts for their knowledge of the different contexts, a straightforward method was conducted to gain general insights into the contexts *and* quantify their importance. A critical condition is that the expert knows all the contexts. Also, as the significant advantage of subjective MCDMs, you get the real-life insights of people, which moves the researcher a little bit away from their ivory tower while gaining quantitative insights.

This research showed that local context can significantly affect the outcomes of a BWM study. So far, the outcomes of a BWM are interpreted in such a way that the results would apply to a whole region, country or perhaps even the entire western culture. As is seen in the results, the global weights differ significantly from the weights of the local contexts. The outcomes differ for different contexts, such as the most important factor. That context may be broad, such as different geographical locations or land layouts, but it can also be significant on a tiny scale. There may be different outcomes within even one neighbourhood. This research demonstrated that it is essential to be critical of who, where, and when MCDM results apply.

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