Strengthening decision-making in the heat transition

A study on how to include non-techno-economic criteria into the decision-making process for the heat transition in the Netherlands.

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Summary

This research focused on the heat transition in the Netherlands. To reach the climate goals of the Paris agreement, the Dutch society has to make a transition from heating with natural gas, towards heating with sustainable heating sources. Sustainable heating sources are for example geothermal heat, waste heat or hydrothermal heat. Different strategies are possible to make this transition. For example district heating networks with renewable heating sources, or all electric strategies with electric heat pumps. To assess which strategy is the most suitable for a specific location, different criteria are relevant.

The technical and economic criteria are very important in this assessment, and they are being thoroughly researched for every strategy and location. However, the environmental and social aspects of this transition are currently considered less frequently. Even though these criteria are very important, especially considering there are many different stakeholders in this transition, with all very different values and interests. This research has therefore focused on creating a tool which includes all these criteria, and takes the different interests from the stakeholders into consideration.

This was done through a multi-criteria analysis, a method with lends itself very well for this type of tool. Using an interval standardization method, the different criteria can be assessed and compared, while different weighing factors facilitate the incorporation of the different views from stakeholders.

The tool was assessed using a sensitivity analysis, and through two municipalities who tested the tool. In addition, the interval standardization method was compared with another, more complicated, MCA method, the PROMETHEE method, to assess if a more complicated method leads to different results. It was found that the added value of the PROMETHEE method is limited for this type of tool, since the difference was small, and simplicity makes the tool more transparent. This is an important feature for municipalities, the target audience of the tool.

List of abbreviations

Table 1. List of abbreviations

Abbreviation	Dutch	English
PBL	Planbureau voor de Leefomgeving	Dutch Environmental Assessment Agency
ECW	Expertise Centrum Warmte	Centre of Heat Expertise
RVO	Rijksdienst Voor Ondernemend Nederland	Netherlands Enterprise Agency
CHP	Warmtekrachtkoppelingsinstallatie	Combined Heat and Power
CBS	Centraal Bureau voor de Statistiek	Statistics Netherlands
PAW	Programma Aardgasvrije Wijken	Natural gas-free Neighborhoods Programme
VNG	Vereniging Nederlandse gemeentes	Association for Dutch municipalities
SCP	Sociaal cultureel planbureau	Dutch social cultural assessment agency
Weq	Woningequivalent	Home equivalent (1 weq = 130 m^2 surface)

List of translations

Because many Dutch terms had to be translated to English, a list is provided with the original Dutch terms as a reference.

Table 2. List of translations

English	Dutch
Climate agreement	Klimaatakkoord
Heat transition vision (HTv)	Transitievisie warmte (TvW)
Neighborhood-implementation plan	Wijkuitvoeringsplan
Start analysis	Startanalyse
Guidelines for local analysis	Handreiking voor locale analyse
Aquifer thermal energy storage (ATES)	Warmte koude opslag (WKO)
Hydrothermal energy from surface water	Thermische energie uit oppervlaktewater TEO
Home owner association (HOA)	Vereniging van Eigenaren (VvE)
End-user costs	Eindgebruikers kosten
Combination opportunities	Meekoppelkansen
District boundaries	Wijk- en buurtindeling

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1. Introduction

1.1 Context of the research

Because of the rising temperatures on earth due to higher concentrations of greenhouse gas (GHG) emissions, many countries signed the Paris agreement. This agreement states that all countries must pursue efforts to limit the global temperature increase to 1.5 °C above pre-industrial levels (UN, 2015). This will be achieved through energy efficiency improvements and the switch to renewable energy sources.

More than half of the energy that is yearly consumed in the Netherlands is used for heating. This heat is divided over the built environment, industry and agriculture. In total a quarter of the national energy demand goes to heating the built environment (houses and utilities), see Figure 1. In numbers this adds up to 1008 PJ of heat demand in total, of which 474 PJ is used in the built environment in 2017. From this 474 PJ, 76% came from natural gas, 5.7% from a renewable energy source and the other 18% came mostly from residual gases from oil and coal (Segers, van den Oever, Niessink, & Menkveld, 2019). Over the last fifteen years these percentages have remained fairly stable. Just energy from renewable sources has increased from 2% in 2000 to 5.7% in 2017, reducing the use of natural gas slightly (Segers et al., 2019). This clearly shows that there is still a massive transformation necessary to reach the goals of the Paris agreement. The national change from natural gas to sustainable alternatives is an enormous and complex matter, which involves many stakeholders. This research will focus on the heat transition in the built environment in the Netherlands.

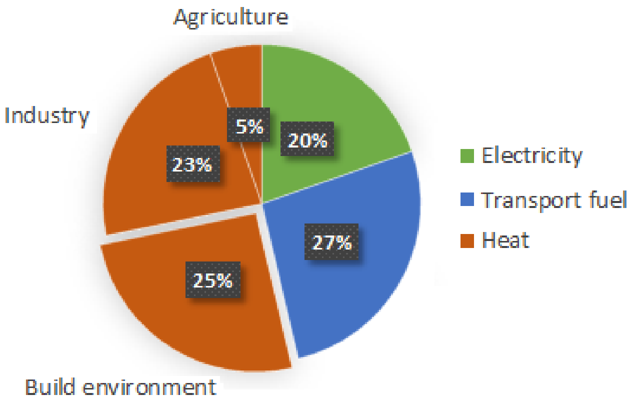

Figure 1. The total final energy use in the Netherlands in 2017, divided over the three major energy carriers (Segers et al., 2019).

The Dutch *climate agreement* states a vision that the built environment will be climate neutral in 2050. The Paris agreement is not the only motivation to quit the use of natural gas in the Netherlands. Natural gas extraction projects in the region Groningen have caused small earthquakes, which has caused a lot of damage to buildings in the area. To reach the climate goal for 2050, 1.5 million houses have to be disconnected from the natural gas grid in 2030 and over 7 million in 2050. This means the insulation needs to be improved and natural gas needs to be replaced by a renewable heating source (low-carbon heat networks, (green) electricity, green gas or hydrogen) (Klimaatakkoord, 2019).

Municipalities have a big role in the Dutch heat transition, due to the local character of the heat supply. They are designated to create a proposal on how to execute the heat transition. This will be done in two steps, the *heat transition vision* (TvW) and the *neighborhood-implementation plan*

(Klimaatakkoord, 2019). The TvW consists of two aspects; which neighborhoods will be disconnected from the grid in the period up to 2030, and which heating strategies might be used in these neighborhoods. This vision has to be finished before the end of 2021. Subsequently, they must also make a *neighborhood-implementation plan* in which the exact strategies are defined. This document goes further than the TvW, and provides the procedure on how to execute the TvW in the neighborhoods that will be disconnected from the grid before 2030. At the same time the provinces have to make a regional energy strategy (RES), in which they provide the possible locations and strategies for the generation of renewable energy. These three documents will together form the basis for the heat transition in the Netherlands (Klimaatakkoord, 2019).

This is a big undertaking for municipalities, who have the role to inform citizens, organize participation projects, negotiate between stakeholders, and decide on the heat transition path, while they often have limited expertise, time and money to do this. Among other programs, the Centre of Heat Expertise (ECW) was founded to help municipalities with their tasks, and provide expertise on all the different aspects concerning the heat transition. The Dutch Environmental Assessment Agency (PBL) and the ECW together developed the *Leidraad*, a two-fold tool that consists of the *Start analysis* and the *guidelines for local analysis*.

The first one shows the techno-economic aspects, based on calculations with the Vesta MAIS model, and the second one is a more descriptive document where other criteria are considered and suggestions are made on how to include local data. Table 3 provides an overview of the criteria that are included in the *Start analysis* and the *guidelines*. The *guidelines* provide no data, they only provide an indication on how to include these aspects (ECW, 2019a). It is suggested to classify these criteria in three categories, such as 'high, middle, low' or 'many, average, little' (ECW, 2019a). Classifying the criteria in this way is very subjective, for example; when are the amount of local initiatives high, are all local initiatives relevant, how does the size of an initiative influence the impact it has, etc. Because of this simplistic approach, it is difficult to pinpoint the impact each of these aspects have.

Table 3. Techno-economic criteria in the Start analysis, and the other criteria in the guidelines (Hoogervorst et al., 2020; Jos de Vries, personal communication, March 20, 2020; ECW, 2019a).

Start analysis	***Guidelines for local analysis***
Technical criteria	**Social criteria**
Heat demand	Contractibility
Availability of ambient heat	Social characteristics of the neighborhood
Availability of waste heat (from industry)	Local initiatives
Availability of geothermal heat	**Economic criterion**
Availability of future heat sources (e.g. green gas)	Value of the natural gas network
Spatial distance between houses	**Combination opportunities**
Economic criteria*	Neighborhood development
Installation & investment costs of the technologies	Investment plans real-estate owners
Investment costs insulation	Investment plans infrastructure
Cost of reinforcing the electricity grid	
Cost of removing or replacing the gas grid	
Expected cost of electricity	
Expected cost of renewable gas	
Expected cost of waste heat	
Expected cost of hydrogen	

* These costs are currently based on national costs; they can be expressed in euro/ton CO_2 reduced or euro/year or euro/Weq/year. To calculate the CO_2 reduction potential of the strategies is was assumed that all renewable strategies have zero emissions.

1.2 Problem definition and research gap

The current information that is handed to municipalities by the government is focused mainly on the techno-economic analysis. It is in the interest of the government that the heat transition is completed with the lowest national costs possible. Thus, it makes sense that this is the primary information they have assessed so far. However, there are many other stakeholders that are very important for the heat transition to be successfully completed. These stakeholders have much broader interests than the national costs alone, they evaluate the strategies based on the impact it has on their own lives and businesses. These impacts need to be considered, since the stakeholders play an important role in the heat transition.

Including other stakeholders, local residents especially, is already a high goal of municipalities. However, for some municipalities this is mostly theoretical policy, and little execution. Sometimes the focus lies more on communicating with residents, or in other words, convincing them of the ideas of the municipality, instead of participation. This is because participation processes are expensive and labor-intensive, for which the means are not always available ([1]Schellekens, pc). This depends on the approach of the municipality though, which can diver a lot. It has been demonstrated however, that actively involving stakeholders in the decision-making process will increase their confidence in the final outcome (Greening & Bernow, 2004). Consequently, the municipality can count on more support from the community when executing their plans. Thus, it is important to find a way to increase the participation of the stakeholders in the decision-making process.

A distinction can be made between small municipalities and large municipalities. The large municipalities are often already in an advanced phase of their TvW, and they possess the means and capacity to thoroughly assess the different pathways through the heat transition. Small municipalities on the other hand often hire consultancies to do the research for them, because they do not have the expertise or time (Rosenboom, pc). Although much data is already available; from the *Start analysis*, public data on statistics or data that the municipality possess themselves, it can be difficult to gather all this data and assess the impact that it has (Harmelink, pc). Thus, to gain insight in the broader advantages and disadvantages of every renewable heating strategy in each neighborhood, municipalities need a method to assess the data, and they need a way to facilitate the participation processes.

Next to the abovementioned Leidraad, there are several tools that focus on the energy transition or the heat transition in particular, for example the CEGOIA model (CE-Delft, 2020). With the CEGOIA model scenarios with different heating strategies can be assessed. The model shows the costs, technical options and energy demand of the scenarios. However, this model does not include social or environmental criteria, and is not publicly available. Another model which assesses the impact of different scenarios is the Energy Transition Model (Quintel Intelligence, 2020). With this model several variables can be adjusted to create a scenario, after which the impact on energy use, CO_2 savings, cost and several other indicators is shown. This model is publicly available, but does not include any social criteria either. Furthermore, the model does not provide an overview for a specific neighborhood or municipality, every variable has to be adjusted manually, for which a lot of prior knowledge is required.

Statistics Netherlands (CBS) has developed a 'story map', a framework to tell an interactive story (CBS, 2020a). With this map the energy savings potential of owner-occupied houses is shown. In these maps a criterion is included that indicates the 'willingness of the target group to take measures'.

[1] Reference to interviews that were done, an overview of these interviews with more information is provided in section 2.4.1.

This criterion is based on the income, age, energy use of the occupants, and the energy label of the house. Even though this model includes some social aspects, it is only focused on the energy savings potential, and therefore not suited for comparing different heating strategies.

There are also international tools that focus on the energy transition. The COMBI project, from the Horizon 2020 programme, focused on calculating and operationalizing the multiple benefits due to efficiency improvements for example (Thema & Rasch, 2018). This project included many different criteria, including social and environmental criteria, but it only focused on energy efficiency savings as well. It is also difficult to perform this assessment based on international data, since many parameters are location specific. The heat sources that are available for example are of great importance to the economic and technical criteria, and vary for every location. To the best knowledge of the author, there is currently not a tool or model publicly available which addresses the variety in relevant criteria, provides a method to incorporate the interests of different stakeholders and provides the opportunity to compare different heating strategies.

1.3 Research objective and research question

The main objective of this research is to give insight in the broader picture of the implications of the heat transition, in a way that municipalities can use it. This means not just information on the national costs, but also other important aspects associated with the change to a new heating system. Since real-world systems are multidimensional in nature, it has to be accepted that the evaluation of public projects needs to integrate a broad set of various points of view (Munda, 2004). It is therefore essential to use a multi-criteria evaluation framework. The specific characteristics of the neighborhood can be of great value to assess which neighborhoods are better fitted to act as a frontrunner in the transition, an which neighborhoods are not. This is often considered in the TvW's that have been published already, but especially for small municipalities the challenge is how to take these aspects into account in the decision-making process. Therefore, the objective of this research is to centralize this data, and provide a tool that can assess and compare this data, in order to give an indication of the overall impact.

The second objective is to involve stakeholders in the decision-making process. Through including the values of the different stakeholders in the tool, insight is provided in the main differences and similarities between their values. The tool can be used as a starting point for real-life discussions with the stakeholders, to gain further insight in the current obstacles, and to find a strategy that is acceptable for all parties. The ultimate aim is to assist the municipalities to make a widely supported and informed decision on their TvW and the *neighborhood-implementation plan*. This means that the timeframe of the tool is primarily focused on 2030. But the tool can, perhaps in a modified form, also be used for sequential transition visions, as they should be updated every five years. The transition is evidently not completed after 2030.

The main research question is formulated as follows:

How can the economic, technical, environmental and social aspects of the Dutch heat transition and the interests of important stakeholders be incorporated in a tool that facilitates the decision-making process of the municipality?

Multiple criteria analysis (MCA) is a field in which these different kinds of criteria, that are difficult to relate to each other, can be compared by quantifying them. With MCA methods a weighing is often added to the criteria, which could be used to gather the opinions of stakeholders about the importance of the criteria. This is a very promising tool which would be perfectly fitted for this research. This method and other methods will be further assessed in the chapter theory and concepts.

How this research question will be answered is described in the following chapters. First the relevant theories and concepts will be addressed, this chapter will conclude with the conceptual framework of this research. Thereafter the methodological approach of the construction of the tool and the analysis of the tool will be explained in the chapter methods, followed by the chapter results where all the relevant results will be presented. The limitations are discussed in the chapters methods and results as well. In the final chapter the conclusion of the research is presented, and the implications of this conclusion and recommendations for further research will be discussed.

2. Theory & concepts

In this chapter all the relevant theories and concepts will be addressed to provide a good context of this research. First of all, the stakeholders will be discussed; which stakeholders are relevant, what is their position in the transition and what are their concerns and expectations. Secondly the need for a local approach is addressed. Afterwards the different heating strategies that are considered in this research are explained. When the broader context is clear a literature review of the criteria is presented, including an explanation of how the criteria were collected. Different methods to assess the criteria are described, and relevant MCA methods are discussed. This chapter is concluded with and explanation of the research framework.

2.1 Stakeholders

Many stakeholders are involved in the transition towards sustainable heating in the built environment. This section explains shortly which stakeholders there are, and what their role is. Figure 2 shows an overview of the a few important stakeholders and their concerns.

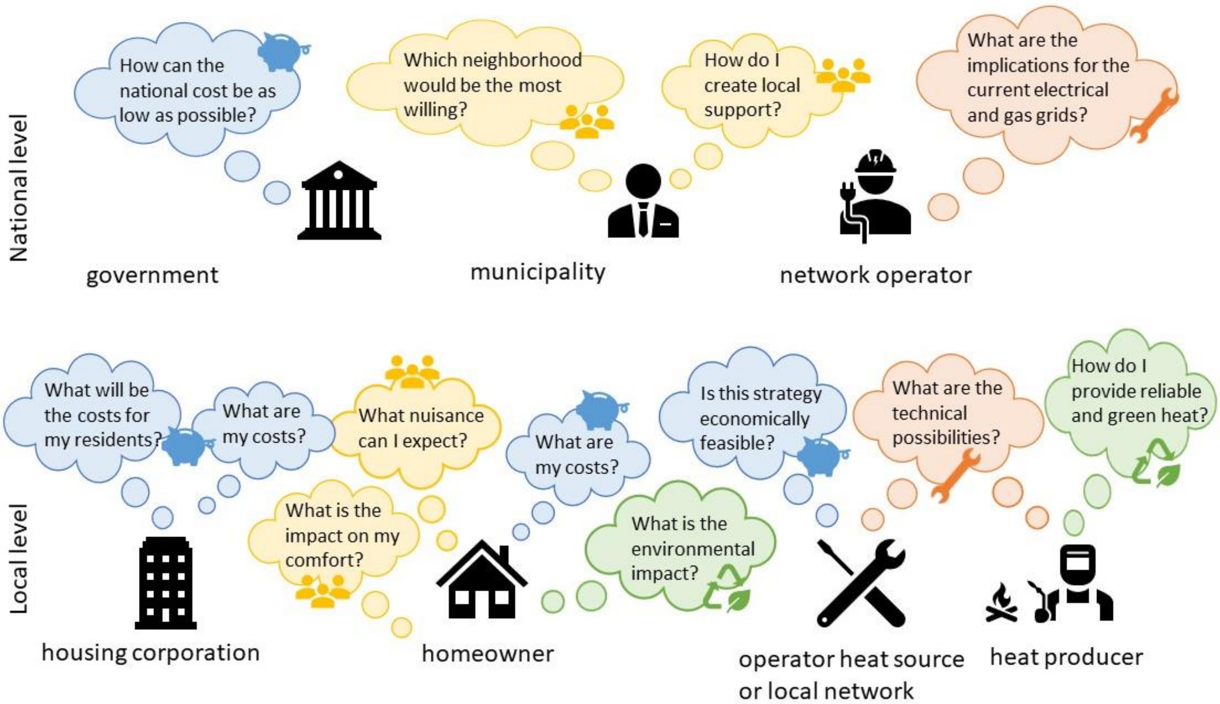

Figure 2. An overview of a few important stakeholders and their concerns. A distinction is made between national actors and local actors.

First of all there is the municipality, they have to make a transition vision for the whole district. This means they have a managing role, they are responsible for bringing the different stakeholders together and protect the interest of everyone. At the same time, they have the responsibility to execute the heat transition, but they currently do not have the legal means to force any stakeholder (Bosselaar, pc).

This is about to change, there is a new legislation under preparation that will increase the power of the municipalities ("Wet collectieve warmtevoorziening," 2020). What this legislation will exactly contain is not sure yet, it is currently under public consultation, but it is very likely that municipalities will get greater control to facilitate the construction and exploitation of collective heating systems, and will receive the instruments to ensure public interests. The goal is for the legislation to enter into force at the end of next year, but there will probably also be a transition period before the law is completely in effect (Bosselaar, pc). The priority of the municipalities is to create a transition vision that has a broad support amongst the stakeholders. At the same time it is expected from the government that they prioritize the lowest national costs, this is determined in the climate agreement (Klimaatakkoord, 2019).

Another stakeholder is the housing corporation, they represent a group of residents with a medium to low income on average, since there is an income limit to qualify for these houses (Rijksoverheid, n.d.). This means that the final costs to pay at end-user level are a very important factor for them. They often own a large amount of houses in a neighborhood, giving them a special position because they can make a decision for a large number of houses at the same time. Although 70% of the residents has to agree before the corporation can force everyone to cooperate. Nevertheless, they have a powerful position, which can be very helpful if they want to cooperate, but also very difficult if they do not. The residents are also dependent on their housing corporation, if they would like to cooperate, but the corporation does not, the residents can also be obstructed. Due to their size, housing corporations can overshadow the individual homeowners in some areas, which is another important stakeholder. It could be a task for the municipality to ensure the voice of the homeowners.

The national costs of a heating strategy are not very relevant for homeowners, they will be mainly concerned about the actual costs they will have to bear, the end-user costs (Bosselaar, pc). They will also prioritize the direct effect that the new heating system might have on their comfort, including the nuisance they might experience during the implementation phase. What they expect from the municipality will differ highly between neighborhoods, in some places they have taken the lead in the process, and elsewhere they adopt a wait-and-see approach (HIER opgewekt, 2019). For example, in the small town Garyp, in the north of the Netherlands, local residents have already realized the biggest cooperative solar park of the Netherlands (PAW, n.d.). Currently they want to tackle the heat transition, they already disconnected 30 houses from the natural gas network, and they are preparing to scale-up this project.

Then there are also the network operators, who manage the transport of energy through the country, the heat producers and operators of the heat source or heat-distribution grid. They are responsible for the technical picture, and want to make a viable business case (ECW, 2019b). When all-electric strategies are implemented it can be necessary to reinforce the electricity grid, the network operator has to execute these reinforcements (ECW, 2019b). Removing or replacing the current natural gas grid is also the responsibility of the network operator. The municipality and the network operators have to cooperate to facilitate these transformations.

The heat producers will be forced to decarbonize their heat supply when the new heat law will take effect ("Wet collectieve warmtevoorziening," 2020). They will have to conform to maximum CO_2 emission quotas, that are reduced every year up to 2030. Since the municipality will get more control over the exploitation of the heating systems when the new legislation takes effect, and the municipality is dependent on the reliability of the heat producers, they are mutually dependent. The heat producers prioritize the technical (in)possibilities, and the feasibility of their business case.

The operators of the heat source or distribution grid have to ensure the technical part of the heat extraction or distribution. They also have to do the investment for the heat extraction strategy and the distribution system. They are therefore responsible for the technical and the economic feasibility, and prioritize these aspects.

This list of stakeholders is not exhaustive, because the situation is different for every neighborhood, the stakeholders involved are also situation dependent. Therefore, some flexibility is build-in the tool, to facilitate municipalities to include the relevant stakeholders for their situation. Most stakeholders will fall in one of the previous described categories however.

2.2 The local approach

Because the situation is very different between every municipality, neighborhood, street and even house, a one-size-fits-all strategy is simply not possible. Municipalities have to make it appealing for residents to participate in this transition, and to achieve this, a personal approach is very important. Irma Straathof (pc), a participation and communication expert at PAW, explained that getting to know and trusting each other, are essential to get residents on board. It is essential to talk to people and ask them about their motivations, they can be very different from what you expect them to be (Hoogerbrugge, pc).

It can be very difficult to reach residents and homeowners. Surveys and panels are not always very representative, because only a certain group is reached (Harmelink, pc). Sometimes residents are united in a residents initiative group, which could be energy related as well, but this is not always the case (PAW, n.d.). Other ways to reach these residents are to connect to social structures or organizations such as schools, community centers, religious communities or sports clubs for example. These organizations can be used to reach to a large group of people at once. It is clear that a local approach is very important, but also very difficult because it is time intensive and motivations and priorities of residents can be very inhomogeneous within a neighborhood.

2.3 Heat transition strategies

There are five different renewable heating strategies defined for the Netherlands in the *Start analysis*. The main options are district heating (low temperature or high temperature), an electric heat pump and renewable gas. District heating networks are similar to the current natural gas networks, but instead of transporting natural gas, they transport warm water, which is directly used for space heating. An electric heat pump utilizes electricity to pump heat from a heat source, often the air or ground, inside. Renewable gas can be used in a very similar way as natural gas. Renewable gas can be produced from many different types of organic materials.

These strategies can be implemented in many different forms, in total thirteen different sub strategies are defined (ECW, 2019b). The information provided by the *Start analysis* turns out to be difficult for municipalities, they can be bit overwhelmed by the amount of possibilities, and how to interpret them (Schurink, pc). This is why the ECW has planned to create a sort of manual that can filter out some strategies or neighborhoods to consider with a few simple steps (Schurink, pc). Using the expertise of the ECW, municipalities can be guided to limit the possibilities, and this way a doable number of strategies and possible neighborhoods to start with, are selected. This pre-selection can make the use of the tool that was developed in this research much more efficient.

For example, one of the strategies is green gas. There is a limit on the availability of this gas, and the current production capacity of this gas is very small. Therefore, the limited amount of green gas is already appointed to certain neighborhoods, where other strategies are not viable, and they are allowed to use this strategy (Hoogervorst et al., 2020). Another strategy is hydrogen gas, this is however not available before 2030, because it is still in the development stage. These two strategies can therefore be taken out of consideration in this research, because they will probably not play a role in the TvW of 2030.

In addition to eliminating the green gas and hydrogen strategies, a selection was made from the district heating strategies with a low temperature heat source. This was done to reduce the number of alternatives, and because the differences in impact between the sub strategies was expected to be small, considering the criteria that were chosen. This strategy was divided in a district heating network with individual upgrading of the temperature and a district heating network with collective upgrading of the temperature.

The following strategies were considered in this research, the codes correspond to the ones used in the *Start analysis*, except for S0 (ECW, 2019b):

- S1: An Individual electric heat pump, two variants are considered;
  S1a. Air source heat pump
  S1b. Ground-source heat pump
- S2: A District heating network with an average- or high temperature heat source. Four different heat sources are considered;
  S2a. Waste heat. The source is not specified
  S2b. Geothermal at favorable sites[2]
  S2c. Geothermal everywhere[3]
  S2d. CHP with green gas as input source
- S3: District heating with a low-temperature heat source, the source is not specified. Two different variants are considered;
  S3a. Delivery at 30 °C – individual upgrading, inside the house
  S3b. Delivery at 70 °C – collectively upgraded, for a multitude of houses
- S0: This strategy corresponds to the 2018 reference strategy defined in the *Start analysis*. This strategy represents the current situation where the main energy source is natural gas.

For waste heat and low-temperature heat sources, the specific heat source is not included in the tool. This was done because these sources are not specified in the strategies mentioned above. The *Start analysis* does consider different sources in the calculations, but they are location specific, and can therefore not be generalized for the strategy.

2.4 Literature review of the criteria

The *guidelines* were used as a starting point for the criteria selection. An overview and description of the criteria can be found in Table 4. This section starts with an explanation of which of these criteria are included in the tool. This is followed by an explanation of how the other criteria were collected.

The value of the natural gas network was not included in the criteria because there is no public data available on this. This criterion can be very interesting for municipalities to consider, but this can be done separately, they often have this data for their own district, or they can request this from the network operators.

The combination opportunities are also a very important aspect that municipalities often take into consideration. What is meant with this, is the possibility to combine heat transition projects with other construction work in the area. If these renovations can be combined, the street only has to open once for both projects, which saves time, money and a lot of disturbance to the residents.

[2] This means estimations of the suitability of the site is taken into account.
[3] This means that it is assumed that it can be applied everywhere.

Table 4, overview of the criteria included in the guidelines, including a description of the criteria (ECW, 2019a).

Criteria from the guidelines	***Description***
Social criteria	
Contractibility	The number of parties that own the local properties. Thus, the number of houses owned by housing corporations or real estate owners.
Social characteristics of the neighborhood	Willingness of the residents to participate in the heat transition. It is suggested to consider lifestyle, sustainability profiles an income distribution.
Local initiatives	The presence of initiatives from residents to make the transition to natural gas-free heating.
Economic criterion	
Value of the natural gas network	The current monetary value of the network can be considered, to prevent the destruction of valuable property. The age of a network gives a good indication of the value.
Combination opportunities	
Neighborhood development	The municipality also has a policy on increasing the livability or safety of a neighborhood for example. These plans can be combined with the heat transition.
Investment plans real-estate owners	The heat transition might be combined with construction plans of real-estate owners. For example, increasing the insulation levels of the house can be combined with other renovation plans.
Investment plans infrastructure	The heat transition might be combined with construction plans of the local infrastructure. For example, the sewer system, the drinking water pipes or the electricity grid.

The problem with these combination opportunities, however, is that the added advantage depends highly on the local situation. For example, the digging expenses are relatively high, so combining the construction of a district heating network with the replacement of old pipes could be an interesting opportunity to reduce costs. But a district heating network has to be placed entirely before it can be used, while old gas pipes can be replaced piece by piece, during which the segment in renovation is bypassed. If only a segment of the network is non-operational, residents may have a day without gas. But installing a district heating network can take months, and leaving residents for months without heat is not acceptable. Thus, while the idea of combining construction projects sound very promising, in reality it is much more complicated (Bosselaar, pc).

One way these opportunities are currently included is by turning the reasoning around. For example, when a district heating network is placed, it can be examined if a sewer pipe is in need of replacement in the same place. This is done in Utrecht for example (Harmelink, pc). This way the previous problem is avoided, because a sewer pipe can be replaced piece by piece as well. Another way the combination opportunities are viewed, is by using them as compensation for the disturbance. Placing a district heating network is often not in the interest of residents, so combing the placement of the network with the construction of a nice park or square can increase the local support (Schellekens, pc). The combination opportunities are difficult to include in the tool because the added value of the criterion depends on the opinion of the municipality, and on how they are included. It is therefore difficult to generalize this criterion, which is why combination opportunities are not included in the tool. However, it is a very important criterion to consider, which is why it was still discussed briefly. The other three criteria from the *guidelines*; contractibility, social characteristics and local initiatives, were incorporated in the tool.

2.4.1 Researching the criteria

There are many different criteria that can be relevant when considering the heat transition. There is a lot of research that performs a multi criteria analysis on energy strategy alternatives. Every research uses different criteria, and different approaches (Kumar et al., 2017). There is no recipe for the perfect list of criteria, it has to be tailor-made to the specific situation. What does stand out is that there are a few categories that are almost always included. These are economic criteria, technical criteria, environmental criteria and social criteria (Kumar et al., 2017). Possible criteria were collected through literature research, and exploratory interviews with experts were held to gather background information in addition to the literature research. An overview of the interviews and the expertise of the interviewees is shown in Table 5.

These interviews have provided insight in the challenges that municipalities face with the heat transition. A lot of information was gathered on the different heating technologies, and diversity of the possibilities. The interviews also provided insight in the experience of municipalities with resident-participation, and other difficulties that municipalities face on the path towards sustainable heating. The interviews also provided input for possible criteria to include in this research.

Table 5. Overview of the exploratory expert-interviews, including the expertise of the interviewees and the date of the interview.

Name	Organization	Expertise	Date of pc
Lex Bosselaar	ECW	General expert heating strategies.	Between 17-02-2020 and 31-06-2020
Leo Brouwer	ECW	Hydrogen expert, supervises innovation projects and advises on district heating networks.	28-02-2020
Roy Blokvoort	ECW	Oversees the *guidelines for local analysis* and district heating networks expert.	25-03-2020
Michiel Hillenius	ECW	Process advisor for municipalities in Zuid-Holland (ZH) on the heat transition. He has direct experience with the difficulty's that municipalities face.	04-03-2020
Hein-Bert Schurink	ECW	Advisor CE Delft, expert on the *Start analysis*.	02-04-202
René Schellekens	PAW	Participation and communication expert, 20 years of experience working with municipalities.	25-03-2020
Irma Straathof	PAW	Participation and communication expert.	27-03-2020
Mirjam Harmelink	Consultant	Consultant energy and climate regulations, involved in the TvW of Utrecht.	14-04-2020
Yvette Rosenboom	RVO	Project leader process advisors heat transition in ZH.	17-04-2020
Gerdien van de Vreede	VNG	Data specialist.	22-04-2020
Inge Hoogerbrugge	RVO	Process advisor heat transition for municipalities in ZH.	08-05-2020

A research on the multiple impacts of renewable energy options mentioned the importance of health or wellbeing, energy security, disposable income and reduced pollution for example (Ürge-Vorsatz et al., 2016). A report of the Dutch social cultural assessment agency (SCP) showed the relation between social demographic factors and the support for climate policies (Scholte, Kluizenaar, Wilde, Steenbekkers, & Carabain, 2020). The criteria gender, education level, age, income and political orientation were mentioned as important influencers on the support for climate policies.

A literature review on multiple impact quantification methodologies, from the earlier mentioned COMBI project, also included an extensive list with possible criteria (Ürge-Vorsatz et al., 2015). The following criteria were mentioned, for example; comfort benefits, emission reductions and reduction in waste materials.

Several review papers on multi criteria analysis of renewable energy technologies showed which criteria are often used in these analyses (Kumar et al., 2017; Wang, Jing, Zhang, & Zhao, 2009). Some other papers that use MCA to prioritize renewable energy alternatives were used as inspiration on possible criteria (Haralambopoulos & Polatidis, 2003; Yan, Rousse, & Glaus, 2018; Yang, Ren, Solgaard, Xu, & Nguyen, 2018).

The criteria that were regarded by the author as possibly relevant for the heat transition were included in a list of possible criteria, this list, including remarks, can be found in Appendix A.

2.5 Methods for multiple criteria assessment

There are several methods to assess the impact of renewable energy strategies, for example; Life Cycle Analysis (LCA), Cost-Benefit Analysis (CBA), Input-Output analysis (IO-analysis) or decomposition analysis (Ürge-Vorsatz et al., 2015). These analyses all focus on one aspect of the technology, LCA for example on the environmental impact, CBA and IO-analysis on the economic impact and decomposition analysis is used to unravel the different factors that influence a change in energy or emissions scenarios. This means that these methods can be interesting to assess the impact of specific criteria, but not to compare all these different criteria that are relevant in the heat transition.

As is mentioned shortly in the introduction, MCA or MCDA (multi criteria decision analysis) techniques are very promising for this research because of the possibility to compare a wide range of criteria, and because of the incorporation of weights in the model (Siksnelyte-butkiene, Zavadskas, & Streimikiene, 2020). By assigning different weight to all the criteria, the influence of each criteria on the ranking of the alternatives is modified according to the motivations of whoever decides the weights. This can be used to gain insight in the differences and similarities between stakeholders in what they find important. It is even more interesting if the weights of multiple stakeholders can be included in the tool, and viewed separately. This way a nice overview is provided showing the impact of the different weights on the ranking of the alternatives.

MCA models are able to compare very diverse and uncertain criteria, which are measured in different units (from euros to rankings to plusses or minuses), with different weights, with each other (Pohekar & Ramachandran, 2004). MCA models have been around for a while, originally they were used in a wide arrange of sectors; agriculture, immigration, education, defense, health etc. In recent years the techniques have been applied to the renewable energy sector as well (Kumar et al., 2017). In the green revolution many different types of renewable energy sources, all with their own specifications, are introduced. Especially in the heat sector a transformation has to be made to a wide variety of heat sources; electricity, green gas, hot water or maybe even hydrogen gas. There is also a shift towards collective solutions, with district heating for example, where multiple neighborhoods have to cooperate. This makes the transition towards renewable heating a very complex and multidisciplinary issue. With the use of MCA tools this issue can be simplified. There are many different types of MCA methods, Wang et al. (2009) already lists 23 different methods. A selection of these methods will be discussed in the following section.

2.5.1 Relevant MCA methods

Wang et al. (2009) lists a few methods that are useful for sustainable energy decision making processes. They mention the weighted sum method for example. This is a very simple method where the score of each alternative is simply the sum of the score times the weight of each criteria. This means this method can only be used if all criteria have the same unit, otherwise they can't be compared directly.

Another method is the analytical hierarchy process (AHP), this is a more descriptive method that uses a pair-wise comparison to evaluate each criterion and alternative. A complex decision is decomposed into a hierarchy with the goal at the top and the alternatives at the bottom (Wang et al., 2009). This method is not suited for this research due to the descriptive nature, which makes it less suitable to use in a model.

Fuzzy set methods are also often mentioned as relevant to compare energy technologies. Fuzzy methodology uses a very complex method to convert linguistic variables (good, average, bad) into numbers (Greco, Ehrgott, & Figueira, 2016). Fuzzy sets can be combined with other methods, but the added value of them is debated. They can also be seen as a kind of sensitivity analysis, it does not always result in a more meaningful result than simply matching scores with the linguistic variables. However, quantifying qualitative variables is a difficult part of multi criteria decision analysis, and fuzzy set theory contributes some kind of conversion method from qualitative data to quantitative data.

Then there are the so-called outranking methods; "Preference ranking organization method for enrichment evaluation" (PROMETHEE) and "The elimination and choice translating reality (ELECTRE)" method (Wang et al., 2009). Both these methods have been improved over the years, resulting in different versions of the methods. The benefit of these methods is that they allow incomparability between the criteria. This means that criteria with different units can be compared. Both methods perform a pair-wise comparison between the scores of each alternative to rank them. They also use threshold values, this way small differences can be filtered out. PROMETHEE uses preference functions to measure the difference between two alternatives for each criterion. This results in an index between 0 and 1 for each criterion, which is why criteria with different units can be compared (Greco et al., 2016).

Another simple way to compare the criteria is to normalize the criteria using interval standardization, which is a very similar method as the linear preference function that PROMETHEE uses, and then apply the weighted sum method to calculate the final score of each alternative (Hoefnagels, 2020)[4].

The methods PROMETHEE and interval standardization have been used in this research. Both methods have been included to assess the added value of the more complicated method PROMETHEE.

2.6 Conceptual research framework

In order to provide an overview of the approach to this research, a conceptual framework is constructed, see Figure 3. The input was discussed in chapter 2. First the criteria were quantified, secondly a concept version of the tool was built. How this is done is explained in chapter 3; methods,

[4] Source from Blackboard UU, not publicly available.

construction of the tool. Thereafter the three different analyses were done on the tool; a sensitivity analysis on the outcome of the tool, an assessment of the tool by two municipalities and a comparative analysis of the two MCA methods that were selected in the previous section. The final output is the answer to the research question; *How can the economic, technical, environmental and social aspects of the Dutch heat transition and the interests of important stakeholders be incorporated in a tool that facilitates the decision-making process of the municipality?*

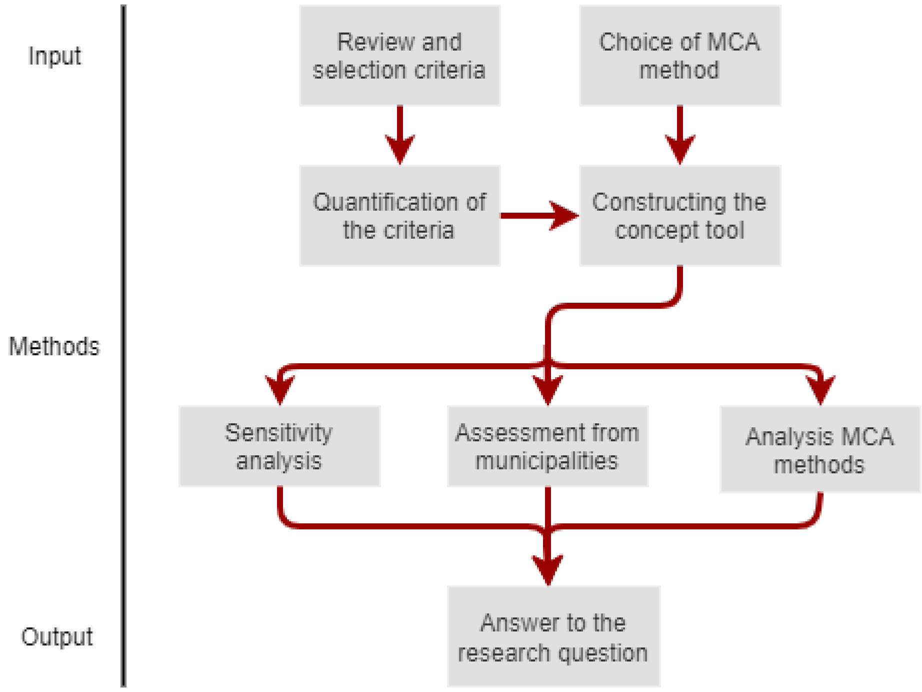

Figure 3. Conceptual framework

3. Methods and limitations

In this chapter the conceptual framework will be operationalized. This chapter is divided in four main sections; the criteria selection, the quantification of the criteria, the building blocks of the tool and the analysis of the results. The results were analyzed with three different methods, a sensitivity analysis, an assessment by municipalities and a comparison of the two MCA methods.

3.1 Method for criteria selection

The criteria were selected based on relevance for the Dutch heat transition. It was also attempted to create as little overlap between the criteria as possible, and it was aimed to provide a complete picture of the important criteria. By studying the list in Appendix A, it was found that some of the items could be indicators for a broader criteria, for example; age, income, educational level and political views can all be indicators for the intrinsic willingness of the local population to make the transition to sustainable heating in their neighborhood. It provides a characteristic of the neighborhood. To select the relevant criteria, it was considered what would be important to the different stakeholders.

For the municipality the following elements have been pointed out to be key during the selection of the neighborhoods to move to a new heating system. It is important to have a broad support from the local residents for the strategy. Because municipalities cannot force anyone to switch to sustainable heating, they have to be on board with the project, or nothing will happen. This means that the characteristic of the neighborhood and the presence of housing corporations are very important to the municipality. Housing corporations can assist the municipality with getting support in the neighborhood, because they are connected with a large quantity of dwellings. On the other hand, the presence of a housing corporation not always an advantage, because they can also resist the change, and complicate things (Harmelink, pc).

Another way to gain local support is through the organizations in a community, this could be a religious community, or maybe there are volunteer groups who support the elderly for example. As is mentioned in section 2.2, this can be a way to reach a larger group of people. There are also neighborhoods where there are already bottom-up initiatives to make their neighborhood more sustainable. It is important for a municipality to know these communities, and work together with them (Hoogerbrugge, pc). This is also important for the heat suppliers and operators, because they need to connect a lot of houses to make their grid profitable, which is easier if there is broad support in the neighborhoods.

Another important criterion that municipalities should consider is the reliability of the heat source. For example, consider a district heating network that utilizes the waste heat from an industrial company. This industry might not be able to provide the same amount of heat for the next thirty years. They could get hit by an economic crisis for example, and be forced to reduce their production. This is also an important criterion for the heat providers and operators, because they have to guarantee a constant heat flow. If a heat source is unreliable, they have to implement backup options for example. Not only the reliability but also the sustainability of a heat source in important. Not all the strategies are directly sustainable when implemented, this depends on the sustainability of the heat source, and the electricity production. It is important to consider the sustainability of the heat source in the future. These two factors are included in the criterion ‘future-proof heat source’.

The national costs are also important to the municipality, it is stated in the *climate agreement* that they have to implement the strategy with the lowest national costs, or explicitly state why they differ from this if they do (Klimaatakkoord, 2019). They have a responsibility towards the national government.

The local residents have different interests, they care a lot about their comfort levels for example. How will the transition impact their lives; do they have to cook differently, how much will their personal space be impacted by the renovations, can they make the switch at a convenient moment, when they move or renovate their house, will it take more time to heat up their house? These are all questions that are included in the criteria 'comfort'. Another very important criterion for residents are the end-user costs, how will the transition impact their own wallet, how much will their energy bill change every month.

It is also shown that houses with a higher energy label (this means more energy efficient) are worth more on the market (Altum AI, 2019; Havlínová & Dijk, 2019). This is an interesting criteria for the homeowners, because, depending on where they live, they could earn back the investments of the heat transition in their increased building value.

For any stakeholder considering sustainability as an important criterion in their decision-making, the environmental criteria are relevant. The alternatives all have a different impact on climate change, not only the direct heat production can cause GHG emissions, but also the material production, transportation and the fabrication of the technology can cause GHG emissions. This impact is considered in the criterion 'global warming potential'. The difference in energy use is especially interesting for the local residents, because this has an impact on their energy bill, but also because if the energy use is reduced, due to insulation and more efficient heating, the comfort in their house also increases.

Housing corporations have very similar interest as the residents, because they want to keep their tenants happy. This means they are concerned about the comfort levels, the end-user costs and the energy use. Following the arguments above, a list of criteria and indicators was created, see Table 6.

Table 6. List of the final criteria and their indicators.

Category	Criterion	Indicators
Social criteria	Presence housing corporation	-
	Characteristics of the neighborhood	Age Income political views Educational level
	Organization of the neighborhood	-
	Comfort levels	Nuisance from noise Cooling possibilities Quick heating Hassle/ nuisance from renovation Flexibility in moment of switch Adaptation for electric cooking.
Environmental criteria	Energy use	-
	Global warming potential	-
Economic criteria	National costs	-
	End-user costs	-
	Increase in building value	-
Technological criteria	Future-proof heat source	-

3.2 How to quantify the criteria

In this section the criteria from Table 6, section 3.1 are further explored, and the method for assessing these criteria and their indicators is explained. The national costs and energy use are not explained because they are directly copied from the *Start analysis*, thus no assessment is needed.

3.2.1 Social criteria: Presence housing corporation

Sometimes it is convenient to cooperate with a housing corporation, in this case it is important to know the distribution of housing corporations in the different neighborhoods in an area. Working together could be interesting for a municipality because housing corporations 'only' have to convince 70% of the tenants, and the rest will have to follow. This is especially interesting when a district heating network is considered, because they are only viable if enough houses are connected to the grid.

It is important to note that it does not mean that cooperating with a housing association is a guaranteed recipe for success. Even if they only have to convince 70% of the tenants, this can be very difficult. Also, not every housing corporation is very motivated to get involved in the heat transition, if they are not in favor of a district heating network, it could also be a disadvantage (Harmelink, pc)

This criterion is assessed by measuring the percentage of houses in a neighborhood that is owned by a housing corporation. The data was retrieved from the CBS, "*kerncijfers wijken en buurten"* (CBS, 2018). Data from 2018 was used, because the current *Start analysis* is based on the district boundaries from 2018, the names and corresponding codes of the neighborhoods and districts change every year, so this way the data all corresponds to the same areas.

3.2.2 Social criteria: Characteristics of the neighborhood

The social demographic characteristics of a neighborhood can give an indication of their intrinsic motivation to act against climate change. Recent studies show that education, gender, age, income, political orientation and values have a significant impact on someone's environmental concerns (Scholte et al., 2020; Tijs & van Meegeren, 2016). The impact of gender is sometimes ambiguous, and not very strong (Scholte et al., 2020). Mayor differences in gender distributions in neighborhoods was also not expected, which is why gender was not taken into account. Values is a very difficult indicator, because there is no data on this, and this is probably inhomogeneous within a neighborhood. This should be considered at an individual level, and data at that detail level is not available. This is why values are also not included in this research. This means there are four indicators left; education, age, income and political orientation. The impact of each indicator is explained in the following sections.

For every indicator an index was constructed, as is explained in the following sections. These indexes are values between 1 and 5, and after the indexes are defined, they are weighted and added. Resulting in an overall indicator value between 1 and 5. This is similar to the method described by Yan et al. (2018), but instead of using values between -3 and 3, only positive values are used, and in a smaller range. It was decided to use a smaller range since the data could not provide more detail, and the negative values complicated the calculations in excel, but this has no effect on the result otherwise. An example is shown in Table 7.

Table 7. Example of the scoring for the criteria characteristics of the neighborhood, with random numbers.

	strategy 1	***strategy 2***	***strategy 3***	**weight**
Education	5	2	3	*0.15*
Age	5	1	3	*0.10*
Income	1	5	1	*0.50*
Political orientation	5	4	1	*0.25*
Total no weighing	16	12	8	
Total including weighing	3	3.9	1.5	

3.2.2.1 Education

Higher educated people have, on average, stronger concerns about climate change, there seems to be an increase in concerns, when the education level increases (Van Dalen & Henkens, 2019). For this indicator, a low education means primary school and/or low vocational education. An average education means high vocational education and/or high school, and high education means university level, post academic and/or doctorate level. A study from the Dutch social cultural assessment agency (SCP) shows that highly educated people show significantly more support for the natural gas-free policy of the Netherlands than lower educated (Scholte et al., 2020). The average educated show a slight increase in support for the natural gas-free policy. Another study also shows that citizens with a high education level are more interested in sustainable energy and feel more responsible for the transition (Tijs & van Meegeren, 2016).

It is important to note, that high concerns about climate change, do not automatically mean that someone will take action to prevent climate change. Whether or not someone will make the transition to renewable heating depends on more than just their intrinsic willingness. Which is why many other criteria are considered in this study. This indicator, and the three others, can only give an indication of the willingness of the residents in a certain neighborhood.

To quantify this indicator, data about the education level from CBS is used; "*Opleidingsniveau to wijk en buurt*" (CBS, 2019a, 2019b). This data shows the percentage of the population between 15 and 74 years, that have completed a low, average or high education. The education-index is based on the group with the highest percentage, meaning that in that specific neighborhood the respective education group is represented the best. Since the higher the education, the stronger the concerns, the education-index is constructed as follows: If the high education group is represented the most, the neighborhood has an education-index of 5, if the average education group is represented the most, an education-index of 3, and if the low education group is represented the most, an education-index of 1, see Table 8. This is a very rough estimate though, a small difference in percentage can make a big difference in education-index.

Table 8. Overview of the education-index.

Best represented education level	**Education-index**
high education	5
average education	3
low education	1

The data on education level is only available for a selected number of neighborhoods. Two datasets were combined to increase the coverage; one dataset covered a selection of 44 municipalities (CBS, 2019b), and the other, 17 municipalities in the metropolitan region of Amsterdam (CBS, 2019a). In the end 3835 neighborhoods are included in the dataset, which is 28.8% of the total number of neighborhoods. As a consequence, the other 71.2% of neighborhoods could not be included in this indicator. When using the tool, the possibility is given to complement this data, if this is available to the user.

3.2.2.2 Age

The impact of age on concerns about climate change is a more difficult indicator. There is no clear trend visible, concerns do not grow or decrease when you get older, but there is an age-effect on the support for natural gas-free policy. Research shows that younger residents are more open to technical adjustments in their house, and use less heat in general (Tijs & van Meegeren, 2016). The SCP study has found that the age group 45-54 shows the lowest support for natural gas-free, followed by 65-74 and then 35-44. The age group 75 and up, together with 55-64 and 18-34 show the most support for the policy (Scholte et al., 2020). For more details see Table 9.

Table 9. Results from SCP research (Scholte et al., 2020). The age-effect is in reference to the youngest age group (18-34). Negative values mean that they show less support for a natural gas-free policy.

Age	Age-effect
18-34	0
35-44	-0.37
45-54	-0.44
55-64	-0.19
65-74	-0.41
75>	-0.24

Based on the research of Scholte et al. (2020) an age-index was constructed. For this indicator data from the CBS, "*kerncijfers wijken en buurten"* (CBS, 2018) was used. This data contains the number of inhabitants in five age groups for every neighborhood. The first age group (0-15 years) is disregarded, because children are not in the position to make decisions about the heat transition. No distinction could be made between 16 and 17 year residents and older residents. They were therefore included in the youngest age group, 18 to 34. The data from CBS is less specific than the data provided in Table 9, thus, in order to give an indication of the effect for each CBS-age group, the data from Table 9 had to be averaged. Table 10 shows how this was done. The age-index ranges from 1 to 5, like all indicators for this criterion, and this was determined based on the age-effect. Since negative values indicate less support for natural gas-free policy, 0 was the highest score, and was assigned an age-index of 5. The two oldest age groups had a very similar, and the lowest, score on the age-effect, and were therefore assigned the age-index of 1. The age group 25 to 44 scored roughly in between the other groups, and was therefore assigned the age-index of 3.

The differences are very age-specific, and some of the age-impact that is seen in the data from Table 9 is averaged out when combining the age groups in Table 10. More specific data on the age of the inhabitants would be needed in order to make a good estimation of the neighborhoods concerns about climate change.

To allocate the age-index to each neighborhood a similar approach as for the education-index is applied. The age group with the highest percentage of the population is the most dominant one, and decides the age-index. In order to make a fair comparison, the percentage in age group 15-25 is doubled, because this group only contains a 10 year range, where the other groups contain a 20 year range.

Table 10. Age-index, based on the results from (Scholte et al., 2020).

Age group CBS	Age-effect*	Age-index
15-24	**0**	5
25-44	AV(0;-0.37) = **-0.185**	3
45-64	AV(-0.44;-0.19) = **-0.315**	1
65 >	AV(-0.41;-0.24) = **-0.325**	1

*Age-effect based on the average (AV) of the two groups in Table 9.

3.2.2.3 Income

Multiple articles show that there is a positive correlation between a households income and their willingness to invest in sustainability (Scholte et al., 2020; Tijs & van Meegeren, 2016; Zografakis et al., 2010). Scholte et al. (2018) suggest that it is not necessarily the income that indicates whether someone will invest in sustainable heating, but how much money is left after fulfilling their basic needs. Two households can have the same income, but very different spending patterns, for example due to the number of children in a household. Despite this nuance, it is still true that financial vulnerability is still mostly present in the lowest income group.

Due to the lack of more specific data the neighborhoods were categorized in three groups; firstly, all households in the Netherlands are divided in the categories "40% households with the lowest income" (group 1) and "20% households with the highest income" (group 2). Secondly, in every neighborhood the number of households in both groups was counted. Resulting in a percentage of households in the first group, and in the second group, for every neighborhood. This was done by the CBS ((CBS, 2018).

Each neighborhood was given an income-index, see Table 11, based on the following criteria; if more than 40% of the households fall in group 1, the neighborhood has a lower income on average, and get the income-index 1. If more than 20% of the households fall in group 2, the neighborhood has a higher income on average, and get the income-index 5. If this is not the case, the income is more evenly spread, neither group stands out, and it gets the income-index 3. If there are less than 100 income recipients there is no income data available, and an income-index of 0 was given.

Table 11. Overview of the income-index.

% of households in each group	Income-index
>40% in group 1	1
>20% in group 2	5
Neither is true	3

3.2.2.4 Political orientation

A research on citizen perspectives in the Netherlands by the SCP shows how much funds voters would like to allocate to the international environmental issues and climate change (Dekker, Ridder, Houwelingen, & Broek, 2016). A clear division between left-wing voters and right-wing voters can be seen, see Table 12. A research in 2018 shows a similar picture, where GL voters worry the most about climate change, followed by PvdA, CU and D66. They also found that PVV voters worry the least about climate change (Van Dalen & Henkens, 2019). The abbreviations are also explained in Table 12.

There is not sufficiently detailed data on results of the last elections for the whole country. But because it is an important indicator of the intrinsic motivation of citizens, it should be included in the model by the local municipality if they possess more detailed information on this, when using the tool. This can be done based on the data from Table 12. A political-view-index is attributed to every party using five ranges in the desired change in expenditures (DCE) from Table 12. Table 13 shows the political-view-index for every range that was used in the tool. The length of the ranges (L_r) is based on the following formula:

$$L_r = \frac{max - min}{5} = 19.8$$

Where max is the maximum DCE value and min is the minimum DCE value. The total range from Table 12 was divided by 5 since the political-view-index should range from 1 to 5, like the other indicators. This resulted in the ranges shown in Table 13. If the most popular party is known for a neighborhood (the one with the most votes), the political-view-index that is attributed to this party can be used as an indicator.

There are more parties than were included in the research of Dekker et al. (2016). If the most popular party is not included in the list of Table 12, the political-view-index can be estimated based on the position of the party on the left-wing to right-wing parties' axis, compared to the positions of the parties that are included.

Table 12. Desired change in expenditures to the international environmental issues and climate change for every mayor Dutch political party. (Dekker et al., 2016)

English translation	Dutch party	*DCE	**index
GreenLeft – left-wing (focus on green policy)	GroenLinks (GL)	68	5
Party for the Animals – left-wing	Partij voor de Dieren (PvdD)	66	5
Democrats 66 – centre	Democraten 66 (D66)	46	4
Labour Party – centre-left	Partij van de Arbeid (PvdA)	45	4
Christian Union - centre	ChristenUnie (CU)	16	3
Socialist Party – left-wing populist	Socialistische Partij (SP)	9	3
Christian Democratic Appeal – centre-right	Christen-Democratisch Appèl (CDA)	7	2
People's Party for Freedom and Democracy – centre-right	Volkspartij voor Vrijheid en Democratie (VVD)	-5	2
Reformed Political Party – right-wing	Staatkundig Gereformeerde Partij (SGP)	-5	2
Pensioners' Party – centre	50PLUS	-10	2
Party of Freedom – right-wing populist	Partij voor de Vrijheid (PVV)	-31	1

*DC = Desired change in expenditures (in percentage points)

**index = political-view-index

Table 13. The political-view-index for every range in DCE.

Range DCE	Political-view-index
68 to 48.2	5
48.2 to 28.4	4
28.4 to 8.6	3
8.6 to -11.2	2
-11.2 to -31	1

3.2.3 Social criteria: Organization of the neighborhood

The organization of a neighborhood can also be described as social cohesion or the presence of a strong social network. If the social cohesion is strong, it is usually easier to start participation projects in this neighborhood. And since the support for the transition strategy is stronger when residents are part of the decision-making process, this is an important criterion. According to process advisor Hoogerbrugge (pc), many municipalities use participation projects to construct their heat transition strategy. If there is little organization or participation projects, they stimulate this actively.

A neighborhood can be organized in different ways, a religious community can provide a strong social cohesion, or a school, or a strong network of volunteers for example. Because not every one of these organizations provides the same social cohesion, it can't be measured what the organization level is. This is why the municipality is asked to provide insight in the organization level of the neighborhood when using the tool. A list was provided, see Table 14, from which they can choose the organization level, which corresponds to an organization-index. Scaling a criterion this way is used in literature as well to quantify linguistic variables (Yang et al., 2018).

Is was decided to range this criterion from 1 to 5 as well, to ensure consistency between the criteria, to keep the tool straightforward and easy to understand. This does have an impact on the accuracy of the criterion however. Not every bottom-up sustainability initiative has the same impact, for example. Increasing the range, and therefore options, provides a more accurate insight in the organizational level of the neighborhood.

Table 14. Options that can be selected when using the tool, and the corresponding organization-index.

Organization	**Organization-index**
Bottom-up sustainability initiatives	5
Strong social cohesion and many bottom-up initiatives, but not on the subject sustainability	4
Medium social cohesion and some bottom-up initiatives	3
Medium social cohesion but no initiatives	2
No social cohesion or initiatives.	1

3.2.4 Social criteria: Comfort

Comfort is a very important criteria, especially for the residents. People are used to a certain amount of comfort, and they are in general very reluctant to cut back on their comfort for a more sustainable house. Which is logical, investing in a heating technology is expensive, thus it is not preferred to end-up with an uncomfortable house.

The criterion comfort is based on six indicators, each heating strategy is scored on each criterion. The scoring system is similar to the one used in the criterion 'characteristics of the neighborhood', but instead of scoring from 1 to 5, it is scored from 1 to 6. This scale was chosen to facilitate more nuances in the scores. The scoring was based on the opinion of a heat-expert, Lex Bosselaar, an expert at the Centre of Heat Expertise (ECW) (Bosselaar, pc). The scoring of each strategy is compared to the reference situation, S0 (natural gas), which scores neutral (4) on every criterion. A motivation of the scores is explained for every heating strategy below, and an overview of the scores is provided in Table 15.

To validate the scores it would be best to include the opinion of more experts, this was not included due to the time limit. This is recommended for future research.

Table 15. The scores of every comfort-indicator, based on the expertise of L. Bosselaar.

Indicator	S0	S1a	S1b	S2	S3a	S3b
Nuisance from noise	4	3	4	5	4	5
Cooling possibilities	4	5	6	4	6	4
Quick heating	4	3	3	4	3	4
Adaptation for electric cooking	4	3	3	3	3	3
Hassle/ nuisance from renovation	4	2	1	2	2	2
Flexibility in moment of switch	4	3	3	1	2	1

3.2.4.1 Common characteristics of the strategies

All the sustainable alternatives that are considered in this research force the residents to switch to electric cooking. Some people see this as an advantage over cooking on gas, but installing the technology is always a hassle. A stronger electric cable is also often required, and the purchase to new pans in most cases. All strategies get a score of 3 for this criterion.

The nuisance from renovation, or the hassle factor, is very similar for all renewable strategies. Installing the strategies is always a hassle because renovations are required and new technology has to be installed. The hassle depends on the space that is available for the technologies, the location of the current boiler in the house and the accessibility of the house. But for every strategy the boiler has to be replaced and pipes have to be installed in and/or around the house. For all the low temperature strategies the radiator also has to be replaced. This hassle is expressed in a score of 2.

The only strategy that stands out is the ground-based heat pump, because the heat is extracted from the ground. This means that a heat exchanger has to be placed outside, in a garden for example. The most popular approach is to do a vertical drilling, 100 m deep. This means more hassle when the technology is installed, because the garden has to be overturned. To which extend this causes nuisance depends on the garden, and the effort that was put into it. Due to this added hassle, this strategy was given one point less.

3.2.4.2 Air-based heat pump: S1a

There is slight nuisance from noise because the air-based heat pump has a unit outside, in the garden for example, which makes some noise. This could bother the neighbors, and also the occupants if they want to enjoy the peace and quiet of their own garden. But recent models of the heat pump have very strict noise requirements, so the nuisance is limited and a score of 3 is given.

The air-based heat pump can also cool a little, this is comparable to an air conditioner. Thus, a score of 5 is given. Both heat pumps warm the space a little slower than a natural gas fired boiler, so they score one point less on this criterion.

Both types of heat pumps are relatively flexible in moment of switch, because it is not necessary to switch with the whole neighborhood at the same time. The gas grid can stay until every house has made the switch, which makes it possible to plan the renovations at a convenient moment for the resident. For example, when more renovations are planned on the house, or when new people move in. It is of course less flexible than doing nothing, so a score of 3 is given.

3.2.4.3 Ground-based heat pump: S1b

An advantage of this heat pump is that there is no nuisance from noise, because there is no unit outside. The boiler inside makes some noise as well, but similar to the noise a natural gas fired boiler makes. Another advantage is that this heat pump can cool very well, and for free. For this reason, the heat pump was given a high score of 6 for cooling. If the summers stay as warm as the last few years, this could be a very good selling point of this heat pump.

3.2.4.4 District heating network, average/high temperature (HT): S2

A high temperature network does not cause much noise disturbance, the only sound is the running of water. Since a natural gas fired boiler does make some noise, a slightly higher score was given, a 5. Regarding the thermal comfort, there is no cooling possible, and the space-heating time is similar to a natural gas boiler.

It is the least flexible alternative (together with S3b) because the whole street has to switch at the same time. They will only open up the street once, and then the new grid has to be placed, and the old one taken out. This is why a score of 1 was given.

3.2.4.5 District heating network, low temperature (LT), locally upgraded: S3a

This alternative is scored very similar to a ground-based heat pump, because the upgrading system inside the house is very similar. This means no nuisance from noise, cooling possibilities, and slightly slower heating time.

The flexibility indicator scores in between the heat pumps and the HT network, because a LT network is cheaper to build. LT networks are slightly cheaper because only minimal insulation of the pipes is needed, and there is no mayor local investment needed. This means that it is easier to make a business case, and not everyone in the street has to connect directly to the network. However, the switch time is not as long as with an electric heat pump.

3.2.4.6 District heating network, low temperature (LT), collectively upgraded: S3b

This strategy scores exactly the same as the MT/HT network, because the situation inside and around the house are the same. Because it is collectively upgraded, the network provides high temperature water.

3.2.5 Environmental criteria: Global warming potential

According to the ECW, which reflects the official opinion of the Dutch government, all the renewable strategies are free of CO_2 emissions, if the energy source is sustainable. They argue that they do not directly use fossil fuels, and are therefore sustainable (ECW, 2019b). It is mentioned that the current energy supply is often not yet free of emissions; electricity is not yet generated from 100% renewable sources, 18% of the electricity was generated from renewable sources in 2019, and the heat supply for a district heating network is not always from a renewable source (CBS, 2020b). However, in the calculations of the *Start analysis,* the sustainability of future energy sources is considered. It is assumed that all sources will then be fossil-fuel-free. Consequently, all renewable strategies are considered free of CO_2 emissions (ECW, 2019b).

The Dutch electricity mix is expected to be fully dependent on renewable technologies in 2050 (Klimaatakkoord, 2019). This means that in the coming thirty years the electricity mix is not fully generated from renewable sources. Since the average lifetime of a heat pump is about 15 to 25 years, it is very relevant to consider the current electricity mix when assessing the sustainability of the technology (Staffell, Brett, Brandon, & Hawkes, 2012).

Besides the emissions of the energy source, the renewable technologies also have to be constructed. The materials that are used are, mostly, made with the use of fossil fuels. Life cycle assessment (LCA) studies calculate the different impacts of these technologies. They often provide many different indicators for environmental impact, such as global warming potential, ozone formation, terrestrial acidification, marine ecotoxicity, mineral resource scarcity.

It is clearly important to consider other environmental impacts than are currently incorporated in the *Start analysis*. However, calculating the exact impacts of the different heating strategies requires a full LCA analysis on every strategy. Some LCA studies have been done in other countries on the renewable heating strategies, but this is highly dependent on the specific situation. For example, the electricity mix of a country has a high impact, the type of technology that is used, the number of houses connected to one district heating network, the energy source of the network, the distance between the houses etc. It is not possible to do this analysis for this research due to time restrictions, therefore an estimation of only the global warming potential was made, based on two sources.

The first source is an LCA study from literature, this study compares an individual gas boiler with a district heating network with a geothermal energy source (Bartolozzi, Rizzi, & Frey, 2017). The second source compares three scenarios; an individual gas boiler, an air to water heat pump (corresponding to S1a) and a borehole heat pump (corresponding to S1b). Both sources provided a global warming potential for the heating strategies in (kg CO_2 eq/MWh heat). Since no specific data of the different types of heating networks was available, the global warming potential from Bartolozzi et al. (2017) was used for al district heating strategies; S2, S3a and S3b. The global warming potentials of the different strategies is shown in Table 16. Additional information about the methods that were used to calculate these values is provided in Appendix B.

Table 16. Global warming potential of the strategies

Data source	System	Global warming potential (kg CO_2 eq/MWh heat)
SimaPro	Natural gas	275
	Air-water heat pump	211
	Borehole heat pump	154
Bartolozzi et al.	Natural gas	263.3
	District heating geothermal	174.5
Average of the two sources	Natural gas	*269.15

*The maximum deviation of the average value is 4.44%.

3.2.6 Economic criteria: End-user cost

Currently the *Start analysis* only includes the national costs, this is the overall cost for society. Subsidies and taxes are not included in these costs for example, because these are costs that stay within the system boundaries, the country in this case (Hoogervorst et al., 2020). However, for the end-user, homeowners for example, including these costs and benefits can make a significant difference. Thus, whether or not they are interested in a strategy, depends highly on the costs at end-user level.

The end-user costs were supposed to be included in the new version of the *Start analysis*, however, this will not be the case (Hoogervorst et al., 2020). Instead a product will be developed by PBL to estimate these costs, when these costs are available this should be included in the tool (Bosselaar, pc).

3.2.7 Economic criteria: Increase in building value

Research has focused on the relation between the energy label of a house, and the prices for which the houses have been sold (Altum AI, 2019; Havlínová & Dijk, 2019). Different studies show different results, but the overall consensus is that a green label (A,B or C) has a positive effect on the value of your house, and that a red label (E,F or G) has a negative effect on the value of your house, and this negative effect is stronger than the positive effect (relative to label D). Improving your house from label G to A can increase your building value with 7.34% to 16.4% in the Netherlands.

It is also found that there can be significant differences in the impact between different locations (Altum AI, 2019). The effect in the four major cities (the *Randstad*) in the Netherlands is smaller than in other cities. In Amsterdam the effect is the lowest, due to the extreme stress on the housing market. Because affordable houses are very rare, other factors, such as location, have a much stronger impact on the price. The maximum increase in building value is here 7.34% when the energy label is upgraded from G to A. Between cities outside of the 'R*andstad'* there are also significant differences between the measured effects on the building value (Altum AI, 2019). A study in Wales (UK) even shows increasements of 19.3% on the building value, when improving your house from F to A/B (Fuerst, Mcallister, Nanda, & Wyatt, 2016). The energy label also has an effect on the time that is needed to sell your house, an A label can increase the time with more than 50 days, and a G label can decrease the time with up to 65 days (Brounen, 2017).

Because the exact impact of the different heating strategies on the building value is unknown, an estimation has to be made based on the measures that are done to receive a certain energy label. Besides, there are different ways to get the same energy label; depending on the type of building and the year it was build. But there are some general statements that can be made.

An energy label A means that the building is optimally insulated, contains a heat pump and/or has solar cells to provide sustainable electricity. An energy label B is sufficiently insulated and has a high efficiency boiler, but no heat pump (Milieu centraal, n.d.). In the *Start analysis* all buildings are upgraded to 'shell-label' B, this is an indicator of the insulation level, very similar to the energy labels. So even heating strategies that do not require this level of insulation are extensively insulated. This means that the only difference in energy label comes from the installment of a heat pump. This is why it was assumed that the implementation of strategies with an individual electric heat pump (S1a and S1b) will result in an energy label A, and the district-heating strategies (S2, S3a and S3b) will result in an energy label B. Table 17 shows how this criterion was included in the tool, and the following section will explain how this was calculated.

Table 17. Average of two studies on impact of energy labels on market value of the house (Altum AI, 2019; Havlínová & Dijk, 2019). The column 'to label B' was added to calculate the impact of strategy S2, S3a and S3b.

To label A (S1a, S1b)		**To label B (S2, S3a, S3b)**	
B to A	0.34%	C to B	1.89%
C to A	2.23%	D to B	4.28%
D to A	4.62%	E to B	5.39%
E to A	5.74%	F to B	7.11%
F to A	7.46%	G to B	10.62%
G to A	10.96%		

3.2.7.1 How the increase in building value was calculated

The average of two studies have been used to give an approximation of the market value impact for the whole country (Altum AI, 2019; Havlínová & Dijk, 2019). One of the studies gives more detailed information for a few different cities, for this study the average of the cities outside of the '*Randstad'* where used (Altum AI, 2019). Because the ‘R*andstad’*-cities are less representative for the whole country. This is still a rough estimation, and the impact in smaller villages could be different. A municipality can ask for more detailed information about their area to get a better idea of the real impact, Altum AI does research on this. The average impact that was calculated is shown in Table 17, and from this data, the impact of improving to label B was calculated.

To get an indication of the average increase in building value in a neighborhood the average shell-label of a neighborhood was calculated. The *Start analysis* contains data about the amount of houses in every neighborhood in every shell-label. From this the average shell-label per neighborhood (A_{sl}) was calculated with the following formula:

$$A_{sl} = \frac{(1 * \mathrm{N}_A) + (2 * \mathrm{N}_B) + (3 * \mathrm{N}_C) + (4 * \mathrm{N}_D) + (5 * \mathrm{N}_E) + (6 * \mathrm{N}_F) + (7 * \mathrm{N}_G)}{N_{tot}}$$

Where N_A is the number of houses with label A, N_B is the number of houses with label B etc. and N_{tot} is the total number of houses. This resulted in a number between 1 and 7 for every neighborhood, a number between 1 and 1.5 was labeled ‘average energy label A’, a number between 1.5 and 2.5 was labeled ‘average energy label B’ etc. With these average energy labels, the average increase in building value can be read from table 17. For example, if a neighborhood has an average shell-label (A_{sl}) of 4.8, the average energy label is E. This means that the average increase in building value is 5.74% for the electric heat pump strategies (S1a and S1b), and the average increase in building value is 5.39% for the district-heating strategies (S2, S3a and S3b).

3.2.8 Technological criteria: future-proof heat source

An energy source is future proof when it is fairly certain that the source will still be there in the future, for example thirty years from now, the average lifetime of the renewable technologies. Natural gas and electricity are future proof because it is very unlikely that these sources will become scarce in the next thirty years. This is why the strategies S0, S1a and S1b have been given the default value of 5. The other strategies will be filled in by the municipalities based on the following information, which is based on personal communication with Lex Bosselaar.

Waste heat from industry is usually not very future proof, because they can’t guaranty that they will be there for the next thirty years, and provide the same amount of heat. It depends on the type of industry how reliable they are. A waste heat source in possession of the municipality is more reliable. Geothermal energy is relatively future-proof, the main uncertainty is whether there actually is a heat source. This can only be known for sure when the drilling started. A geothermal source is more reliable when owned by the municipality, and when promising locations are pre-selected. Biomass is a controversial source, there is a lot of discussion about the environmental impact of biomass. There is also a limited amount of biomass available, and it could be argued that this is of more value in other sectors that do not have good alternatives.

For low temperature heat the following sources were included: hydrothermal energy, low temperature geothermal heat, low temperature waste heat and Aquifer thermal energy storage (ATES). Low temperature heat sources are in general more reliable than high temperature sources. Hydrothermal energy is very future-proof, because the surface water is not likely to disappear. Low temperature geothermal heat is similar to the high temperature variant, the main difference is that it better known which sites are favorable, which makes it more reliable. Low temperature waste heat is also similar to the high temperature variant, but there is a lower chance that the company can use the waste heat themselves, which makes it slightly more reliable. ATES is reliable, the main heat source that is used when additional heat is needed is air, which is a future-proof source.

When using the tool, the options from Table 18 can be chosen for each heat source. The corresponding future-proof-index will be filled in automatically.

Table 18. Future-proof-index.

	Future-proof-index
Very future proof	5
Reasonably future proof	4
Neutral	3
Moderately future proof	2
Not future proof	1

3.2.9 Further limitations of the criteria assessment

There is not one method through which all social criteria can be assessed. For economic and environmental criteria there are several methods to accurately assess the impact of an alternative, for example CBA or LCA, because these criteria can be assessed quantitively. When assessing social criteria however, often only qualitative data is available. Furthermore, the impact of a criterion can be viewed differently by different individuals. For example, the nuisance that someone experiences from the noise of a heating strategy is dependent on the association they have with the noise. The noise a boiler makes in the morning can be viewed as pleasant when this reminds someone that their house will be warm and comfortable when they get up in an hour. But the noise can be viewed as highly annoying when someone is prevented from sleeping through the noise (Bosselaar, pc).

This makes it extremely difficult, if not impossible, to assign one true value to a criterion. Therefore, the possibility was incorporated in the tool for municipalities to adjust the values of each criterion, if found necessary. Some limitations of the criteria assessment were already mentioned in the previous sections, here, further limitations are addressed.

The characteristics of the neighborhood contain many limitations. Part of the limitation is due to the absence of detailed data on the indicators. Another limitation are the assessment methods. For the education and age index, a method was used where the largest group determined the index-value. This method has some serious limitations, because a small difference in group size can make the difference in an average or high index-value. Whether the distribution of the residents over the index-groups is homogeneous or inhomogeneous is not taken into account with this method.

A more accurate representation of the situation in a neighborhood can obtained by using the percentage of residents in each group and multiplying this with the index-value. An example in shown in Table 19. The disadvantage of this method is however that inhomogeneous neighborhoods can be represented poorly through this method. Consider for example a neighborhood where 45% of the residents are in the lowest education group, and 45% of the residents have a high education, the weighted average index value would be 3, even though only 10% of the residents have an average education level. Especially for the age-indicator this would be problematic, since there is no clear trend that indicates an increase in concern for global warming when the age increases or decreases.

There is some discussion about the added value of the criterion energy use, because the impact of a reduced energy bill is also included in the end-user costs. This could cause double counting of the effect, depending on how the end-user costs are calculated exactly. Perhaps energy use should be modified to the efficiency of the technology, which could be interesting for some stakeholders.

Table 19. An example of an alternative method to calculate the index-value.

% of residents in group	Index
30%	1
45%	3
25%	5
Weighted average	*2.69

* The alternative index-value is calculated as follows: (30%*1)+(45%*3)+(25%*5) = 2.69

All criteria have a high uncertainty due to the assumption they are based on, including the economic criteria calculated in the *Start analysis*. The cost, for example, are based on many assumptions concerning the technological development of a product and the expected production growth. In this research the cost were evaluated in € per CO_2 reduction potential. This could cause an overlap with the global warming potential, since the CO_2 emissions are included here as well. Since the *Start analysis* only considers the direct emissions from the incineration of natural gas, the overlap is limited, but could still be relevant. The *Start analysis* also provides the cost in € per year or € per house per year.

It might also be beneficial to include other criteria than are currently assessed. For example, human health might be an interesting criterion. For example, low temperature heating is realized through radiation heat. This method of heating causes less air displacement, which can be very beneficial to people suffering from asthma (Schellekens, pc). Other effects could be in place with an effect on human health. The impact of material use might also be interesting to incorporate in the tool. Research showed that renovation in the housing sector is responsible for one third of the environmental impact of construction materials. This is expected to increase toward 2030, partly due to the increasing quality requirements and policy on sustainable materials (Arnoldussen et al., 2020).

3.3 Building blocks of the tool

The overall idea of the tool is to create a conversation starter. By gathering the weighting factors of the different stakeholders an overview can be provided of the impact these weights have. It is shown and which strategies and neighborhoods are popular alternatives for each stakeholder. The tool can be used in two ways, one way is to look into one neighborhood and compare the heating strategies selected in section 2.3. The other way is to analyze a maximum of ten neighborhoods, and compare the favorite neighborhood of each stakeholder, and compare the neighborhoods per stakeholder.

The tool has four main building blocks; input from the user (municipalities), input from data sources, the calculations and the presentation of the results. Figure 4 provides an overview of the building blocks of the tool, the green shapes, and the two ways that the tool can be used. These building blocks are elaborated further in the following sections.

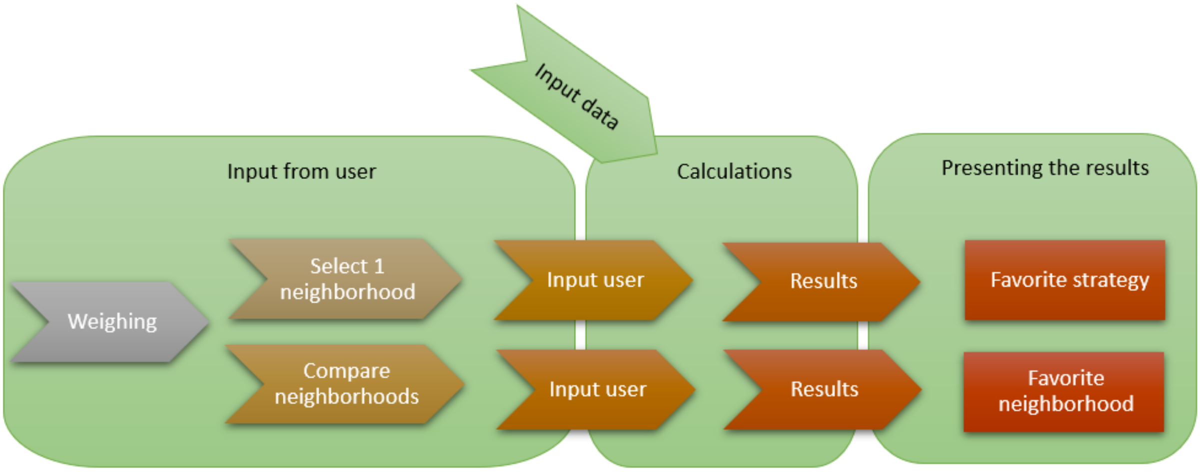

Figure 4. Overview of the functioning of the tool. The green shapes indicate the four building blocks, and the colored arrows represent the steps a user of the tool goes through.

3.3.1 Input from user

As was explained in the previous sections, not all data could be obtained for the whole country. Some data has to be added by the user of the tool, which are the municipalities, who often possess much more data than is publicly available. The data that is requested from the municipalities are the available heat sources, the future-proof-index of these sources and the organization level of the neighborhood. Another important input from municipalities are the weighing factors.

The possibility to add weighing factors is included in two steps. First the municipality can add their own weighting factors. They are instructed to divide 30 points over the ten criteria. They are given the possibility to allocate all the points to one criterion, to allocation zero points to a criterion, and everything in between. They were given the information in Table 20, to assist with the allocation of the points. If only one neighborhood is assessed, three social criteria cannot be included, because they only provide information about the neighborhood, and when the different strategies are compared, this has no influence. These criteria are the presence of housing corporations, characteristics of the neighborhood and the organization of the neighborhood. Thus, they also have to divide 21 points over the seven criteria that are left. Figure 5 shows how the process of choosing weighing values is designed in the tool. Secondly, the municipality has to do the same thing for the other stakeholders, naturally this information has to be gathered from the stakeholders first. How this can be done exactly is not a part of this research. The main stakeholders are included in the tool, but there is also the option to add another stakeholder, or to change the names of the stakeholders.

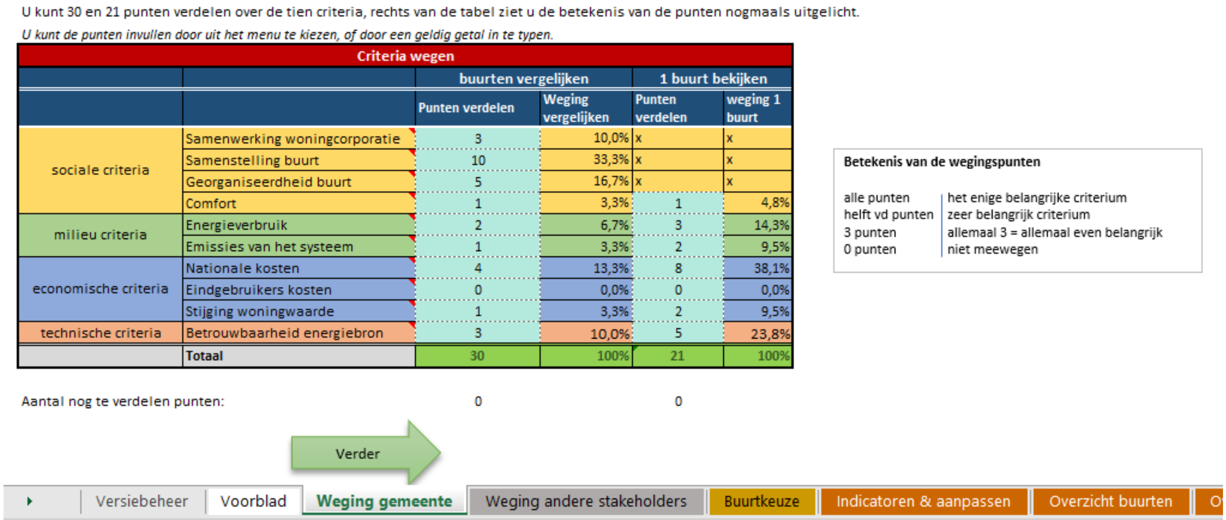

Figure 5. Illustration of the section "weighing the criteria for municipalities". Dummy weights are filled in to illustrate how the tool works.

After the weighing factors are collected, the municipality has to choose the neighborhoods or neighborhood, and add some data about them. They are asked to add data on the available middle/high and low temperature heat sources in the surroundings of the neighborhood, and make an estimation on how future-proof that heat source is. The available heat sources can be found in the *Start analysis*, however, some sources might not be included there because the data of the source is not publicly available, or because new sources have become available (Bosselaar, pc). It is therefore requested from the municipality to add this information. The selection options are given in Table 21, and the selection options on the future-proof indicator is shown in Table 18, from section 3.2.8. The municipalities were also asked to provide an estimation of the organization level of the neighborhood, as is explained in section 3.2.3.

Table 20. Information provided to allocate weighting factors to the criteria.

Meaning of the weighting factors	
All points	The only important criterion
Half of the points	A very important criterion
3 points	All 3 = all equally important
0 points	Ignore the criterion

Table 21. Selection options for the available heat sources.

Middle/High temperature heat sources	**Low temperature heat sources**
Waste heat industry	Hydrothermal
Geothermal at favorable sites	Low temperature waste heat
Geothermal everywhere	Low temperature geothermal heat
CHP with green gas as input source	Aquifer thermal energy storage

3.3.2 Input from data

Besides the information that was added by the municipalities a lot of data from the other criteria was added to the tool. Which data was used and how they were adjusted to provide a final value for each criterion is explained in previous section 3.2. Table 22 shows how this data is presented for the users in the tool. The values of the indicators from the characteristics of the neighborhood and the comfort levels is presented in different tables, where municipalities are provided the opportunity to adjust these values. This can be done when additional data is available, on political views for example, or when a municipality does not agree with the value that is given.

Table 22. This overview is given for every selected neighborhood in the tool. $V_{i,j}$ represent the final value for that criterion and alternative.

	Name neighborhood						
Criterion	**Unit**	**S0**	**S1a**	**S1b**	**S2**	**S3a**	**S3b**
Presence housing corporation	%	$V_{1,1}$	$V_{1,2}$	$V_{1,3}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Characteristics of the neighborhood	Score 1 to 5	$V_{2,1}$	$V_{2,2}$	$V_{2,3}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Organization of the neighborhood	Score 1 to 5	$V_{3,1}$	$V_{3,2}$	$V_{3,3}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Comfort levels	Score 1 to 6	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Energy use	GJ/house/year	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Global warming potential	Kg CO_{2-eq}/MWh	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
National costs	€/ton CO_2 reduction	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
End-user costs	€/house/year	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Increase in building value	%	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$
Future-proof heat source	Score 1 to 5	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$	$V_{i,j}$

Additional data was added to the tool to provide context to the results. The average building value, the percentage of owner-occupied houses, the percentage of rental properties and the number of inhabitants was added, from the data source *“kerncijfers wijken en buurten”* (CBS, 2018).

3.3.3 Calculations

When all the data was gathered, some calculations were done to calculate a ‘final score’ of each alternative. This final score indicates how attractive each alternative is. The alternative with the highest score is the most favored strategy, and the one with the lowest score the least favored. This way the strategies are ranked from most attractive, to least attractive. The method to calculate this final score is different for the two MCA methods that were selected. Both methods are explained shortly in this section.

3.3.3.1 The interval standardization method

The method to calculate the final score of the comparison of neighborhoods is slightly different from the method to calculate the final result of just one neighborhood. First the method for one neighborhood is explained. This method is based on a lecture from Hoefnagels (2020).

Since all the final values from Table 22 of the previous section, $V_{i,j}$, are defined in different units, the first step is to normalize these values. Normalizing these values means they are converted to a value between 0 and 1. This way the different criteria can be compared. There is a difference between criteria that are maximized, and criteria that are minimized. If a higher value means the criterion should come out higher in the ranking, the criterion should be maximized, if a higher value means it should come out lower in the ranking, the criterion should be minimized. For example, costs have to be minimized, because higher costs are not desired. Table 23 shows which criteria are minimized and which criteria are maximized.

For the interval standardization method, the following formula was used to normalize maximized criteria:

$$I_{i,j} = \frac{V_{i,j} - V_{i,min}}{V_{i,max} - V_{i,min}}$$

Where $I_{i,j}$ is the normalized value of criterion i and alternative j, $V_{i,j}$ is the value of criterion i and alternative j, $V_{i,min}$ is the lowest score of criterion i, and $V_{i,max}$ is the highest score of criterion i. For minimized criteria the formula was adjusted to:

$$I_{i,j} = \frac{-(V_{i,j} - V_{i,min})}{V_{i,max} - V_{i,min}} + 1$$

The final score of alternative j was calculated with the weighted sum method:

$$F_j = \sum_{i=1}^{i} I_{i,j} w_i$$

Where w_i is the weight of criterion i. The final scores of the interval standardization method are values between 0 and 1.

For the comparison of multiple neighborhoods the same method was used, but in this case the lowest score of criterion i is the lowest score of all the neighborhoods combined for criterion i. And the same goes for the highest score.

Table 23. List of the criteria and whether they are maximized (+) or minimized (-).

Criterion	**+/-**
Presence housing corporation	+
Characteristics of the neighborhood	+
Organization of the neighborhood	+
Comfort levels	+
Energy use	-
Global warming potential	-
National costs	-
End-user costs	-
Increase in building value	+
Future-proof heat source	+

3.3.3.2 The PROMETHEE method

The PROMETHEE method was only used to assess the alternatives of one neighborhood, not to compare different neighborhoods. It was decided to limit the assessment of the two MCA methods this way, since the calculations would become increasingly cumbersome when more different neighborhoods are compared with this method.

The explanation in this section is based on the book 'Multiple Criteria Decision Analysis' from Greco, Ehrgott and Figueira (2016). The PROMETHEE method performs a pair-wise comparison of the alternatives. For each criterion, the differences between the values for each alternative are calculated. This variable is called D_i. For example, the calculation of Di for the difference between alternative S0 and S1a is as follows:

$$D_i(S0, S1a) = V_i(S0) - V_i(S1a)$$

Where V_i (S0) the value of criterion i is of strategy S0, and V_i (S1a) the value of criterion i from strategy S1a. Subsequently the preference function is defined, this is very similar to the normalization process in the interval standardization method, and results in a value between 0 and 1. However, the PROMETHEE method introduces two threshold values; the threshold of indifference, called q, and the threshold of strict preference, called p. The preference threshold is the smallest deviation which is considered as sufficient to generate a full preference of one alternative over another. And the indifference threshold is the largest deviation which is considered as negligible. The values that were chosen for these thresholds are explained in section 3.4.1, 'comparison of the MCA methods'. Figure 6 shows the preference function, with the p and q thresholds. Every D_i that is higher than p, results in a preference index of 1, and every D_i lower than q, results in a preference index of 0. The thresholds can differ for each criterion. For the D_i values in between p and q, the following formula is used to calculate the preference index, $P_i(D_i)$:

$$P_i(D_i) = \frac{D_i - q_i}{p_i - q_i}$$

Where p_i and q_i are the thresholds for criterion i. Subsequently the so-called outranking degree is calculated, Π, through multiplying the preference index with the weights. This is done for every possible combinations of the alternatives. Thus, for example for the D_i (S0,S1a):

$$\Pi\ (\mathrm{S0}, \mathrm{S1a}) = \sum_{i=1}^{i} P_{i,} w_i$$

Lastly the final score is calculated, in the PROMETHEE method this is called the outranking flow. The outranking flow, F_j is calculated by adding the negative, $\emptyset^-$, and the positive, $\emptyset^+$, outranking flow, they are calculated as follows, using the example of S0:

$$\emptyset^+(\mathrm{S0}) = \frac{\Pi(\mathrm{S0},\mathrm{S1a}) + \Pi(\mathrm{S0},\mathrm{S1b}) + \Pi(\mathrm{S0},\mathrm{S2}) + \Pi(\mathrm{S0},\mathrm{S3a}) + \Pi(\mathrm{S0},\mathrm{S3b})}{\mathrm{n}-1}$$

$$\emptyset^-(\mathrm{S0}) = \frac{\Pi(\mathrm{S1a},\mathrm{S0}) + \Pi(\mathrm{S1b},\mathrm{S0}) + \Pi(\mathrm{S2},\mathrm{S0}) + \Pi(\mathrm{S3a},\mathrm{S0}) + \Pi(\mathrm{S3b},\mathrm{S0})}{\mathrm{n}-1}$$

Where n the number of alternatives is. Using these formulas the final score of S0 is calculated as follows:

$$F_{S0} = \emptyset^+(\mathrm{S0}) - \emptyset^-(\mathrm{S0})$$

Or in general:

$$F_j = \emptyset^+(\mathrm{j}) - \emptyset^-(\mathrm{j})$$

With the PROMETHEE method, the final ranking is scored between -1 and 1, where the interval standardization method is scored between 0 and 1.

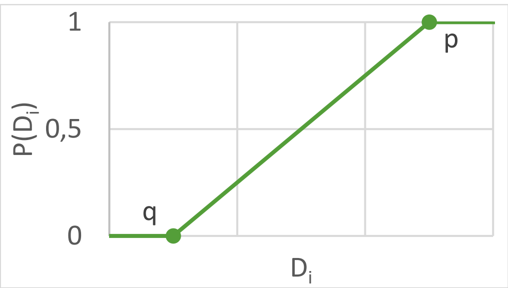

Figure 6. Example of the preference function from the PROMETHEE method.

3.3.4 Presenting the results

The results of the assessment are presented differently for both ways to use the tool. When the results for one neighborhood are presented, the favorite strategy per stakeholder is shown, together with the context values from section 3.3.2. The average energy label, the percentage of housing corporation houses, the average age, the average education level and the average income level, using the calculations from section 3.2, are also presented with the context values. The ranking for each stakeholder is also shown, including the decomposition of the criteria. Figure 7 shows an example of how the results are presented. Lastly the distribution of the weighting factors is shown in a pie diagram for each stakeholder

When different neighborhoods are compared, the favorite neighborhood per stakeholder is shown, and the favorite strategy for every neighborhood per stakeholder. The distribution of the weighting factors is shown as well.

Figure 7. Illustration of the section "results of one neighborhood".

3.4 Analysis of the results

The results are analyzed with three different methods. First the two MCA methods were compared, secondly a sensitivity analysis was performed, and two municipalities assessed the tool. The two MCA methods were compared to assess the added value of the more complicated PROMETHEE method. A sensitivity analysis was done on the weighing factors and some criteria, to assess the impact they have on the final ranking of the strategies. Lastly the tool was assessed by two municipalities, this way the user-friendliness was assessed by the actual user.

3.4.1 Comparison of the MCA methods

The sensitivity analysis of the weighing factors was executed with both MCA methods, the interval standardization method and the PROMETHEE method. First of all, the difference in final ranking was analyzed. Both methods provide a ranking based on the final scores, it was analyzed how these final rankings differed between the two methods. Secondly the percentual difference between the final scores of the alternatives was analyzed. This was done by comparing the difference in final score of two consecutive strategies with the maximal range in final scores of all the strategies. The following formula was used:

$$PD_{1,2} = \frac{F_1 - F_2}{F_{max} - F_{min}}$$

Where $PD_{1,2}$ indicates the percentual difference between the strategies with rank 1 and 2, F_1 the final score of the strategy with rank 1, F_2 the final score of the strategy with rank 2 and F_{max} and F_{min} the maximal and minimal final scores. This was done for both methods, and consequently the difference between the percentual differences was calculated. The percentual difference was calculated because both methods provide their final scores in a different range, see section 3.3.3. This way the final scores of the two MCA methods could be compared.

Because the outcome of the PROMETHEE method is highly dependent on the p and q variables, see section 3.3.3, two different p values were analyzed. The preference threshold (p) is the smallest deviation which is considered as sufficient to generate a full preference of one alternative over another. To get the best representation of the data, it was considered that all deviations are relevant, therefore, the difference between the maximal value and the minimal value, within each criterion, was used to calculate p_1. Usually the thresholds are defined by experts, but this was not possible for this research. Therefore, another method to calculate the preference threshold was taken from literature research. Haralambopoulos & Polatidis (2003) used the following formula to calculate p:

$$P_2 = \frac{V_{i,max} - V_{i,min}}{n}$$

Where n is the number of alternatives. The same formula was used to calculate the alternative p value for this analysis, p_2. The q variable, or indifference threshold, was set to zero, because every deviation was regarded important. Due to time limits, the analysis with the alternative p value was only performed for the sensitivity analysis of the weighing factors of one neighborhood, while three different neighborhoods were analyzed for the sensitivity analysis.

3.4.2 Sensitivity analysis

A sensitivity analysis was done on the weighting factors, and the following criteria; the global warming potential and the comfort levels. There criteria were chosen because of the high uncertainty in the data that was used for these criteria. Not all criteria could be analyzed because of time limits. However, it is important to keep in mind that all criteria have a certain level of uncertainty. A sensitivity analysis on the weighing factors was done to analyze the impact this has on the final ranking of the alternatives.

For the analysis of the weights, the weight of one criterion was varied, while the other weights stayed constant. For every criterion five alternative weights were assessed, and the scenario were the weight were the same for all criteria. The minimal weight that was assessed was 6%, and the maximum weight 100%, which means it is the only criterion that is included in the calculations.

For the analysis on the criteria, a change in parameter of 30% was chosen. Since the total values for comfort all fit within a small range, between 3.17 and 4.0, the change of 30% had a significant effect. The range between the global warming potentials is bigger, roughly between 270 and 150, however, to be consistent, the same change in parameter was used. For the analysis on the global warming potential the strategies S2, S3a and S3b were assessed as one, because they are all assumed to have the same impact, see section 3.2.5. For the assessment of the criteria only was neighborhood was used, Matenhoeve, because the values for the criteria that were used, do not differ between neighborhoods.

Because the results are different for every neighborhood, and not all (13305) neighborhoods could be analyzed, three neighborhoods were selected to be analyzed. The selected neighborhoods were from the municipality of Apeldoorn, and according to the municipality these neighborhoods are very diverse. The first neighborhood (De Parken) has a relatively high average income and education level, relatively old houses and on average double the building value of the other two neighborhoods. The second neighborhood (Loenen), has a relatively low income and average education level, a section of the national park 'De Hoge Veluwe' is part of this neighborhood. The third neighborhood has many inhabitants, an average income and education level and on average relatively high energy labels (Matenhoeve). See Table 24 for an overview of the background information.

Table 24. Background information on the three neighborhoods that were selected for the sensitivity analysis. This information was gathered from the tool.

	Matenhoeve	**De Parken**	**Loenen**
District (*wijk*)	Zuidoost	Noord	Loenen en omgeving
Number of inhabitants	4795	2420	2165
Average age	Older than 45	Older than 45	Older than 45
Average education level	Average	High	Average
Average income	Average	High	Low
Average energy label	C	F	D
% owner-occupied houses	72%	88%	63%
% rental properties	28%	10%	37%
% housing corporation	23%	2%	32%
Average building value (x1000€)	199	458	254

To execute the sensitivity analysis, the data input that is required from the municipality had be filled in in the tool. Thus, additional information on the neighborhoods was researched, which is discussed shortly. The *Start analysis* provided the MT/HT and LT heat sources, the one with the lowest cost was chosen. For Loenen and Matenhoeve no LT heat source was given in the *Start analysis*. It was found that for Matenhoeve there is the possibility to utilize hydrothermal surface water as a LT heat source (Energiek Apeldoorn, 2019). For Loenen, no possible LT heat source could be found, therefore it was assumed that this is not an option. The future proof criterion was assessed based on the information from section 3.2.8, the input data that was used can be found in Table 25.

In the Matenhoeve there is some level of participation, there was a conversation session where a lot of residents showed up, therefore this neighborhood was given a score of 4 for organization of the neighborhood (Energiek Apeldoorn, 2019). For the neighborhood De Parken it was found that there is an initiative from residents 'initiative group sustainable Parken' that focuses on the heat transition, therefore this neighborhood got the maximal score for the criterion organization of the neighborhood (De Parken - wijkraad Apeldoorn, 2020). In the neighborhood Loenen there is a complete participation-plan (Eerbeek Loenen 2030, 2020). However, no actual activities could be found, therefore this neighborhood was given a score of 2. These scores can be found in Table 25 as well. All these input variables are very rough estimations, but since this is just an example of how the tool works, this is deemed sufficient.

Table 25. Input data for the three neighborhoods.

	Matenhoeve	De Parken	Loenen
MT/HT energy source	Waste heat industry	Geothermal at favorable sites	Waste heat industry
LT energy source	Hydrothermal	Aquifer thermal energy storage	-
Future proof MT/HT source	Moderately future proof (2)	Very future proof (5)	Moderately future proof (2)
Future proof LT source	Reasonably future proof (4)	Reasonably future proof (4)	-
Organization of the neighborhood	Strong social cohesion and many bottom-up initiatives, but not on the subject sustainability (4)	Bottom-up sustainability initiatives (5)	Medium social cohesion but no initiatives (2)

3.4.3 Assessment of municipalities

Two municipalities have assessed a draft version of the tool. There was not enough time to include the weighting factors of other stakeholders, however, they have made an estimation of these weighting factors to be able to assess the entire tool. Before the municipalities tested the tool, the tool was shortly explained by the author of this thesis. Afterwards the tool was sent to them, and unlimited time was given to test the tool. If they had questions during the test, they were allowed to ask them, but this possibility was not utilized. The municipalities were asked to provide written or verbal feedback after filling in the tool.

The municipalities that assessed the tool are the municipality of Lansingerland and Apeldoorn. Lansingerland is a relatively small municipality in the west of the Netherlands, just above Rotterdam. The municipality had 61,155 inhabitants in 2018 (CBS, 2018). The official that took part in the assessment was Rob Wijsman, senior advisor sustainability. Apeldoorn is a bigger municipality with 161,156 inhabitants in 2018 (CBS, 2018). Apeldoorn is a municipality in the center of the Netherlands. The official that took part in the assessment of the municipality of Apeldoorn was Theo van Es, senior advisor energy transition.

4. Results and limitations

4.1 Comparison MCA methods

The comparison of the two MCA methods, interval standardization and PROMETHEEE, was done with two threshold values. For the second threshold value, p_2, only the sensitivity analysis on the weighing factors of one neighborhood was used, as was mentioned in the method. Since there are six criteria analyzed, five different weighing options were compared for every criterion, and the scenario where all criteria have the same weight, 31 scenarios were analyzed with p_2.

When the preference threshold p_1 was used, both MCA methods showed exactly the same results. The ranking of the alternatives was always exactly the same, and the percentual difference between the positions of the alternatives in the ranking as well. This indicates that the pair-wise comparison of the alternatives used by the method PROMETHEE, has no added value compared to the interval standardization method, when the preference threshold is maximized.

An impact was found however when preference threshold p_2 was used. In 51.6% of the 31 scenarios the final ranking of the alternatives was the same. In 45.2% of the scenarios there was one alternative that ended up at a different place in the ranking. See for example Table 26, in this case S0 goes from 3rd place with the PROMETHEE method, to 5th place with the interval standardization method. The order of the other strategies is the same with the both methods. In 3.2% of the scenarios there were two strategies that ended up in a different place in the ranking order. The absolute position of the alternatives was also analyzed, with this the absolute ranking position is meant, thus 1st place, 2nd place, 3rd place etc. In Table 26, for example, three strategies are ranked at a different absolute position, and three strategies are ranked at the same absolute position. It was found that 78.0% of the strategies were ranked at the exact same position with both methods.

Table 26. Example of the ranking of alternatives with the two different methods.

	PROMETHEE with p_1	**PROMETHEE with p_2**
1st place	S1b	S1b
2nd place	S1a	S1a
3rd place	S3a	S0
4th place	S3b	S3a
5th place	S0	S3b
6th place	S2	S2

The percentual difference between the positions of the alternatives was also calculated. The average difference between the position of the alternatives was 15.3%, and the maximal difference that was found was 64.4%.

Figure 8 shows an example of the preference function $P(D_i)$ from the PROMETHEE method, where the two different preference thresholds p_1 and p_2 are visualized. In this graph, D_i represents the difference between two values of one criterion. When p_1 is used, $P(D_i)$ equals 1 when D_i has the maximum value. When p_2 is used, $P(D_i) = 1$ when D_i is bigger than the value of p_2, but this does not have to be the maximum value (Greco et al., 2016). In practice this means that much more often $P(D_i)$ equals 1 or 0, while when p_1 is used as a preference function, $P(D_i)$ more often equals a number between 0 and 1. This explains why the different preference threshold provide different rankings. In the opinion of the author, part of the nuance between the alternatives is lost when a lower preference threshold is used.

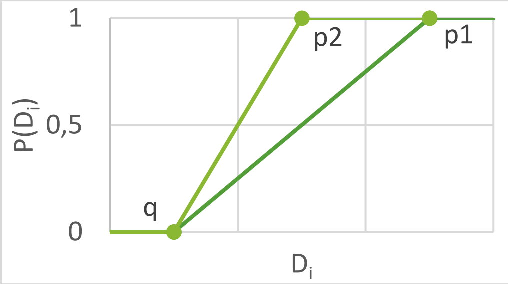

Figure 8. Example of the P(d) function from the PROMETHEE method.

4.2 Sensitivity analysis

Since no mayor impact was found from using the PROMETHEE method, the results of the sensitivity analysis are presented from the calculations based on the interval standardization method.

4.2.1 Sensitivity analysis on weights

The impact of different weighing factors was assessed for the three neighborhoods. Overall all the criteria showed a high sensitivity to the weighing factors, which is positive, as this is an important part of the functioning of the tool. The range of the final scores of the heating strategies is relatively small when the weighing factors are close together. As one criterion gains in weight, a separation between the strategies is seen. Some strategies become more attractive, and move towards a final score of 1, and some become less attractive, and move towards 0. This effect was found in all the criteria and assessed neighborhoods. This happens because as one criterion is singled out, the final outcome diverges towards the ranking in that particular criterion. This effect can be seen in Figure 9.

For the criteria comfort, global warming potential and building value there is not a very big difference between the sensitivity analyses of the three neighborhoods. Figure 9 shows the sensitivity analysis for the criterion comfort. At the points were two lines intersect, the ranking of the strategies changes. It can be seen that in all neighborhoods the final ranking, and final score, of the strategies is the same when the weight of comfort goes to 100%. The same happens for global warming and building value. This happens because the input data does not differ for comfort and global warming potential, and the increase in building value is always lowest for S0 (zero) and highest for S1. Thus, if the weight of these criteria is stronger, the ranking always diverges to the same order. The criterion comfort is given as an example, since the other criteria show the same effect, these are not shown.

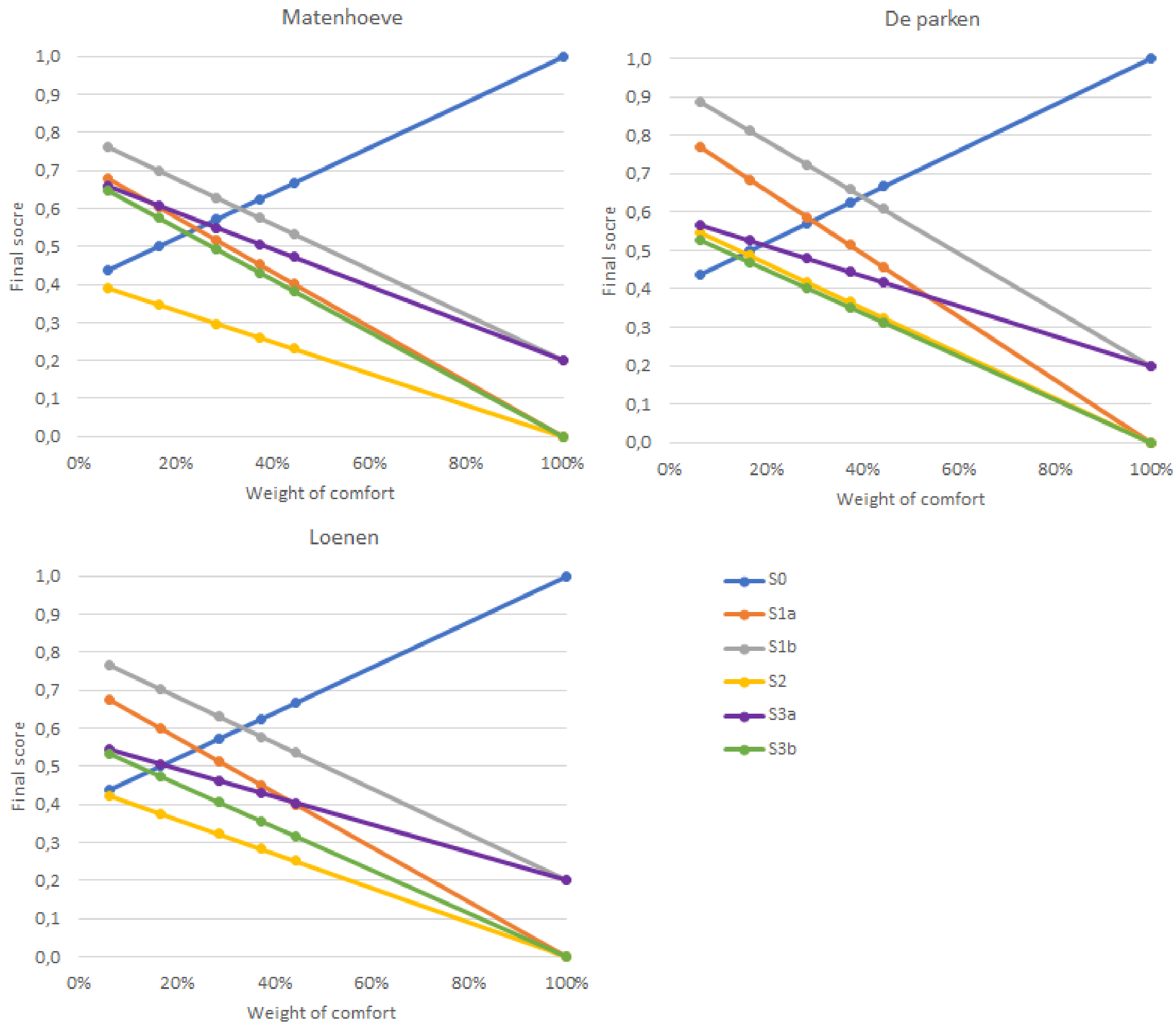

Figure 9. Sensitivity analysis of the weights of comfort for the three neighborhoods.

When the weights of the national costs were analyzed, a variance between the neighborhoods was seen, see Figure 10. What stands out is that S0 always goes to 1 when the weight is increased. The variance between the neighborhoods is due to the difference in national costs per strategy in the different neighborhoods. However, strategy S0 always diverged to the highest ranking because the costs per emission reduction are zero for this strategy in every neighborhood, since there is no emission reduction. It can be seen that the most expensive strategies go to zero at 100%. It can be seen that in Loenen the costs of all renewable heating strategies are close together, while in De Parken strategy S2 is much more expensive than all other renewable strategies, which are closer to S0 than S2.

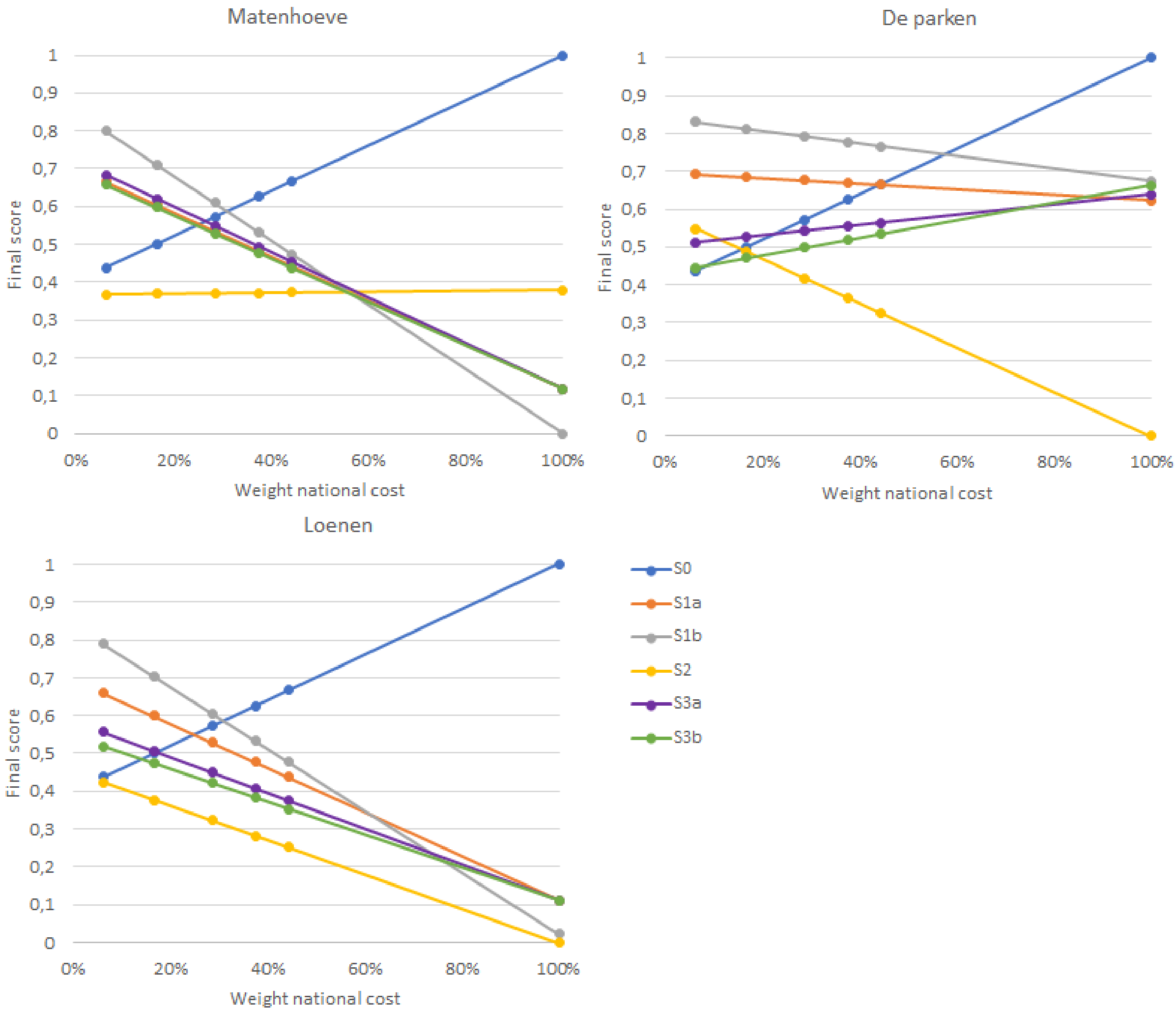

Figure 10. Sensitivity analysis of the weights of national cost for the three neighborhoods.

The sensitivity analysis on the criterion future-proof heat source also showed some diversity between the neighborhoods, see Figure 11. But something different stands out here, because the strategies S0, S1a and S1b all converge toward 1, meaning they are the most favorable strategies. This criterion was assessed by the author, as is explained in the methodology, but only the strategies S2, S3a and S3b can vary in this criterion. The other strategies always receive the maximal score for this criterion, because gas and electricity are very future-proof. Therefore, they all converge towards the maximal score if this criterion is weighted heavily.

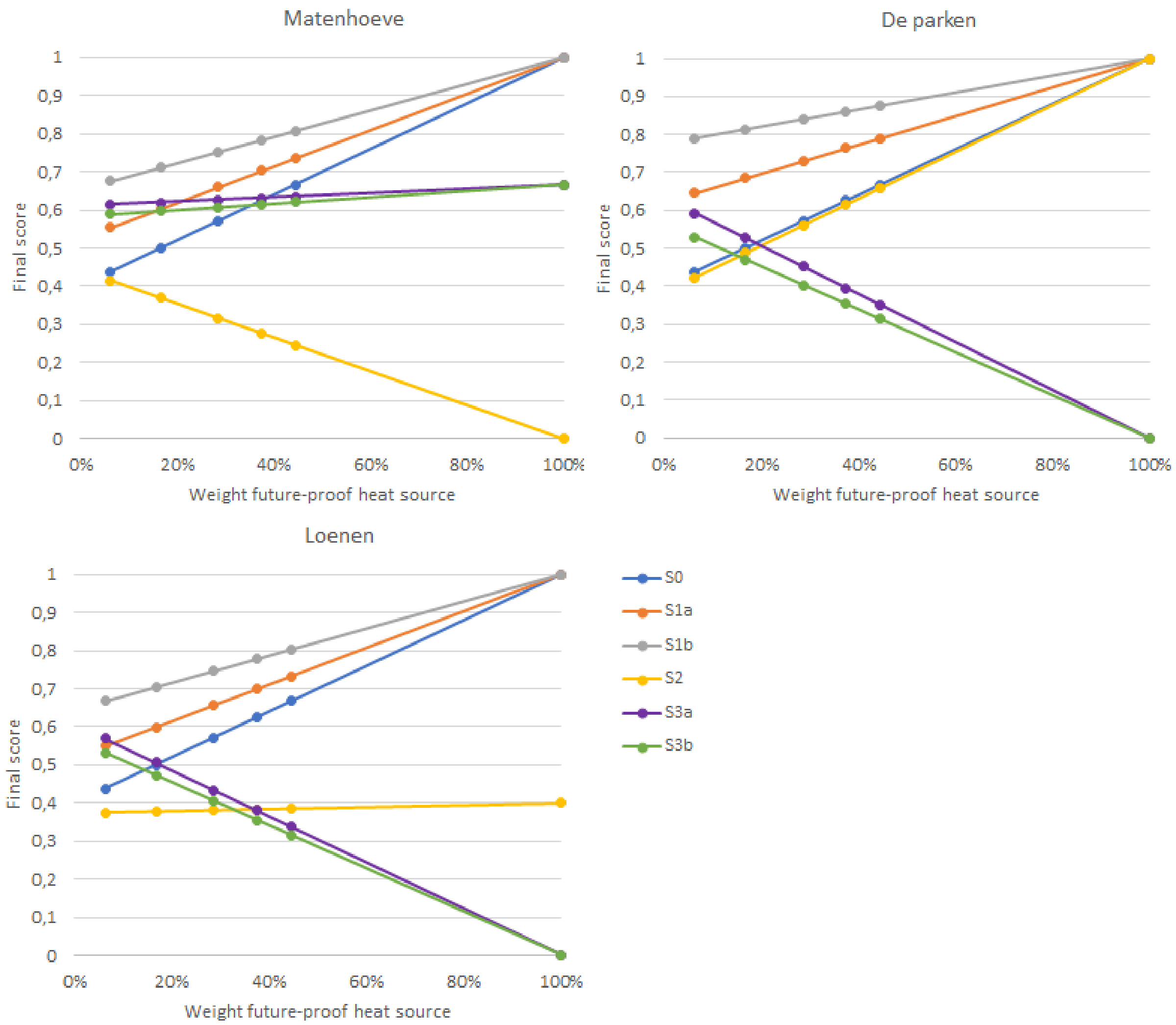

Figure 11. Sensitivity analysis of the weights of the future-proof criterion for the three neighborhoods.

It can be seen in Figure 12 that the sensitivity analysis of the criterion energy-use also differed between the neighborhoods. This is because the energy use differs for each neighborhood. The energy use of strategy S0 and S2 is usually relatively high compared to the other strategies, and this can be seen in these three neighborhoods as well. They both drop in the ranking when the energy use is weighted heavily. In De Parken, the energy use of the different strategies lies closer together, this can be seen as the strategies are more evenly spread when the criterion is weighted 100%.

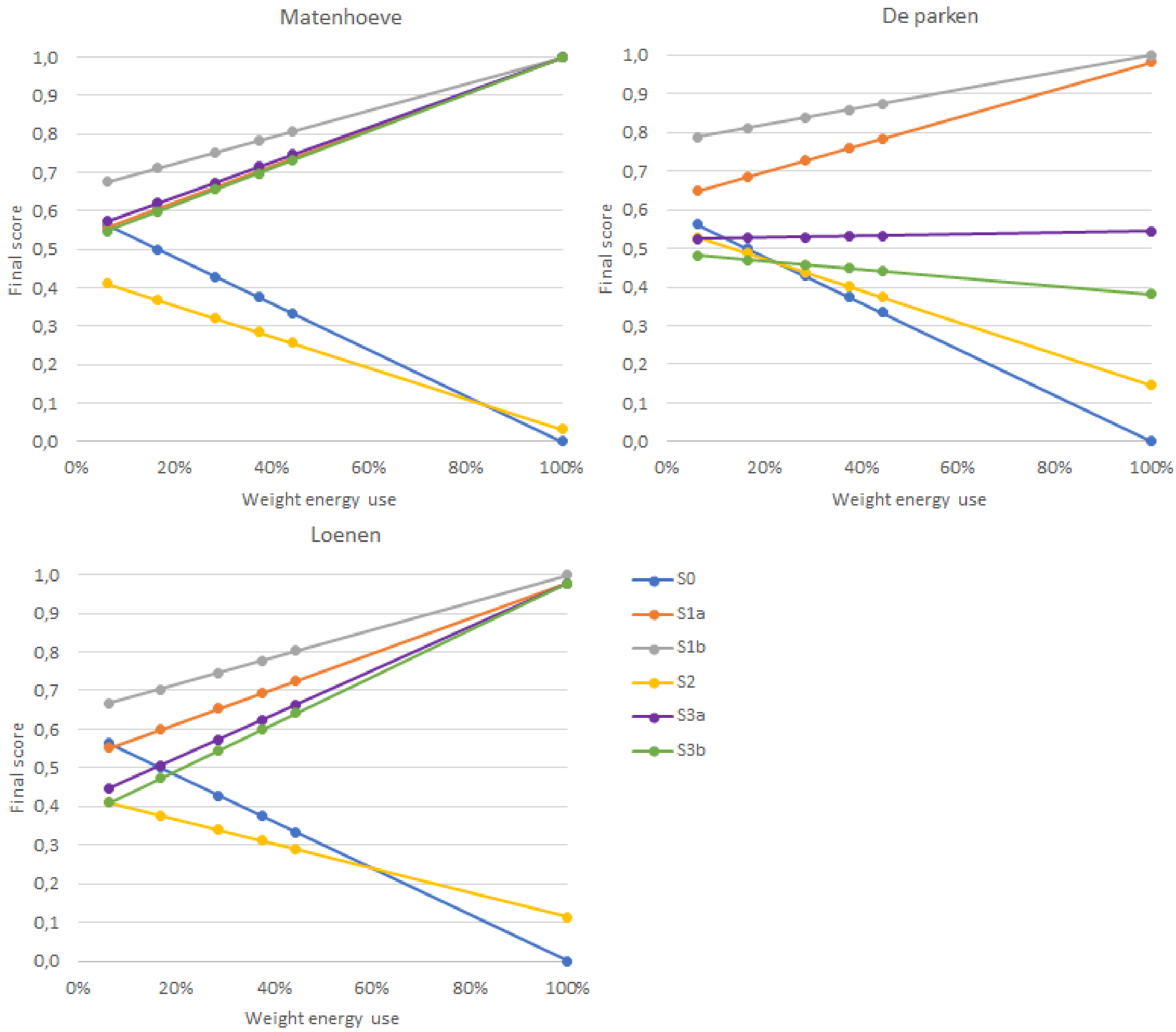

Figure 12. Sensitivity analysis of the weights of the energy use for the three neighborhoods.

4.2.2 Sensitivity analysis on the criteria

A sensitivity analysis was done on two criteria; the global warming potential and comfort. The sensitivity analysis of the global warming potential showed that this had limited effect on the ranking of the strategies in most cases, see Figure 13. When the global warming potential of strategy S1a was changed, this only had a significant effect on S1a, which consequently goes up in the ranking the impact decreases, and down in the impact increases. The effect when the global warming potential of S1b is varied is a little different, because this strategy started with the smallest global warming potential, therefore the final score cannot increase, but only decrease when the global warming impact increases.

The strategies S2 and S3 all react similar to varying their global warming potential, they show an increase in final outcome when the impact decreases and a decrease in outcome when the impact increases. The strategies S1a and S1b show the opposite reaction, because they score relatively higher on the criterion global warming potential, when the other strategies score lower, and only relative change is considered in both MCA methods. This increases the overall effect of changing the global warming potential for S2 and S3. The strategy S0 has the highest global warming potential, even when the effects are increased with 30%, except when the impact of S1a is increased. In this case the global warming potential of S1a increases to 274.3 kg $CO_{2\text{-eq}}$/MWh, which is slightly higher than the global warming potential of S0, which is 269.15 kg $CO_{2\text{-eq}}$/MWh. This can be seen as a slight increase in the final score of S0, while in all other cases the score of this strategy shows no impact.

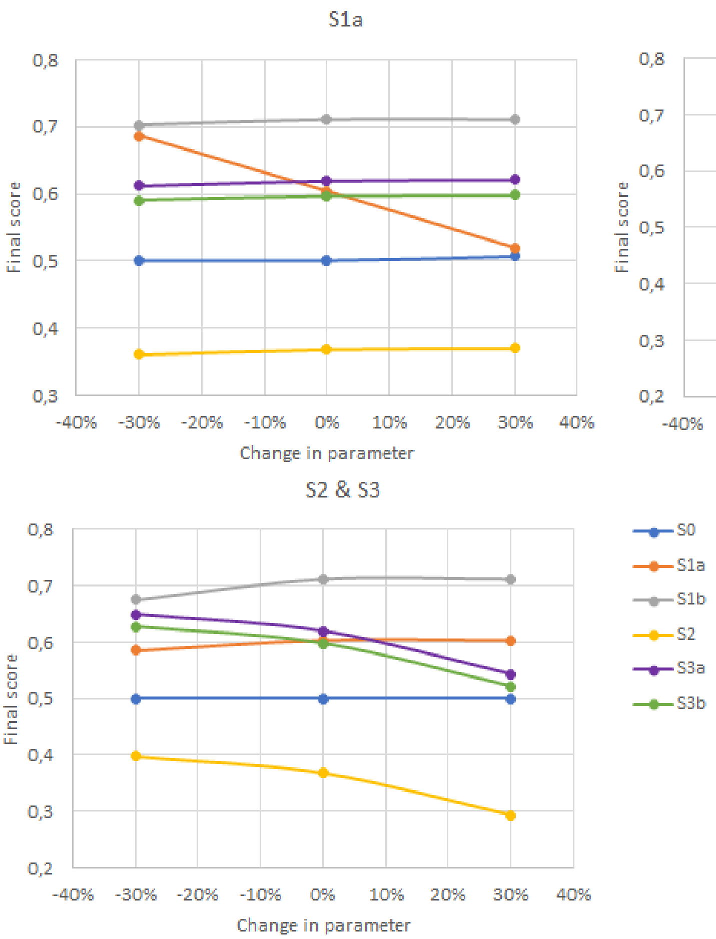

Figure 13. Sensitivity analysis on the criterion global warming potential, for the three different input parameters of the renewable strategies.

Changing the variables of the criterion comfort has a big impact on the ranking of the strategies, see Figure 14. Changing the variables of one strategy has impact on all the other strategies as well. This is because the scores for comfort are much closer together than the scores for global warming potential for example. Consequently, the rank of highest score to lowest score is impacted much more. It is therefore recommended to decrease the uncertainty of this criterion by gathering the input of more experts.

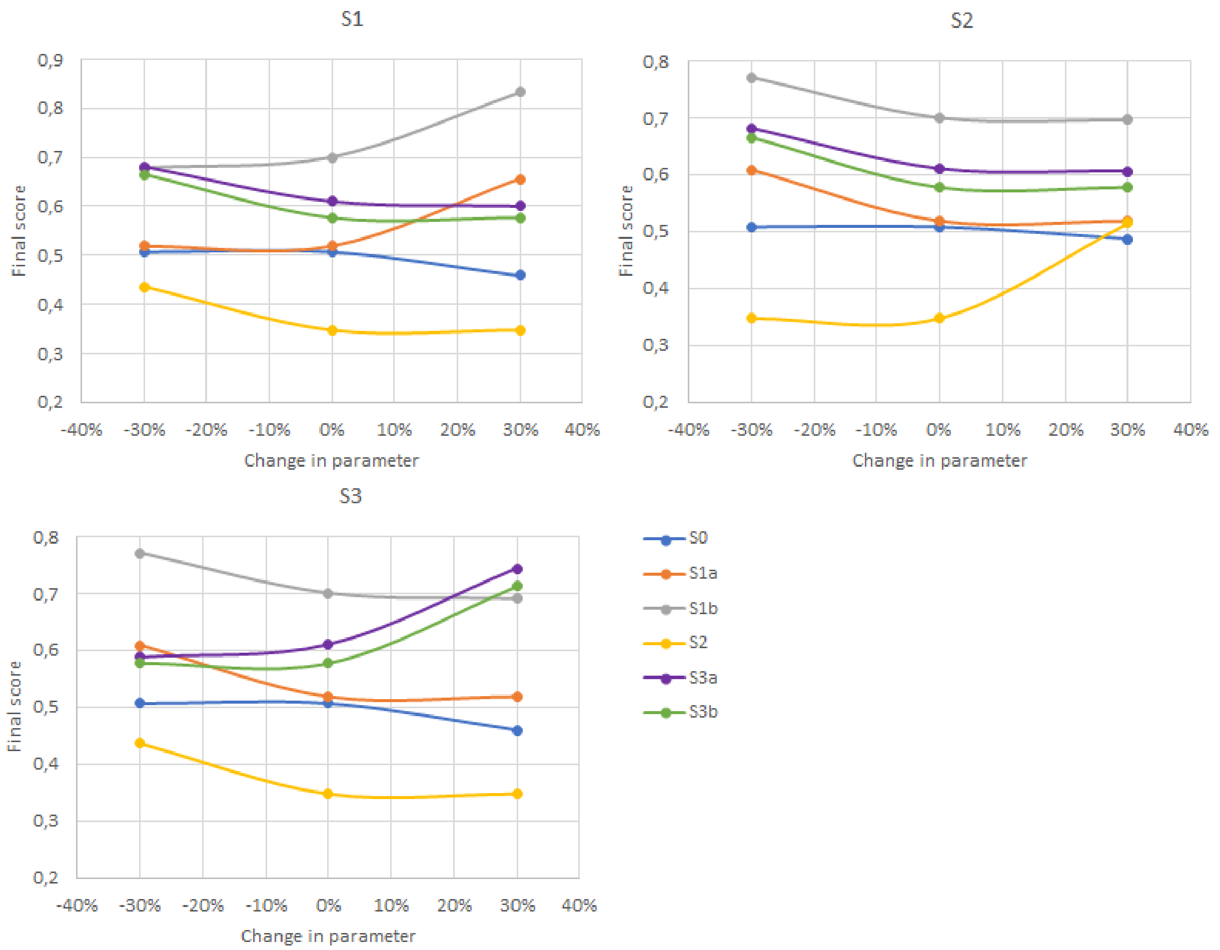

Figure 14. Sensitivity analysis on the criterion comfort, for the three different input parameters of the renewable strategies.

4.3 Assessment of municipalities

Two municipalities have tested a draft version of the tool. In this section their findings are presented. Rob Wijsman, from the municipality of Lansingerland, mentioned that he expected energy use to be a less interesting criteria for most stakeholders, but it should be included in the tool because it is important for the government since saving energy through efficiency improvements is an important goal of the government. He further suggested that it would be easier to interpret the results of the tool when more context information was given of the neighborhood. This was included in the updated version of the tool. He lastly suggested that more information could be given about the results of the analysis when neighborhoods are compared. This can be included in an updated version of the tool.

Theo van Es, from the municipality of Apeldoorn, suggested to change the criterion energy use to 'use of network capacity'. Since the energy use of a strategy depends on the insulation level, it can be more insightful for a network company to know how much the strategy contributes to limiting the overuse of the network capacity. It was further suggested to increase the number of neighborhoods that can be compared, which is currently ten. He would like to compare all the neighborhoods within the municipality of Apeldoorn. He would also prefer it if the stakeholders that are considered can be chosen freely. He would prefer to include energy corporations and other local citizen-initiatives as stakeholders instead of heat producer for example. This was included in an updated version of the tool.

Rob Wijsman found the tool to be useful and insightful, and the elements that he expected to be included in the tool were there. Theo van Es also saw the added value of considering the broader impacts of the heat transition, and he indicated that he would like to apply the tool in Apeldoorn. Some results from the test of Theo van Es are presented below.

The distribution of weights from the perspective of the municipality, and the expected weights of three other stakeholders; the homeowners, the housing corporations and the heat producer, in the opinion of Theo van Es, is shown in Table 27. Some results from the analysis that he did on three neighborhoods are shown in Figure 15, 16, 17 and 18.

Table 27. Weighing of the criteria by Theo van Es, municipality Apeldoorn.

Criteria	Weighing municipality	Weighing homeowners	Weighing housing corporations	Weighing heat producer
Presence housing corporation	16,7%	10,0%	23,3%	20,0%
Characteristics of the neighborhood	6,7%	10,0%	33,3%	6,7%
Organization of the neighborhood	10,0%	13,3%	6,7%	16,7%
Comfort levels	3,3%	26,7%	13,3%	16,7%
Energy use	13,3%	13,3%	13,3%	3,3%
Global warming potential	3,3%	0,0%	3,3%	23,3%
National costs	33,3%	3,3%	0,0%	3,3%
End-user costs	3,3%	20,0%	6,7%	3,3%
Increase in building value	10,0%	0,0%	0,0%	0,0%
Future-proof heat source	0,0%	3,3%	0,0%	6,7%

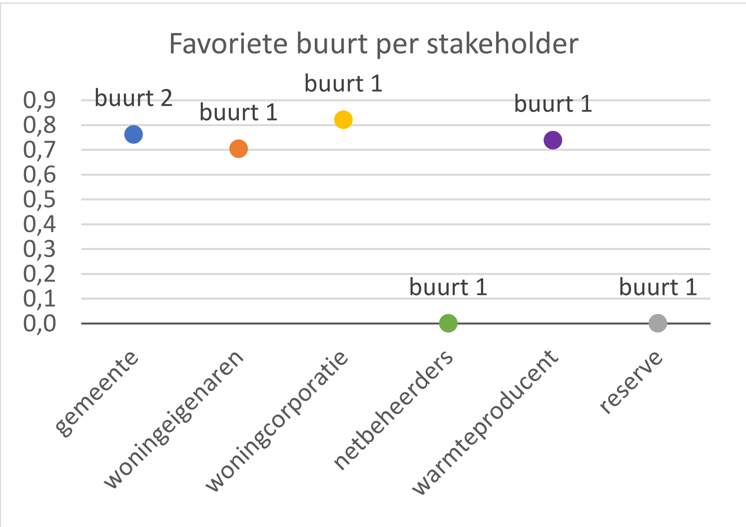

Figure 15. The favorite neighborhood per stakeholder.

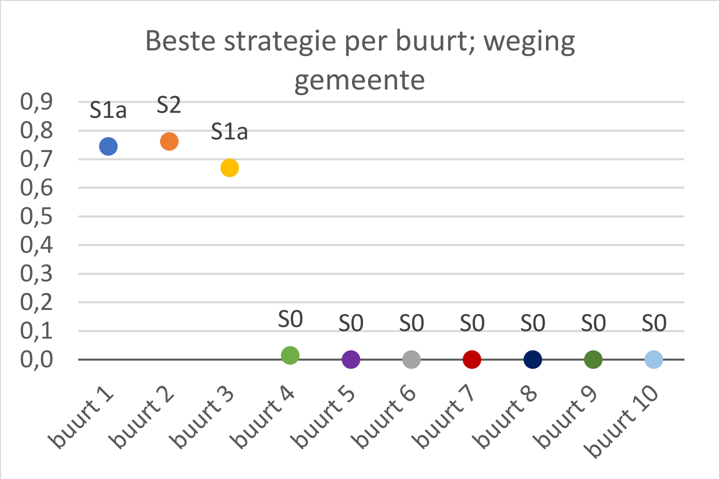

Figure 16. The favorite strategy per neighborhood with the weighing factors of the municipality.

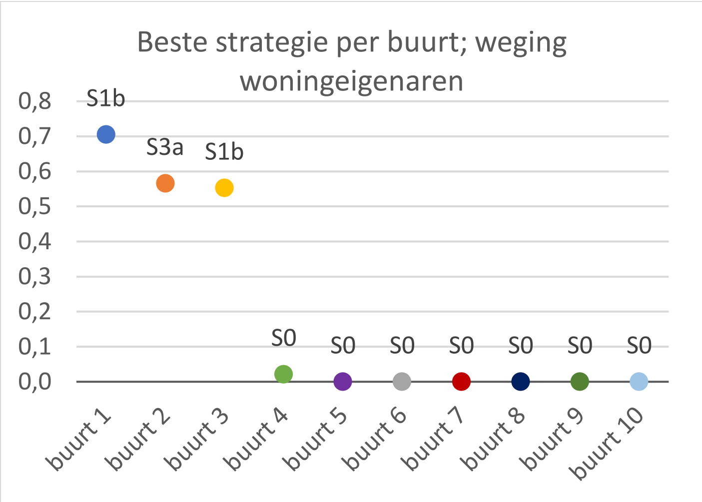

Figure 17. The favorite strategy per neighborhood with the weighing factors of the homeowners.

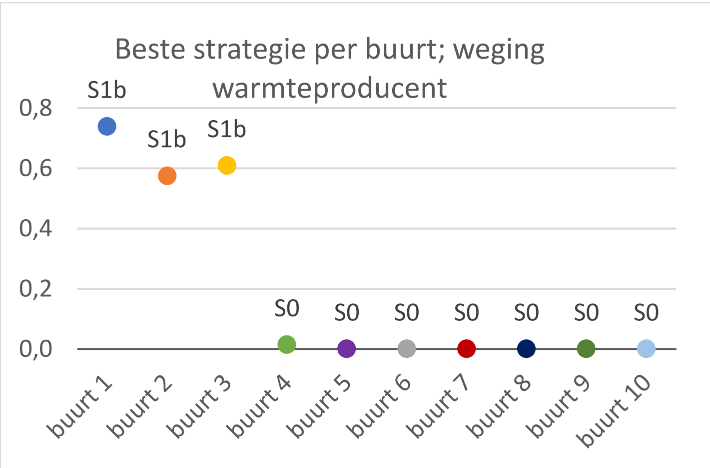

Figure 18. The favorite strategy per neighborhood with the weighing factors of the heat producer.

5. Conclusion and discussion

This research aimed to gain insight in the criteria that play a role in the heat transition, and to construct a tool that could incorporate these criteria and facilitate the decision-making process of the municipality. To realize this research aim, the following research question was formulated: *How can the economic, technical, environmental and social aspects of the Dutch heat transition and the interests of important stakeholders be incorporated in a tool that facilitates the decision-making process of the municipality?*

To answer this research question the relevant criteria and MCA methods were identified. Subsequently the relevant criteria were quantified, and two MCA methods were selected to analyze the criteria. The chosen methods were the interval standardization method, a weighted sum method with relatively simple calculations, and the PROMETHEE methods, that incorporates a pair-wise comparison of the alternatives. With these elements a tool was constructed to assess the selected criteria for the heat transition strategies, and for different neighborhoods. Three methods were used to assess the tool; a comparison of the two MCA methods that were selected, a sensitivity analysis on the weighing factors and two criteria and a qualitative assessment by two municipalities.

The assessment of the tool showed that the outcome of the MCA is highly dependent on the weighing factors. Since the weighing factors are chosen by multiple stakeholders, and the different results this generates are compared in the tool, a sensitivity analysis on the weights is embedded in the tool. Municipalities can directly see the impact the different weighing factors have on the result of the analysis. A sensitivity analysis on the values could be included in the tool to increase the transparency of the tool. This sensitivity analysis can also give insight in the tipping points that are present, at which points the order of the ranking changes. Transparency is a very important requirement for municipalities, because they are ought to defend their transition vision to the board. It is important to gain insight in the exact drivers that cause one heating strategy to be preferred over another. Since this could be determined better with the interval standardization method, it was decided to use this method for the final tool.

The final score of a heating strategy can be directly decomposed in the contribution of each criterion, providing a very clear overview of which criteria are important factors to consider in a specific neighborhood. Furthermore, the PROMETHEE method is only of added value when a preference threshold is applied. This decreases the transparency since this threshold has no default value, in most cases this value is chosen by experts, which means that there is not one ideal value. This should therefore be assessed for each situation specifically, which makes the tool less accessible, and decreases the transparency. Due to the simplicity, and therefore transparency, and the inclusion of weighing factors, the interval standardization method is perfectly suited for a tool that incorporates the economic, technical, environmental and social aspects of the Dutch heat transition and the interest of important stakeholders and which facilitates the decision-making process of the municipality.

However, a limited comparison of the two method could be provided in this research. It would be recommended to increase the number of scenarios that were assessed with the two preference thresholds in order to verify the results that were found in this research. In addition, other preference thresholds should be assessed as well, preferably based on expert opinions. This would provide better insight in the additional value of the PROMETHEE method.

Additionally, this research provided insight in which criteria are relevant when heat transition strategies are compared. Moreover, methods are provided on how to include these criteria in an MCA.

These methods can be improved through further research, and access to more detailed data. The global warming potential could be improved through an extensive LCA study on the specific strategies that are considered in the Netherlands.

The tool can also be improved through further experiments in municipalities. Extensive case studies can improve the user-interface, and the criteria selection might be expanded through input from stakeholders. It would furthermore be recommended to increase the scope of the assessment by including other stakeholders to assess the tool. Lastly, it might be valuable to increase the number of possible strategies for the *neighborhood-implementation plans*.

6. Acknowledgements

I would like to thank my three supervisors, Robert Harmsen, Sara Herreras Martinez and Lex Bosselaar, for all the feedback and guidance during this project. Additionally, I would like to thank the ECW-team for including me in their team, and sharing all their knowledge. I also want to express my gratitude to the two advisors of the municipalities, Theo van Es and Rob Wijsman, for taking the time to assess the tool, and for their interest in a possible further development of the tool. Lastly, I would like to thank the interviewees for the open conversations that we had.

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Appendix

Appendix A. List of the considered criteria.

Table A.1. List of all the criteria considered.

Criteria	Incl.	Excl.	Remarks
Ratio rental/buy		X	Instead the presence of housing corporations is included, if both are included this would be double counting because all houses owned by housing corporations are rental.
Presence of housing corporations	X		
Age	X		
Income	X		
Political views	X		
Educational level	X		
Organization of the neighborhood	X		
Nuisance from noise	X		
Cooling possibilities	X		
Increase in insulation level		X	Not directly, but indirectly through the increase in building value
Heating time	X		
Change of behaviour necessary	X		Changed to 'adaptation for electric cooking', because this is the only behavioral change necessary.
Hussle / nuisance from renovation	X		
Flexibility in moment of switch	X		
Human health		X	Not enough time to really look into the possible effects.
Employment		X	It was considered not to have a mayor impact, and it is very difficult to find data to support this criteria.
Combination opportunities		X	Not included in the tool, due to the complexity, but a very important parameter.
Risk		X	The sensitivity analysis can be used for a robustness assessment, and the risk of the heat source is already considered in another criteria.
Increase in building value	X		
Energy poverty		X	Not enough time to really look into the possible effects.
Air pollution	X		Through global warming potential.
Resource depletion		X	No data found, probably not a mayor impact.
Air quality		X	No data found
Waste production		X	Not possible to generalize for the whole country, no specific data available.
Harm to ecosystems		X	No data found.
Land use		X	There is not a substantial amount of land necessary for any of the alternatives.

Energy use	X		
Embodied energy use		X	Outside of the scope of this research.
Reliability of the heat source	X		
End-user costs	X		(But not yet available)
National costs	X		

Appendix B. Details on the quantification of the global warming potential

The analysis is based on 70 borehole heat exchangers of 150 m long, with each an extraction power of 50 W/m. The network provides heat for 1000 inhabitants, with a peak heat consumption of 525 kW (Bartolozzi et al., 2017).

The LCA is from cradle to grave in this case, this means from assembly stage to end of life stage, including the dismantling of the technology. The assembly stage includes the construction of the energy production systems and other materials/technologies. Between the assembly and the end of life stage there is also the operational stage, this includes the energy production, delivery and maintenance operations. The operational stage is responsible for most of the environmental impact; 96.6 % for the natural gas scenario and 95.4% in the district heating scenario (Bartolozzi et al., 2017).

For the second source, the LCA software SimaPro Multi user 8.5.2.1 is used, compared with the Ecoinvent 3.0 database. The method ReCiPe 2016 Midpoint (H) was applied for the assessment of the global warming potential. Three scenarios were assessed; a natural gas system, an air to water heat pump (corresponding to S1a) and a borehole heat pump (corresponding to S1b). The scope Europe without Switzerland was used, this is the most accurate data available, and assumed to give representative values for systems in Europe. More data on the databases that were used can be found in Table B.1. The impact of natural gas was calculated with both data sources. The resulting values are relatively close together, this suggests that both data sources can be combined. In the tool the average of the two values is used as input.

Table B.1. Info on the databases for the LCA with SimaPro.

	Borehole HP	Air-water HP	Natural gas
Process	1 kWh Heat, borehole heat pump {Europe without Switzerland}| market for floor heating from borehole heat pump | APOS, S (of project Ecoinvent 3 - allocation at point of substitution - system)	1 kWh Heat, air-water heat pump 10kW {Europe without Switzerland}| market for floor heating from air-water heat pump | APOS, S (of project Ecoinvent 3 - allocation at point of substitution - system)	1 kWh Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | APOS, S (of project Ecoinvent 3 - allocation at point of substitution - system)
Geography	Average one family house in Switzerland, extrapolated to European conditions.	Average one family house in Switzerland, extrapolated to European conditions.	
Heat capacity	10 kW	10 kW	
Seasonal performance factor	3.9	2.8	
Lifetime	20 years for the heat pump and floor heating system, 50 years for the borehole heat exchanger	20 years for the heat pump and floor heating system	
Temperature	40 C inlet, 30-35C return	40 C inlet, 30-35 C return	
Heat source	Geothermal	Air	25% from CHP plants, 75% from heat plants.