Assessing alternative heating strategies in a Dutch neighborhood using a life cycle perspective and multiple household decision-making factors

Contributing to the heat transition in Dutch dwellings

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This thesis represents the final step of my academic journey. After discovering that I was deeply interested in sustainability during my bachelor studies, I decided to pursue a degree in Industrial Ecology. For the past two years I have been happily studying at both the TU Delft and Leiden University, while learning how to analyze sustainability problems with an interdisciplinary view. Staying on track with this thesis has been a challenge in these working from home times and in this section I would like to express my gratitude to those who played an important role in the completion of this project.

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Samenvatting

De Nederlandse gebouwde omgeving is al vele decennia grotendeels afhankelijk van aardgas, maar hier komt in de komende jaren verandering in. Deze afhankelijkheid is deels te danken aan de ontdekking van aardgas reserves in Groningen in de jaren 50. Tot op de dag van vandaag is ongeveer 85% van de verbruikte warmte in de gebouwde omgeving opgewekt met aardgas. De afgelopen tien jaar hebben een verhoogd maatschappelijk bewustzijn en (inter)nationaal beleid, zoals het Energieakkoord (2013), het klimaatakkoord van Parijs (2015) en het recente Nederlandse Klimaatakkoord (2019), het gebruik van aardgas in de gebouwde omgeving onder druk gezet. In het Klimaatakkoord is afgesproken dat er maatregelen genomen moeten worden om 7 miljoen woningen van het aardgas af te krijgen in de komende 30 jaar. Deze zogenoemde warmtetransitie is een enorme opgave waarin veel verschillende actoren zoals huishoudens en woningeigenaren, energie bedrijven en publieke organisaties een rol spelen.

In Nederland bestaan er verschillende ondersteunende besluitvormingsinstrumenten om verwarmingsstrategieën te evalueren. Deze strategieën maken gebruik van alternatieve warmtesystemen om een huis te verwarmen, zoals verwarming via elektriciteit met behulp van een warmtepomp, of via een warmtenet. Het blijkt echter dat deze methodes en tools enkel kijken naar de totale kosten van een strategie, en in enkele gevallen worden ook de CO2 emissies berekend die bespaard worden over de gebruiksfase.

Echter, de emissies die ontstaan bij productie en levering van de benodigde warmtesystemen worden in deze berekeningen buiten beschouwing gelaten. Een levenscyclus perspectief mist in deze methodes en instrumenten. Bovendien worden andere beslissingsfactoren die belangrijk kunnen zijn voor bewoners, zoals gedoe tijdens werkzaamheden, benodigde ruimte en beschikbaarheid van experts buiten beschouwing gelaten. Daarom is in dit onderzoek gekeken welke factoren nog meer een rol spelen in de besluitvorming van huishoudens voor alternatieve verwarmingsstrategieën, terwijl er rekening wordt gehouden met emissies die ontstaan over de levenscyclus.

Dit heeft geleid tot de volgende onderzoeksvraag van deze studie: "*Hoe kunnen alternatieve verwarmingsstrategieën beoordeeld worden in wijken in Nederland, terwijl rekening wordt gehouden met de levenscyclus van die verwarmingsstrategieën en met meerdere factoren die invloed hebben op huishoudelijke voorkeuren?".*

Om deze vraag te beantwoorden, werd een enkele casestudie onderzoeksopzet met kwalitatieve en kwantitatieve methodes gebruikt. De casestudy omvatte een Nederlandse buurt waarin de woningen verwarmd worden door aardgas. Ook overwegen huishoudens in deze buurt te investeren in alternatieve verwarmingsstrategieën. Verwarmingsstrategieën worden in deze studie gedefinieerd als een combinatie van zowel warmtesystemen en installaties als potentiële isolatiemaatregelen die nodig zijn om het huidige aardgas warmtesysteem te vervangen. De gebruikte kwalitatieve methodes waren desk-studie, open en semigestructureerde interviews en een enquête. De gebruikte kwantitatieve methodes waren de numerieke analyse van de enquête resultaten en een Multi-criteria analyse (MCA).

Het onderzoek bestond uit vier stappen. In de eerste stap zijn relevante factoren voor huishoudelijke besluitvorming met betrekking tot verwarmingsstrategieën geïdentificeerd. Er is literatuuronderzoek gedaan om een aantal factoren die een rol spelen in het besluitvormingsproces van huishoudens met betrekking tot dit onderwerp te identificeren. Na dit literatuuronderzoek is een semigestructureerd interview gehouden met een academisch expert om de selectie van relevante beslissingsfactoren te valideren. De geselecteerde factoren zijn totale kosten, CO2-equivalente uitstoot, ruimte die warmte

systemen innemen in woningen, beschikbaarheid van experts, en gedoe tijdens renovatiewerkzaamheden.

Als tweede hebben we initiële informatie verzamelend en de casus gedefinieerd. Deze initiële informatie was een beschrijving van de woningen in de buurt (hoeveelheid, bouwjaar en energie label). Om de casus te definiëren hebben we vijf representatieve woningen en zes verwarmingsstrategieën geconceptualiseerd, welke gebruikt zijn in de verdere analyse. Hiervoor hebben we deskstudie uitgevoerd met online bronnen, één semigestructureerd en twee open interviews met een groep vertegenwoordigers van de buurt, en een semigestructureerd met een academisch expert gehouden. We hebben de representatieve woningen gevalideerd met de vertegenwoordigers van de buurt, en de verwarmingsstrategieën met de academische expert.

De derde stap was het verzamelen van informatie en het uitvoeren van de MCA. Hiervoor is een individuele analyse uitgevoerd voor alle geïdentificeerde beslissingsfactoren. Vervolgens zijn gewichtensets gebruikt om elke strategie te beoordelen op basis van de individuele factoren. Een set gewichten bepaalde het gewicht dat werd toegekend aan de resultaten van elke individuele beslissingsfactor. Door deze gewichten te vermenigvuldigen met deze resultaten, verkregen we MCA-resultaten.

Er zijn vier gewichtensets gebruikt. Gewichten-set 1 kent het hoogste gewicht toe aan totale kosten, en het laagste gewicht aan gedoe tijdens renovatie. Gewichten-set 2 kent het hoogste gewicht toe aan zowel totale kosten als CO2 uitstoot, en het laagste gewicht aan gedoe. Gewichten-set 3 kent het hoogste gewicht toe aan CO2 uitstoot en de beschikbaarheid van experts, en het laagste gewicht aan gedoe en benodigde ruimte. Gewichten-set 4 kent het hoogste gewicht toe aan gedoe en benodigde ruimte, en het laagste aan totale kosten.

De MCA resultaten laten zien dat voor alle gewichtensets, de all-electric of het midden temperatuur (MT) warmtenet de hoogst beoordeelde strategieën waren. In gewichten-set 1 presteert de all-electric strategie beter, aangezien dit de strategie is met de laagste totale kosten voor alle representatieve woningen. In gewichten-set 2 is de all-electric strategie het best presterende alternatief voor rijwoningen en appartementen, terwijl de MT-warmtenet strategie de best presterende strategie is voor hoekwoningen en twee-onder-een-kap woningen. Omdat de MT-warmtenet strategie een van de best presterende strategieën is op het gebied van CO2-uitstoot, gedoe en benodigde ruimte, had deze strategie de hoogste score in sets van gewichten 3 en 4.

De resultaten van de MCA laten zien dat all-electric en midden temperatuur (MT) warmtenetten de meest geprefereerde strategieën zijn, afhankelijk van de gewichten. In gewichten-set 1, scoort de all-electric strategie beter, aangezien deze de laagste kosten heeft voor alle representatieve woningen. In gewichten-set 2 is de all-electric strategie het meest geprefereerd voor rijwoningen en appartementen, terwijl het MT-warmtenet de voorkeursstrategie is voor hoekwoningen en twee-onder-een-kap woningen. Omdat de MT-warmtenet strategie een van de meest geprefereerde strategieën is op basis van CO2 emissies, gedoe en ruimte, scoort deze strategie het beste in gewichten-set 3 en 4.

Deze resultaten zijn berekend voor het basisscenario, waarin een disconteringsvoet van 3,05% en een CO2-emissiefactor voor de Nederlandse elektriciteitsmix van 0,475 kg CO2/kWh is toegepast. We gebruiken echter ook drie andere scenario's om te onderzoeken hoe veranderingen in deze twee externe factoren de rangschikking van alternatieven zouden beïnvloeden. Elk scenario is een combinatie van de twee externe factoren. De eerste externe factor is de disconteringsvoet, die we hebben gewijzigd van 3,05 naar

4,5%. De tweede externe factor is de CO2-emissiefactor, die we hebben aangepast door een jaarlijkse reductiefactor van 5% toe te passen.

Daarom hebben we in scenario 1 een disconteringsvoet van 4,5% en de emissiefactor van de huidige elektriciteitsmix gehanteerd. In scenario 2 hebben we een disconteringsvoet gehanteerd van 3,05% en een jaarlijks afnemende emissiefactor van de elektriciteitsmix met 5%. In scenario 3 hebben we een disconteringsvoet gehanteerd van 4,5% en een jaarlijks afnemende emissiefactor van de elektriciteitsmix met 5%.

De resultaten van de scenario's waren als volgt. In Scenario 1 ontdekten we dat een hogere disconteringsvoet resulteerde in een voorkeur voor de referentiestrategie in appartementen, onder gewichten-set 1. Voor de andere woningtypen laten de referentiestrategie en MT-warmtenet strategie een stijging zien in de uiteindelijke rangorde, maar de all-electric strategie blijft de strategie die iets meer de voorkeur heeft dan de andere strategieën. Onder gewichten-set 2 had de MT-warmtenet strategie de voorkeur voor alle woningtypen, behalve voor oude rijwoningen, waar de all-electric strategie nog steeds het voorkeursalternatief was. In Scenario 2 ontdekten we dat een afnemende emissiefactor van de elektriciteitsmix resulteerde in een voorkeur voor de all-electric strategie, onder de gewichtensets 1, 2 en 3. Alleen voor oude twee-onder-een-kap en hoekwoningen was de MT-warmtenet strategie nog steeds het geprefereerde alternatief. In Scenario 3 ontdekten we dat een combinatie van de twee externe factoren leidt tot een voorkeur voor de all-electric strategie onder gewichtensets 1 en 2. Voor gewichten-set 3 laten de resultaten een voorkeur zien voor ofwel de all-electric of de MT-warmtenet strategie, afhankelijk van het woningtype. Onder gewichten-set 4 werden in geen enkel scenario veranderingen waargenomen, aangezien er aan de totale kosten en emissies weinig gewichten werden toegekend en deze dus niet werden beïnvloed door de verschillende scenario's.

Door een levenscyclusperspectief te hanteren, laten de resultaten zien dat de gebruiksfase de grootste bijdrage levert aan de totale CO2-uitstoot. De emissies in deze fase worden beïnvloed door zowel de energievraag als de emissiefactor van de gebruikte energie. Daarom zal toekomstig beleid zich niet alleen moeten richten op het beperken van de vraag maar ook op de manier waarop de energie wordt opgewekt.

Het uitgevoerde onderzoek bevat een aantal beperkingen. Het MCA-model dat was gebruikt om het onderzoek uit te voeren, maakt gebruik van verschillende aannames en theoretische data. Validatie van experts is nodig om te bepalen of de gebruikte data representatief is voor de daadwerkelijke situatie in de buurt. Tevens is het onzeker of en hoe de constructiekosten van warmtenetten aan de eindgebruikers zullen worden doorberekend. Een andere factor is dat de analyse van gedoe tijdens renovatie zich beperkt heeft tot overlast binnenshuis. Overlast in de openbare ruimte die kan optreden door bouwwerkzaamheden zoals het (ver)plaatsen van leidingen en kabels wordt niet meegerekend. Deze factoren kunnen mogelijk de resultaten van de individuele analyses beïnvloeden, en dus ook de MCA-resultaten.

Daarnaast zijn de resultaten van de MCA specifiek voor de casus. Iedere wijk in Nederland bestaat uit een andere samenstelling van woningtypen, uit verschillende bouwjaren, met verschillende isolatieniveaus. Ook kunnen de beschikbare warmtebronnen per regio verschillen. Dit betekent dat het niet mogelijk is om de bevindingen uit de casestudie te generaliseren naar andere wijken in Nederland

Wat de MCA resultaten echter wel laten zien, is dat de verwarmingsstrategie met de laagste totale kosten voor de eindgebruikers niet noodzakelijk de meest geprefereerde alternatieve verwarmingsstrategie is. Door alternatieve verwarmingsstrategieën op verschillende factoren te beoordelen en daarbij gebruik te maken van gewichten op basis van de voorkeuren van bewoners, kan inzicht worden verkregen in de verwarmingsstrategieën die de bewoners daadwerkelijk prefereren. Dit is informatie die meerdere belanghebbenden bij de warmtetransitie kunnen gebruiken bij het opstellen van warmtevisies en plannen voor de uitvoering van verwarmingsstrategieën voor hun buurt.

Dit onderzoek heeft aangetoond hoe MCA kan worden gebruikt om verschillende beslissingsfactoren van huishoudens op te nemen in de beoordeling van alternatieve verwarmingsstrategieën vanuit een levenscyclusperspectief. Een MCA maakt het gebruik van verschillende sets gewichten mogelijk om inzicht te krijgen in hoe deze alternatieve verwarmingsstrategieën zich verhouden tot elkaar op basis van verschillende beslissingsfactoren. We hebben de selectie van beslissingsfactoren voor huishoudens en van alternatieve verwarmingsstrategieën gevalideerd met academische experts. Door dit te doen, probeerden we ervoor te zorgen dat de voorkeuren van huishoudens nauwkeurig werden vastgelegd en dat verwarmingsstrategieën werden beoordeeld die praktisch geschikt zijn om uiteindelijk in de casusbuurt te worden toegepast.

Toekomstig onderzoek zou kunnen kijken naar het betrekken van duurzame elektriciteitsopwekking bij de beoordeling van alternatieve verwarmingsstrategieën, bijvoorbeeld door gebruik te maken van zonnepanelen. Daarnaast wordt een suggestie gedaan om verder onderzoek te richten op het valideren van de data en aannames die in dit MCA-model worden gebruikt door validatiegesprekken te voeren met academische experts en aannemers, werkzaam in de warmtetransitie. Bovendien zou het voor toekomstig onderzoek interessant kunnen zijn om te kijken naar manieren om de constructiekosten van warmtenetten, en openbare verstoringen te kwantificeren, om zo met deze factoren rekening te houden in de beoordeling van alternatieve verwarmingsstrategieën.

Executive Summary

The Dutch built environment depends on natural gas for heating; however, this is expected to change over the coming years. This reliance upon natural gas can be traced back partly to the discovery of natural gas reserves in Groningen, in the northern part of The Netherlands, in the 1950s. To this day, natural gas accounts for approximately 85% of the consumed heat in the built environment. Over the last decade, increased social awareness and (inter)national policies, such as the 2013 *Energieakkoord* (Dutch energy agreement), 2015 Paris agreement, and the 2019 *Klimaatakkoord* (Dutch climate agreement) have put pressure on the use of natural gas in the building environment. Following from the Klimaatakkoord, the national government now requires over 7 million Dutch dwellings to be renovated to achieve a natural gas-free residential sector in the next 30 years. This so called heat transition is a significant challenge that involves stakeholders such as households and homeowners, energy companies, and public organizations.

Within the Netherlands, different decision-making support tools exist to evaluate heating strategies. These strategies use alternative heating systems to heat up dwellings, for example by making use of electrical heat pumps or through district heating networks. These tools are mainly used to find cost-effective solutions, and in some cases, they also enable the calculation of the associated CO2 emissions over the use stage.

However, emissions that occur due to the production and decommissioning of the required heating systems are often excluded from the calculations of tools. Thus, a life cycle perspective is missing. Moreover, other factors that can influence the decision-making process of residents, like disruption during renovation, occupation space, or availability of experts are disregarded. Hence, this research looked into other factors that play a role in household decision-making for alternative heating strategies, while accounting for the emissions that occur over the life cycle.

Accordingly, the main research question of this study was: "*How to assess alternative heating strategies in neighbourhoods in The Netherlands while accounting for the life cycle of those heating strategies and for multiple factors that influence household preferences?".*

To answer this question, a single case-study research design with qualitative and quantitative methods was used. The case study consisted of a neighborhood in which dwellings use natural gas and households are considering investments in alternative heating strategies. We defined a heating strategy as a combination of heating systems and insulation measures. The qualitative methods were desk-research, open and semi-structured interviews, and a survey. The quantitative methods were the numerical analysis of survey results and a multi-criteria analysis (MCA).

The research consisted of four research steps. In the first step, factors relevant to household decision-making regarding heating strategies were identified. A literature review was performed to identify a set of factors that play a role in the decision-making process of households regarding this topic. Afterwards, a semi-structured interview with an academic expert was used to validate a selection of relevant decision-making factors within the original set. The resulting factors were costs, CO2-eq, space that a heating system occupies in a dwelling, availability of experts, and disruption during installation.

Second, we gathered initial information and defined the case study. The initial information was a description of the dwellings in the neighborhood (the amount, construction year and energy label). To define the case study, we conceptualized a set of five representative dwellings and six heating strategies that we used for further analysis. To this aim, we conducted desk research with online sources, one semi-

structured and two open interviews with a group of representatives within the residents of the neighborhood, and a semi-structured interview with an academic expert. We validated the set of representative dwellings with representatives of the neighborhood, and the heating strategies, with the academic expert.

The third step was to gather information and conduct the MCA. To this aim, we conducted an individual assessment for each of the identified decision-making factors, and then, used sets of weights to evaluate each strategy based on those factors. A set of weights determined the weight that was assigned to the results of each individual decision-making factor. By multiplying these weights with the individual results, MCA results were gathered.

We used four different sets of weights. Set of weights 1 assigns the highest weight to total costs, and the lowest weight to disruption during renovation. Set of weights 2 assigns the highest weight to both total costs and CO2 emissions and the lowest weight to disruption. Set of weights 3 assigns the highest weights to CO2 emission and availability of experts and the lowest weights to disruption and occupation space. Set of weights 4 assigns the highest weights to disruption and occupation space and the lowest weight to total costs.

The results of the MCA show that, for all sets of weights, either the all-electric or the middle temperature (MT) district heating strategy were the highest ranked heating strategies. In set of weights 1, the all-electric strategy performs better, as this is the strategy that comes with the lowest overall costs for all representative dwellings. In set of weights 2, the all-electric strategy is the highest performing alternative for terraced houses and apartments, while the MT-district heating strategy is the highest performing strategy for corner houses and semi-detached houses. Because the MT-district heating strategy is one of the highest performing strategies on CO2 emissions, disruption and occupation space, this strategy had the highest ranking in sets of weights 3 and 4.

These results were calculated for the baseline scenario, in which a discount rate of 3.05% and a CO2 emissions factor for the Dutch electricity mix of 0.475 kg CO2/kWh were applied. However, we also use three other scenarios to explore how changes in these two external factors would influence the ranking of alternatives. Each scenario is a combination of the two external factors. The first external factor is the discount rate, which we changed from 3.05 to 4.5%. The second external factor is the CO2 emission factor, which we changed by applying an annual reduction factor of 5%.

Therefore, in Scenario 1, we used a discount rate of 4.5% and the emission factor of the current electricity mix. In Scenario 2, we used a discount rate of 3.05% and an annually decreasing emission factor of the electricity mix with 5%. In Scenario 3, we used a discount rate of 4.5% and an annually decreasing emission factor of the electricity mix with 5%.

The results of the scenarios were as follows. In Scenario 1, we found that a higher discount rate resulted in a preference for the reference strategy in apartments, under set of weights 1. For the other dwelling types, the reference strategy and MT-district heating strategy show an increase in the final ranking, but the all-electric strategy remains the strategy that is slightly more preferred than the other strategies. Under set of weights 2, the MT-district heating strategy was the preferred strategy for all dwelling types except for old terraced houses, where the all-electric strategy was still the preferred alternative. In Scenario 2, we found that a decreasing emission factor of the electricity mix resulted in a preference for the all-electric strategy, under sets of weights 1, 2 and 3. Only for old semi-detached and corner houses, the MT-district heating strategy was still the preferred alternative. In Scenario 3, we found that a combination of the two external factors leads to a preference for the all-electric strategy under set of weights 1 and 2. For set of weights 3, results show a preference for either the all-electric or MT-district heating strategy, depending on the dwelling type. Under set of weights 4, no changes were observed in any scenario, as little weights were assigned to total costs and emissions and these are thus not influenced by the different scenarios.

By considering a life cycle perspective, results show that the use stage is the highest contributor in total CO2 emissions. The emissions during this stage are influenced by both the energy demand and the emission factor of the used energy. Therefore, policies to target either or both of these factors should be explored.

There are several limitations to the performed research. The MCA-model that is used to conduct the research relies on several assumptions and theoretical data. Validation of experts is needed to determine if the used data is representative for the actual situation in the neighborhood. Likewise, it is uncertain if and how the construction costs of district heating networks will be charged to end-users. Another factor is that the analysis of disruption during renovation is limited to in-home disruption. Public disruption that can occur due to construction works for the (re)placement of pipes and cables is not accounted for. These factors can potentially influence the results of the individual analyses, and thus also influence the MCA results.

In addition, the results of the MCA are specific for the case neighborhood. Every neighborhood in the Netherlands consists of a different composition of dwelling types, from different construction years, with different insulation levels. Also, the available heating sources can differ per region. This means that it is not possible to generalize the findings from the case study to other neighborhoods in The Netherlands.

However, what the MCA results do show is that the heating strategy with the lowest total costs for the end-users, is not necessarily the most preferred alternative heating strategy. By assessing alternative heating strategies on different factors, while making use of weights based on the preferences of residents, insights can be gained in the heating strategies that are actually preferred by residents. This is information that multiple stakeholders in the heat transition can use in the composition of heat visions and plans for the implementation of heating strategies for their neighborhood.

This research has shown how to use MCA to include different household decision-making factors in the assessment of alternative heating strategies from a life cycle perspective. An MCA allows for the use of different sets of weights to gain insight in how these alternative heating strategies compare with each other based on different decision-making factors. We validated the selection of household decision-making factors and of alternative heating strategies with academic experts. By doing so, we tried to ensure that the preferences of households were accurately captured, and that heating strategies were assessed that are practically suitable to be eventually applied in the case neighborhood.

Future research could look into the inclusion of renewable electricity generation in the assessment of alternative heating strategies, for example by making use of solar panels. Additionally, it is suggested that further research should be directed at validating the data and assumptions that are used in this MCA model by conducting validation interviews with academic experts and contractors in the field of the heat transition. Moreover, it might be interesting for future research to look into ways to quantify the district heating network construction costs and public disruption, in order to account for these factors in future studies that asses alternative heating strategies.

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List of Supplementary materials

Throughout this thesis, several references are made to supplementary material. The following supplementary material is available upon request from the author:

- A Life Cycle Costing model
- A Life Cycle Assessment model
- A Multi-Criteria Analysis model

List of Abbreviations

ACM	Authority for Consumers and Markets
ATES	Aquifer Thermal Energy Storage
BAG	Basic register Addresses and Buildings
BWM	Best-Worst Method
CBA	Cost-Benefit Analysis
CBS	Central Bureau of Statistics
GHG	Greenhouse Gas
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LT	Low Temperature
MCA	Multi-Criteria Analysis
MT	Middle Temperature
NPV	Net Present Value
WTA	Warmte Transitie Atlas
WWTP	Wastewater Treatment Plant

AP_new	Apartment in the new part of the neighborhood
TH_old	Terraced house in the old part of the neighborhood
TH_new	Terraced house in the new part of the neighborhood
SD&TC_old	Semi-detached and terraced house (corner) in the old part of the neighborhood
SD&TC_new	Semi-detached and terraced house (corner) in the new part of the neighborhood

Chapter 1. Introduction

1.1. Problem introduction

The discovery of natural gas reserves in Groningen, at the end of the 1950s has led to a Dutch built environment that is heavily reliant on natural gas. The Dutch built environment encompasses over 7 million residential- and 1 million utility buildings. Currently, the built environment comprises 28 percent of the total energy consumption in the Netherlands (EBN, 2019). This energy demand is largely fueled by natural gas, which accounts for approximately 85 percent of the total heat consumption. Currently, within Dutch dwellings, cooking, showering and heating systems are mainly fueled by natural gas boilers (van Leeuwen, De Wit, & Smit, 2017). However, increased social awareness, (inter)national policies regarding sustainability, and the signing of the Paris agreement in 2015 put pressure on the use of natural gas in dwellings. To reduce the share of natural gas in the built environment, in order to achieve the ambitions of the government, a shift in the energy system from fossil fuels to renewable energy sources is required.

In 2013, the Socio-Economic council, an advisory body of the Dutch government, published the *Energieakkoord (Energy agreement)*. This agreement was signed by the central Dutch government and over forty public and private organizations. It included binding guidelines to achieve increased energy efficiency in the built environment until 2023 (SER, 2013). The agreement introduced the energy label, which gives an indication of the energy performance of dwellings from F (lowest) to A++ (highest). Specifically, this agreement states that social housing corporations need to renovate their housing stock to an average energy label B by the end of 2020. For the private rental sector, at least 80% of the stock should have energy label C. By 2030, all Dutch dwellings (including privately owned property) should have an average energy label of A and newly built dwellings should be energy neutral (SER, 2013).

More recently, in 2019, the Dutch climate agreement was signed by the central Dutch government and several public and private organizations. By signing this agreement, all involved parties commit to achieve the set targets. The central goal of this agreement is to reduce greenhouse gas (GHG) emissions in the Netherlands with 49 percent compared to 1990 (Rijksoverheid, 2019).

One of the pillars within this agreement focusses on the built environment specifically. The government aims to reduce the CO2 emissions in the residential sector with 3.4 Mton by 2030, which corresponds to 1.5 million dwellings that need to be renovated (Rijksoverheid, 2019). These renovations focus on moving away from natural gas-fired cooking and heating systems. One of the ways to do this is to reduce the energy demand in dwellings through insulation of roofs, facades, windows and floors. At the same time, or alternatively, a switch can be made to alternative energy carriers, through the installation of appliances that can heat up dwellings without the use of natural gas. By gradually insulating dwellings and implementing alternative energy carriers on a neighborhood-level, the Dutch government aims to achieve a natural gas-free built environment in 2050 (Rijksoverheid, 2019).

To stimulate the energy transition, the Dutch government has made adjustments to the Environment and Planning Act (in Dutch: *Omgevingswet*). Within this act, there is a now a need for municipalities to draft a vision regarding the heat transition (in Dutch: *Transitievisie Warmte)* before the end of 2021 (VNG, 2019). This vision should give insight at what time certain neighborhoods can disconnect from the natural gas grid and what options are available within the municipalities.

The knowledge institute ECW facilitates the use of a techno-economic tool called the *Startanalyse*, for municipalities and other stakeholders. This tool shows heating system options as well as relevant societal costs for these options on a neighborhood-level (Rijksoverheid, 2019). Besides the Startanalyse, other calculation tools have been developed to give stakeholders in the built environment an initial overview of alternative heating strategies. These tools are further discussed in section 2.1.4.

Apart from implementing policies and stimulating municipalities to look into alternative heating systems, the government also facilitates platforms where individuals (*Verbeterjehuis.nl*) and professionals (*Energiebesparingsverkenner*) can get information on how to renovate their property (Milieucentraal, 2019b; RVO, 2019a). By giving an overview of possible insulation measures, energy savings, available subsidies and total cost savings, these platforms are designed to stimulate home-owners and professional market parties to take the first steps in renovation measures on a household level. In addition to the actions of the government, market parties have emerged that focus on identifying energy inefficiencies by performing scans of residential dwellings (HomeQgo, 2020; Woningscans, 2018).

It can thus be concluded that within the Netherlands, several policies are introduced, and businesses emerge that aim to stimulate the heat transition in the built environment to a natural gas-free sector. This transition calls for the integration of technical, economic, social and environmental aspects. Alongside these aspects, a variety of stakeholders are involved in this transition.

Within this research, we regard residents – home-owners in particular – as problem owners, as they are the end-users in the heating strategies and are the primary decision-makers. Therefore they are the main stakeholder that is considered in this thesis.

We focus in this research on the implementation of alternative heating strategies in residential buildings. We define *heating strategies* in this study as strategies that provide an alternative way to supply a dwelling with space heating and hot tap water, without being fully fueled by natural gas. These strategies combine specific installations that are required for each dwellings, such as heat emitting systems and heating systems (e.g. boilers, heat pumps or other types of heat exchangers) and insulation measures. Throughout this thesis, combinations of these installations and insulation measures are also referred to as *energy renovation measures*.

1.2. Problem statement

Approximately 1.5 million dwellings need to be renovated by 2030. On the longer term, this number increases as more than 7 million dwellings need to become natural gas-free by 2050 (Rijksoverheid, 2019). This calls for a significant heat transition in the Dutch built environment. Within this transition many factors such as financial feasibility and the preferences of the end-users must be taken into account. Additionally, many actors such as municipalities, residents, and knowledge institutes are involved. Cooperation between these actors is required for the heat transition to be successful. Taking this societal relevance in account, the following problems have been identified by means of literature review:

- Residents are influenced by several personal and contextual decision-making factors, when making decision to renovate their dwellings, or implement new heating systems. Other factors than financial drivers or barriers are generally not considered by methods and tools to assess alternative heating strategies.
- Initially developed tools to support decision-making do not explicitly consider a life cycle perspective (see section 2.1.4). Environmental considerations are generally only accounted for during the operation stage of the selected heating strategy (Schepers et al., 2019, pp. 202-203). Emissions during production and commissioning of the implementation of the heating strategies are often left unaddressed. It is important to consider a life cycle perspective when the environmental burdens are assessed, to retrieve a more complete picture of the actual environmental impact of alternative heating strategies, as emissions are not limited to the operation stage.

These identified problems lead to the following problem statement that forms the main area of research in this thesis project:

There is a need for a way or tool to compare alternative heating strategies by using more decision-making factors than costs and CO2 emissions over the operation stage, that includes a life cycle perspective.

1.3. Relevance to Industrial Ecology

The energy transition is a topic that is closely related to industrial ecology. The goal of the energy transition is to lower emissions through the reduction of (fossil) energy sources. In the design of new energy systems, the *Trias Energetica* plays a central role. The *Trias Energetica* is a three step strategy that aims to (1) reduce the energy demand, (2) aims to use renewable energy sources and (3) use fossil energy sources efficiently (Duijvestein, 1996).

This shows similarities with the field of industrial ecology, which studies the flows of materials and energy in industrial and consumer activities and aims to minimize material and energy inputs in systems (Lifset & Graedel, 2002). According to Lifset and Graedel (2002) industrial ecology "places human technological activity in the context of the larger ecosystems that support it, examining the sources of resources used in society". Lowering emissions by using alternative resources instead of fossil fuels, like natural gas, is a way to improve environmental resilience and preserve the ecosystems on earth that are utilized by humanity.

Industrial ecology goes beyond the economic system and takes a systematic approach. To avoid narrow analyses that overlook important variables, it is important to take a systems perspective to analyze the heat transition in the Dutch residential sector. When taking a systems perspective it is possible to account for factors such as technical and economic feasibility and social acceptance of certain types of heating strategies.

Embedded in the systematic approach of industrial ecology is the life cycle perspective. By taking a life cycle perspective, the environmental impacts of energy systems can be considered from the production stage to the end-of-life stage. It will become clear from the literature review in chapter 2 that currently applied decision support tools in the Dutch energy transition only account for a part of the product system's life cycle. These models rather take a gate-to-gate approach and most of the time only account for emissions that occur during the operation stage. By taking a life cycle perspective, additional information can be presented to the decision-makers that go beyond the boundaries of the current applied methods.

1.4. Research question

The main research question that this thesis seeks to answer is:

"How to assess alternative heating strategies in neighbourhoods in The Netherlands while accounting for the life cycle of those heating strategies and for multiple household decision-making factors?"

1.4.1. Sub questions

In order to answer the research question, several sub questions are formulated:

1. Which methods and tools are currently used to asses alternative heating strategies and what is missing in these methods and tools?
2. How to apply these tools and methods to support decision-making for the heat transition in a neighborhood?

3. How do alternative heating strategies perform in a specific neighborhood, when the life cycle of those heating strategies is accounted for and multiple decision-making factors are considered?
4. What can we learn from this specific case study for the heat transition in other neighborhoods in The Netherlands?

1.5. Scope

This research focuses on individual or household preferences. The opinions of households function as the basic judgements that were used in this thesis to asses different heating strategies. However, the energy transition is complex and many stakeholders are involved. The results of this thesis may therefore only represent the views of households.

1.6. Audience

The target audience of this research are the parties that are involved in decision-making processes regarding the heat transition in the Dutch residential sector. These parties can be, but are not limited to, municipalities, network operators, households and energy suppliers.

1.7. Thesis structure

This thesis consists of nine chapters which are structured in the following order. In the first chapter, an introduction to the research is given, an overview of the research topic is presented, and several research questions were formulated. In Chapter 2, a literature review is presented on currently applied methods and tools in the built environment to assess heating strategies. Furthermore, literature is examined on residential decision-making factors that play a role in the selection of alternative heating strategies. By reviewing this literature, we aim to provide an answer to sub question 1.

Following from the literature review is the research approach, which is described in Chapter 3. In the research approach, we elaborate on the research methods that we use to assess alternative heating strategies. By doing so, we aim to provide an answer to sub question 2.

Chapter 4 describes the case study that will be examined in this research. A description of the case neighborhood is presented and the heating strategies that are assessed in this research are selected. As part of the case study, a survey is conducted among the residents of the case study. In Chapter 5, we discuss the results of this survey.

Chapter 6 presents the results of the individual assessments that are used to assess the alternative heating strategies. By combining the findings from Chapter 5 and 6, Chapter 7 discusses the results of the Multi-Criteria Analysis (MCA), and shows how the alternative heating strategies compare to each other. This includes a scenario analysis in which different external factors are changed to see how these affect the final outcomes. The results from the individual assessments and the MCA are used to provide an answer to sub question 3.

After gathering the results, in Chapter 8, a discussion is presented on how the MCA results compare to the preferences of the residents of the case study, how the model performs, and what the potential users of this model can obtain from working with this model. Additionally, we elaborate on the lessons that we can learn from the performed case study. By doing so, we provide an answer to sub question 4.

Finally, Chapter 9 presents the overall conclusion for this thesis, and recommendations for the residents of the case study are presented. This chapter is used to provide an answer to the main research question of the thesis. The structure of this thesis is visualized in Figure 1.

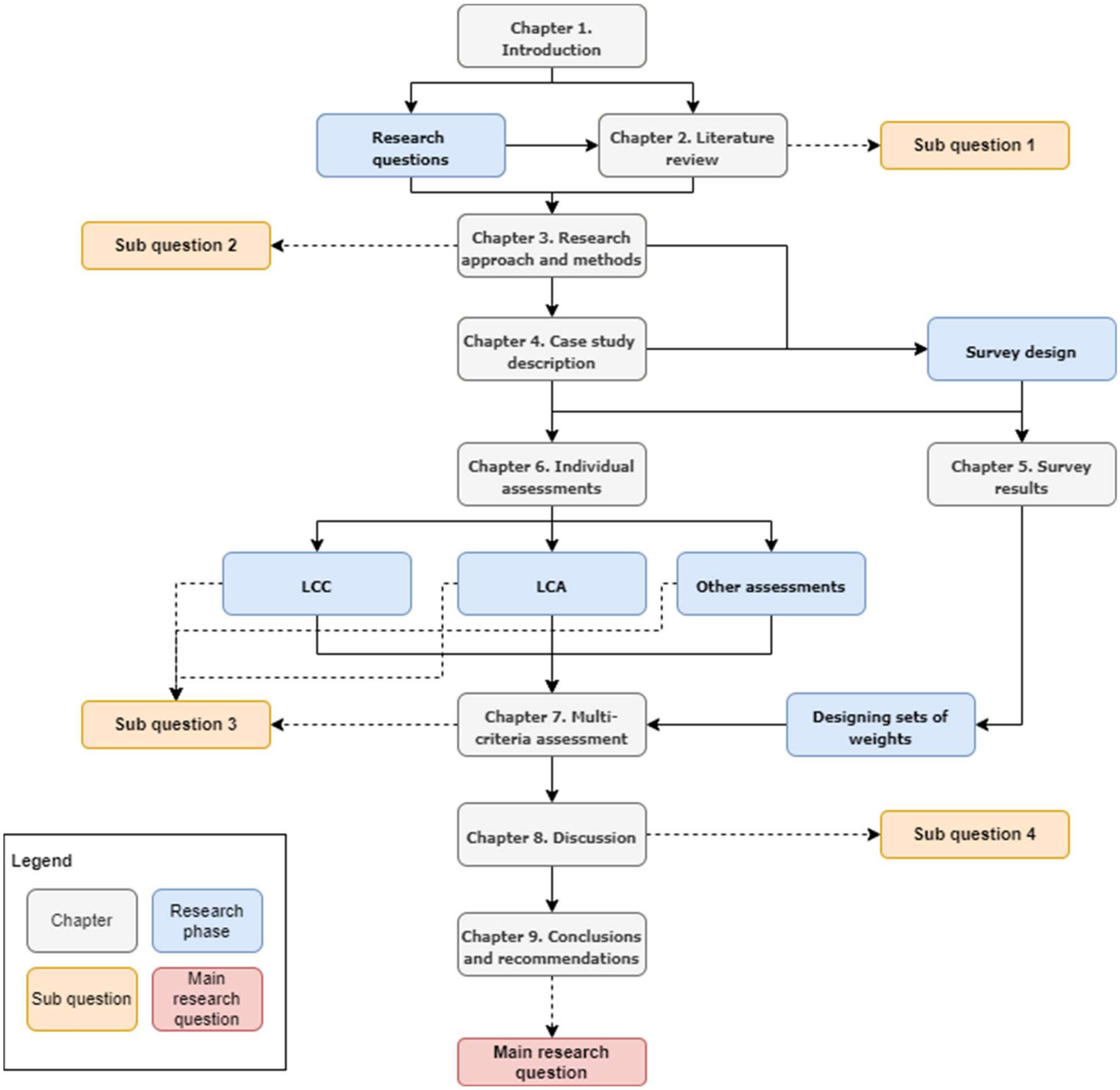

Figure 1 Research flow diagram.

Chapter 2. Literature review

The literature review of this study consists of two parts. In the first part of this review, we examine literature to get insight in which methods and tools are currently applied in the residential building sector to assess heating strategies.

In the other part of the literature review, we focus on decision-making factors related to the implementation of heating strategies. This part consists of literature in the field of decision-making, as well as literature on how currently applied methods in the residential building sector account for factors that influence household decision-making.

Together, these two parts of the literature review are used to identify the currently applied methods and tools and to identify what these methods are missing in the assessment of heating strategies. The information that we gather in this chapter can be used to provide an answer to sub question 1.

2.1. Thermal energy efficiency assessment

A literature review is carried out to find out which methods are currently used as decision support tools in the residential building sector. A search was conducted in the Scopus database and searches included the terms “assessment OR evaluation OR comparison”, “energy efficiency OR energy renovation”, “dwellings OR buildings OR “built environment”” and “decision support OR policy making” in title, abstract or keywords. This search was conducted to get an initial overview and additional literature was retrieved through the snowballing-method.

Based on the relevant literature, assessment methods are classified into direct approach methods, optimization models and simulation models. In this literature study, direct approach methods represent methods that make calculations based on definite values. On the other hand, optimization models represent models that aim to optimize the benefits of solutions by considering multiple competing objectives. Simulation models represent models that rely on the simulation of input data to perform calculations.

Additionally, several calculation tools have been developed to support Dutch built environment stakeholders in decision-making. These tools are also further described in this section.

2.1.1. Direct approach methods

Within the scientific literature, several methods are described as decision-making support tools for alternative heating strategies in dwellings. One of the methods that has been used is cost-benefit analysis (CBA). Goodacre, Sharples, and Smith (2002) used CBA to assess the potential costs and benefits that occurred when the heating systems in the English housing stock were renovated. This type of analysis can provide decision-makers with insight in the monetary value of heating strategies. Friedman, Becker, and Erell (2014) used CBA to establish the cost-effectiveness of retrofitting buildings to conserve energy. Other CBA research has been done to assess investment options for renewable energy systems and to assess the building performance (Burhenne, Tsvetkova, Jacob, Henze, & Wagner, 2013; Morrissey, Meyrick, Sivaraman, Horne, & Berry, 2013). According to Friedman et al. (2014), further research efforts should be made to evaluate non-energy benefits, such as improved health through better indoor conditions, which cannot be quantified in cost-benefit analysis.

Besides heating systems, the cost effectiveness of several insulation types has also been measured using the life cycle costing (LCC) method to calculate the net present value of energy savings (Morrissey & Horne, 2011; Tommerup & Svendsen, 2006). Due to uncertainty about energy savings, energy consumption patterns and system degradations, economic analyses are sometimes extended with risk assessment to better determine the benefits of the investments (Gustafsson, 1998; Menassa, 2011). Economic methods such as CBA and LCC cover the energy savings by expressing this in monetary terms.

However true environmental impact assessment, which goes beyond reduction of energy consumption, should include the emissions of production, installation and use of the applied interventions.

One of the methods used to compare the environmental impact of heating strategies over the whole product life cycle is life cycle assessment (LCA). In an LCA, the environmental burden over the full life cycle of a product system are characterized in selected indicators such as GHG emissions and acidification (J. B. Guinée et al., 2002). In the built environment, LCA has been performed to support decision-making for energy renovations regarding insulation in the built environment (Brás & Gomes, 2015; de Larriva, Rodríguez, López, Raugei, & Fullana i Palmer, 2014) and to assess new construction projects (Säynäjoki, Heinonen, & Junnila, 2012). Besides solely focusing on the environmental impacts, LCA has also been combined with a life cycle costing approach to align economic and environmental interests (Ristimäki, Säynäjoki, Heinonen, & Junnila, 2013).

However, according to Vilches, Garcia-Martinez, and Sanchez-Montanes (2017) building refurbishment LCA's leave social and cultural aspects and consequences unaddressed. Ostermeyer, Wallbaum, and Reuter (2013) mention that some of the social criteria, such as impacts on users during construction and operation phase, should be considered when assessing the renovation interventions in dwellings, as social acceptance is an important factor for architects and building planners.

Renovating the existing residential sector towards a natural gas-free future relies on complex decisions. Many actors are involved, which are concerned with different criteria when selecting heating strategies (e.g. financial, social and environmental). Due to the involvement of multiple actors and criteria, multi-criteria analysis (MCA) can be a useful method to increase the understanding, transparency, robustness and acceptability of decision-making (Beinat, 2001). With MCA it is possible to go beyond typical economic and environmental performance assessments that are used in the built environment. Within MCA, a distinction can be made between multi-objective and multi-attribute decision-making. Multi-objective decision-making methods deal with an infinite set of alternatives, whereas multi-attribute decision-making methods consider finite and known alternatives (Zavadskas, Turskis, & Kildienė, 2014). Within heating system research in the built environment, multi-attribute methods are primarily used.

Gero, D'Cruz, and Radford (1983) were one of the first to use a multi-criteria model based on Pareto-optimization in building design. Yingkui Yang, Ren, Solgaard, Xu, and Nguyen (2018) applied MCA to examine three renewable heating technologies for residential heating in Denmark, using a compensatory ranking method called TOPSIS. Besides economic factors, also environmental and (socio)technical factors were considered, with criteria such as GHG emission reduction, reliability and easiness to use. Kontu, Rinne, Olkkonen, Lahdelma, and Salminen (2015) used Stochastic Multicriteria Acceptability Analysis (SMAA) to identify suitable heating systems for a new residential area.

Other compensatory ranking methods that are used in heat transition research are AHP and MAUT, which allow for simple computation (Huang, Keisler, & Linkov, 2011; Yulan Yang, Li, & Yao, 2010). These compensatory ranking methods assign utility values to each alternative, but in real-life situations it is sometimes hard to assign numerical values to different criteria (Baumann, Weil, Peters, Chibeles-Martins, & Moniz, 2019).

Other multi-attribute methods that are used revolve around the principle of outranking, in which alternatives are eliminated that are particularly dominant. The primarily used outranking approaches are PROMETHEE and ELECTRE, which have been used in heating strategy and heating and ventilation system design research (Avgelis & Papadopoulos, 2009; Seddiki, Anouche, Bennadji, & Boateng, 2016). Criticism on these outranking methods is that they are very complex to apply and are rather arbitrary (Baumann et al., 2019; Guitouni & Martel, 1998).

One of the advantages of MCA is that besides assessing economic and environmental indicators, also social indicators can be included in the analysis of heating strategies. Research by Sopha, Klöckner, Skjevrak, and Hertwich (2010) has shown that social factors influence household decision-making when comparing heating systems.

Lizana, Molina-Huelva, and Chacartegui (2016) applied MCA to a Spanish residential energy retrofitting case and included several different packages of energy measures within their analysis. Additionally, a set of economic, environmental and social variables (e.g. duration of renovation and inconvenience due to construction) were included in the MCA, and the different packages of energy measures were evaluated using the *Effectiveness Index*. This index is based on the weighting of the variables by different stakeholder groups such as end-users and public administrations (Lizana et al., 2016). When the most effective solutions according to the requirements of these intervening stakeholders are taken into account, end-users and public administrations can improve their decision-making in regard to the renovation of their dwellings.

Even though MCA enables the combination of multiple criteria, especially the environmental criteria stay rather shallow. Environmental criteria that are applied mainly consider the energy that is saved with new measures (Seddiki et al., 2016), the share of renewable energy that is consumed (Yingkui Yang et al., 2018), and the CO2 or GHG emission reductions during consumption (Lizana et al., 2016; Seddiki et al., 2016; Yingkui Yang et al., 2018). Emissions that occur during production and installation of the technologies are not considered. Therefore, environmental assessment is mainly performed from gate-to-gate and does not consider the full life cycle, which is considered in individual environmental assessment methods like LCA. Avgelis and Papadopoulos (2009) consider the GHG emissions which are produced during construction and operation of heating and ventilation systems during a product lifetime of 20 years and therefore aim to take a life cycle perspective. However, as transport, electric wirings and electronic equipment are excluded in the analysis, there are limitations to the analysis of the environmental burdens of the product system.

2.1.2. Optimization models

Besides these direct approach methods, optimization models are also used to support decision-makers with selecting alternative heating strategies. These optimization models are used to optimize the merits of potential solutions under multiple competing objectives. These models are used to support decision-makers by estimating the energy performance of alternative heating strategies. Multi-objective optimization models quantitatively assess the technology choices for different heating strategies to optimize the renovation costs and energy savings (Asadi, da Silva, Antunes, & Dias, 2012b; Sharif & Hammad, 2019). To limit the computation times of these models, simplified models are developed with limited objectives (Asadi, Da Silva, Antunes, & Dias, 2012a).

2.1.3. Simulation models

When looking solely at heating system networks, other techno-economic modelling approaches are applied by making use of simulation models. In the literature, simulations are performed with several methods, such as Monte Carlo simulation (Gu et al., 2018) and the Visual Basic programming tool (Ahmed & Mancarella, 2014). These simulation models generally focus on limited technology systems (e.g. insulation or one type of district heating). Therefore, broader assessment in multi-energy systems where heating, electricity and cooling networks on individual and collective level interact, is not possible (Mancarella, 2014). In a recent study, Nava Guerrero, Korevaar, Hansen, and Lukszo (2019) used an agent-based modelling method for energy transitions in the built environment. The authors exemplified how such transitions can be studied for a neighborhood by focusing on individual households and their interactions.

2.1.4. Decision-making support tools applied in The Netherlands

Several calculation tools have been developed that can be used to get insight in regional possibilities for the heat transition in The Netherlands. An overview of these calculation tools is presented in Table 1. This overview is based on a report from Brouwer (2019) on six decision-making support tools from six different research institutes. The Startanalyse, as mentioned in section 1.1, is a specific interface built with the Vesta MAIS tool and is therefore classified under the name of Vesta MAIS.

Table 1 An overview of the used calculation tools in the Netherlands, adapted from Brouwer (2019).

Calculation tool	Type of model	Indicators	Pricing level
Caldomus (Innoforte)	*Building model*: No limits on energy sources	CO2-emissions; Cost-effectiveness (Mans, Verheul, & Kerckhoffs, 2017)	Present day
CEGOIA (CE Delft)	*Source model*: Limited availability of energy sources	Cost-effectiveness (CE Delft, 2019)	Adjustable learning curve
Vesta MAIS (PBL)	*Source model*: Limited availability of energy sources	CO2-emissions; Cost-effectiveness; Energy savings (van den Wijngaart, van Polen, & van Bemmel, 2017)	Adjustable learning curve
Warmte Transitieatlas (Overmorgen)	*Building model*: No limits on energy sources	Cost-effectiveness (Brouwer, 2019; Over Morgen, 2018a)	Present day
ETM (Quintel)	*Reasoning model*: User can adapt variables, therefore this is not an optimizing model	CO2-emission reduction; Costs of measures (Quintel, 2019)	Present day (but learning curve can be adjusted)
Aardgasvrije wijken (DWA)	*Building model*: No limits on energy sources	Cost effectiveness; Energy Savings (DWA, 2019)	Present day

These six models can be categorized into two main categories: *optimizing models* and *reasoning models* (Brouwer, 2019). In reasoning models, the users can change all variables from the benchmark, to seek changes in different outcomes. An optimizing model would do this for the user. Additionally, optimizing models seek the most cost-effective ways based on the boundary conditions.

These optimizing models can then be further distinguished into *building models* and *source models*. Building models assume that supply follows demand and this does not put limits on the availability of energy sources (Brouwer, 2019). Contrary to these models are source models, in which supply can be limited by the users, based on scarcity of an energy source.

Besides cost-effectiveness, some of the optimizing models make use of different indicators to present their calculation results. The Vesta MAIS and Caldomus tools both show the CO2-emissions during operation of the selected heating strategy (Mans et al., 2017; van den Wijngaart et al., 2017). The Vesta MAIS and DWA models both present the energy savings for the selected heating strategies (DWA, 2019; van den Wijngaart et al., 2017). The Warmte Transitie Atlas (WTA) and CEGOIA only present their results in a cost-effectiveness indicator (CE Delft, 2019; Over Morgen, 2018a). The reasoning model of ETM presents its results in two indicators; it gives the CO2-emission reduction and the total costs, based on the selected variables by the user (Quintel, 2019).

In order to measure the costs of different measures over time, these models have set standards on the pricing level that they include in their models. Over time, one can imagine that the costs of for example a heat pump decrease over time due to the involved learning curve of production. Some models choose not to adjust for a learning curve, but instead make use of present day technology prices (Brouwer, 2019). In this way it is possible to see what measures are already economically feasible in neighborhoods. Other models include a learning curve to show when alternative measures become feasible in the future.

These different calculation tools make use of the same starting point, as data from the *Central Bureau of Statistics* (CBS) and the *Basic register Addresses and Buildings* (BAG) are used to model the neighborhoods and the related energy demand (Brouwer, 2019). The different techniques and installations used in these models are centered around three heating strategies: Low-temperature district heating networks, high-temperature district heating networks, and all-electric solutions. Even though small differences occur between these models, based on pricing levels of technologies and the ways in which solutions are implementable, the outline of these tools are similar.

Besides ETM, all tools generally focus on finding cost-effective solutions per neighborhood, based on a cost-benefit principle. ETM differs from the other tools since the user has to adapt all the variables. Therefore this model is not optimizing based on costs. Furthermore, ETM is the only model that considers emissions beyond the energy use phase. The emissions from extraction, processing and transport of each fuel alternative can be accounted for the by the user of the model (Quintel, 2020). The other tools that consider emissions only calculate the CO2 emissions related to the operation or use phase (Mans et al., 2017; van den Wijngaart et al., 2017).

Thus, the emissions related to the production and commissioning of energy are not accounted for in the other tools. This can be seen from the functional background report of the Vesta MAIS model, where CO2 emissions are only calculated for the amount of heat that is supplied, and the CO2 emission factor of the related energy carrier (Schepers et al., 2019, pp. 202-203). Moreover, emissions related to the production and commissioning of the implementation of heating strategies and heating installations are not considered in any tool. Therefore, it can be concluded that a life cycle approach is missing in these tools.

2.1.5. Conclusion

Based on the literature review on methods and tools, it can be concluded that current used decision-making support tools generally include economic assessment and sometimes also include environmental assessment. These decision support tools are mainly used to find cost-effective solutions.

Multi-criteria analysis can be an adequate method to combine the primarily used economic assessment with environmental- and social assessment to get a more complete analysis of energy technologies when multiple renovation interventions are considered.

However, when environmental criteria are integrated in MCA studies, the life cycle of the product system is not considered in its entirety. This is also the case for the applied tools in the Netherlands, where the main environmental assessment involves measuring CO2 emission reduction during the use phase.

Integrating a life cycle perspective in the analysis of product systems gives a more complete overview of how these different systems perform. Environmental burdens that occur during production, commissioning and end-of-life should be considered in the assessment. In this way, a more complete overview of the impact and emissions of certain product systems can be presented, which can support decision-makers in the selection of heating strategies. Therefore, in this research a life cycle perspective is included in a MCA of alternative heating strategies to account for all impacts that occur over the life cycle of the identified heating strategies.

2.2. Criteria classification in MCA

Multi criteria assessment has been used in many studies to support stakeholders with decision-making problems related to renewable energy. Wang, Jing, Zhang, and Zhao (2009) have identified four main classifications for criteria in studies that perform multi criteria assessments to support renewable energy decision-making. Besides focusing on economic and environmental impacts of these renewable energy technologies, MCA studies also consider technical and social criteria (Wang et al., 2009). In this review section, specific literature regarding MCA of heating strategies is further examined. This leads to an identification of what can be considered as 'social' and 'technical' criteria in the selection process of alternative heating strategies.

2.2.1. Social criteria

Lizana et al. (2016) have included several social criteria in their MCA of energy retrofits of Spanish dwellings. According to Lizana et al. (2016), social criteria should be included in energy retrofit strategies to account for the specific needs of the residents, and should allow to improve their quality of life. 'Duration of the works', 'inconveniences to tenants' and 'prejudices about the benefits of the measures' were social variables that have been considered during the construction stage of the alternative heating strategies. During the use stage, 'real uses of the measures', 'comfort level' and 'impact and visibility of the measures' have been considered. These variables were measured qualitatively by means of an absolute scale.

According to Kontu et al. (2015), social aspects in sustainable development are intangible and hard to model. Social aspects usually cover themes such as employment, poverty, health and safety and participation. In their study about heating choices in a new residential area in Finland, the authors consider 'domesticity', 'promotes new technologies', 'popularity' and 'several competing energy providers' as social criteria. Even though several criteria are mentioned, the authors do not address how their definition of social criteria relates to the previous mentioned social aspects in sustainable development. Additionally the authors also include another criterion, 'usability' with factors such as 'ease of use' and 'care free', as the authors argue that users play a key role in choosing, procuring and using heating systems. Yet, a clear definition of the what can be considered as 'usability' is missing.

Chen et al. (2019) included a social assessment in a MCA of different combinations of heating strategies to include the views of various actors on the selected combinations of applicable renovation measures required for each heating strategy. They state that research that includes energy saving, economic, environmental and social impacts is limited and thus deserves more attention (Chen et al., 2019). They use the following criteria to assess the social impact; 'disturbance to occupants', 'indoor air quality and comfort' and 'building aesthetics'. These impacts were defined by Chen et al. (2019) based on an earlier conducted survey of the same authors, that aimed to understand the demand and the concerns of residents during renovation.

Mokhtara, Negrou, Settou, Gouareh, and Settou (2019) included 'public acceptance' and 'job creation' as social criteria in the selection process of best energy efficiency measures for plus-energy buildings in Algeria. However, the authors do not provide any details on why these criteria are included in the MCA.

Seddiki et al. (2016) have shown that 'summer comfort', 'inconvenience caused by the thermal renovation' and 'duration of the renovation work' are considered as social impact categories by decision-makers in the building sector. In this study, a specific method called Delphi was applied and decision-makers had to make a list of important criteria. This initial list was then narrowed down to only include the most important (or desired) criteria. The list with combined criteria was then revised and narrowed down. This process was repeated until decision-makers could not narrow down the list any further and only the most important criteria, according to them, were left. As a result, none of the identified social criteria were considered in the conducted MCA.

The amount of MCA studies which have been performed to assess the heating strategy of buildings that include social criteria is rather limited. Chen et al. (2019) acknowledges this research gap and states that research that evaluates the impacts of energy measures on energy saving, economic, environmental and social benefits deserves more attention. According to Lizana et al. (2016), assessing the effectiveness of heating strategies is rather complex. Thus, in the relevant literature generally only two objective functions are used, which are related to the energy consumption and the life cycle costs. Yet, Lizana et al. (2016) argue that social factors are relevant for real implementation of heating strategies and should be included in order to make effective decisions.

All of the identified papers specifically use the term *social criteria* to describe the impacts that are embedded in social aspects. Therefore, sometimes criteria of a more technical nature are also included as social criteria, such as thermal comfort and indoor air quality. The literature does not specifically address what can be considered as a social criterion, or what social impacts are. Though, Kontu et al. (2015) and Lizana et al. (2016) emphasize the involvement of the end-users, i.e. the residents, as important social actors. On the other hand, other authors such as Mokhtara et al. (2019) place social impact in a broader context and consider the benefits to society in general (e.g. by using job creation as a social criterion).

2.2.2. Technical Criteria

Contrary to social criteria, technical criteria can be more clearly defined. Technical criteria generally relate to the technical characteristics and capabilities of heating systems and installations (Yingkui Yang et al., 2018). Yingkui Yang et al. (2018) have included technical criteria in their MCA of renewable heating technologies for Danish dwellings. The authors used 'reliability', 'heating time', 'easy to use' and 'few reparations' as technical criteria since these criteria directly relate to the technical complexity of the examined heating technologies. Kontu et al. (2015) consider 'flexibility' and 'reliability' of the heating systems as technical criteria. These criteria measure the modification and installation possibilities and the probability of malfunctioning.

Other studies do not explicitly distinguish between economic, environmental and technical or social classifications when defining their criteria. However, criteria that can be classified as technical criteria due to the underlying technical capabilities that influence the performance of the defined criteria are thermal comfort and indoor air quality. Thermal comfort has been considered in several MCA studies as it serves as an important indicator of residents' satisfaction (Avgelis & Papadopoulos, 2009; Chantrelle, Lahmidi, Keilholz, El Mankibi, & Michel, 2011; Kamari, Jensen, Christensen, Petersen, & Kirkegaard, 2018). Indoor air quality is considered in several MCA studies to measure the performance of the ventilation systems (Avgelis & Papadopoulos, 2009; Chen et al., 2019). As mentioned before, these criteria are also sometimes considered as social criteria due to the authors unambiguous interpretation of social criteria.

2.2.3. Conclusion

Besides economic and environmental criteria, other criteria that can be considered important for residents can also be included in the MCA of alternative heating strategies. In MCA literature, these criteria are generally classified as technical or social criteria.

In this research, we aim to measure different type of impacts that alternative heating strategies may have on residents. These impacts may be caused by the technical characteristics of the heating strategies, but there are more factors that can play a role here. In line with the current MCA studies, some factors can also be considered to have a 'social' impact.

However, no unambiguous definition of social impacts is presented in the literature on MCA regarding alternative heating strategies. The classification of these criteria depends on the factors that are included in the MCA. Therefore, the following section identifies factors that influence the decision-making process of residents related to the selection of alternative heating strategies. After selecting the factors that are included in the MCA, the classification of these factors will follow accordingly.

2.3. Literature on renovation decision-making of residents

This review presents a theoretical background of the decision-making process of residents related to alternative heating strategies. Besides focusing on heating strategies as a whole, in this review we also consider smaller or individual renovation measures that are undertaken in households. Literature on these 'smaller' renovation decisions also provide insight in what factors residents find important when they are going to renovate their dwelling. Based on the findings from this review, a selection is made of the factors that are included in the MCA.

This literature overview consist of scientific literature as well as grey literature that has been recommended by an expert from a technical university in the Netherlands, working in the fields of behavioral science and the energy transition. Additional literature was collected through a search in the Scopus database with search terms "Renovation AND decision" AND "home OR households OR dwellings" AND "behaviour OR behavior" in the title, abstract and keywords. To narrow down the results, the search was limited to English journal articles from 2014 onwards.

2.3.1. Scientific literature

According to Ebrahimigharehbaghi, Qian, Meijer, and Visscher (2019) the decision-making process of residents can be divided into two factors that influence decisions. *Personal factors*, such as cognitive awareness, attitudes and beliefs, experience and skills play a role in the individual factors that households consider when deciding to renovate their homes. *Contextual factors* are factors that depend on household characteristics (e.g. size), socio-demographic variables (e.g. age and education level), and property characteristics (e.g. construction year) (Ebrahimigharehbaghi et al., 2019).

Research on contextual factors has shown that younger homeowners that are wealthier and have a high education level, have greater concern for the environment and to save energy and are therefore motivated to perform certain renovation measures (Bravo, Pardalis, Mahapatra, & Mainali, 2019). With increased age, homeowners become less motivated to save energy and this negatively affects their interested in performing energy renovations. Pardalis, Mahapatra, Bravo, and Mainali (2019) conducted an online survey to study the renovation intentions of Swedish home owners. They found that any kind of renovation that has been carried out in previous years, negatively influences the decision to perform any type of new renovation measure in the future (Pardalis et al., 2019). This is contrary to the findings of Fyhn and Baron (2017), who researched homeowners perspectives regarding renovation decisions through interviews with Danish and Norwegian households. They argue that many small renovation add up to larger projects and can act as a stimulating factor for taking large renovation decisions (Fyhn & Baron, 2017).

According to Wilson, Pettifor, and Chryssochoidis (2018), renovation decisions are influenced just as much by factors that relate to measures to improve the convenience of the dwelling, as they are by a desire to improve the energy efficiency of a dwelling. These renovation decisions are perceived as ways of resolving certain problematic conditions or issues within homes. By conducting a survey amongst homeowners in the UK, the authors also found that smaller and older properties, and larger households or those with young children are more likely to balance the competing commitments for the use of space at home. Elderly people are more likely to experience thermal discomfort. Balancing the competing commitments of design and space, and experiencing thermal discomfort are conditions that show a tendency to change things around the house, including renovating (Wilson et al., 2018).

Klöckner and Nayum (2017) studied the psychological determinants of the decision-making process regarding heating strategies by conducting a survey in a large sample of Norwegian home owners. They identified that barriers and drivers for heating strategies do not apply to all population and housing groups in the same way. People living in tenant-occupied housing may therefore experience other drivers and barriers than those living in privately owned dwellings. People with limited economic resources do not necessarily stay away from thinking about energy efficiency upgrades. This is rather seen as a driver because potential energy savings are relevant for this group (Klöckner & Nayum, 2017). However, in the planning phase they may encounter barriers regarding the costs of the heating strategies.

Broers, Vasseur, Kemp, Abujidi, and Vroon (2019) conducted an interview with Dutch homeowners to identify influencing factors in non-adopters and adopters of energy renovation measures. They give an overview of the amount of times a certain factor is mentioned in the interviews. From this paper, it seems that *saving energy costs* is mentioned in 75% of the interviews. Additionally *environmental concern* (61.54%), and *total costs of renovation measures* (59.62%) are both mentioned very often. Another important factor are the property characteristics, which is approximated by the variable *technical restrictions in homes,* which is mentioned by 44.44% of the interviewees.

The findings on the motivational factors from Broers et al. (2019) are in line with the findings from Organ, Proverbs, and Squires (2013), who conducted an extensive literature review on motivations of individuals to perform energy efficiency renovations. These authors found that energy bill savings, increasing comfort and reducing environmental impact are the three key reasons that affect their motivation to renovate.

Ebrahimigharehbaghi et al. (2019) studied what the drivers and barriers of Dutch home owners are when making decisions about performing energy efficiency measures. The authors analyzed the WOON2012 database, a large scale survey about energy use in tenant-occupied, owner-occupied and social housing, to identify the drivers and barriers to energy efficiency renovations. They found that drivers related to energy efficiency renovations are mainly caused by the desire to enhance the comfort within a home, rather than obtaining financial benefits (Ebrahimigharehbaghi et al., 2019). Though, costs savings and protecting the environment are also important drivers. The main barrier is identified as the cost of the renovation measures, but also other barriers have been identified. Transaction costs, i.e. any hidden costs that are not included in a cost analysis, are significant influencing factors of the decision-making process of home owners (Wilson, Crane, & Chryssochoidis, 2015). These transaction costs lead to barriers such as the lack of available subsidies for energy efficient renovations. These barriers can be connected to other obstacles such as the complexity in applying for subsidies or unawareness about certain subsidies. Furthermore, two important transaction costs that form barriers have been mentioned as well: Finding reliable information and experts, and mess and nuisance or disruption (Ebrahimigharehbaghi et al., 2019; Wilson et al., 2015).

This hassle factor has been specifically studied by De Vries, Rietkerk, and Kooger (2019). The authors argue that hassle factors form an important psychological barrier when it comes to renovating a home to become more energy efficient. There are multiple forms of hassle which have been identified, such as complex public information, finding a reliable contractor and arranging construction works, perceived disruption during renovation works and applying for loans and subsidies (De Vries et al., 2019).

Other psychological factors, such as p*sychological reactance* may also influence the decision-making process. Psychological reactance is a form of emotional arousal that is activated when people feel that their behavioral freedom is threatened. De Vries (2017) argues that people can experience this phenomenon when they perceive positive framing of technologies or measures as manipulative. This psychological reactance may lead to public opposition, i.e. the resistance of citizens to prevent the implementation of a certain project (De Vries, 2017). In the case of energy renovations this may lead to rejection of certain heating strategies.

Hesselink and Chappin (2019) systematically reviewed existing agent-based modelling studies that have modelled energy efficient technology adoption by households. In this review, they identified specific barriers that prevent households from adopting energy efficient technologies. Four specific barriers were identified that relate to residential heating systems; the lack of capital, lack of information, high upfront costs (Cagno, Worrell, Trianni, & Pugliese, 2013) and inertia (Moglia, Cook, & McGregor, 2017), which relates to the tendency of people to stick to the status quo.

2.3.2. Grey literature

Within the Netherlands, several research institutes and private companies are also conducting research to gain a better understanding of heating strategy decision-making. Recently, a report was published by research institute TNO on drivers and barriers for home owners when it comes to renovate their dwellings to become natural gas-free. This report has shown that costs form an important barrier for residents. However, costs can also be a driver as temporary subsidies and pilot projects may give residents a feeling of 'now or never' (de Koning, Kooger, Hermans, & Tigchelaar, 2020). Another important barrier comes in the form of hassle, when heating systems are installed. This comes with organization issues and household disruption due to renovation, which puts people off (de Koning et al., 2020).

Research of market research agency Ipsos has shown that Dutch consumers are driven by cost reductions when performing energy renovations. The Dutch consumers also have the motivation to become 'better for the environment' especially when they implement hybrid or regular heat pumps (Bracke & Hardeveld Kleuver, 2019). However, research from ABN AMRO has shown that only 55% of the inhabitants have a positive e when it comes to heat-recovery systems and heat pumps. These people already have implemented this type of heating systems in their homes, or are open to do so. (Menkveld, Caris, & Raes, 2019).

2.3.3. Conclusions

Within the literature on energy renovation measures, many drivers and barriers were identified that influence the decision-making process of households when it comes to undertaking energy renovation measures. This led to the development of several frameworks have been applied to categorize the drivers and barriers related to the decision-making process. Wilson et al. (2015) divided acknowledged barriers in the literature into three categories: information, finance and decision-making, as these cover all the known barriers. Bjørneboe, Svendsen, and Heller (2018) argue that there is no completely right or wrong answer when categorizing barriers as they can often spread over more than one category. Yet, they distinguish barriers in a related way by dividing into three similar categories (Information, finance and process.

In line with this categorization of Wilson et al. (2015) and Bjørneboe et al. (2018), all of the identified drivers and barriers that are found in this literature review are categorized in the following categories: (1) *Information* (related to gathering information and increasing awareness of energy renovations), (2) *Finance* (all economic aspects of the renovation, e.g. potential cost savings and subsidies) and (3) *Process* (includes the transaction costs of making decisions, the physical and social context and regulations). The findings from the literature are categorized according to these categories and an overview is presented in Table 2.

Table 2 An overview of the drivers and barriers in the decision-making process of residents when adopting energy renovation measures.

Factors	**Information**	**Finance**	**Process**
Drivers	Having environmental concerns (Broers et al., 2019; Organ et al., 2013)	Limited economic resources (Cagno et al., 2013; Klöckner & Nayum, 2017)	Balancing design and space (Wilson et al., 2018)
		Saving energy & costs (Bracke & Hardeveld Kleuver, 2019; Broers et al., 2019; Organ et al., 2013)	Enhancing comfort (Ebrahimigharehbaghi et al., 2019; Organ et al., 2013; Wilson et al., 2018)
			Becoming self-sufficient (Broers et al., 2019)

			Previous renovation works (Fyhn & Baron, 2017)
Barriers	Unaware of subsidies (Ebrahimigharehbaghi et al., 2019)	Costs of energy renovations (Broers et al., 2019; Cagno et al., 2013; de Koning et al., 2020; Ebrahimigharehbaghi et al., 2019)	Previous renovation works (Pardalis et al., 2019)
	Time and effort in gathering information (Cagno et al., 2013; Ebrahimigharehbaghi et al., 2019; Wilson et al., 2015)	Lack of subsidies (Ebrahimigharehbaghi et al., 2019)	Reliability of experts (De Vries et al., 2019; Ebrahimigharehbaghi et al., 2019)
	Complex public information (De Vries et al., 2019)		Disruption during renovation works (De Vries et al., 2019; de Koning et al., 2020)
	Psychological reactance (De Vries, 2017)		Balancing design and space (Wilson et al., 2018)
	Inertia (Moglia et al., 2017)		Applying for subsidies (De Vries et al., 2019)

The identified factors are relevant in the decision-making process of households. In the selection process of heating strategies, these factors can play a role and it is therefore required to examine how these factors could be implemented in the selection process. As this research performs a MCA of alternative heating strategies, the identified factors were used to make a selection of new criteria for the assessment of these measures.

2.3.4. Selection of factors

A variety of factors were encountered in the literature, yet some factors are more commonly identified than others. In this study, a selection is made of those factors that are commonly identified. Including only the commonly identified factors leads to a higher validity of the research results, as these factors are more likely to be considered by Dutch residents when they are in the decision-making process of renovating their dwellings.

Wilson et al. (2015) have presented an extensive overview of commonly identified factors that influence the decision-making process of the residents. The final selected factors are adapted from this overview and are validated by an expert from a technical university in The Netherlands, working in the field of decision-making regarding energy efficient renovation measures.

Wilson et al. (2015) identify three common drivers, costs savings, environmental benefits, and increasing thermal comfort. The first driver, costs savings, was included to a certain extent in the MCA by measuring the variable *total costs.* Besides seeking to obtain financial benefits from renovation, the costs of heating strategies also play a role in the decision-making process, and can be perceived as a barrier. By including the total costs of the heating systems in the MCA, both the financial drivers and barriers are measured in one variable. This variable accounts for available subsidies, costs of technologies and installation, and savings on the energy bill.

In this MCA, the environmental benefits are measured by expressing the amount of CO2-equivalent emissions that occur due to implementing alternative heating strategies. In this way, residents can get insight in the actual environmental benefits, or environmental harm, of alternative heating strategies.

According to the interviewed expert, the factor for increasing thermal comfort occurs in the considering stage of decision-making. As alternative heating strategies are inherently linked with improving thermal comfort, end-users will be beyond the considering stage when they are assessing different alternative heating strategies. Therefore, we decide to not include this factor in the MCA as it was not relevant in this research.

When it comes to the decision-making barriers, finding reliable experts and finding reliable information are factors that are very important for residents when they are going to make renovation decisions, according to the interviewed expert. However, the degree of reliability is difficult to quantify, as people follow their own social environment. The degree of reliability is thus based on the subjective value judgement of people and is therefore difficult to evaluate. Actual reliability is therefore not measurable, but there is an alternative option. The availability of certified contractors, or experts, is used as a proxy to represent the amount of certified contractors for specific renovation measures and installation works, in close proximity to the case study area.

Moreover, according to Ebrahimigharehbaghi, Qian, Meijer, and Visscher (2020), for energy efficient renovations, maintenance and installation companies, and construction stores are the main source of information for households. If the available experts are certified, it is plausible that they have reliable information. Therefore, the availability of experts is used as a proxy variable for finding both reliable experts and reliable information. In this way, the barriers of finding reliable experts and information were included in the MCA. Residents may prefer one heating strategy over another one if there are reliable contractors available that can present them with the right information and perform the required renovation measures for a specific strategy.

Another barrier that is commonly identified according to Wilson et al. (2015), and which is dependent on the type of heating strategy, is the disruption factor. This factor is included by measuring the time that disruption is caused inside and outside of the household, related to the implementation of a specific heating strategy.

The final commonly identified factor that is considered is the occupational size of a specific heating strategy. This factor is included by measuring the space that the required installations for the different heating strategies take up. For people with limited space in their dwellings, the size of the installations can influence their decision, based on whether or not they are willing to sacrifice potential living area for heating purposes.

Ultimately, five factors were included in the MCA. An overview of these factors is presented in Table 3.

Table 3 Factors that are included in the MCA.

Factor	Measurable unit	How to include
Cost of energy renovations	Total costs	By expressing the total costs of a heating strategy in euros.
Reliability of experts	Availability of certified contractors in the area, for each heating strategy (government or environmental agency certified)	As a dummy variable. Measure the availability of certified contractors [0 for no contractors, 1 for available contractors].
Disruption during renovation works	Time of renovation works, inside and outside the dwelling	By measuring the construction time for each heating strategy in hours.

Balancing design and space	Size of heating installations	By measuring the in-home area that the heating strategy requires in square meters.
Environmental benefits	CO2 emissions	By calculating the CO2 emissions of the heating strategy.

2.3.5. Classification

The selected factors were included in the MCA because they are commonly identified decision-making factors that can be evaluated differently for different types of heating strategies. In the literature on renovation decision-making, the influencing factors are classified as drivers or barriers. In line with this field of research, this study considers this classification as part of the MCA. Thus, this study deviates from other MCA studies that consider economic, environmental, technical and social criteria.

The motivating criteria, or drivers, of renovation decisions, are represented by including the cost savings and the environmental concern factor. These factors are expressed in the total costs, and total CO2-equivalent emissions of the different heating strategies. The constraining criteria, or barriers, are included by expressing the impact of the reliability of experts, the disruption during renovations and the occupation space, for all heating strategies.

Chapter 3. Research approach and methods

In this chapter, the research approach and used research methods are presented. First the research approach is described. Then, the research methods that are used throughout the thesis are defined. The chapter proposes a way to apply a combination of research methods to support the decision-making process for the heat transition. By doing so, the proposed research approach provides an answer to sub question 2.

3.1. Research approach

In this research, we use a mixed approach with both qualitative and quantitative methods, applied to a case study. Our approach is as follows:

In the first step of the research, literature was reviewed to identify decision-making factors and state of the art decision-making tools that are currently used in the Netherlands. After the literature review, we use a semi-structured interview with an academic expert to validate a selection of relevant decision-making factors.

Second, we gather information regarding a specific Dutch case study in which most households currently use natural gas. We use a case study approach to demonstrate how alternative heating strategies can be assessed in a specific neighborhood, as the feasibility of a heating strategy is depended on the availability of specific heat sources in the analyzed area.

The information for the case study is gathered through desk research with online sources and two semi-structured and one open interview with residents of the case neighborhood. We use a semi-structured interview with an academic expert to validate a selection of heating strategies that are applicable in the neighborhood. Additionally, a survey is conducted to determine the relative importance of the relevant decision-making factors and the preferences of the residents.

The next step is to gather information for an MCA model. This model consists of the following five sub-assessments:

a. A life cycle costing approach.
b. A life cycle assessment
c. An assessment on the perceived disruption during renovation works.
d. An assessment on the occupational space of installations required for heating strategies.
e. An assessment on the ability to find reliable experts to perform renovation works.

We combine these individual assessments and apply different sets of weights to gather MCA results. A set of weights determines the weight that is assigned to the results of each individual assessment. We use the MCA to explore the ranking of heating strategies based on these different sets of weights. Some of these weights are based on the survey, some of them are based on literature.

3.2. Research methods and data collection

The sub questions of this research are answered through the collection and analysis of data. Both quantitative and qualitative data are collected in order to answer these proposed questions. This section describes how this data is collected.

3.2.1. Open interviews

As part of this research project, several interviews were conducted with representatives of the case study. One semi-structured and two open interviews were conducted with these representatives, through an online environment. By conducting these interviews we have collected specific information on the case neighborhood which is used in the description of the case study.

3.2.2. Validation interviews

In this study, several decisions are made in regards to the scope of the research. In order to support the findings from the desk study, expert interviews were conducted to validate the findings. The first expert interview is held with an expert from a technical university in The Netherlands, in the field of decision-making in regards to the heat transition. This interview has helped in validating the selecting of decision-making factors that were considered in this research. The second interview is held with an expert from a technical university in The Netherlands that works in the energy transition of the built environment. This interview is used to validate the selection of heating strategies that were modelled as part of this research.

3.2.3. Life cycle costing approach

An economic assessment is performed through the use of a life cycle costing approach (LCC). In this assessment all costs that occur during the construction and use phase, including investment, operation, energy consumption and maintenance should be estimated. According to Dhillon (2009), LCC is a useful method when comparing the costs of competing projects or alternatives over their different lifetimes. In order to allow for calculations over the lifetime, an appropriate discount rate should be applied.

The data required for this assessment is obtained through desk study, which includes an exploration of data sources that are used by current decision-making tools that perform economic assessments. By making use of spreadsheet software Excel, the final LCC assessment is performed.

3.2.4. Life cycle assessment

The environmental assessment consists of a life cycle assessment (LCA). In this study, we follow the ISO 14040 framework for life cycle assessment (International Organization for Standardization, 2016). This means that the LCA consists of a goal and scope definition, an inventory analysis, an impact assessment and finally an interpretation of the results. The environmental impact of the alternative heating strategies are expressed in kilograms of CO2-equivalent, by making use of the ‘climate change’ impact category of the CML 2001 baseline characterization model (J. B. Guinée et al., 2002). By making use of the Ecoinvent 3.4 database, existing life cycle inventories and LCA’s on heating systems, and available online reports, the emissions over the life cycle can be collected. Additionally some processes are calculated through the use of CMLCA software. The outputs of the LCA are presented in a separate Excel file, which can be found in the supplementary material.

3.2.5. Assessment of other factors

Data for the assessment of the other decision-making factors that are included in the MCA; the reliability of experts, disruption during renovation, and occupation space, is collected by means of desk study. Publicly available empirical reports from previous heating strategy implementation projects and information from constructors and installation companies are consulted as part of this data collection.

We measure the reliability of experts by means of a proxy variable that measures the availability of experts, and we express this in a dummy-variable. The dummy-variable indicates whether or not there are enough experts available in the close proximity of the case study. This factor is measured by consulting different quality registers that include certified contractors.

Disruption during renovation is expressed in hours, by measuring the in-house installation times of all appliances and of the potential insulation measures that are required for each heating strategy. Online sources are consulted in order to collect information on these installation times.

The occupation space of installations is examined by measuring the volume of the specific installations that are required for each heating strategies. We consult online available reports to collect information on the average sizes of these installations.

The alternative heating strategies are assessed based on the provided information by the different data sources. By normalizing the values for each strategy, relative values are obtained that are used in the final MCA calculations.

3.2.6. Survey

In this study an online survey was carried out among the residents of the neighborhood. We used an online survey as conducting face-to-face interviews is very time intensive and not anonymous (Baarda & Kalmijn, 2010). The main advantage of conducting an online survey is the fact that the responses can be recorded anonymously and that responses are less sensitive to socially desirable answers (Baarda & Kalmijn, 2010). Additionally, by making use of an online survey, data can be collected from a larger sample.

Therefore, we prepared an online survey and forwarded this to the case representatives in the form of an anonymous link. The case representatives have forwarded the survey to the residents of the case neighborhood. In this way, there was no direct contact with the residents, and there was no collection of personal information from survey respondents.

The survey is used to obtain insight into the information sources that residents consult, what their current information levels are about energy renovation measures. Moreover, we look at the preferences of residents regarding alternative heating strategies.

3.2.7. Multi-criteria analysis

For the last part of this research, an MCA is performed. As described in the literature review, many ranking methods exist to express the importance of each of the selected criteria. As this study uses the preferences of the residents as judgements, a subjective ranking category is selected to derive the weights for the MCA. This study uses the Best-Worst Method (BWM), as developed by Rezaei (2015) to do so. The ranking of the criteria is performed based on the input of the residents, and supplementary literature. In this case, the survey respondents compares different decision-making factors, or 'criteria', by identifying the best and the worst criteria. Based on these responses and the supplementary literature, pairwise comparison matrices are constructed. These pairwise comparison matrices are then used to run a linear programming model which determines the optimal weights for the different criteria.

3.2.7.1. Best-Worst Method (BWM)

In the BWM, pairwise comparison for an *n* number of criteria is executed using a numeral scale from 1 to 9 (Rezaei, 2015). This results in a matrix (1) where a_{ij} shows the relative preference of criterion *i* to criterion *j.*

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \quad (1).$$

If a_{ij} = 1, criterion *i* and *j* are of equal importance. If a_{ij} > 1, criterion *i* is more important than factor *j*, with 9 being the most extreme importance of *i* to *j*. In order for the matrix to be reciprocal, a_{ij} needs to equal the inverse of a_{ji} (a_{ij} = 1/a_{ji}). Additionally, the diagonal of the matrix equals 1, for all *i* relative to *i* and all *j* relative to *j*.

In order to find the optimal weights, a linear programming model needs to be solved (Rezaei, 2016). The following model is implemented:

$$\min \xi^L$$
s.t.

$$|w_B - a_{Bj} w_j| \leq \xi^L, \text{for all } j$$

$$|w_j - a_{jW} w_W| \leq \xi^L, \text{for all } j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{for all } j$$

In this model, a_{Bj} is the preference of the best criterion *B* over criterion *j*, and a_{jW} is the preference of criterion *j* over the worst criteria *W*. Solving this model results in the optimal weights $(w_1^*, w_2^*, \dots, w_n^*)$ for each criterion. Finally, ξ^L can be considered as an indicator of consistency. When five criteria are considered, values of ξ^L lower than 0.2087 indicate a high consistency level (Liang, Brunelli, & Rezaei, 2019).

3.2.7.2. Normalization

In order to appropriately rank the alternative heating strategies, the results of the individual assessments need to be normalized. This is done to overcome the differences in scales (e.g. Euros, CO2-equivalent emissions and hours). By normalizing the individual assessment scores to values between 0 and 1, an equal scale is created, for which the scores can be multiplied by the calculated weights to obtain the final results. Normalization will be performed by making use of Equation 1:

$$x^{normalized} = \begin{cases} \frac{X - \min(x)}{\max(x) - \text{mi} \quad (x)}, for\ positive\ factors\ (high\ value\ of\ x\ is\ better) \\ 1 - \frac{X - \min(x)}{\max(x) - \min(x)}, for\ negative\ factors\ (low\ value\ of\ x\ is\ better) \end{cases} \quad (1).$$

For each individual assessment and representative dwelling, X represents the value that is normalized and min(x) and max(x) represent the minimum and maximum value of the analyzed heating strategies, respectively.

Chapter 4. Case study description

In this chapter, the case study is outlined. First the neighborhood is described and based on this description five representative dwellings are conceptualized. These representative dwellings are validated by representatives of the case neighborhood. Next, an overview of potential heating systems is presented. After this overview, a specific selection is made for options that could be applied in the case neighborhood, and that are considered in the modelling work of this thesis.

4.1. Neighborhood description

The case study focuses on a neighborhood in the Randstad, which is described using online sources. The Startanalyse (PBL, 2019a, 2019b) is the first consulted source. This is an interactive tool to visualize energy related issues in Dutch neighborhoods, based on data from both the Central Bureau of Statistics (CBS) and the *Basic register Addresses and Buildings (BAG)* (Kadaster, 2019). Additionally, it provides municipality reports with a variety of information on the neighborhood characteristics within each municipality. This tool is used to gather information like the dwelling typology and dwelling construction years. Additionally, data from the CBS is consulted to get an overview of the amount of addresses in the case neighborhood (CBS, 2019a). The final consulted source is the website of the network operator Liander (Liander, 2020), where data regarding the specific energy demand of the different dwellings in the neighborhood is consulted. This data is used to calculate the new energy demand for the dwellings under each alternative heating strategy.

4.1.1. Grid connections

The CBS classifies neighborhoods based on the density of addresses in the neighborhood, and expresses this in the degree of urbanity (CBS, 2019b). The case neighborhood can be classified as *highly urban* which indicates that there are 1,500 to 2,500 addresses per square kilometers (CBS, 2019a).

4.1.2. Construction year

The neighborhood has dwellings with different construction years, as consulted in (PBL, 2019a, 2019b). In general terms, some dwellings were built before 1965. The remaining dwellings were built after this year, and most of them, after 2005. We refer to these groups of dwellings as “old area” and “new area” of the neighborhood, respectively.

4.1.3. Dwelling typology

There are different types of dwellings in the neighborhood, as consulted in (PBL, 2019b). The old area consists mostly of terraced houses followed by semi-detached houses, and the new area, mostly of apartments followed by terraced houses. There are also some detached houses in the neighborhood.

4.1.4. Energy labels

In order to get a better understanding of the insulation level of dwellings, an indicator such as the energy label can be used. This energy label gives insight in the energy performance of a dwelling (RVO, 2020). Energy labels are obligated for dwellings that are sold, rented out, or newly constructed. As energy labels are only obligated in the previous mentioned occasions, many dwellings have not requested an energy label. In 2015, all homeowners without an energy label have received a preliminary energy label, based on the construction year (Milieucentraal, 2019a). This means that since 2015, every dwelling in the Netherlands either has a registered or preliminary energy label.

The neighborhood has a mix of energy labels (PBL, 2019a). Most dwellings have an energy label of B or higher, or E or lower. The former are mainly located and are mainly located in the new part of the neighborhood, and the latter, in the old part. Most of the other dwellings have an energy label of E or lower and are located in the old part of the neighborhood.

4.1.5. Conceptualizing representative dwellings

Based on the description of the neighborhood, a set of representative dwellings was conceptualized. The representative dwellings have features that are common in the neighborhood and are used as an example in this study. The set was validated with the case representatives. Below is the resulting set.

For the new area of the neighborhood, the following three representative dwellings were conceptualized:

- Apartment with energy label ≥ B.
- Terraced house with energy label ≥ B.
- Semi-detached / Terraced houses (corner) with energy label ≥ B.

For the old area of the neighborhood, the following two representative dwellings were conceptualized:

- Terraced houses with energy label ≤ E.
- Semi-detached / Terraced house (corner) with energy label ≤ E.

For this classification, we decide to group the semi-detached and cornered terraced houses together. The dwellings of these typologies have a similar surface area, similar architectural properties and similar energy consumption (CBS, 2018; NEN, 2012a, 2012b). As the average dwellings have similar properties and energy consumption, we expect that this has a limited effect on the modelling results.

4.1.6. Energy demand

Besides the energy label of a dwelling, dwelling characteristics also play a role in the amount of energy that is consumed. Network operator Liander provides an overview of the energy demands of different dwelling types, per construction year (Liander, 2020). The energy demands of Liander are presented for different household compositions. Based on the available data, the average energy demand for the representative dwellings is calculated by making use of Equation 2:

$$CD_j = \frac{\sum(AV\ _{1j}+AVG_{2j}+\ldots+AVG_{ij})}{i} \quad (2).$$

where CD = the current energy demand per dwelling type j, AVG = the average energy demand per household composition 1 to i, and i = the total amount of different household compositions included in the data.

Table 4 gives an overview of the annual electricity and natural gas demand of the representative dwellings.

Table 4 The assumed energy demand for the representative dwellings.

Energy demand	Terraced house (old)	Semi-detached & corner house (old)	Terraced house (new)	Semi-detached & corner house (new)	Apartment (new)	Source
Current electricity consumption (kWh)	3041	3570	3381	4000	2760	Liander (2020)
Current natural gas consumption (m3)	1756	2180	1256	1637	1059	Liander (2020)

4.2. Heating strategies

In Appendix B an overview is presented of those heating strategies that are applicable for all neighborhoods in The Netherlands in general. However, these options are not necessarily applicable in each neighborhood, as that depends on the availability of heating sources. Moreover, there might be potential restrictions in the use of certain heat sources in specific areas.

In order to select the heating strategies that could be applied to the case neighborhood, the Startanalyse, Vesta MAIS and Warmte Transitie Atlas (WTA) are consulted to see which heating sources these models consider for the case neighborhood. Based on these results, a selection is made of heating strategies that are used in the modelling part of this research.

This selection is validated in an interview with an expert from a Dutch technical university, that is specialized in the heat transition in the built environment. In the interview, we presented a list of heating strategies and based on the local conditions the expert gave feedback on which measures would be feasible and how they would be adapted. This feedback is integrated in the final selection of heating strategies.

4.2.1. Selected heating strategies

In Table 5, an overview is presented of the selected heating strategies. After this, each heating strategy is explained.

Table 5 Characteristics of the selected heating strategies.

Strategy	Heating source	Individual Installation	Insulation level	Collective installation
All-electric	Air	Individual heat pump + Low temperature-radiators	Renovate to label B	Electricity grid
Middle temperature district heating	Geothermal / Industrial residual heat	Connection to heating network	Renovate to label D	MT-district heating network
Low temperature district heating	Aqua thermal	Connection to heating network + Individual heat pump + Low temperature - radiators	Renovate to label B	LT-network
Renewable gas	Hybrid heat pump + green gas	Hybrid heat pump + Low temperature - radiators	Renovate to label B	Electricity and gas grid
Renewable gas	Hybrid heat pump + Hydrogen	Hybrid heat pump + Low temperature - radiators	Renovate to label B	Electricity and gas grid

Heating strategy 1: All-electric

In all-electric strategies, electric heat pumps are used to fill up the demand for space heating and hot tap water. The consulted models consider two main types of heat pumps: air-water and water-water heat pumps. In this heating strategy, dwellings should be renovated to at least energy label B.

According to the expert-interview, in practice, installing individual water-water heat pumps for every individual house in the case neighborhood would be very inefficient and costly. For this reason, according to the interviewed expert it would make more sense that dwellings will have individual air-water heat pumps. As the heat delivery within the dwelling is low temperature, appropriate radiators would need to be installed in the dwellings. Furthermore, the electricity grid, and individual connections to the grid would need to be reinforced.

Heating strategy 2: Middle temperature district heating

A district heating network that uses middle temperature (MT) heating sources could be constructed. These sources are defined as sources that supply heat at a temperature level of approximately 70°C, which is sufficient for the direct use of hot tap water and space heating (Hoogervorst et al., 2020). Examples of these type of sources include geothermal energy and industrial residual heat. If these heat sources are available in enough capacity in a neighborhood, they could be used locally. An alternative could be to transport the heat from a region with sufficient capacity.

Therefore, the second strategy is MT-district heating. According to the expert-interview, for heat supply at MT level (70˚C) an energy label of D is recommended, to lower the energy losses inside the dwelling.

Heating strategy 3: Low temperature district heating

The neighborhood could have access to low temperature (LT) heating sources. These source are defined as sources that supply heat that has an insufficient temperature in order to be used directly for hot tap water and often also needs to be adapted for space heating (Hoogervorst et al., 2020). Examples of these type of sources that could be applied in the case neighborhood include aquifer thermal energy storage (ATES), residual heat, surface water bodies, or aqua thermal heat from wastewater treatment plants (WWTP).

For this strategy and as an example, a low temperature aqua thermal source is selected as the LT-district heating source. An aqua thermal energy source would supply temperatures of approximately 17˚C. If such a source could consistently supply 11 MW of heat, as described in the Startanalyse (PBL, 2019b), it would be sufficient for the case neighborhood. Dwellings would then need individual heat pumps to heat up the supplied temperature to adequate temperature levels for space heating and hot tap water. Additionally, the electricity grid would need to be strengthened, and dwellings would need to be insulated to an energy label of B. This strategy would further require the installation of low-temperature radiators in the dwellings.

For simplicity, this research assumes that all apartments would also make use of an individual heat pump, as the total amount of apartments per building is unknown. If the amount of apartments per building was known, the capacity of a collective heat pump could be calculated based on the total heat demand of the building. However, since we do not know this, it is not possible to determine the capacity of a collective heat pump for these apartments.

Heating strategy 4 and 5: Renewable gas

There is high uncertainty about the availability of renewable gas in the future, and how much would become available for the built environment. Due to this uncertainty, the WTA does not consider renewable gas as a large-scale solution for the built environment (Over Morgen, 2018b). Vesta MAIS and the Startanalyse assume that by 2050, 2 bcm of green gas would be available for the Dutch built environment (Hoogervorst et al., 2020). This would be divided among back-up boilers for district heating and individual buildings. For individual buildings, this results in approximately 1.5 bcm green gas, which also be used in utility buildings. It is therefore likely that green gas only becomes a suitable option in neighborhoods where the costs of other strategies would be very high.

Based on the limited availability of green gas for individual dwellings, the choice is made to only consider a hybrid strategy in which the hybrid heat pump would take care of the usual demand. On cold days, an HR-boiler that uses renewable gas would make up for the increased heating demand. Instead of using green gas, hydrogen gas could also be considered as an energy carrier. Neither of the examined calculation models currently consider hydrogen in their heating strategies, as it is uncertain when hydrogen becomes available for usage in residential heating systems. However, recent reports from TNO and network operator STEDIN have indicated that hydrogen could potentially play a role in the built environment from 2030 onwards (van Groot Battavé, van Beek, & Bontenbal, 2020; Weeda & Niessink, 2020).

4.2.2. Excluded options

There are several heating strategies that could theoretically be applied in the case neighborhood, but that are not selected. By making use of a collective heat pump, an LT-heat source could be collectively heated to the MT-level of 70˚C. However, according to the expert-interview, this would not make much sense as it would be more efficient to keep the supplied temperature low and individually heat this up to prevent heat losses in the distribution.

Another option would be to collectively heat up the heating source to 50˚C, to be suitable for space heating. This strategy would require an additional booster heat pump to get hot tap water. According to the interviewed expert, keeping the supplied energy at a low temperature and individually heating it up with heat pumps would result in the lowest amount of energy losses during distribution. Thus, it was selected to keep the supplied heat at a low temperature for the LT-district heating strategy.

Moreover, if the heat could not be supplied consistently, a combination with an ATES would be required. This would make it possible to store heat in the ATES during the summer, and thus have more heat available in the winter. However, since we assume that the LT-heat could be supplied consistently, we do not consider this strategy in the modelling part of this thesis.

4.2.3. Insulation level of the dwellings

For most of the selected heating strategies, the interviewed expert suggested to insulate the dwelling to a minimum insulation level of B, in order to be efficient. As the representative dwellings in the newly built area already have an energy label of B or higher, there was no direct need for additional insulation measures. However, possibilities to further increase the insulation levels of these dwellings may lead to a further reduction of their energy demand.

For the old representative dwellings there would be need to insulate the dwellings in all of the selected heating strategies. An initial indication of the insulation level of these dwellings is collected through the knowledge platform Milieucentraal (2019b). On a website from Milieucentraal called verbeterjehuis.nl, it is possible to get insight in the average insulation levels of several type of dwellings (Milieucentraal, 2019b). This website then presents options to renovate the dwelling to improve the energy efficiency. We select several of these presented options to achieve an energy label of B in these dwellings:

- For the terraced houses, we assume that the dwelling will need to insulate their floors and roofs with 13-20 centimeters insulation material. Additionally, cavity wall insulation of 5-7 centimeters should be added, if it is not already there. The final step for insulation would be to replace the glass windows in the living room and bedrooms with HR++ glass. Taken together, these measures lead to an energy label of B.
- For semi-detached houses and corner terraced houses similar measures should be undertaken. These dwellings need to insulate the floor and roof with 13-20 centimeters of insulation material. Additionally, cavity wall insulation of 5-7 centimeters should be added, if this is not already there.

The final step for insulation would be to replace the glass windows in the living room and bedrooms with HR++ glass. However, this only gives these dwellings an energy label of C. To get to label B, triple glazing (HR+++ glass) can be installed instead of HR++ glass.

For the MT-district heating strategy, it is recommended to have an energy label of D. To achieve this for the dwellings, the following measures should be considered:

- For the terraced houses, we assume that the dwelling will need to insulate their roofs with 13-20 centimeters insulation material. The final step for insulation would be to replace the glass windows in the living room and bedrooms with HR++ glass. Taken together, these measures lead to an energy label of D.
- For semi-detached houses and corner terraced houses similar measures should be undertaken. These dwellings need to insulate the roof with 13-20 centimeters of insulation material. The next step for insulation would be to replace the glass windows in the living room and bedrooms with HR++ glass. Undertaking these measures only leads to an energy label of E, and is therefore not sufficient. Therefore, cavity wall insulation of 5-7 centimeters should be added, if this is not already there. This would lead to an average energy label of C for these type of dwellings.

4.2.4. New energy demand

As described in the previous section, insulation measures would have to be applied to the representative dwellings to improve the energy label, in each of the analyzed strategies. These insulation measures will lead to a decrease in the demand for space heating. Based on the thermal transmittance value of the applied measures, the theoretical energy savings can be calculated.

However, several scholars have identified that there is a performance gap between the theoretical energy savings and the actual energy savings (Filippidou, Nieboer, & Visscher, 2019; Majcen, Itard, & Visscher, 2013). In practice, energy-efficient dwellings consume more energy than is expected. Filippidou et al. (2019) have conducted a longitudinal data analysis with actual energy consumption data from Dutch households. In their analysis, these authors found that for different combinations of energy saving measures, different ratios of the mean actual savings and the predicted savings occurs. They found that in 2898 cases where a combination of insulation measures for roof, façade, floor and glazing were applied, the ratio between the mean actual and predicted savings was 0.40.

For the purpose of this thesis, the ratio between the mean actual savings and the predicted savings is assumed to be 0.40, based on the presented value in Filippidou et al. (2019). However, the energy performance gap is highly dependent on occupant behavior and that the ratio between the mean actual and predicted savings may differ in the per household of the case study.

The theoretical energy savings that the dwellings can achieve are calculated by making use of the *verbeterjehuis* tool of Milieucentraal (2019b). For the different representative dwellings, the current energy consumption was filled in according to the current energy demand of the dwellings. Then, the selected insulation measures are applied to get the dwellings either to energy label D, or energy label B. It turns out that the insulation measures have no influence on the electricity demand. Therefore, we assume that the electricity demand remains constant.

The presented new natural gas demand, for the two reference dwellings of the old area of the neighborhood, are adapted according to the energy performance gap ratio, in order to calculate the actual expected natural gas savings. The actual natural gas demand is calculated according to the formula as presented in Equation 3:

$$AD = CD - (CD - ND) * 0.40 \qquad (3).$$

where, AD = the actual natural gas demand (in m3), CD = the current natural gas demand before insulation (in m3), ND = the new natural gas demand according to *verbeterjehuis* (in m3).

The values for the actual electricity and natural gas demand that are used in the model are presented in Table 6. For each heating strategy, the actual heat demand is also calculated, by multiplying the actual natural gas demand with the lower heating value of natural gas. This resulted in the actual heat demand in MJ. Depending on the energy carrier that is used in each heating strategy, the final demands are calculated. An overview of the used electricity and heat demand that is used in each heating strategy can be found in Appendix C.

Table 6 Actual energy demand when the dwellings are insulated to energy label B, including induction cooking.

Dwelling type	Actual electricity demand (kWh)	Actual natural gas demand – Energy label D (m3)	Actual natural gas demand – Energy label B (m3)
Terraced house	3216	1436	1267
Semi-detached & corner house	3745	1634	1572

Chapter 5. Survey results

This chapter describes the findings from the survey. We use a survey to get insight into the information sources the residents of the case study consult, their current information levels, and their preferences regarding alternative heating strategies.

Additionally, the survey is also used to determine the relative importance of five decision-making factors that play a role in household decision-making in regard to alternative heating strategies. The survey responses are used to determine some sets of weights that are used in the final MCA calculations. An overview of all survey questions and a summary of the results is presented in Appendix A.

5.1. Target population

The population of interest for the survey were the residents from the case study, that were at least 18 years old, and that could make decisions regarding renovation of their dwellings. By agreeing with the opening statement of the survey, respondents confirmed that they were at least 18 years old and were able to make renovation decisions.

5.2. Sample size

The research sample consists of residents of the old area of the case neighborhood. These people are all homeowners and are thus able to make renovations to their dwellings. Note that since there are no respondents from the 'new' area of the neighborhood, results are not necessarily representative of the entire neighborhood.

5.3. Cleaning data

The survey had 35 responses. One of these responses was completely blank and was therefore marked as invalid and removed from the sample. The resulting 34 responses are equivalent to a response rate below 20%. Most of the respondents provided answers to all questions, but in some cases, some answers were left blank.

From the 34 respondents, two respondents indicated that they did not use natural gas to heat up their dwellings. The answers from these two respondents were excluded in the analysis of the survey, as this was not the group of interest for this research. This led to a sample size of 32.

Several answers were invalidated or had information removed. In some responses, question 14 and question 16 were incorrectly filled in. These responses either did not contain values within the required numerical range, or they identified the same factor as both the most important and the least important factor. A total of 16 responses were removed for this reason. Moreover, in question 6, one respondent filled in personal contact information. Following the data management plan, personal contact information was immediately deleted by the research team.

Note that respondents were able to leave questions unanswered and that the percentages in each question are based on the number of responses received for that particular question. Therefore, not all percentages are representative of the entire sample.

5.4. Representativeness of the sample

From the sample, about 71% of respondents stated that they are involved in the local sustainability project. This is an overrepresentation compared to the actual population in the old part of the neighborhood. In the old part of the neighborhood, only about 24% of the population is involved in the local sustainability project. Therefore there is a bias in the sample, as these people have already expressed their interests in sustainability issues by being involved in the local sustainability project.

Regarding types of dwellings, the sample resembled the neighborhood in that most respondents reported living in a terraced house, followed by respondents living in a semi-detached or detached house.

5.5. Information level

The results of the survey indicate that a large share of the residents did not yet conduct any research on alternative heating systems. Of the respondents from the project group, 44% have indicated that they did not conduct any research on alternative heating systems. In the non-project group, 56% of respondents have indicated that they did not conduct research on alternative heating systems. When asked if respondents have enough information to decide on implementing an alternative heating systems, a total of 68% of respondents stated that they did not have enough information to do so. For the respondents of the project group, this share was 78%. On the other hand, only 38% of respondents from this group state that they do not have enough information to make a decision.

When looking at insulation measures, 30% of respondents from the project group stated that they did not conduct any research on insulation measures. For the non-project group, this number is 14%. Even though 70% of respondents from the project group stated that they have conducted research on insulation measures, 50% of respondents from the project group did not agree with the statement that they have enough information to make a renovation decision regarding insulation measures. The respondents from the non-project group have indicated that they are either neutral, or agree that they have enough information to make a decision.

5.6. Opinions of residents

Within the survey, a specific question was asked to get a better understanding about the specific opinions of the case residents, towards alternative heating systems. The heating strategies that were included in this question are not limited to those that are used in this thesis. Heating strategies that use different heat sources based on geothermal energy and ATES, as described in Appendix B, were also included.

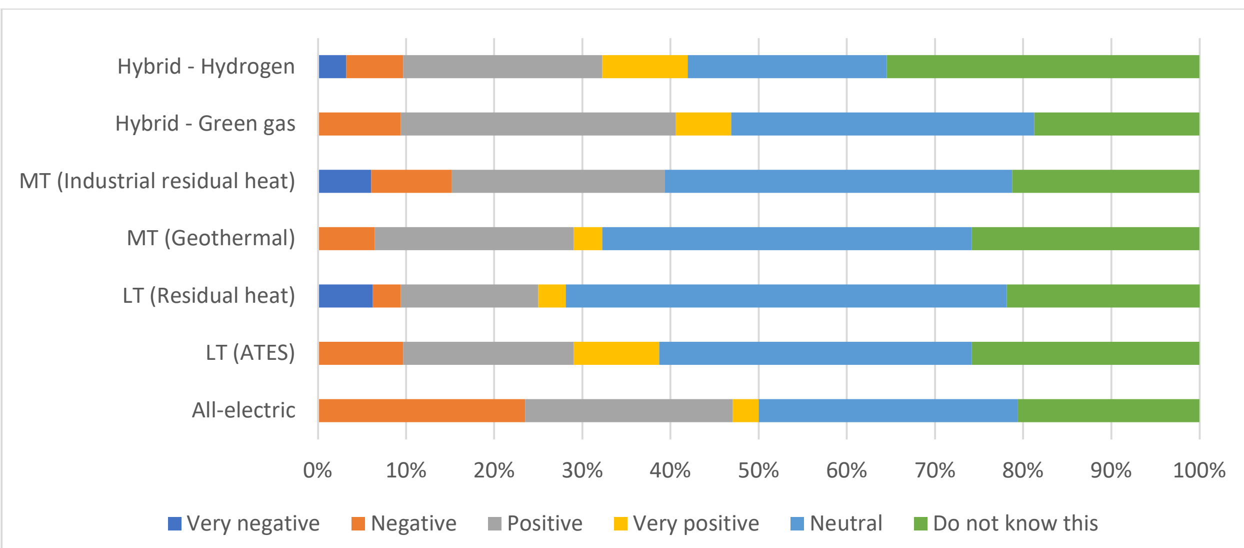

Figure 2 The opinion of respondents towards different heating strategies.

Figure 2 shows that over 50% of respondents report to be either neutral about all the heating strategies, or they do not know what these strategies entail. The all-electric strategy seems to be one of the strategies that is the least desired, as 24% of respondents stated that they have a negative opinion towards this strategy. The hybrid strategy with green gas is perceived as the strategy with the most positive opinion, as

39% of respondents stated that they have a positive opinion towards this strategy. Approximately 20-25% of the respondents do not know what these heating strategies entail. More respondents (approximately 35%) reported lack of knowledge for the hybrid-hydrogen strategy.

5.7. Importance of decision making factors

Participants in the survey were asked to state what factors they found the most and least important factors when they would make renovation decisions.

The survey results show that total costs was identified as the most important factor, by 65% of the respondents. CO2 emissions were mentioned in 19% of the responses. Occupation space was mentioned by 10% of respondents as the most important factor. Reliable experts and disruption during renovation were mentioned by 3% of the respondents.

Disruption during renovation was perceived as the least important factor, by 48% of the respondents. Reliable experts was selected by 16% of the respondents. Total costs and occupation space were selected by 13% of the respondents. CO2 emissions was selected by 10% of the respondents.

5.8. Conclusion

Due to the small sample size, it is not possible to draw general conclusions for the neighborhood. However, the following observations are made for the sample. Results suggest that residents that are part of the project group might need more information in order to make a decision. Moreover, in regards to the opinion of the residents, the results show that a large amount of respondents is neutral about the various heating strategies. Another considerable share of respondents did not state their opinion as they did not know the mentioned heating strategies. Therefore, it is hard to draw any conclusions on the preferences for one heating strategy over the other.

In the survey, respondents were not asked to motivate their response. Therefore it is not possible to get a better understanding of what the motivations are behind their responses. Further research could look into the specific motivations behind the opinions of respondents towards the different heating strategies.

From the results on the importance of decision-making factors can be concluded that total costs is perceived as the most important factor, followed by CO2 emissions. For the least important factor, a wider variety of answers was presented. Based on the responses, it can be stated that disruption during renovation is perceived as the least important factor, followed by reliable experts, occupation space and total costs.

To generalize any observations to the neighborhood, a more extensive study would be necessary.

Chapter 6. Individual assessments

In this chapter, the individual assessment models are described. In the first section, we describe the LCC model. In the second section, the LCA model is described. Next, we describe the assessment of the amount of disruption during renovation. Fourth, the occupational space that is required for each heating strategy is described. Finally, we describe the assessment of the reliability of experts by examining the availability of certified contractors. The results from each of these individual assessment are used in the final MCA calculations, of which the results are presented in Chapter 7.

6.1. Life cycle costing approach

An LCC approach is used to assess the costs of the alternative heating strategies over the lifetime. By conducting an LCC, insights are obtained in the total costs of each heating strategy. These results are then used to represent the total costs decision-making factor in the final MCA calculations.

According to Hastings (2015), LCC can assist in making acquisition decisions by considering the life cycle costs of different options. Besides initial investment costs, LCC gives attention to matters like operating costs, product lifetimes, maintenance and consumables (Hastings, 2015).

In this study, the life cycle costs are calculated according to Equation 4:

$$LCC = C_I - S + C_M + C_O + C_R \quad (4),$$

where LCC = the total life cycle costs of the applied heating strategy, C_I = initial investment costs, S = available subsidies, C_M = costs of maintenance, C_O = costs of operation and C_R = costs of replacing and disposing.

The life cycle costs will be calculated over a time period of 30 years, starting in 2021. By calculating the net present value (NPV) of the life cycle costs, insight can be obtained about the present value of the total investments for the heating strategies, while accounting for available subsidies. In this study, a distinction is made between the costs that are relevant for the end-users (the households within the case neighborhood) per type of dwelling, and the life cycle costs that occur due to the changes in the energy network (i.e. natural gas pipelines, electricity network and district heating networks). The LCC results for the end-users are used in the MCA calculations.

6.1.1 Discounting

Discount rates are often used in economic assessments, including LCC, to determine the present value of future cash flows. They are used to account for the time value of money, to prevent wrong valuation of cash flows over time. According to Van den Boomen, Schoenmaker, Verlaan, and Wolfert (2017), discount rates are commonly misinterpreted, and in order to perform and appropriate LCC analysis, an accurate discount rate should be applied. In this study, we also apply a discount rate to calculate the end-user costs.

The heat transition requires public infrastructure projects, as it involves adaptations to the public infrastructure such as the natural gas and electricity grids. For public infrastructural projects, discount rates are recommended in the range of 3% to 5%, with a recommended societal discount rate of 4.5% specifically for public infrastructure projects (Werkgroep discontovoet, 2015, p. 56). For private investments from households, a standard discount rate of 3.05% is recommended by the Werkgroep discontovoet (2015, pp. 79-82).

In line with the recommendations of the Werkgroep discontovoet (2015), this LCC uses a discount rate of 3.05% to calculate the end-user costs. Additionally, a scenario analysis is performed in which the discount rate is changed to represent the societal discount rate of 4.5%. Furthermore, this study assumes that consumer prices remain constant.

6.1.2 Lifetime of installations and infrastructure

For the different heating strategies, different installations and network infrastructure are required. It is important to note that there is a difference in the product lifetimes of these installations and networks (Table 7). Thus, over the analyzed life cycle period of 30 years, replacement of (parts) of these installations and networks may be required.

Table 7 The related life times of the analyzed installations and infrastructure.

Product	Lifetime (years)	Source
High efficiency boiler	15	(CE Delft, 2018b)
Heat pump	15	(CE Delft, 2018b)
Hybrid heat pump	15	(CE Delft, 2018b)
LT-Emitting system	30	(CE Delft, 2018b)
HT/MT-Emitting system	30	(CE Delft, 2018b)
Induction cooking system*	15	(CE Delft, 2018a)
Insulation measures	30-50	(AGC Glass Europe, 2013; Warmerhuis, 2019)
District heating network	50	(Bartolozzi, Rizzi, & Frey, 2017)
Natural gas distribution network	50	(Oliver-Solà, Gabarrell, & Rieradevall, 2009a)
Electricity distribution network	70-80	(Jones & McManus, 2010)

* For each of the analyzed strategies, it is assumed that cooking systems will be replaced by induction cooking systems as an increasing amount of households makes a switch to these systems (CE Delft, 2018a).

For all of the different strategies, we assume that at the starting year, all current installations are replaced with the installations that are required for the heating strategy. Furthermore, for each strategy, the heat emitting system of the dwelling are replaced by either LT- or MT-radiators. We also assume that all dwellings replace their natural gas fired cooking system with an induction cooking system, at the start of the analysis. For dwellings with induction cooking systems, it is recommended to upgrade to a 3x25A connection (CE Delft, 2018a). Thus, for each strategy an upgraded electricity connection is considered.

6.1.3. Energy carriers

This section explains the prices for the different energy carriers that were used in the model. An overview of the applied prices is presented in Table 8. In this model, we do not decouple taxes and energy prices. Taxes and energy prices are modelled together, similar to how end-user costs are calculated in the Vesta MAIS model (Schepers et al., 2019, pp. 114-117).

Natural gas

In the LCC, the current average price for the end-user of 0.0965 €/kWh is used (Eurostat, 2020b). It is uncertain how this price will develop over the near future. However, as taxes on natural gas are rising (Rijksoverheid, 2020), it is expected that the natural gas prices for end-users will rise over the upcoming years. Therefore, an annual growth rate of 3% of the natural gas price is included in the model, in line with the expected growth rate of Milieucentraal (2020b).

Electricity

The current average end-user price for electricity of 0.2055 €/kWh (Eurostat, 2020a) is applied at the starting year of the analysis. We assume that electricity prices for end-users are rising as network operation costs are expected to rise due to increased maintenance of the networks (NOS, 2019), and potential removal of gas grids, or implementation of infrastructure for heating networks. Therefore, an annual growth rate of 2% of the electricity price is included in the model, in line with the expected growth rate of Milieucentraal (2020b).

Green gas

There is a lot of uncertainty about the availability of green gas for residential gas networks (Hoogervorst et al., 2020, pp. 49-50). This uncertainty about the availability also leads to an uncertainty about the price developments of green gas. In this study, we base the end-user price of green gas on the expected price from Hoogervorst et al. (2020, p. 57). We assume that green gas becomes available for the end-users in 2030, for a price of 1.03 EUR/m3.

Hydrogen

There is a lot of uncertainty about the costs and availability of hydrogen. Similar to green gas, we assume that green hydrogen becomes available for use in residential gas networks in 2030. Production costs for green hydrogen are estimated in the range of 2-4 EUR/kg (IEA, 2019; van Wijk & Hellinga, 2018; Weeda & Niessink, 2020). These costs exclude taxes and distribution and network operation costs. To overcome the uncertainty of the projected price developments, in this study, two price scenarios are considered. In the first scenario, hydrogen becomes available for a competitive final price of 3.5 EUR/kg.

In the second scenario, hydrogen becomes available for a non-competitive final price of 4.5 EUR/kg. In the LCC calculations, both of these values are considered and results are presented for both price development scenarios.

District heat

The maximum price that energy suppliers can charge for district heating is decided by the *Authority for Consumers and Markets* (ACM, 2020). Besides deciding on maximum tariffs for connecting to existing and new district heating networks, ACM also decides on the maximum tariffs for the price per GJ of consumed energy. This maximum price is set at 26.06 EUR/GJ (ACM, 2020).

The heat tariff is currently linked to the price of natural gas. However, there are recent developments that are looking into uncoupling the price of heat tariffs from the gas price. Yet, it is uncertain when this will happen, and how this will influence the price of heat in heat networks (Wiebes, 2019). Due to this uncertainty, we assume that the price of heat remains constant over the course of the analysis.

Table 8 Overview of the estimated prices that are applied in the LCC.

Energy carrier	Price (EUR/kWh)	Growth rate (%)	Source
Natural gas	0.0965	3	(Eurostat, 2020b)
Electricity	0.2055	2	(Eurostat, 2020a)
Green gas	0.11716	-	(Hoogervorst et al., 2020)
Hydrogen gas	0.104132 (Competitive)	-	(IEA, 2019; van Groot Battavé et al., 2020; van

	0.133884 (Non-Competitive)		Wijk & Hellinga, 2018; Weeda & Niessink, 2020)
District heat	0.093816	-	(ACM, 2020)

6.1.4. Insulation packages

The old representative dwellings are insulated to either energy label D or energy label B, depending on the selected heating strategy. The amount of insulation material that is required to perform the appropriate measures for each strategy is based on the standard sizes of Dutch dwellings, for different construction years (Agentschap NL, 2011). We assume that the corner terraced houses have similar surface areas as semi-detached dwellings.

When replacing windows with triple glazing, window frames need to be replaced as well (Duuzaam Bouwloket, 2020). The costs for the windows including the window frames are calculated based on the assumption that the total window frame area is 25% of the total glass window area (ISSO, 2015). Table 9 presents an overview of the different surface areas.

Table 9 Standard size of Dutch dwellings, per type (Based on (Agentschap NL, 2011; ISSO, 2015)).

	Terraced house	**Terraced house (corner) & Semi-detached**	**Unit**
Average flat roof area	-	15.4	m^2
Average tilted roof area	57.3	63.7	m^2
Average facade area	42.3	97.8	m^2
Average floor area	47	66	m^2
Average window area	21.4	26	m^2
Average window frame area	5.35	6.5	m^2

The costs for the different insulation measures are calculated based on average market prices per square meter (Duuzaam Bouwloket, 2020; Slimster, 2020a, 2020b, 2020c, 2020d). Currently, as the Dutch government is stimulating homeowners to undertake energy efficient measures in their dwellings, a subsidy is available for the insulation of dwellings. Since 2019, Dutch homeowners can get a subsidy if they implement at least two insulation measures. This subsidy is called the *Subsidie Energiebesparing Eigen Huis (SEEH)* (RVO, 2019b). By making use of a tool of RVO (2019b), homeowners can calculate the amount of subsidy they can receive, based on the surface areas of the different parts of their dwelling. Table 10 presents an overview of the projected costs for the different insulation measures, and the energy label that was achieved with these measures.

Table 10 Costs of insulation measures, per dwelling type and required energy label.

	Terraced house	**Terraced house**	**Terraced house (corner) & Semi-detached**	**Terraced house (corner) & Semi-detached**
	Label D	*Label B*	*Label D*	*Label B*
Inner roof insulation costs	€ 2,005.50	€ 2,005.50	€ 2,768.50	€ 2,768.50
Cavity wall insulation	-	€ 846	€ 1,956	€ 1,956

Floor insulation	-	€ 1,880	-	€ 2,640
HR++ glass costs	€ 3,103	€ 3,103	€ 3,770	-
HR+++ glass costs	-	-	-	€ 6,240
Total without subsidies	€ 5,108.50	€ 7,834.50	€ 8,494.50	€ 13,604.50
Available subsidies (RVO, 2019b)	€ 1,895	€ 2,436	€ 2,981	€ 5,133
Total	**€ 3,213.50**	**€ 5,398.50**	**€ 5,513.50**	**€ 8,471.50**

6.1.5. Thermal capacity of heating installations

In this study, we assume that the different dwelling types all make use of heating installations with similar capacities. The high efficiency condensing boilers that were applied in the reference strategy and the hybrid strategies have a capacity of 24 kW. A boiler with this capacity has a CW value of 4 (CE Delft, 2018b, p. 6). The CW value represent the amount of hot water that can be delivered per minute. Boilers with a CW value of 4 are the current standard for (re)placement of boilers in dwellings (Vattenfall, 2019, p. 3).

According to (RVO, 2014), the standard capacity of a heat pump for a well-insulated average dwelling is around 5 kW. We assume that a heat pump with capacity of 5 kW is applied in the LT-district heating strategy. For the hybrid strategies, a heat pump with a capacity of 4 kW should be sufficient, as the high efficiency-boiler takes care of the peak demand. For the all-electric strategy, a heat pump of 6 kW is considered in the model, due to the lower seasonal performance factor (i.e. the efficiency) compared to the heat pump in the LT-district heating strategy (Hoogervorst et al., 2020).

6.1.6. End-user costs

The final data for the LCC, as well as all sources and modelling decisions can be found in the supplementary material. This section describes the costs that are made by the residents of the representative dwellings.

Figure 3 shows that the initial investment costs in the older representative dwellings are significantly higher than in the newer representative dwellings. This is due to the insulation measures that need to be undertaken in these strategies. Figure 3 also shows that the initial investment costs of the LT-district heating strategy are the highest for each dwelling type. The difference between the investment costs for the other low temperature strategies (all-electric and hybrid), is mainly caused by the costs of connecting to a district heating network. The model assumes that the heat supplier will charge the maximum price for each connection, according to ACM (2020) regulations.

However, when district heating networks are constructed it can happen that the project operator demands a one-time connection fee, additional to the price of connecting to the network (Bouwmeester, 2019). For these connection fees, these is no unambiguous price range and connection fees seem to vary between projects. Based on a survey performed by platform *Zeer Energiezuinige Nieuwbouw (ZEN)*, total connection costs, including the ACM maximum connection fees can go up to a €9508.89. As this fee is dependent on the specific type of project, this cost factor is not accounted for in LCC calculations. However, to illustrate the effect that these additional costs may have on the investment costs, Figure 3 provides margins to which extent the investment costs for the district heating strategies may increase. Since the model assumed that the maximum connection price, according to ACM (2020), is charged for individual connections the additional project fee could go up with approximately €5,000.

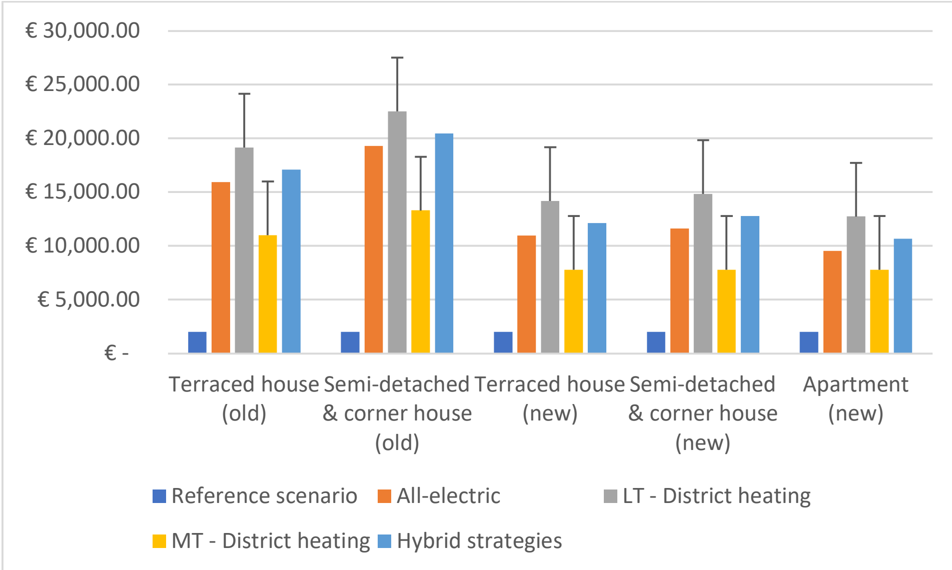

Figure 3 Initial investment costs per heating strategy.

The results of the NPV calculations are presented in Table 11. This table shows the NPV of the life cycle costs that were made by the end-users, over a period of 30 years. The results show that the all-electric strategy has the lowest NPV for each dwelling type. Furthermore, semi-detached and corner houses show the highest NPVs for each strategy. This is due to the fact that the energy consumption in these dwelling types is higher, and thus more costs are made during operation. Additionally, the old semi-detached and corner houses have to make additional investment costs, due to insulation of these dwellings to either energy label D or label B. A visualization of the NPVs of the different heating strategies is presented in Figure 4.

Table 11 Net present value of the end-user costs.

	Terraced house (old)	**Semi-detached & corner house (old)**	**Terraced house (new)**	**Semi-detached & corner house (new)**	**Apartment (new)**
Reference strategy	€ 69,410.10	€ 82,956.23	€ 58,594.70	€ 69,505.70	€ 50,297.41
All-electric	€ 56,750.95	€ 66,695.39	€ 53,012.61	€ 61,646.63	€ 45,510.68
LT - District heating	€ 61,903.26	€ 71,426.08	€ 58,230.68	€ 66,339.86	€ 51,001.01
MT - District heating	€ 65,940.76	€ 74,343.12	€ 60,956.35	€ 70,551.81	€ 54,060.98
Hybrid - Green gas	€ 61,786.62	€ 72,516.83	€ 57,925.73	€ 67,537.87	€ 50,234.40
Hybrid - Hydrogen - C	€ 62,478.65	€ 73,019.03	€ 58,647.37	€ 68,023.20	€ 51,078.62
Hybrid - Hydrogen - NC	€ 65,177.19	€ 76,368.04	€ 61,244.45	€ 71,430.01	€ 53,255.67

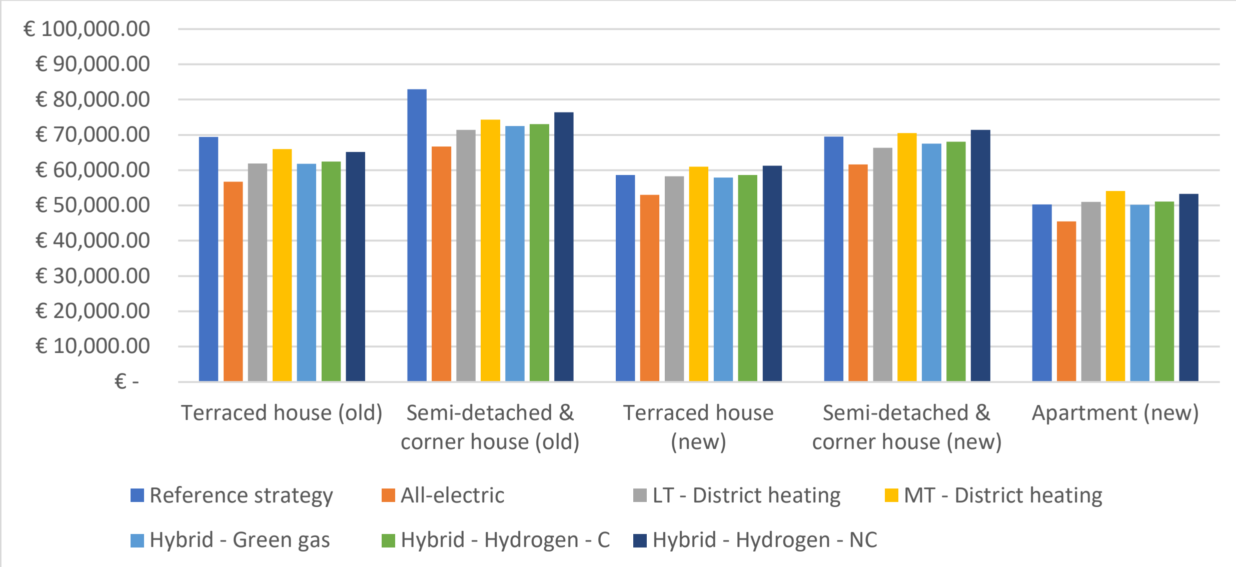

Figure 4 Net present values for the representative dwellings per heating strategy.

It can be observed from the results that the all-electric strategy results in the lowest NPV for each dwelling type. In the dwellings from the old area, the reference strategy results in the highest NPV, whereas for the dwellings of the new area, the non-competitive hydrogen strategy results in the highest NPVs, followed by the MT-district heating strategy. Table 12 illustrates how the different heating strategies perform, respective to the alternative with the lowest NPV.

Table 12 Respective increase of the NPV of the different heating strategies, compared to the all-electric strategy.

	Terraced house (old)	**Semi-detached & corner house (old)**	**Terraced house (new)**	**Semi-detached & corner house (new)**	**Apartment (new)**
Reference strategy	+22%	+24%	+11%	+13%	+11%
All-electric	0%	0%	0%	0%	0%
LT - District heating	+9%	+7%	+10%	+8%	+12%
MT - District heating	+16%	+11%	+15%	+14%	+19%
Hybrid - Green gas	+9%	+9%	+9%	+10%	+10%
Hybrid - Hydrogen - C	+10%	+9%	+11%	+10%	+12%
Hybrid - Hydrogen - NC	+15%	+15%	+16%	+16%	+17%

6.1.7. Scenario analysis

This study does not seek to present only one specific outcome. As future prices are uncertain, it is not possible to provide any definite results. Therefore a scenario analysis is performed, to demonstrate the effect that certain variables have on the final outcomes of the LCA. By applying different discount rates, growth rates for electricity and natural gas prices, different potential future scenarios are analyzed. Afterwards, these scenarios are compared to the LCC baseline scenario.

We define the LCC baseline scenario as the scenario that contained the standard values that were applied in the LCC calculations as presented in the previous sections. An overview of these values, and the different values that are used in the scenarios is presented in Table 13.

Table 13 Applied LCC scenarios.

Scenario	**Discount rate**	**Growth rate electricity price**	**Growth rate natural gas price**
Baseline scenario	3.05%	2%	3%
Discount rate	4.5%	2%	3%
Natural gas price	3.05%	2%	5%
Electricity price	3.05%	0%	3%

6.1.7.1. Discount rate

The LCC calculates the present value of the cash flows over a period of 30 years. Due to this long time period, an increase or decrease in the applied discount rate could result in relatively large differences between future cash flows. To demonstrate this effect, Figure 5 visualizes the results of the LCC when a societal discount rate of 4.5% is applied (Werkgroep discontovoet, 2015). The growth rate of the electricity and natural gas prices are 2% and 3% respectively, in line with the baseline scenario.

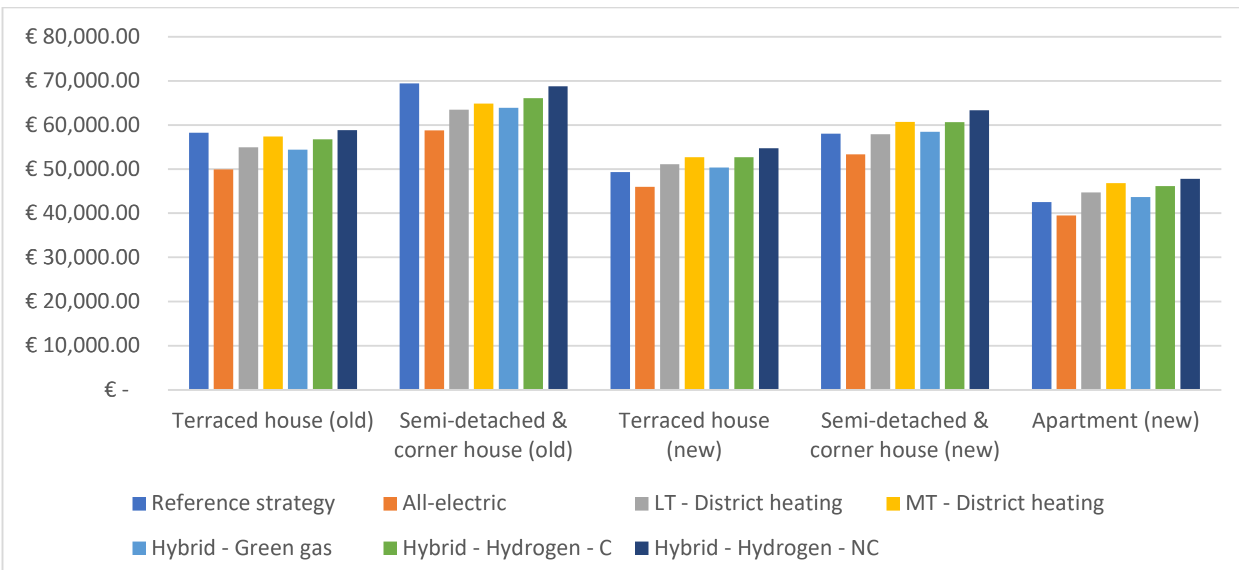

Figure 5 NPVs for the different heating strategies, when a discount rate of 4.5% is applied.

Figure 5 shows that increasing the discount rate leads to lower NPVs for the different heating strategies. Additionally, the higher the NPVs of the heating strategies in the baseline scenario, the more they are affected by an increased discount rate. As energy consumption has a significant contribution to the overall costs over a lifetime of 30 years, strategies that consume the highest amounts of energy, like the reference strategy, show the highest reduction of overall costs.

Furthermore, it is observed that the all-electric strategy remains the strategy with the lowest NPV for all dwelling types. For the older dwellings, the reference strategy remains the strategy that comes with the highest NPV. For the newer dwellings, the non-competitive hydrogen strategy remains as the strategy with the highest NPV. An overview of how the ranking of all of the strategies with respect to each other, compared to the baseline scenario, changes is presented in Appendix D. Furthermore, Table 14 presents an overview of the percentual difference between the increased discount rate scenario and the baseline scenario.

Table 14 The percentual difference between the NPVs for the heating strategies of the scenario, compared with the baseline.

Percentual difference	Terraced house (old)	Semi-detached & corner house (old)	Terraced house (new)	Semi-detached & corner house (new)	Apartment (new)
Reference strategy	-16.1%	-16.3%	-15.8%	-16.5%	-15.5%
All-electric	-12.0%	-11.9%	-13.2%	-13.6%	-13.3%
LT - District heating	-11.3%	-11.2%	-12.3%	-12.7%	-12.3%
MT - District heating	-13.0%	-12.8%	-13.6%	-13.9%	-13.4%
Hybrid - Green gas	-12.0%	-11.9%	-13.1%	-13.4%	-13.1%
Hybrid - Hydrogen - C	-9.2%	-9.5%	-10.2%	-10.8%	-9.7%
Hybrid - Hydrogen - NC	-9.7%	-10.0%	-10.6%	-11.4%	-10.2%

6.1.7.2. Natural gas prices

To demonstrate the effect of natural gas prices on the final NPVs, this scenario considers an annual natural gas growth rate of 5%. The discount rate and electricity price rate are similar compared to the baseline scenario. Figure 6 visualizes the NPVs for the different heating strategies.

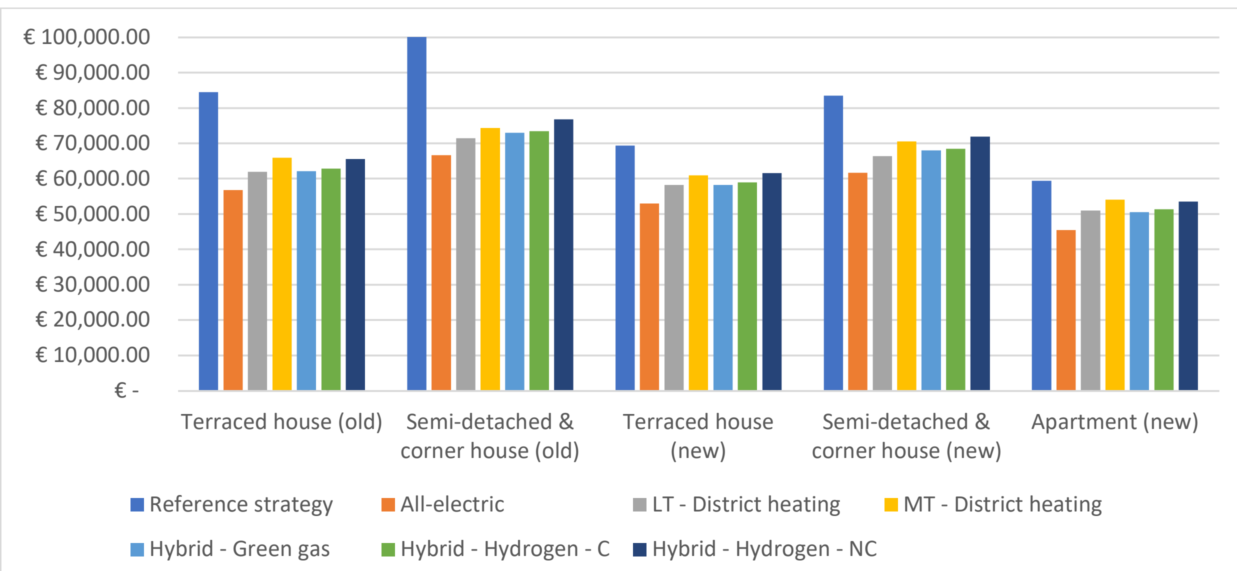

Figure 6 NPVs for the different heating strategies when annual natural gas prices are increasing with 5%.

It is concluded that when the natural gas price increases with a higher rate, the reference strategy is significantly impacted, as the NPVs increases with approximately 18 to 23%, depending on the dwelling type (Table 15). The only other strategies that are affected by an increase in natural gas price are the hybrid strategies, as they are assumed to keep using natural gas in peak demand hours, up to 2030. Though, as these strategies are primarily using electricity for their heat demand, the impact is not as significant as for the reference strategy. The NPVs of the hybrid strategies are increasing with less than 1% in this scenario.

This is due to the fact that the hybrid strategies only make use of natural gas in peak demand hours, up until 2030. Thus, the growing natural gas prices only affects them for a short period of time, for a reduced amount of natural gas.

Figure 6 shows that the all-electric strategy still has the lowest NPV for each dwelling type. The reference strategy has the highest NPV for all dwelling types in this scenario. An overview of how the ranking of all of the strategies with respect to each other, compared to the baseline scenario, changes is presented in Appendix D.

Table 15 The percentual differences between the increasing natural gas price scenario and the baseline.

Percentual difference	**Terraced house (old)**	**Semi-detached & corner house (old)**	**Terraced house (new)**	**Semi-detached & corner house (new)**	**Apartment (new)**
Reference strategy	+21.7%	+22.5%	+18.4%	+20.2%	+18.0%
All-electric	0.0%	0.0%	0.0%	0.0%	0.0%
LT - District heating	0.0%	0.0%	0.0%	0.0%	0.0%
MT - District heating	0.0%	0.0%	0.0%	0.0%	0.0%
Hybrid - Green gas	+0.6%	+0.6%	+0.6%	+0.7%	+0.6%
Hybrid - Hydrogen - C	+0.6%	+0.6%	+0.6%	+0.7%	+0.6%
Hybrid - Hydrogen - NC	+0.5%	+0.6%	+0.6%	+0.6%	+0.5%

6.1.7.2. Electricity prices

To demonstrate the effect of electricity prices on the final NPVs, this scenario considers a scenario in which electricity prices would not increase. The discount rate and natural gas price rate are similar compared to the baseline scenario. Figure 7 visualizes the NPVs of each heating strategy for the representative dwellings.

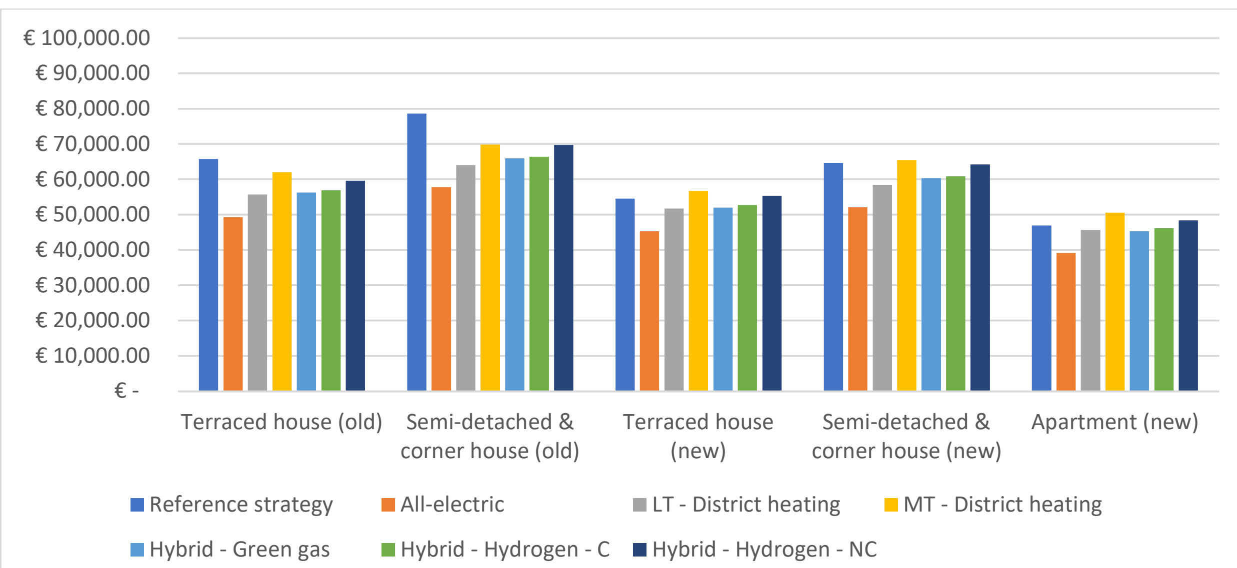

Figure 7 The NPVs for the different heating strategies when electricity prices remain constant.

Figure 7 demonstrates that when electricity prices remain constant, the strategies that consume the most electricity are affected the most. For the all-electric heating strategy, which has a relatively high electricity demand, the NPVs are reduced with approximately 13.1 to 15.5%, depending on the dwelling type (Table 16). Table 16 shows that when electricity prices remain constant, strategies that primarily use electricity to heat up the dwellings are affected the most. The results show that all-electric remains the strategy with the lowest NPV for each dwelling type. For the new dwellings, the MT-district heating strategy becomes the strategy with the highest NPV, instead of the non-competitive hydrogen strategy in the baseline scenario. An overview of how the ranking of all of the strategies with respect to each other, compared to the baseline scenario, changes is presented in Appendix D.

Table 16 The percentual differences between the constant electricity price scenario and the baseline scenario.

Percentual difference	Terraced house (old)	Semi-detached & corner house (old)	Terraced house (new)	Semi-detached & corner house (new)	Apartment (new)
Reference strategy	-5.3%	-5.2%	-7.0%	-7.0%	-6.6%
All-electric	-13.1%	-13.4%	-14.6%	-15.5%	-14.1%
LT - District heating	-10.0%	-10.3%	-11.2%	-12.0%	-10.6%
MT - District heating	-5.9%	-6.1%	-7.1%	-7.2%	-6.6%
Hybrid - Green gas	-8.5%	-8.5%	-9.6%	-10.0%	-9.2%
Hybrid - Hydrogen - C	-8.4%	-8.5%	-9.5%	-9.9%	-9.1%
Hybrid - Hydrogen - NC	-8.6%	-8.7%	-9.7%	-10.1%	-9.2%

6.1.8. Network operation costs

This section illustrates the additional network costs that could be generated when a specific heating strategy is implemented in the case neighborhood. Maintenance costs of the infrastructure are included in the energy prices that consumers pay and are therefore not considered in this overview of network operation costs. The costs calculations are not considered in the MCA calculations, but are merely used to demonstrate that when the whole neighborhood changes to an alternative heating strategy, changes in the energy networks are required which could potentially result in additional costs for the residents.

6.1.8.1. All-electric

In the all-electric strategy, the natural gas grid is removed, as natural gas will no longer be used. Moreover, the electricity grid needs to be reinforced, to account for the increased energy demand in the neighborhood. Data on the length of the natural gas network and the electricity network is taken from Liander (2019). The costs for removal of the natural gas network, and the costs for reinforcing the electricity grid are taken from Schepers et al. (2019). Finally, it is assumed that the capacity of the medium voltage spaces in the neighborhood doubles, to ensure enough grid capacity.

6.1.8.2. District heating

In both the LT- and MT-district heating strategies, the natural gas grid is removed. For the LT-strategy the electricity grid needs to be strengthened. Additionally, three new medium voltage spaces are placed, one less than for the all-electric strategy, as the final electricity demand is lower.

Besides these changes to the conventional energy network, a new district heating network is constructed for both the LT- and MT-strategies. The length of district heating networks is depended on the amount of connections. In a study by Van den Ende (2018), an economic model for district heating network costs is presented. This model assumed an average network length of 15 meters per connection. Based on this, this study also assumes a network length of 15 meters per connection. For illustrative purposes, it was assumed that there are 1,100 network connections in the neighborhood. However, for a detailed calculation, the actual number of connections in the neighborhood would have to be used.

For the LT-district heating strategy an additional transport infrastructure length of 500 meter is assumed, to connect the district heating network to the residual heat source. For the MT-district heating strategy, an additional transport infrastructure length of 2,500 meter is assumed, as the supplied MT-heat is assumed to come from outside the case study area.

In both strategies, additional costs are made for placing heat stations, substations, connecting to the residual heat sources itself, and constructing secondary infrastructure. These costs are calculated based on data that is used in Van den Ende (2018). For an overview of the variables that are used in the costs calculations, please consult the supplementary material.

6.1.8.3. Hybrid strategies

In both hybrid heating strategies, the natural gas grid is removed, and the electricity grid is strengthened. Additionally, three new medium voltage spaces are placed, one less than for the all-electric strategy, as the final electricity demand is lower. For the green gas strategy, the natural gas grid is adjusted to ensure that it is suitable for green gas transport. Data for the adjustment costs are collected from Hoogervorst et al. (2020, p. 42). For the hydrogen gas strategy, the natural gas grid is adjusted to ensure that it is suitable for hydrogen gas transport. Data for the adjustment costs are collected from Weeda and Niessink (2020, p. 20).

6.1.8.4. Results

Figure 8 shows the calculated additional network operation costs, compared to the reference strategy. The results show that the construction of district heating networks comes with high additional costs. However, the calculations of the district heating network costs depend on assumptions about the length of the network. In practice, the length of the network may be different, as the density of dwellings across the neighborhood also plays a key role in the final length of the network. Future research should be performed to determine the size of the actual network length.

In the calculation of the LCC for the end-users, the costs for constructing the district heating network are not considered. However, in many cases, the construction costs of the heating networks are eventually charged to end-users as well (Vereniging Eigen Huis, 2019). Therefore, it is likely that the LT- and MT-district heating strategies will result with an extra cost component for the end-users, which will increase the related NPVs for these strategies.

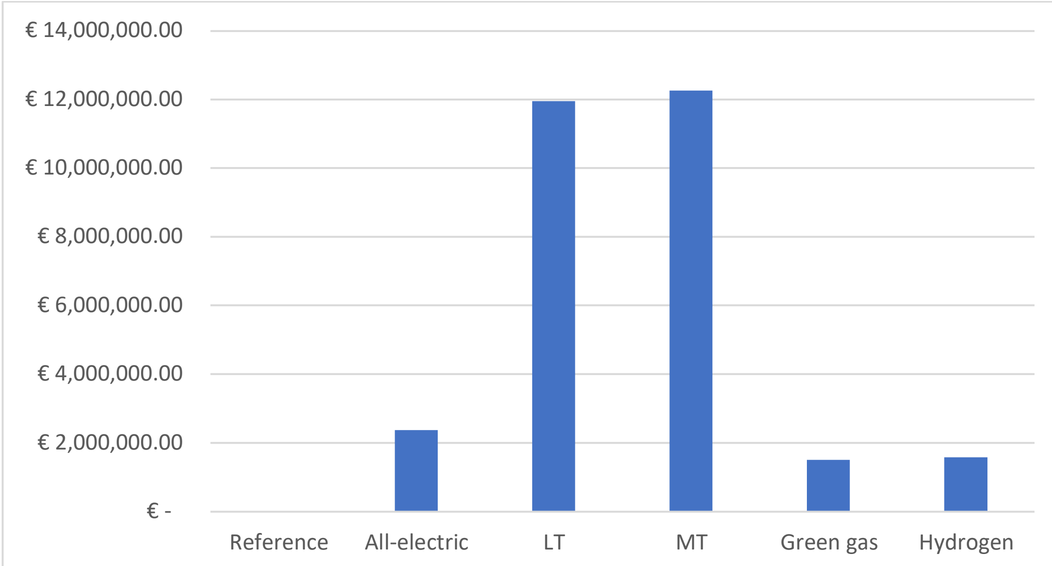

Figure 8 Additional network operation costs, compared to the reference strategy.

6.1.9. Discussion

The LCC results show that in the baseline scenario, the all-electric strategy has the lowest NPV. As the future is uncertain, several scenario analyses are performed to demonstrate the effect of certain variables on the final outcomes. When a higher discount rate is applied, all strategies and dwelling combinations show a reduction of NPV. Strategies that come with high operation costs, such as the reference strategy, benefit the most from this increase in discount rate as future operation costs are valued lower.

Within the LCC calculations, the energy prices and taxes are not decoupled. Therefore it is not possible to make changes to either the prices of the related energy taxes separately. The only variable that is considered in the LCC calculations and the scenario analyses is the final costs for the end-user. The energy costs are adjusted in two scenarios to demonstrate the effect of changing energy prices.

Increasing the natural gas price resulted in significantly higher costs in the reference strategy. The hybrid strategies are not affected as much, as the natural gas demand is much lower compared to the reference strategy, and it is only used up until 2030.

Changes in the electricity price show to affect strategies with high electricity demands such as the all-electric and LT-district heating strategies the most. Decreasing the electricity price shows to reduce the NPVs of these two strategies with over 10% for all dwelling types. It would be interesting for further research to examine how individual electricity generation with PV-panels would influence the LCC results.

One has to be cautious with interpreting the results from this LCC, as the investment costs for the different insulation measures and heating installations are not validated by experts. It may well be that some of the cost components in the calculations were over- or underestimated. It would be interesting for future research to examine whether all costs that were involved in the heating strategies were adequately covered. Additionally, future research should indicate whether the construction of district heating network will lead to additional project fees that are going to be charged to end-users. Including the additional network construction costs in the LCC may significantly influence the outcomes of the results, as the initial investment costs can potentially increase with approximately €5,000.

6.2. Life cycle assessment

A life cycle assessment (LCA) is conducted to quantify the CO2-equivalent emissions that occur over the life cycle of the modelled heating strategies. By conducting this LCA, each heating strategy is individually assessed on its environmental performance. The results from this assessment are used to represent the CO2 emission decision-making factor in the final MCA calculations.

6.2.1. Goal and scope definition

The goal of the LCA is to identify the CO2-equivalent emissions that occur over the lifetime of the modelled heating strategies. By quantifying the emissions of the different heating strategies, decision-makers can obtain insight in environmental performance of these strategies. The quantified emissions are then used as part of the MCA model, to make a comparison between the different strategies, based on the multiple criteria.

The geographical scope of the LCA is limited to a specific case study within the Netherlands. Thus, data is collected that is representative for the region of Western-Europe. This study uses the most recent data that is available in the scientific literature and data gaps are filled with secondary data sources, or assumptions based on the scientific literature. Additionally, the Ecoinvent 3.4 database is used as a background dataset (Wernet et al., 2016).

In this LCA, a cradle-to-gate analysis is performed. The coverage starts from the production of basic material inputs that are required for the installations, insulation and relevant infrastructure for the different heating strategies. After raw material extraction and production of the required installations and materials, the construction phase is considered. Finally, the use phase is considered for each heating strategy.

This LCA does not include end-of-life treatment as there are significant data gaps on end-of-life treatment for different materials and installations that are used in the heating strategies. According to Bahlawan, Poganietz, Spina, and Venturini (2020) accurate data on the end-of-life treatment of heat pumps is unavailable. Other studies that are consulted that do include end-of-life stages in their LCAs such as Vignali (2017) assumed that the disposal phase of installations includes landfilling. However, this data is not accurate in regards to the geographical scope of the current LCA study, as landfilling is the least preferred waste disposal method in the Netherlands (Rijkswaterstaat, 2020). Thus, it is not possible to rely on the related emissions that are presented in such studies. Therefore, this study does not consider the end-of-life stage.

6.2.2. Inventory analysis

6.2.2.1. System boundaries

In each strategy the underlying premise is to reduce the natural gas consumption as much as possible. This goes hand in hand with switching from natural gas based cooking systems to electrical cooking systems such as induction cooking. We assumed that in any strategy the cooking system will need to change, which leads to similar impacts for each households. Therefore, we choose to not model the emissions that are related to this switch in cooking systems.

We assume that at the start of the analysis, all heat emitting systems (radiators) have to be replaced by appropriate MT- or LT-radiators, depending on the selected strategy. While LT-radiators take up approximately 2.5 times the space of MT-radiators (CE Delft, 2018b, p. 44), they are designed with higher material efficiency (Radson, 2012). As there is no data available on the specific materials that are used in LT radiators, we assume that the CO2-equivalent emissions of the MT and LT radiators are in the same order of magnitude. For the sake of simplicity, the heat emitting systems are therefore left out of the system boundaries.

Installation of the heating system installations (boilers, heat pumps) is not considered, as the installation work is similar for these types of installations (Greening & Azapagic, 2012). Any differences between the emissions due to installation are expected to be negligible. Additionally, the installation phase of insulation measures mainly comprises of manual labor, as no heavy machinery is used. Therefore, the installation related emissions are likely to be negligible, and are thus left out of scope of the research.

6.2.2.2. Alternatives

In this LCA, six different product systems are analyzed. The CO2-equivalent emissions are calculated for a reference strategy, an all-electric strategy, a LT-district heating strategy, a MT-district heating strategy, a hybrid strategy with hydrogen gas, and a hybrid strategy with green gas. The functional unit is defined as fulfilling the energy demand of a representative dwelling over the course of 30 years.

6.2.2.3. Data collection and relating data to unit processes

First, the data collection process for the insulation materials is described. These measures are only relevant for the old dwellings, as the new dwellings already have a minimum energy label of B. This means that these dwellings already have sufficient insulation and can therefore switch to a different heating strategy without having to undertake additional insulation measures.

6.2.2.3.1. Insulation measures

First, the data collection process for the insulation measures is described. For all insulation measures, it is described what material is considered, and how the data is collected.

HR++ glass

Data for HR++ glass is collected from AGC Glass Europe (2013). The reference product has an U-value of 1.1 W/m^2*K which is in line with the currently used U-value for HR++ windows (Milieucentraal, 2018). In the LCA performed by AGC Glass Europe (2013) the product system is examined from raw material extraction up until transport to the construction site. As the emissions during installation of the windows is mainly performed by manual labor, the emissions of construction and installation are negligible and are thus not included in this product system. Per square meter of HR++ glass, 36.7 kg CO2-equivalent is emitted.

HR+++ glass

The CO2-equivalent emissions of HR+++ production are based on the weight of the glass compared to the HR++ glass. According to AGC Glass Europe (2013), over 80% of the emissions from insulation glass comes from the manufacturing of the flat glass component. The extra wide HR++ glass as reported by AGC Glass Europe (2013) is taken as a proxy to represent the emissions of HR+++ glass. Per square meter of HR+++ glass, 44.2 kg CO2-equivalent is emitted.

Roof insulation

Several materials can be used for the insulation of roofs. Pargana, Pinheiro, Silvestre, and de Brito (2014) have performed an LCA of insulation materials and found that expanded cork agglomerate is the material with the lowest CO2 emissions per square meter. However this is also one of the most costly materials and it is therefore not used that often. For roof insulation, the most used materials are glass wool, EPS (i.e. Tempex) and polyurethane (PUR) foam. In this study, we assume that EPS will be used as insulation material for roofs. In this way, the insulation material can be placed on the interior of the roof, without taking up too much space. Per kg of applied EPS, 5.47 kg CO2-equivalent is emitted (Pargana et al., 2014).

Floor insulation
For the insulation of the floor several materials can be used. This study assumes that PUR foam is to be applied for floor insulation. The main advantage of using PUR foam for the insulation of floors is that it will not be harmed by vermin, and that it is still applicable when there is a lot of piping in the crawl space (GreenHome, 2016). Data for the emissions of PUR foam is collected from Pargana et al. (2014). Per kilogram of applied PUR, 4.11 kg CO2-equivalent is emitted.

Cavity wall insulation
We assume that cavity wall insulation will be installed by making use of PUR foam. PUR foam can be applied in any cavity wall, contrary to other materials that are used for cavity wall insulation (Isolatiewaarde, 2020). The CO2-equivalent emissions of PUR foam are taken from Pargana et al. (2014).

Transport of insulation materials
The product system of the insulation materials that are considered by Pargana et al. (2014) & AGC Glass Europe (2013) comprise raw material extraction up until the manufacturing of the materials. Transport to the construction site is not included in these studies. Therefore, we assume an average transport distance of 200 kilometers to transport the required materials to the neighborhood. The materials are assumed to be transported by lorries of 16 to 32 ton, for which specific data is collected through the Ecoinvent 3.4 database (Wernet et al., 2016).

6.2.2.3.2. Heating strategies
Second, the data collection process for the heating strategies is described. For all heating strategies, it is described which data is collected, and which installations are considered.

General comments
Table 17 presents the CO2 emission factors for the different energy carriers that are used in the heating strategies. For each heating strategy, it is explained where these emission factors originate from. The energy demand for each heating strategy is taken from the data in Appendix C.

Table 17 CO2 emission factors of different energy carriers.

Variable	Value	Unit	Source
Natural gas	56.6	kg CO2/GJ	(Zijlema, 2019)
Dutch electricity mix	0.475	kg CO2/kWh	(Stimular, 2020a)
Green gas	0.723	kg CO2/m3	(Stimular, 2020b)
Hydrogen gas	1.5	kg CO2/kg	(Bhandari, Trudewind, & Zapp, 2014)

Reference strategy
We consider the reference strategy in this study as the business-as-usual scenario, where natural gas is used to heat up the dwellings. Based on an LCA on conventional and condensing boilers of Vignali (2017), it is concluded that the CO2-equivalent emissions of manufacturing a 24 kW condensing boiler are 149.26 kg. Besides manufacturing the boiler, it needs to be transported to the neighborhood, over an assumed transport distance of 100 kilometers.

Emissions over the operation phase were calculated by making use of the average energy consumption per dwelling type and corresponding construction year (Liander, 2020). The CO2 emission factor of Dutch natural gas is 56.6 kg CO2/GJ (Zijlema, 2019), and the CO2 emission factor of the Dutch electricity market mix is 0.475 kg CO2/kWh (Stimular, 2020a).

All-electric strategy

Bahlawan et al. (2020) conducted an LCA of several heating techniques, including an air source heat pump, and considered its product system from raw material extraction up until transportation to the market. Their reference heat pump has a nominal thermal power of 10 kW. By making use of the inventory data for the heat pump, the CO2 emissions of the manufacturing process of the heat pump are calculated by scaling it to the appropriate thermal capacity. Bahlawan et al. (2020) argued that a scaling factor of 0.67 is appropriate to calculate the CO2 emissions of the heat pump at different thermal capacities.

For emissions over the operation phase, there are two main sources of emissions. The first one is the leakage of the refrigerant that is used in heat pumps. The refrigerant that is used in this LCA is R134a, similar to Johnson (2011) and Bahlawan et al. (2020). This study assumes a leaking rate of 2% per year over the lifetime of 15 years, in line with Johnson (2011). The collected data shows that each year, 11.87 kilograms of CO2-equivalent are emitted in a 10 kW heat pump, due to leakage. This number is scaled to the appropriate thermal capacity of 6 kW.

Hybrid strategy with green gas

For both the green gas and hydrogen gas strategy, it is assumed that green gas will be used in the currently applied gas grid starting from 2030 (see section 6.1.3). The CO2-emission factor of green gas that is used is based on the average green gas production, as described in Stimular (2020b). The applied emission factor is 0.723 kg CO2/m3.

Bhandari et al. (2014) have conducted a review on different LCA's on several hydrogen production technologies. Their review shows that for the production of green hydrogen, using wind generated electricity results in the lowest CO2 emissions per kilogram of produced hydrogen. Wind electrolysis produces 0.97 kg CO2-eq/kg H_2. Using solar PV for the electrolysis of hydrogen would result in approximately twice as much emissions (Bhandari et al., 2014). Within the Netherlands, offshore wind is expected to play a key role in the production of hydrogen gas, with projections up to 53% of the total hydrogen production (North Sea Energy, 2020). As this thesis only considers the production of green hydrogen, the other half of the hydrogen production is assumed to be produced by solar PV. In this LCA, we assume that hydrogen gas will be produced by an equal mix of wind and solar PV electrolysis. This would lead to an overall emission factor for hydrogen gas of 1.5 kg CO2-equivalent emissions per kg hydrogen, based on Bhandari et al. (2014).

District heating with low temperature source

We assume that the emissions of the used heat pumps in this strategy are similar to the used heat pumps in the all-electric and the hybrid strategies, adapted for the appropriate thermal capacity. As this strategy uses a heat pump to individually heat up the supplied residual heat, most of the energy demand over the operation phase is fulfilled with electricity. Besides electricity, residual heat is used.

In this LCA, emissions that are caused by the conversion and transport of the residual heat source are considered as embodied emissions. These are direct emissions that are related to the process of distributing the residual heat source to the neighborhood. Indirect emissions, or emissions that occur in the operational phase of the residual heat plant, are not considered as these emissions occur regardless of whether or not the residual heat is used.

The direct emissions of residual heat supply are calculated by Schepers and Scholten (2016). It is assumed that the low temperature residual heat can be used constantly, without the need to co-fire natural gas to fulfill the peak demand. Therefore, the total emissions of residual heat are 8.6 kg CO2-equivalent emissions per GJ of supplied heat.

District heating with middle temperature source
For MT-district heating, heat exchangers are required in the dwellings. Oliver-Solà et al. (2009a) have presented the material inventory of heat exchangers. By making use of appropriate Ecoinvent 3.4 processes, the CO2-emissions of these heat exchangers are calculated.

Similar to the LT-district heating strategy, an emission factor for the supplied residual heat is considered. However, for the MT-district heating strategy, we assume that natural gas is co-fired in order to maintain the required temperatures during peak demand hours. Therefore, the total emissions of residual heat in this strategy are 20.6 kg CO2-equivalent emissions per GJ of supplied heat (Schepers & Scholten, 2016).

6.2.2.3.3. Network operations
Third, the data collection process for the related network infrastructure is described. For all alternatives, different infrastructure is required to supply the dwelling with electricity and heat.

Electricity network
In some of the alternatives, the electricity grid needs to be reinforced, or upgraded, to account for the increased electricity demand. In order to calculate the emissions related to the reinforcement of the grid, only the distribution network within the case neighborhood is considered. Within the neighborhood, the low voltage electricity distribution network has a length of approximately 12 kilometer (Liander, 2019). For the reinforcement of the grid, the related emissions are based on a study from Jorge and Hertwich (2014), who calculated the environmental costs for the electricity grid. They found that upgrading overhead lines comes with 40 to 60% of the environmental costs of constructing new ones. We assume that for the neighborhood distribution network (which consists mainly of underground lines) the environmental costs are the same. Therefore, in this LCA, the reinforcement emissions of the distribution grid are assumed to be 50% of the construction of a new distribution grid.

The annual maintenance emissions of the electricity grid are based on the findings from Jones and McManus (2010), who report that there is a 2% fault rate for underground electricity lines. In this LCA, emissions related to the maintenance of the electricity grid are estimated to be 2% of the construction of a new distribution grid. Data for the construction of the low voltage grid is taken from the Ecoinvent 3.4 database.

District heating network
Bartolozzi et al. (2017) have conducted an LCA on district heating networks in Italy, and have presented a life cycle inventory of the main components and materials of a district heating system. Besides the materials itself, this inventory also includes the required trench works for the construction of 100 meters of the network. This data is supplemented with data on trench works from Oliver-Solà, Gabarrell, and Rieradevall (2009b)

The total length of the district heating network is calculated based on the assumption from Van den Ende (2018), that every connection requires 15 meters of network. With 1,100 connections this leads to a total network length of 16.5 kilometers. For the LT strategy, an additional 500 meters is added to the network length, as this is the approximate distance to the residual heat source. For the MT strategy, an extra network length of 2.5 kilometers is added, as the neighborhood is expected to connect to the main industrial residual heat network which is further away from the neighborhood than the residual heat source from the LT strategy.

The annual emissions of the network related to maintenance are assumed to be 2% of the construction of the new network, similar to the maintenance emissions of the electricity grid. For a complete overview of the inventory data, consult the supplementary material.

Natural gas network
The emissions of the removal and disposal of the natural gas network in the neighborhood are taken from Oliver-Solà et al. (2009a), who have conducted an LCA of natural gas distribution networks. For the natural gas pipelines, 866 kg of CO2-equivalent is emitted per 100 meter.

The annual emissions of the network related to maintenance are assumed to be 2% of the construction of the new network, similar to the maintenance emissions of the electricity network, and the district heating network. Data for the construction of the natural gas network is taken from the Ecoinvent 3.4 database, which contains a process for the construction of a low pressure natural gas distribution network.

Allocation of network emissions
As the functional unit of this LCA study is based on the fulfillment of the energy consumption of the representative dwellings of the case study, the network operating emissions need to be allocated to individual dwellings. This LCA assumes that every dwelling in the neighborhood makes use of the same technologies, depending on the alternative heating strategies. Therefore, each dwelling has an equal contribution to the emissions of the network infrastructure, as this is independent of energy consumption in this study. Thus, the total network operation emissions were divided by the amount of connections (see section 6.1.8.2.) and added to the overall individual emissions for each representative dwellings.

6.2.3. Impact assessment

6.2.3.1. Impact categories, characterization models, category indicators, characterization factors
Impact assessment is performed using the CML 2001 baseline characterization model, introduced by J.B. Guinée et al. (2002). From this characterization model, climate change is selected as the examined impact category. The related characterization factor that is derived is the CO2-equivalent emissions.

6.2.3.2. Characterization results
In the characterization step, the environmental interventions of all related phases of the product systems are quantified in a common unit. Table 18 gives on overview of the characterization results for the different alternatives.

Table 18 Characterization results.

Alternatives	**TH_old**	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**Unit**
Reference strategy	1.38E+05	1.69E+05	1.16E+05	1.46E+05	9.69E+04	kg CO2-eq
All-electric	9.17E+04	1.11E+05	9.24E+04	1.14E+05	7.71E+04	kg CO2-eq
MT-District heating	7.60E+04	8.90E+04	7.51E+04	9.14E+04	6.24E+04	kg CO2-eq
LT-District heating	7.88E+04	9.48E+04	8.00E+04	9.75E+04	6.67E+04	kg CO2-eq
Hybrid (Hydrogen gas)	8.47E+04	1.02E+05	8.57E+04	1.05E+05	7.14E+04	kg CO2-eq
Hybrid (Green gas)	8.86E+04	1.07E+05	8.95E+04	1.10E+05	7.47E+04	kg CO2-eq

Figure 9 shows the relative impacts for the alternatives for the different dwelling types. From the figure can be seen that the reference strategy has the highest impact, independent of the type of dwelling. The relative impact of the reference strategy is higher for the old dwellings, compared to the new dwellings. This is caused by the energy savings that occur in the old dwellings, due to the insulation measures that are applied.

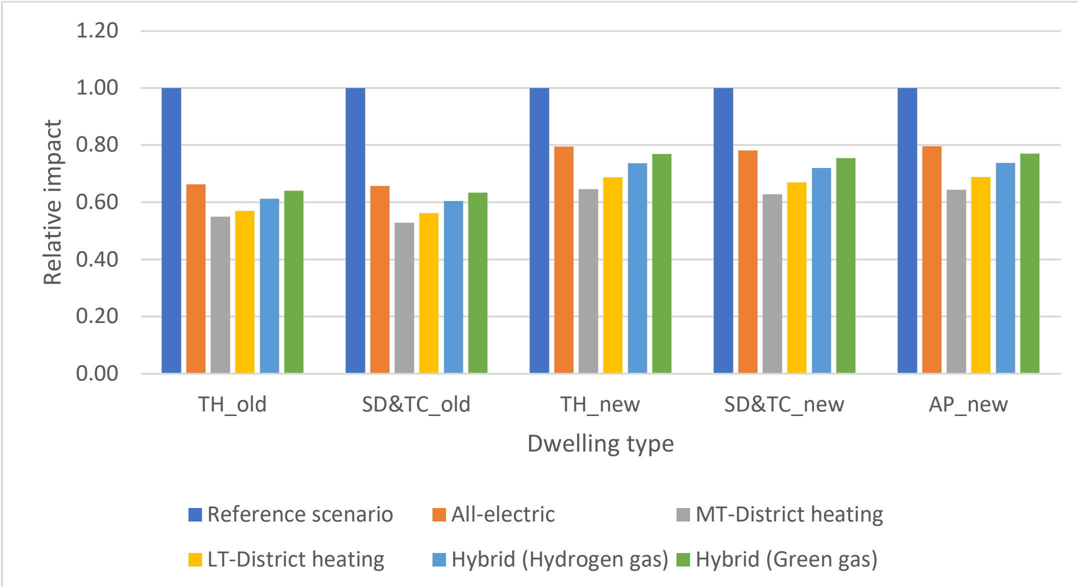

Figure 9 Relative impacts for each dwelling type.

6.2.4. Interpretation

6.2.4.1 Consistency check

The data for this LCA is collected in line with the goal and scope of the study. As the case study comprises a Dutch neighborhood, data sources are collected that represent the geographical coverage as close as possible. In most cases, European data is consulted, as no specific Dutch data was available. In line with the temporal scope of the study, data is collected from 2009 onwards.

6.2.4.2 Completeness check

The results of this LCA have not been reviewed by experts. It is therefore not possible to guarantee that a complete overview of all emissions for each heating strategy is presented.

6.2.4.3 Contribution analysis

A visualization of the contribution analysis for each heating strategy is presented in Figure 10. From this figure can be seen that the use phase is the dominant contributor to CO2-equivalent emissions in each of the scenarios. Other than the use phase, only for the older dwellings, the raw material extraction and construction of all measures shows an impact larger than 1%. This is due to the CO2-equivalent emissions that are related to the raw material extraction and preparation of the insulation materials that are applied in these dwelling types.

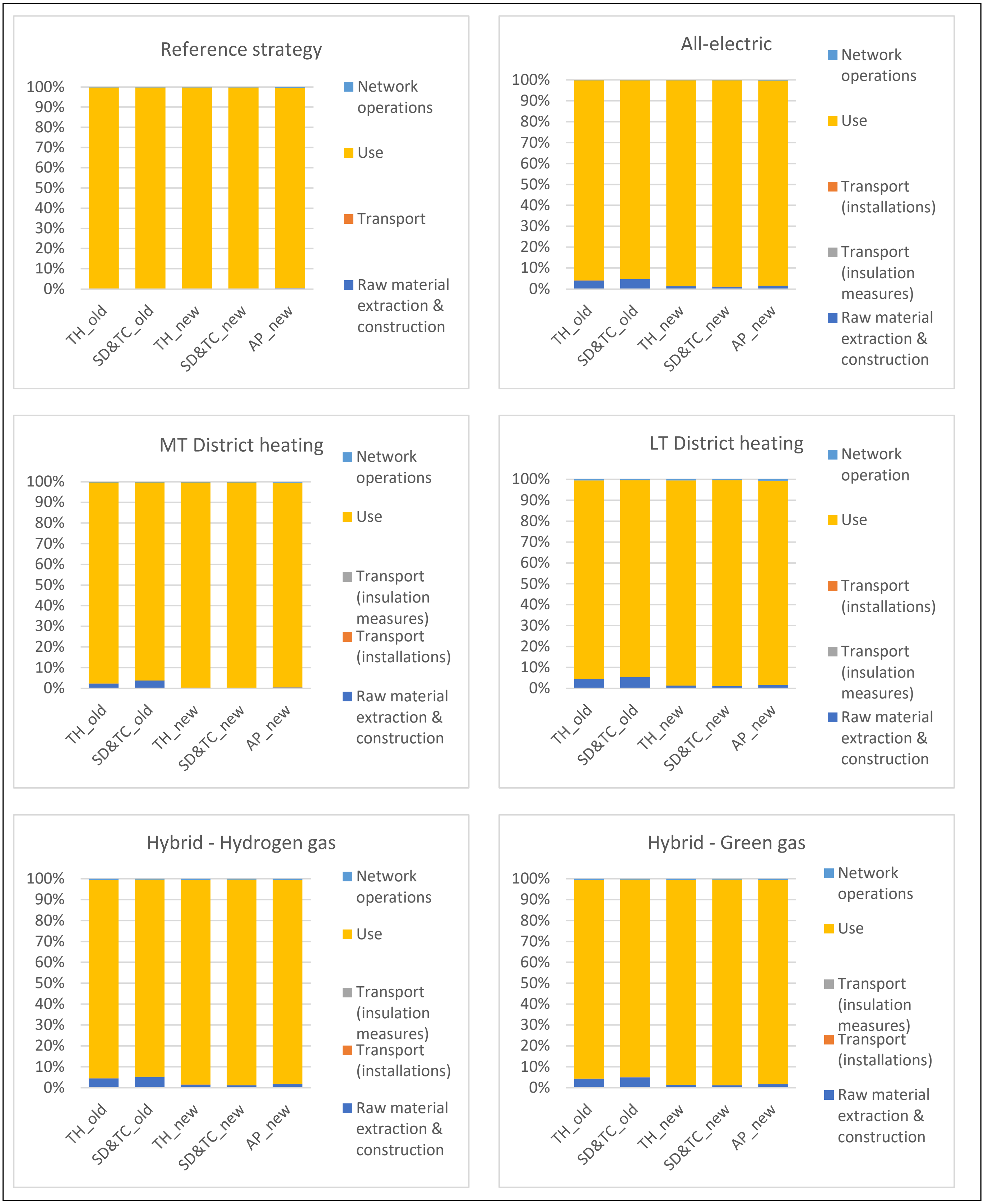

Figure 10 Contribution analysis for all heating strategies.

6.2.4.4 Sensitivity analysis

A sensitivity check is performed to determine how the final results are affected by data uncertainties. The results of the LCA are calculated with the CO2 emission factor of the Dutch electricity mix. However, it is likely that the CO2 emission factor of the Dutch electricity mix of the Netherlands will reduce, as several Dutch policies and targets are designed to reduce the fossil fuel contribution in the electricity mix (Rijksoverheid, 2019, pp. 157-181). Therefore, a scenario analysis is performed where the CO2 emission factor of the Dutch electricity grid will reduce with an annual rate of 5%. The results of this analysis are presented in Table 19. Additionally, the relative impacts of each heating strategy are visualized in Figure 11.

Table 19 Results of the sensitivity analysis.

Alternatives	TH_old	SD&TC_old	TH_new	SD&TC_new	AP_new	Unit
Reference strategy	1.18E+05	1.44E+05	9.33E+04	1.18E+05	7.81E+04	kg CO2-eq
All-electric	5.00E+04	6.08E+04	4.92E+04	6.03E+04	4.12E+04	kg CO2-eq
MT-District heating	5.42E+04	6.36E+04	5.10E+04	6.30E+04	4.25E+04	kg CO2-eq
LT-District heating	4.42E+04	5.35E+04	4.36E+04	5.30E+04	3.65E+04	kg CO2-eq
Hybrid (Hydrogen gas)	5.34E+04	6.49E+04	5.24E+04	6.46E+04	4.39E+04	kg CO2-eq
Hybrid (Green gas)	5.74E+04	6.98E+04	5.62E+04	6.95E+04	4.71E+04	kg CO2-eq

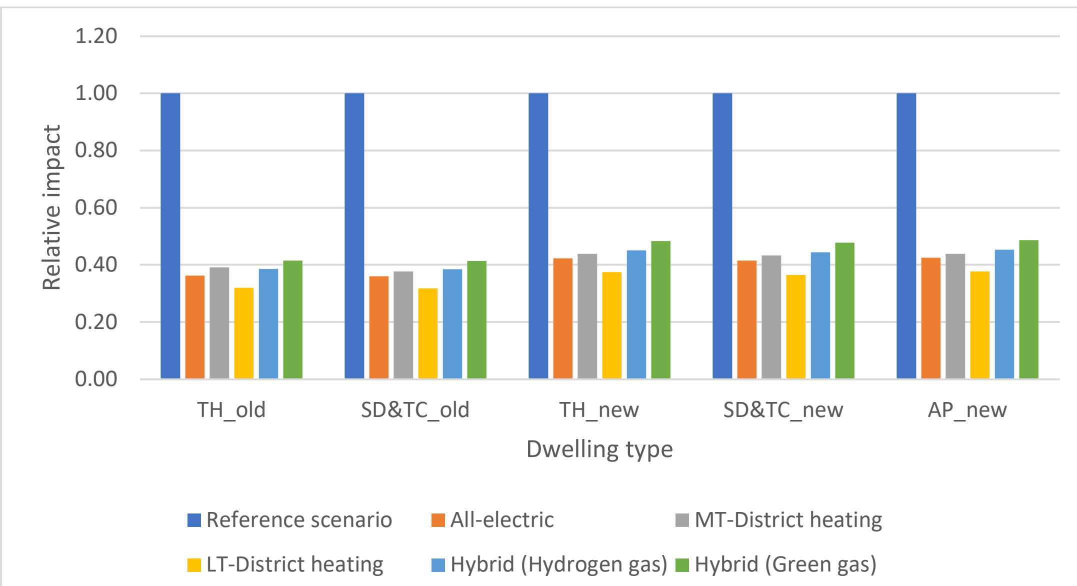

Figure 11 Relative impact of the applied scenario for each dwelling type.

When comparing the results from the relative impacts of the sensitivity analysis with the relative impacts of the baseline scenario (Figure 9), it can be observed that the relative impacts of the alternative heating strategies are significantly reduced. This indicates that the electricity mix has a significant influence on the CO2-equivalent emissions.

6.2.5. Discussion

The results of the LCA indicate that the total amount of CO2-equivalent emissions are highly dependent on the energy consumption during the use phase. This is largely due to the fact that the CO2 emission factors of natural gas and electricity are relatively high. The current Dutch electricity mix is still highly dependent on fossil fuels, which results in a high CO2 emission factor. The sensitivity analysis shows that reducing the carbon contents of the electricity mix results in significantly lower emissions over the lifetime of 30 years. As the energy transition is not only limited to thermal energy, it would also be interesting for future research to demonstrate how privately generated electricity would affect the final CO2-equivalent emissions that are occurring over the operation phase. If households can generate a share of their energy demand, e.g. by making use of PV-panels, they would rely less on the general electricity mix and can thus lower their total CO2 emissions during operation.

The main limitation of this LCA is that a full cradle-to-grave analysis is not performed. In this LCA, a cradle-to-gate analysis is performed, as the end-of-life stage is excluded from the analysis. Further research should be performed on the end-of-life stages for the alternative heating strategies, to demonstrate how inclusion of this stage will alter the final results. Furthermore, the LCA only considers climate change as the only impact category, and thus only CO2-equivalent emissions are calculated. Further research should indicate whether the strategies that perform well on climate change, also perform well on other impact categories (e.g. water depletion, human toxicity, acidification, eutrophication etc.) as climate change is not the only relevant impact category from an environmental perspective.

6.3. Other assessments

Apart from the economic and environmental assessments, three other assessments are performed. This section describes what is included in each assessment and it presents the final outcomes. These assessments are used to represent the final three decision-making factors that are used in the MCA calculations.

6.3.1. Disruption

The total disruption during renovation works, or hassle, that is perceived by the residents of the case study is examined by measuring the installation time of appliances and insulation measures. Public hassle, i.e. the disruption that occurs due to construction works in the public spaces of the neighborhood is not specified in the literature. Thus, it is hard to quantify how the perceived public disruption is perceived by individual households. Therefore, in the assessment of the disruption time, only the disruption that occurs directly inside and outside of the dwellings is accounted for. Furthermore, the lifetime of the products that is used in this assessment are similar to those that are presented in section 6.1.2.

6.3.1.1. Insulation measures

For the dwellings that do not meet the energy label requirements of certain heating strategies, insulation measures need to be undertaken. Table 20 gives an overview of the time it takes to implement these insulation measures, and thus how long the household is disrupted.

Table 20 Disruption time of insulation measures.

Type of insulation	Disruption time (hours)	Source
HR++ glass	8	(Milieucentraal, 2020a)
HR+++ glass	16	(Milieucentraal, 2020a; Van de Beek, 2019)
Roof insulation	8	(Milieucentraal, 2016)
Floor insulation	12	(Diethelm, 2018)
Cavity wall insulation	6	(Natuur & Milieu, 2020)

The difference between the disruption time between HR++ glass and HR+++ glass is the fact that window frames are assumed to be replaced if HR+++ glass is installed, in order to ensure that the glass fits. Therefore, the total disruption time is higher for the installation of HR+++ glass.

6.3.1.2. Installations

The disruption time due to the replacement of the cooking systems to induction based cooking is not considered in this assessment. We assume that all the dwellings switch to induction based cooking, which leads to equal disruption in each household. Additionally, the replacement of radiators for either LT- or new MT-radiators is also not considered in this assessment. The installation time of LT radiators is similar to their conventional counterparts, according to LT-radiator supplier Radson (2020). Therefore, we assume that each dwellings has similar disruption due to the replacement of their radiators. Thus, the only appliances that are considered in this assessment are those that are used to heat up water, and to keep it warm.

The heat pump that is used in the LT-district heating strategy is different from the all-electric strategy. Normally, water-water heat pumps take more time to install, due to the installation of the ground collector (GreenHome, 2017). However, in this case there is no ground collector required as the water from the district heating network is used. Therefore, installation times of these types of heat pumps are assumed to be similar. An overview of the disruption time for the heating appliances is presented in Table 21.

Table 21 Disruption time of heating appliances.

Type of appliance	Disruption time (hours)	Source
High efficiency boiler	4	(Warmgarant, 2020)
Hybrid heat pump	8	(Warmtepompplein, 2020)
Heat pump	12	(GreenHome, 2017)
Heat exchanger	4	*Assumption*: Similar installation time as high efficiency boiler

6.3.1.3. Results

The overall results for each heating strategy are presented in Table 22. This table shows that the low temperature strategies (All-electric, LT-district heating and the hybrid strategies) will come with the highest amount of disruption, due to the extra installation times compared to the reference system, where only a boiler is installed. Compared to dwellings of the new area, the dwellings from the old part of the neighborhood will experience the most disruption, due to the installation time of the required insulation measures for the different heating strategies.

Table 22 Total disruption time (in hours) for the representative dwellings.

	Reference strategy	All-electric	LT-district heating	MT-district heating	Green gas	Hydrogen
Terraced houses < 1964	8	58	58	24	58	58
Semi-detached & Terraced houses corner < 1964	8	66	66	24	66	66
Dwellings in the new area	8	24	24	8	24	24

6.3.1.4. Discussion
In this analysis we only included the private disruption. In reality, disruption time can be significantly higher, due to the hassle that residents may experience as construction works in the streets are performed. For example, when the district heating network is constructed, streets can be broken up and they may not be accessible for periods of time. As there is no quantitative data available about this type of public hassle yet, the analysis was forced to solely focus on in-house disruption. Future research on disruption and perceived hassle should identify how public hassle can be quantified in a private way, in order to rightfully compare the different heating strategies.

6.3.2. Balancing design and space
The amount of space that heating strategies take up, in and around a dwelling, is examined by measuring the volume of the different measures that are applied per heating strategy. By adding up the volumes of the required measures for each strategy, the total amount of required space, in cubic meters, is calculated.

6.3.2.1. Occupational space of different measures
In this assessment, the total amount of space that heating installations take up are measured. Insulation measures are not accounted for, as the selected insulation measures for this research are installed in areas that are not used for living. Windows and frames are part of the wall, and only replace the currently used space. Cavity wall insulation is applied inside the façade, and thus does not require any additional space. The floor insulation is applied underneath the floor and thus, it does not take up any living space. The inner roof insulation is the only measure that actually decreases the living space inside a dwelling. However, due to the large surface areas of roofs, the spatial impact would negatively influence the results, as the actual depth of the roof insulation is relatively small (13 to 20 centimeters), and would be negligible compared to the current situation.

The sizes of heating appliances such as boilers, heat exchangers, and heat pumps were taken from factsheets that are provided by CE Delft (CE Delft, 2018b, 2018c). These factsheets provide an overview of the volumes of high efficiency boilers, inside and outside units of heat pumps and required boilers and buffer tanks for the all-electric and LT-district heating strategy. For the hybrid and all-electric strategies, both an inside and outside unit are required for the applied air-water heat pump. For the LT-district heating strategy, the heat pump is not fed with outside air but with residual heat so only an inside unit is applied.

For the reference strategy and the MT-district heating strategy, the MT-emitting system size is estimated based on the size of an average radiator of 200x50cm (RadiatorXXL, 2020b). We estimate that each dwelling has approximately 5 of these radiators. This is calculated by assuming an average floor area of 100m2 and average temperature of 20 degrees for each room in the dwellings. By making use of an online radiator power calculator (RadiatorXXL, 2020a), the required power of the total emitting system is calculated. According to CE Delft (2018b), LT-radiators are approximately 2.5 times as big as conventional radiators. By multiplying the volume of conventional radiators with 2.5, the volume of the LT-radiators is calculated.

The total volumes for each applied installation are presented in Table 23. These values are used to calculate the final occupation space, based on the specific installation that are required in each heating strategy.

Table 23 Volumes of the applied heating installations.

	Volume (m3)	**Source**
High efficiency boiler	0.084	(CE Delft, 2018b, p. 27)

Inside unit heat pump	0.24	(CE Delft, 2018b, p. 13)
Outside unit heat pump	0.256	(CE Delft, 2018b, p. 13)
Boiler	2	(CE Delft, 2018b, p. 13)
Buffer tank	2	(CE Delft, 2018b, p. 13)
Heat exchanger	0.048	(CE Delft, 2018c)
MT-emitting system	0.5	(RadiatorXXL, 2020a, 2020b)
LT-emitting system	1.25	(CE Delft, 2018b)

6.3.2.2. Results

The heating strategy with highest spatial impact is the all-electric strategy. This is due to the fact that an air-water heat pump consist of both an inside, and outside unit. Additionally, the LT-radiators that are applied in the multiple low temperature strategies take up a lot of space, compared to conventional radiators. For the all-electric and the LT-district heating strategy, an additional boiler and buffer tank are required to ensure hot tap water in the dwellings. These appliances take up a significant amount of space as well. The reference strategy and the MT-district heating strategy have the lowest spatial impact. Besides the high efficiency boiler or the heat exchanger and the conventional radiators, no other measures are required that take up significant space within a dwelling. The final results of this assessment are summarized in Table 24.

Table 24 Occupation space of the installations for each heating strategy.

	Reference strategy	**All-electric**	**LT-district heating**	**MT-district heating**	**Hybrid-Green gas**	**Hybrid-Hydrogen**
Total occupation space (m3)	0.584	5.746	5.49	0.548	1.83	1.83

6.3.2.3. Discussion

In this assessment, the volume of the installations that are applied for the different heating strategies were measured. By doing this, an overview is presented of the total amount of volume that each heating strategy requires, to ensure that all installations can be placed. Besides the volume of the installations, it also matters where these installations are placed, in order to limit the amount of actual living space that these installations take up. If the residents can place certain installations into spaces that are not used in day-to-day living, it could be that the additional space that a heating strategy takes up is not perceived to negatively influence the total amount of living space within a dwelling. Though, with larger installations such as air-water heat pumps with an additional buffer tank, it may be difficult to design the space in a home in such a way that the least amount of living area is lost.

6.3.3. Reliability of experts

As described in section 3.2.5. the reliability of experts is measured through a proxy-variable that measures the availability of certified contractors and installation companies that are operating in the region of the case study. One of the registers that is consulted to find available contractors that are specialized in energy efficient renovations and installations is the *QBISnl* register. This register contains qualified and certified contractors, specialized in specific renovation techniques (QBISnl, 2020a). By making use of the QBISnl register, households can look for certified contractors that specialize in energy renovation measures, within the region of their neighborhood. This register shows that within 10 kilometers, several contractors are available that are certified in installing boilers, air-water and water-water type of heat pumps) and heat emitting systems (QBISnl, 2020b).

The *Wij Isoleren* register contains an overview of contractors that are certified in the installation of insulation measures. This register shows the specific qualities of contractors for each of the installation measures that they provide (Wij Isoleren, 2020a). A search through this register shows that for most of the insulation measures that are applied in this study (see section 4.2.3), certified contractors are available within the zip code region of the neighborhood (Wij Isoleren, 2020b). For slanted roof insulation, it might be harder to find a certified contractor that is specialized in inner roof insulation, as the register does not show one that is in close proximity of the neighborhood. However, there are contractors available that specialize in complete renovation and insulation of slanted roofs (Wij Isoleren, 2020b).

6.3.3.1. Conclusion

We conclude that for all of the strategies there are currently enough certified experts available to perform renovation measures within the dwellings. However, for the hybrid strategies, it remains uncertain whether there is a need for additional changes to currently applied heating systems in dwellings (Hermkens et al., 2018). Thus, it also remains uncertain if the contractors will meet the required standards for working with hydrogen heat pumps, or if extra certifications will be required. As these hybrid heat pumps (that are modified for hydrogen gas) are currently not used, it would be inaccurate to speculate about the required standards. Therefore, we decided to give a lower final score to the hybrid strategy that contains hydrogen gas. The final results of this assessment are summarized in Table 25.

Table 25 Final results of the availability of experts.

	Reference strategy	**All-electric**	**LT-district heating**	**MT-district heating**	**Hybrid-Green gas**	**Hybrid-Hydrogen**
Availability of certified experts [Dummy]	1	1	1	1	1	0

6.3.3.2. Discussion

In this assessment, the availability of experts was used as a proxy for measuring the reliability of experts. Based on specific certifications and the location of contractors, it was determined if there are available contractors in the nearby area of the neighborhood. In practice, residents may not limit themselves to certifications to determine if contractors are reliable. Positive experiences from neighbors or friends and family may also be used as a selection criterion when searching for contractors. Therefore, it may be possible that in practice, it may take some more time to find reliable experts that can perform the desired measures for a specific heating strategy.

Chapter 7. Multi-criteria analysis

In this chapter, the MCA results for the baseline scenario are reported. We define the baseline scenario as the scenario that considers that applies the same values that are applied in the baseline calculations for the LCC and LCA calculations.

The first step of the MCA is to derive the weights that are applied to the predefined criteria. These weights are applied to the normalized values of the individual assessment results (Appendix F). Finally, a scenario analysis is performed to demonstrate the effect of changing variables in the final comparison. The MCA results are used to provide an answer to sub question 3, as these results measure the performance of each heating strategy in the case neighborhood.

7.1. Deriving the weights

One of the objectives of the survey is to let the residents of the case make pairwise comparisons of the different predefined criteria. However, while analyzing the survey results, it became clear that a few survey questions about the relative importance of decision-making factors were filled in incorrectly. This has led to a significant amount of answers that either missed relative comparisons between the criteria, or certain answers identified the same factors as both the most important and the least important criterion in the comparison matrices. Thus, many answers have been marked as incorrect. Therefore, this study does not take the average of the survey answers to obtain the overall weights, opposed to previously conducted studies that apply BWM (Ahmadi, Kusi-Sarpong, & Rezaei, 2017; van de Kaa, Kamp, & Rezaei, 2017). In these studies, interviews were conducted to obtain weights, which has led to a sufficient validity of the responses.

Due to the observed errors in the survey answers regarding the questions about the relative importance of the decision-making factors, the relative comparisons from the survey were not used to present a final answer. However, the identification of the most important and the least important criteria in the survey did not rely on pairwise comparison matrices. These question were rather straightforward and can still provide an insight in the preferences of the residents in the case neighborhood.

7.1.1. Developing sets of weights

The goal of the MCA in this thesis is to demonstrate how the importance of certain factors influence the final results. By making use of different sets of weights, this study demonstrates how the final results are influenced. The sets of weights are developed by combining the results of the survey with literature from Ebrahimigharehbaghi et al. (2019) and Broers et al. (2019). Based on this comparison, weights are assigned to the different decision-making factors.

7.1.1.1. Sets of weights

From the survey responses and the frequency of the decision-making factors in the literature, four sets of weights are proposed. The motivation behind these sets of weights is explained in this section, and an overview of the final weights is given.

Set of weights 1 – Costs first

This set of weights is based on the results from Ebrahimigharehbaghi et al. (2019), who identify that total costs is the most important factor. Based on the relative frequency of the survey responses from Ebrahimigharehbaghi et al. (2019) (see section 2.3.1.), the pairwise comparison matrix is filled in. Occupation space is not mentioned in this paper, thus, we assume that it is of equal importance as reliability of experts. These two factors receive the highest weights after total costs. Emissions are perceived as less important, and disruption is perceived as the least important factor.

Set of weights 2 – Costs & Emissions

This set of weights is based on the results from Broers et al. (2019) which identify that environmental concern (CO2 emissions) and total costs are the most important factors and we assume that they are of equal importance. Based on the relative frequency of the findings from Broers et al. (2019) (see section 2.3.1.), the pairwise comparison matrix is filled in. Reliability of experts is considered of equal importance as occupation space, similar to set of weights 1. These factors received a slightly lower weight compared to set of weights 1, due to the amount of mentions in Broers et al. (2019). Disruption is considered as the least important factor and thus gets the lowest assigned weight.

Set of weights 3 – Emissions & Experts

The third set of weights is based on one of the survey answers that has selected CO2 emissions as the most important factor. Reliability of experts is the second most important factor, followed by total costs and occupation space. Disruption is selected as the least important factor.

Set of weights 4 – Disruption & Space

The fourth set of weights is based on one of the survey answers that has contrary results to the literature. In this case, disruption is selected as the most important factor, followed by occupation space. Total costs are selected as the least important factor. As all other sets of weights consider disruption as the least important factor, this set of weights is chosen to demonstrate how a deviating perception, in which total costs is the least important, influences the final outcome of the MCA.

For the exact values of the pairwise comparison matrices that are used in the four sets of weights, see Appendix G. The final weights are presented in Table 26. All of the sets of weights have a consistency ratio that is below 0.2087, and are thus consistent with the consistency threshold as described in section 3.2.7.1.

Table 26 Final weights for the different decision-making factors.

	Total costs	**CO2 Emissions**	**Occupation space**	**Reliability of experts**	**Disruption**	**Consistency ratio**
Costs first	0.45	0.13	0.17	0.17	0.08	0.06
Costs & Emissions	0.34	0.34	0.13	0.13	0.05	0.06
Emissions & Experts	0.15	0.50	0.08	0.21	0.05	0.12
Disruption & Space	0.06	0.16	0.21	0.16	0.40	0.09

7.2. Ranking of alternatives

To determine how each heating strategy performs, the results from the individual assessments are normalized according to Equation 1 as described in section 3.2.7.2. The normalized results can be found in Appendix F.

7.3. Results

The MCA results of the baseline scenario are presented in Figure 12. In this chapter, the baseline scenario considers the scenario that applies the same values that are applied in the baseline calculations of the individual assessments. So, a natural gas price growth rate of 3%, an electricity price growth rate of 2%, a discount rate of 3.05% and the current CO2-emission factor of the Dutch electricity mix are applied.

The results show that depending on the selected set of weights different alternatives are preferred. When total costs is perceived as the most important factor, and high weights are assigned to this factor, the all-electric strategy seems to be the preferred alternative for most of the different dwelling types. However, for the semi-detached and corner houses of the old part of the neighborhood, the MT-district heating strategy scores slightly better.

When emissions are receiving a higher weight, it can be observed that the MT-district heating strategy overtakes the all-electric strategy as the option with the highest MCA results. This is demonstrated in the second set of weights, where both costs and emissions play an important role. When emissions play an even bigger role and are perceived as the single most important factor, the MT-district heating strategy is the preferred alternative for all dwelling types.

In the final set of applied weights, where disruption is considered as the most important factor, it is observed that the MT-district heating strategy scores the highest for every dwelling type. Even though the reference strategy comes with the least amount of disruption, the MT-district heating strategy gets a higher overall score as it performs significantly better than the reference strategies in the emission and cost factor. Even though these factors still have low weights, they influence the results as the normalized results for disruption and occupation space are somewhat similar. Table 27 shows the highest score for each dwelling type, for each applied set of weights.

Table 27 Highest MCA score of the representative dwellings for each set of weights.

Highest score	**Costs first**	**Costs & Emissions**	**Emissions & Experts**	**Disruption & Space**
Terraced house (old)	All-electric	All-electric	MT-District heating	MT-District heating
Semi-detached & corner house (old)	MT-District heating	MT-District heating	MT-District heating	MT-District heating
Terraced house (new)	All-electric	All-electric	MT-District heating	MT-District heating
Semi-detached & corner house (new)	All-electric	MT-District heating	MT-District heating	MT-District heating
Apartment (new)	All-electric	All-electric	MT-District heating	MT-District heating

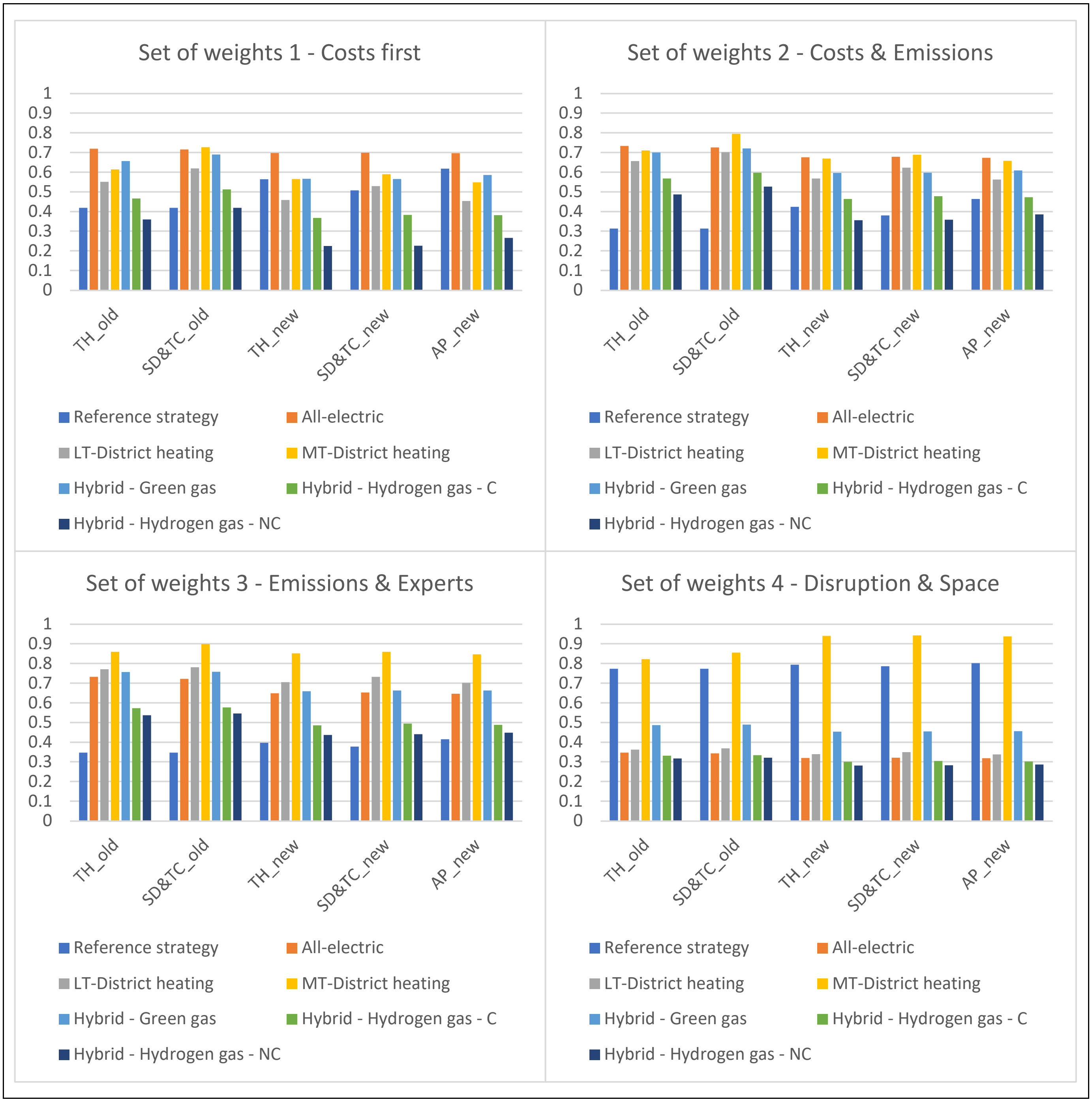

Figure 12 MCA results for the different set of weights.

7.4. Scenario analysis

For scope reasons, not all possible scenarios could be performed. Therefore, we decided to only run three different scenarios. In Scenario 1, a societal discount rate is applied. In Scenario 2, the CO2 emission factor of the Dutch electricity mix is decreasing annually, due to the increased share of renewables in the electricity mix. In Scenario 3, a combination of these variables are included. The results of these scenarios are described in the following sections.

7.4.1. Scenario 1: Societal discount rate

When the applied discount rate increases to 4.5%, to reflect the societal discount rate, other heating strategies are preferred by some dwelling types. However, changes in preferred alternatives only occur when the first two sets of weights are applied, where the total costs get a high weight. In the set of weights where total costs are the most important, the reference strategy scores slightly less than the all-electric strategy in two of the three new dwellings. For apartments, the reference strategy actually scores higher than the all-electric strategy.

In the second set of weights, where CO2 emissions are considered as equally important to total costs, it is observed that the MT-district heating strategy gets a relatively higher score in the new dwellings, compared to the baseline scenario. For the final two sets of weights, the MT-district heating strategy scores the highest for all of the representative dwellings (Figure 13). In these two sets of weights, little to no changes occur in the ranking of overall scores compared to the baseline scenario. Only in the set of weights where emissions and experts are important, a slight change in the ranking occurs, as the non competitive hydrogen strategy overtakes the reference strategy as the lowest score for the new terraced houses and apartments.

Table 28 shows the highest score for each dwelling type, for each applied set of weights in this scenario. For a complete overview of the rankings for each set of weights compared to the baseline scenario, consult Appendix H**.**

Table 28 The highest ranking alternatives in Scenario 1.

Highest score	Costs first	Costs & Emissions	Emissions & Experts	Disruption & Space
Terraced house (old)	All-electric	All-electric	MT-District heating	MT-District heating
Semi-detached & corner house (old)	MT-District heating	MT-District heating	MT-District heating	MT-District heating
Terraced house (new)	All-electric	MT-District heating	MT-District heating	MT-District heating
Semi-detached & corner house (new)	All-electric	MT-District heating	MT-District heating	MT-District heating
Apartment (new)	Reference strategy	MT-District heating	MT-District heating	MT-District heating

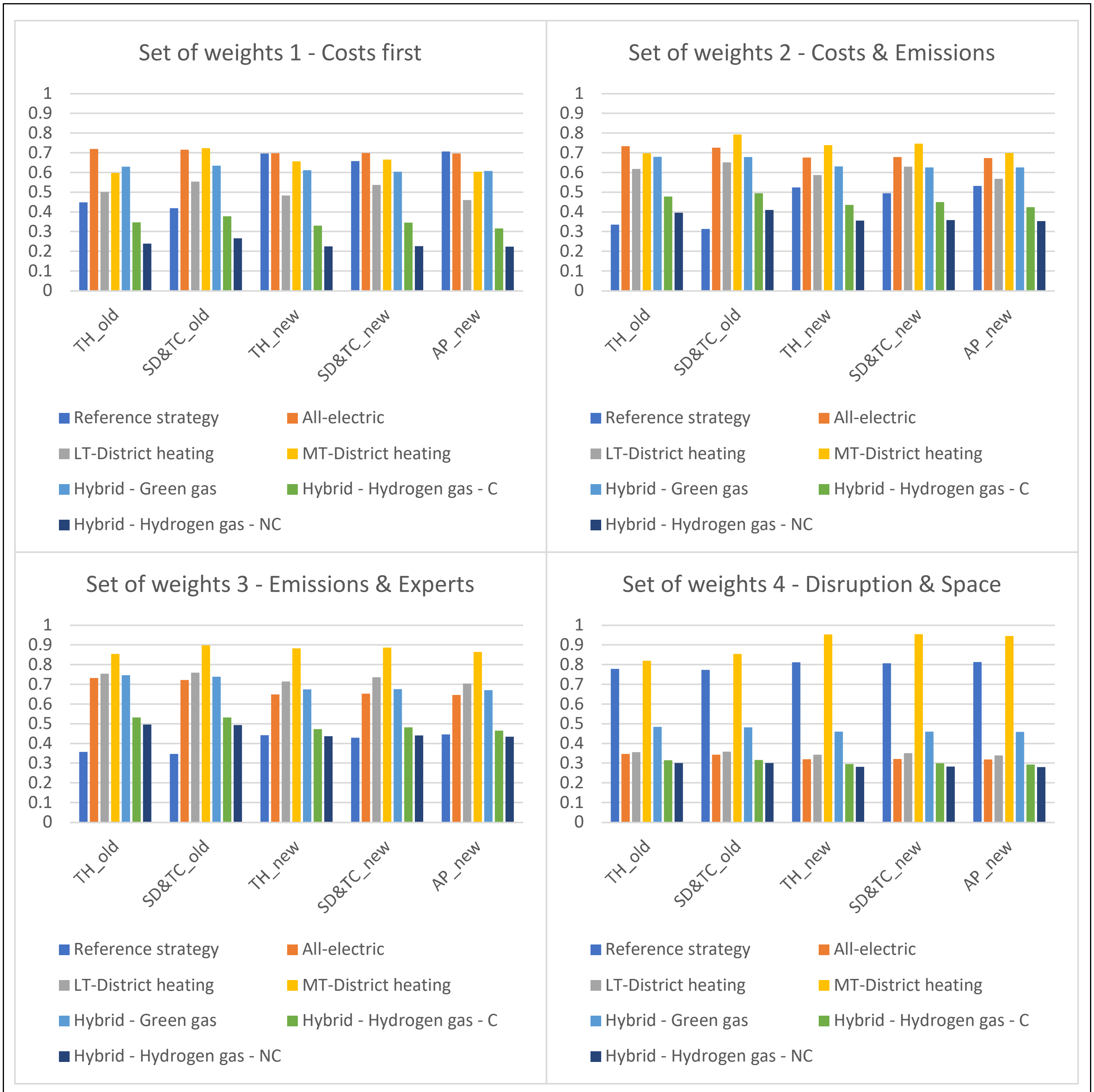

Figure 13 MCA results in Scenario 1.

7.4.2. Scenario 2: Increased share of renewables

Changing the CO2-emission factor of the Dutch electricity mix results in the highest changes in preferred alternatives in the weight scenarios where emissions are given a relatively high weight. Moreover, as seen from Figure 14, the strategies that have relatively high electricity consumption, such as the all-electric and LT-district heating strategies, benefit the most from a decreased CO2-emission factor of the electricity mix. Compared to the baseline scenario, the all-electric strategy becomes the most preferred option in almost all dwelling types when one of the first three sets of weights is applied. When looking at the third set of weights, the performance scores for all dwellings are almost similar to the LT- and MT-district heating strategies. The MT-district heating strategy even perform slightly better for old semi-detached & corner dwellings.

Table 29 shows the highest score for each dwelling type, for each applied set of weights in this scenario. For a complete overview of the rankings for each set of weights compared to the baseline scenario, consult Appendix H.

Table 29 The highest ranking alternatives in Scenario 2.

Highest score	Costs first	Costs & Emissions	Emissions & Experts	Disruption & Space
Terraced house (old)	All-electric	All-electric	All-electric	MT-District heating
Semi-detached & corner house (old)	All-electric	All-electric	MT-District heating	MT-District heating
Terraced house (new)	All-electric	All-electric	All-electric	MT-District heating
Semi-detached & corner house (new)	All-electric	All-electric	All-electric	MT-District heating
Apartment (new)	All-electric	All-electric	All-electric	MT-District heating

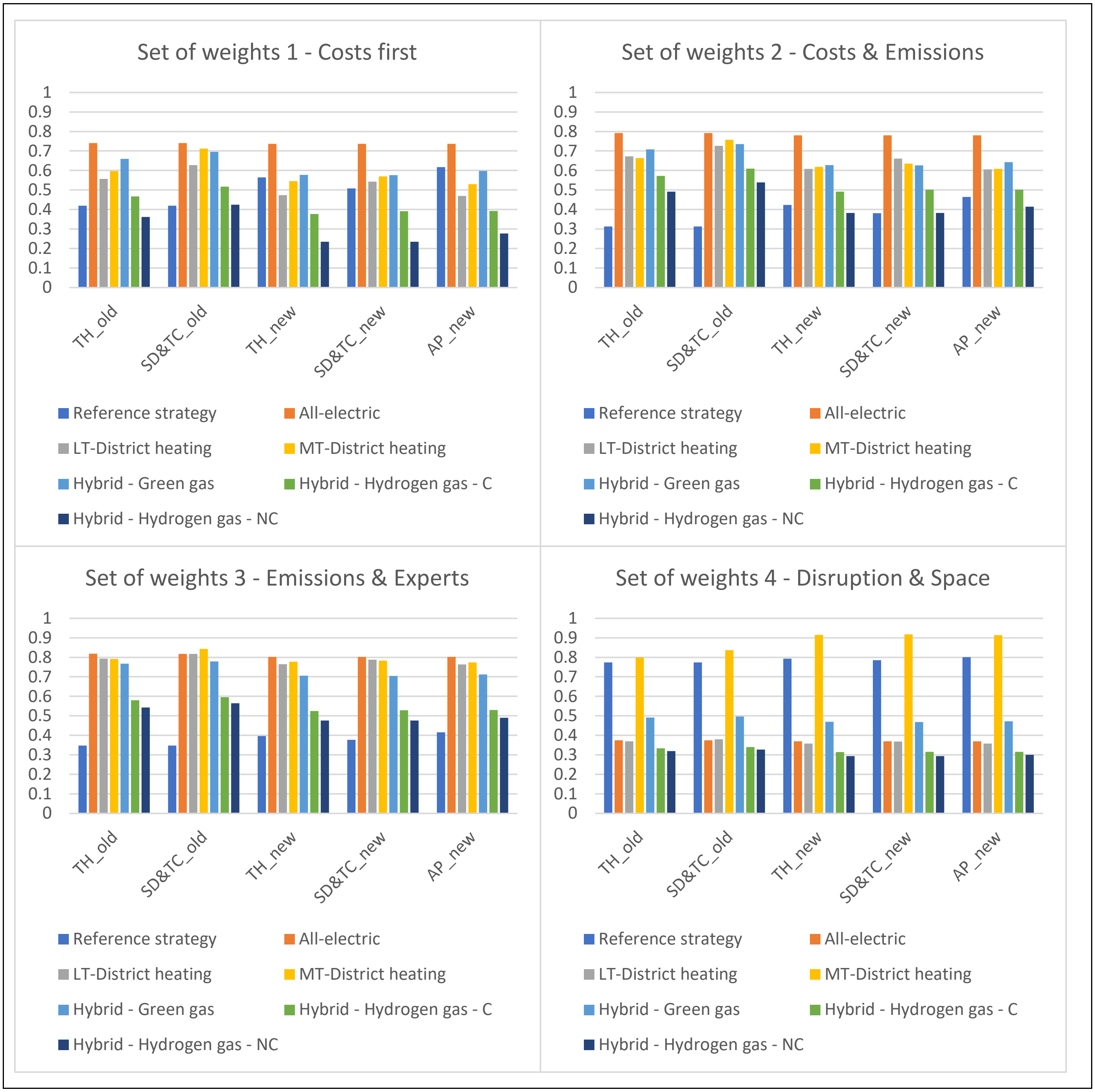

Figure 14 MCA results in Scenario 2.

7.4.3. Scenario 3: Societal discount rate and increased share of renewables

Figure 15 shows the MCA results when both of the applied factors of the previous scenarios are considered. It is observed that the all-electric strategy showed the highest performance scores for the first two sets of weights. For the third set of weights, similar results are observed as in the scenario 2. The all-electric strategy, LT- and MT-district heating strategies perform similarly. However, as the discount rate is also increased in this scenario, MT-district heating scores slightly better as opposed to the previous scenario. Therefore, it scores higher in the new terraced houses and in the new semi-detached and corner houses, compared to Scenario 2.

Table 30 shows the highest score for each dwelling type, for each applied set of weights in this scenario. For a complete overview of the rankings for each set of weights compared to the baseline scenario, consult Appendix H.

Table 30 The highest ranking alternatives in Scenario 3.

Highest score	**Costs first**	**Costs & Emissions**	**Emissions & Experts**	**Disruption & Space**
Terraced house (old)	All-electric	All-electric	All-electric	MT-District heating
Semi-detached & corner house (old)	All-electric	All-electric	MT-District heating	MT-District heating
Terraced house (new)	All-electric	All-electric	MT-District heating	MT-District heating
Semi-detached & corner house (new)	All-electric	All-electric	MT-District heating	MT-District heating
Apartment (new)	All-electric	All-electric	All-electric	MT-District heating

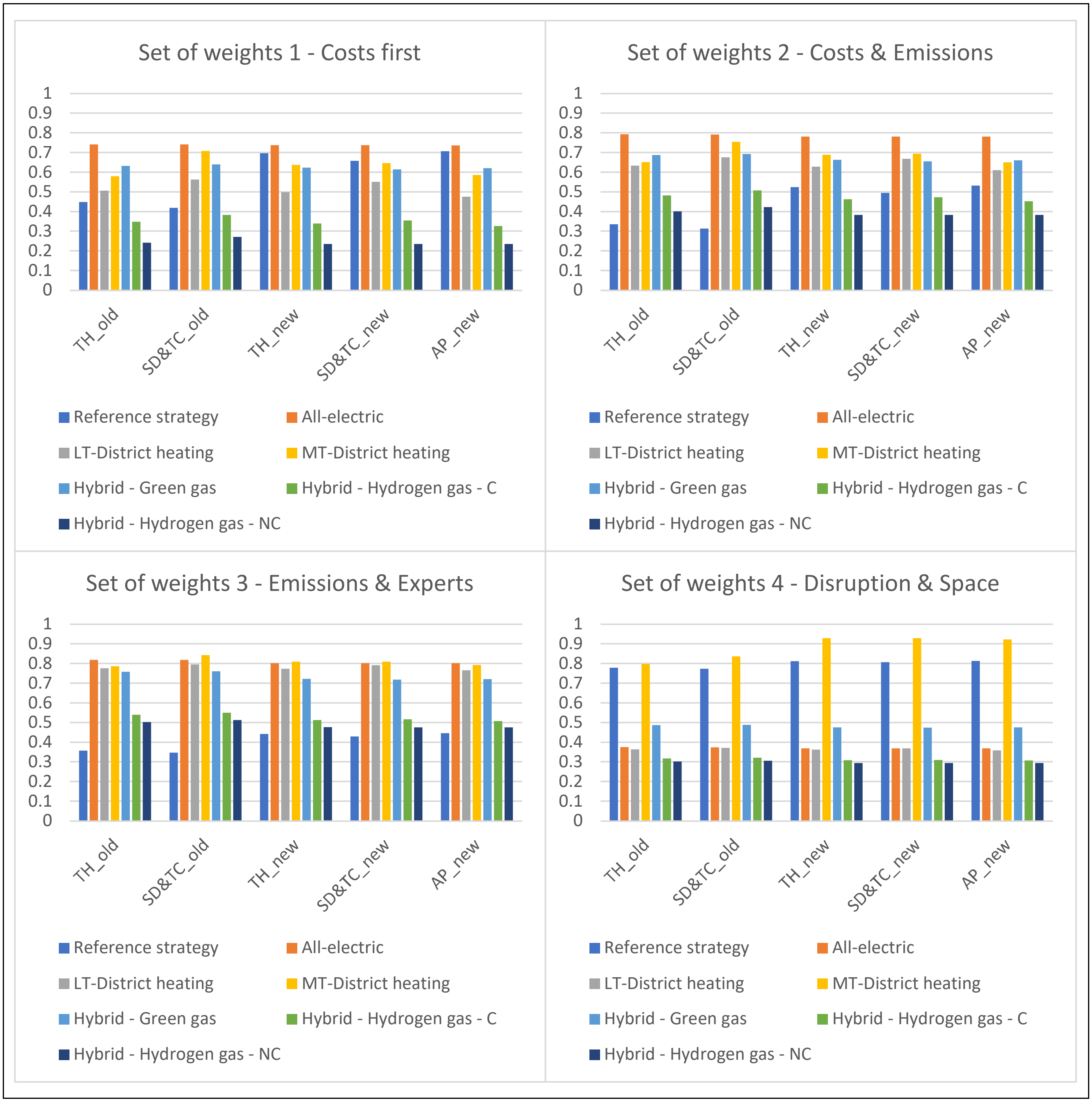

Figure 15 MCA results in Scenario 3.

7.5. Conclusions

From the MCA results we can conclude that the MT-district heating strategy received a high rank in all sets of weights. This is due to the fact that it performs well on the CO2 emissions, occupation space, reliability of experts and disruption factors. When the discount rate was increased (Scenario 1), the MT-district heating showed even more favorable results, as this influenced the total costs factor of the MCA positively.

In Scenario 2, when the CO2 emission factor of the Dutch electricity mix decreased, high electricity consumption strategies were benefitting the most. This led to a higher preferences for these strategies, compared to the baseline strategy, when total costs were considered as an important decision-making factor. For the respective rankings of the CO2 emissions, this resulted in a switch in preferred alternatives. The MT-district heating strategy was overtaken by the LT-district heating and the all-electric strategy in the respective ranking of CO2 emissions. This resulted in an increased ranking for the all-electric strategy over the MT-district heating strategy. Thus, for several dwellings, all-electric became the highest ranked option, when the first three sets of weights were applied.

In Scenario 3, we found that a combination of the two external factors leads to a preference for the all-electric strategy under the first two sets of weights. For set of weights 3, results show a preference for either the all-electric or MT-district heating strategy, depending on the dwelling type. For set of weights 4, no changes were observed in any scenario, as little weights were assigned to total costs and emissions and these are thus not influenced by the different scenarios.

Chapter 8. Discussion

In this chapter the differences between the opinions of the residents of the case study and the final MCA results are discussed. Next, all the decision that are made in the empirical and modelling work of the study, and how they have influenced the results are discussed. We end this chapter with a discussion on the ability to generalize the results from this study. In this discussion we reflect on the lessons that we can we learn from this specific case study and how these lessons could be used for the heat transition in other Dutch neighborhoods. By doing so, we provide an answer to sub question 4.

8.1. Opinions of the case residents

The results from the MCA showed that depending on the set of weights, either the all-electric strategy or the MT-district heating strategy were the strategies with the highest ranking. These alternatives showed the highest score under any applied set of weights or any applied MCA scenario. As the residents of the case study are in the process of selecting an alternative heating strategy for their neighborhood, it is therefore interesting to compare the opinions of the residents with the results of the MCA.

According to the survey responses, the case residents do not seem to have strong opinions about the different heating strategies. For all heating strategies, more than half of the respondents of the survey have indicated that they either do not know what a heating strategy entails, or that they have a neutral opinion towards it. When we look at the specific opinions regarding the MT-district heating strategy, we see that 15% of respondents have specifically stated to have a negative opinion towards MT-district heating from industrial residual heat, while only 6% explicitly state to have a negative opinion towards MT-district heating when a geothermal heat source is used. For the all-electric strategy, 24% of respondents have specifically stated to have a negative opinion towards this strategy. This was the highest percentage among all heating strategies. Thus, it can be concluded that one of the highest ranking alternatives according to the MCA result is actually one of the strategies that comes with the most negative opinion of the case residents.

On the other hand, the results from the survey have shown that a fair share of respondents do not know what any of the heating strategies entail. Additionally, 68% of the respondents have stated that they need more information in order to select an alternative heating strategy. This indicates that there is a lack of information about the alternative heating strategies in the neighborhood.

These findings show that the residents of this specific case study state to need more information on alternative heating strategies. It might be that this lack of information has potentially influenced the preferences of the residents, as half of the respondents indicated to not know what certain strategies entailed, or they expressed a neutral opinion towards the strategies.

Further research could explore the reasons why residents prefer certain heating strategies over their alternatives. This could indicate whether or not the residents base their preferences on the decision-making factors that are accounted for in this study, or if other factors play a role in this as well.

8.2. Survey

As the survey that was used in this study has been spread only among residents of the old part of the neighborhood, only their views were reflected in the survey results. The residents of the new area may have different opinions about heating systems and what decision-making factors they find most important. As this study did not look into the differences in demographic characteristics between the two areas of the neighborhood, generalization of the results to the whole neighborhood area is limited. The survey was biased in another way, as participants of the local sustainability project of the local neighborhood association were overrepresented. Due to their involvement in the local sustainability project, their answers have potentially been influenced.

Another point to reflect on are the survey questions. When asked to state their preferences regarding different heating strategies, examples were given to illustrate what these heating strategies entail. In order to keep the survey concise, the examples were presented in a brief manner. This has potentially biased the answers of respondents, as these examples may have unintentionally influenced the opinions of the respondents.

When analyzing the results, it became clear that some of the questions that were used to determine the weights in the survey were hard to interpret, which has led to several invalid responses. To overcome the potential biases of the survey and the invalid interpretation of certain survey questions, it was decided to supplement these responses with findings from the scientific literature. As the focus of this study was merely to show how a selection of weights leads to a difference in the ranking alternatives, four different sets of weights were designed to reflect the potential views of the residents. Two of these weights were based on individual survey responses. Even though it is uncertain if the responses accurately reflect the intentions of the respondent, the filled in answers can still be used to demonstrate how deviating preferences can influence the outcome of the MCA.

By applying variations of weights for the decision-making factors, the MCA demonstrated how alternating views would lead to difference in the heating strategy ranking.

8.3. The model

The MCA model that was used in this study uses the outcomes of a subset of individual assessments, which have all been based on several data sources, underlying modelling decisions and assumptions. This section aims to give insight in these decisions and how they may have influenced the final outcomes. By explaining these modelling decisions, we provide additional insights in how we assessed the alternative heating strategies, and how this affected the results. By doing so, we provide additional insights that can be used to answer sub question 3.

8.3.1. The LCC

In order to demonstrate how the different heating strategies that were applied in this study compare to each other, several assumptions had to be made. The LCC model assumes that all investments are made in the starting year, where in reality, residents may decide to spread these investments out over the course of several years. Besides influencing the initial investment costs, this would also affect the LCC and LCA outcomes. Resident may for example decide to only implement insulation measures, and after a few years they might decide to make a switch to an alternative heating system. All the individual decisions that households can make, can all have a different effect on the outcomes of the individual assessments, and thus the MCA results. Additionally, this study considered representative dwellings and did not look at specific individual dwellings. Therefore, in reality, certain household may have already applied certain insulation measures like insulation of their façade or roof. Therefore, they may not need to invest in insulation measures, or need to invest less than the total investment costs that were applied in this study.

Another assumption that was included in the LCC model is that all dwelling types make use of the same capacity for heating installations. In reality, the capacity of heating installation may be different for the dwelling types. For apartments, it may be possible that heating installations of lower capacities are sufficient to fulfill the heating demand. This would mean that the investment costs for this dwelling would slightly decrease for each heating strategy. It is expected however that this would have limited effect on the overall LCC ranking for this dwelling type, as every heating strategy would require heating installations of lower capacities.

One of the other limitations of this model is that the investment costs were not validated by academic or professional experts and contractors. Alterations in these costs would not only lead to potentially different outcomes in the LCC, but also in the MCA results. It could be that certain investment costs are an over- or underestimation of actual costs. Investment costs for insulation measures can differ between specific situations and between types of dwellings. For a more accurate indication of specific costs for insulation measures, residents should consult local contractors, and compare their findings with the cost variables that were used in the LCC model.

Even though this research acknowledges that the construction of new district heating networks may come with additional project costs that are eventually charged to the end-users, they were not included in the LCC calculations. Due to the uncertainty about the project costs, and the variety of cost differences between other projects in the Netherlands (Bouwmeester, 2019), it was decided to not include any additional project fees. Future research should indicate whether any additional project fees are required for heat suppliers to cover the total construction costs.

8.3.2. The LCA

One of the main reasons why a life cycle perspective was used in this study was to see whether including a life cycle perspective would result in different outcomes, when compared to other calculations models. These models only consider the CO2-equivalent emission reduction over the use phase, but exclude the construction and delivery of the required installations and materials. However, as the end-of-life stage was not considered in this study, due to a lack of data, this study demonstrated only the effect of a partial life cycle. The results of the LCA showed that the use phase is the main contributor of the total CO2-equivalent emissions, with over 95% of the total emissions. This shows that including more stages of the life cycle in the analysis of the environmental impact does not show significantly different results when compared with other models that only calculate the emissions during the operation phase. However, further research could show how the inclusion of an end-of-life stage influences the results. Additionally, one can look beyond CO2-emissions to determine the environmental impact of heating strategies. With the life cycle assessment methodology, it is possible to also examine the impact of the different heating strategies on acidification potential, human toxicity and other impacted categories. Further research could look into the comparison of the different heating strategies on different impact categories, and how that would influence the LCA results, and potentially the MCA results.

To model the CO2-equivalent emissions of the insulation material, this research has selected PUR and EPS as main materials for these measures. These materials are not the most environmentally friendly materials, as they are both prepared out of plastic compounds. There are a variety of other, more environmentally friendly insulation materials on the market (Duurzaam Thuis, 2020). However, the main disadvantage of these materials are that they are very expensive compared to conventionally used insulation materials. As seen from the contribution analysis of the LCA, the insulation materials account for less than 5% of the total impacts for the old terraced dwellings and semi-detached and corner dwellings in each heating strategy. This would mean that the effect that the selection of other insulation material would have had on the final LCA results would be limited.

In order to model the CO2-equivalent emissions from the consumption of hydrogen gas, this study has assumed that green hydrogen was available by 2030 and would be the only source of hydrogen that will be used at this time. Due to the many uncertainties about the production of hydrogen gas, it is likely that in reality other types of hydrogen gas are used if it is decided to use hydrogen gas as an energy carrier for the built environment. These other ways of producing hydrogen gas are likely to come with more CO2-equivalent emissions, as they use fossil fuels for the electrolysis of hydrogen gas. This would mean that the LCA results would be negatively influenced, and that there would be more CO2-equivalent emissions. However, as the hydrogen heating strategy is currently not preferred in any MCA scenario, under any of the applied weight sets, the potential differences in CO2-equivalent emissions would not negatively affect the outcomes of the MCA at the expense of the hybrid-hydrogen heating strategy too much.

8.3.3. The other assessments

This study has already touched upon the limitations of the other assessments in the discussion of the individual assessments in Chapter 6. However, we reflect upon the decision-making factor disruption during renovation once more, to underline the knowledge gap that exist in the assessment of this factor.

The assessment of disruption during renovation only considered private disruption. This means that all public disruption that can occur due to additional construction works that are required for certain heating strategies has been neglected. This public disruption can also be experienced by private individuals, who can be affected due to the extra noise, mess and nuisance comes along with these construction works. Future research on how this public disruption is experienced by private individuals could help to quantify the disruption due to these construction works. This disruption can then be accounted for in future MCA studies on the implementation of heating strategies.

8.4. Generalizing the results

The results of the MCA are specific for the case neighborhood. Every neighborhood in The Netherlands consists of a different composition of dwelling types, from different construction years, with different insulation levels. Moreover, the heating sources that can be used are depended on the geographical location and the availability of residual or aqua thermal sources as well. For other neighborhoods, other heat sources may be available, or due to the circumstances of the neighborhood different heating strategies may perform better than the ones that perform the best in this case study.

This means that it is not possible to generalize the findings from the case study to other neighborhoods in The Netherlands. However, what the results of the study did show is that the heating strategy that has the lowest total costs is not necessarily the best performing strategy when multiple decision-making factors are considered. Thus, the results indicate that when we also account for other decision-making factors than the ones that are traditionally used in decision support tools for the heat transition, insights can be obtained in the strategies that perform the best according to the preferences of the end-users.

Chapter 9. Conclusions and recommendations

In this chapter, we reflect back on the results from this study and we provide an answer to the main research question. In the first part of this chapter, the main findings from this research are presented and the research questions are answered. After this, the social and scientific contribution of this study is discussed. Finally, recommendations are given to the residents of the case study, and recommendations for future research are made.

9.1. Conclusions

In this study, we aimed to answer how alternative heating strategies can be assessed, while accounting for the life cycle of those heating strategies and for multiple household decision-making factors. In order to provide an answer to the main research question of this study, several sub-questions were formulated. In this chapter, we will provide an answer to these sub questions. After this, a final answer is provided to the main research question.

Sub question 1: Which methods and tools are currently used to asses alternative heating strategies and what is missing in these methods and tools?

In this study, we used a literature review to identify which methods and tools are currently used to assess alternative heating strategies in The Netherlands. We found that different decision-making support tools exist to evaluate heating strategies. These tools are mainly used to find cost-effective solutions, and in some cases, they also consider CO2 emissions over the use stage. However, emissions that occur due to the production and decommissioning of the required heating systems are often excluded from the calculations. Thus, we found that a life cycle perspective is missing in these tools.

Furthermore, we found that besides costs and CO2 emissions, other factors also play an important role in the decision-making process of residents. By reviewing literature, we identified several decision-making factors that play an important role in the decision-making process of household regarding alternative heating strategies.

Sub question 2: How to apply these tools and methods to support decision-making for the heat transition in a neighborhood?

Based on a literature review, we concluded that multi-criteria analysis can be an adequate method to assess heating strategies on more decision-making factors than economic and environmental ones. As a life cycle perspective is generally not considered in multi-criteria analysis studies, we integrated a life cycle perspective in the analysis of alternative heating strategies. In this way, a more complete overview of the impact and emissions of the heating strategies was presented, which can support decision-makers in the selection of heating strategies. Therefore, in this research a life cycle perspective was included in a multi-criteria analysis of alternative heating strategies to account for all impacts that occur over the life cycle of the identified heating strategies.

Moreover, we conducted an interview with an academic expert to validate the selection of five different decision-making factors; total costs, CO2-equivalent emissions, disruption during renovation, reliability of experts and occupation space. These decision-making factors were then individually assessed for six alternative heating strategies. The results of these individual assessments were then combined in a multi-criteria analysis model.

Sub question 3: How do alternative heating strategies perform in a specific neighborhood, when the life cycle of those heating strategies is accounted for and multiple decision-making factors are considered?

In order to provide an answer to sub question 3, we draw conclusions on the results of the individual assessments, as well as the survey results. These results were combined in the final multi-criteria analysis, of which the results will be used to provide an answer to this sub question.

First, by conducting an life cycle cost assessment, insights were presented on how the net present values of different alternative heating strategies compare to each other. This assessment showed that the all-electric heating strategy has the lowest net present value for all representative dwellings in the neighborhood. This strategy shows slightly lower net present values for all dwelling types than the low temperature district heating and hybrid-green gas strategies. It is worth mentioning that even though these strategies result in the lowest net present values over the course of 30 years, they have the highest initial investment costs out of all strategies. This is due to the fact that (hybrid) heat pumps need to be installed and emitting systems in the dwellings need to be replaced to be suitable for low temperature heat emission.

Additionally, the old representative dwellings need to insulate their dwellings to an energy label of B, in order to reduce their energy demands. These insulation measures come with additional high investment costs. Several scenario analyses have also been performed to see how the results are affected by a change in energy prices and applied discount rate. These scenarios did not show any differences in the preferred heating strategy, as the all-electric strategy has shown to have the lowest net present value for all dwelling types under each different scenario.

Second, a cradle-to-gate life cycle assessment was conducted, to gain insight in the total CO2-equivalent emissions that are occurring when the selected heating strategies are implemented. The results have shown that with the current CO2 emission factor of the Dutch electricity mix, the middle temperature district heating strategy resulted in the lowest amount of equivalent emissions. We found that the all-electric strategy performed the worst out of all alternative heating strategies (other than the reference strategy).

When the CO2 emission factor decreased due to an increased amount of renewables in the electricity mix, the low temperature district heating strategy became the strategy with the lowest overall emissions. The all-electric strategy, which performed relatively poor when the current CO2 emission factor was applied, became the strategy with the second lowest overall emissions.

Third, several other assessments have been performed to assess the impact of other decision-making factors that play a role in the decision towards selecting an alternative heating system. Assessment of the in-house disruption during renovation has demonstrated that the all-electric, low temperature district heating, and both hybrid heating strategies will come with the highest disruption time. In-house disruption was the lowest for the reference strategy and the middle temperature district heating strategy.

Assessment of the occupation space of the different installations that were required for each heating strategy has demonstrated that the middle temperature district heating strategy required the least amount of space. In this strategy, current radiators can still be used and the high efficiency boiler is replaced by a slightly smaller heat exchanger to connect to the district heating network. The all-electric and low temperature district heating strategies required the highest amount of space, due to the placement of heat pumps, buffer tanks and low temperature radiators.

Several quality registers were consulted to measure the availability of experts, which was used as a proxy-variable to measure the reliability of experts. Results of this assessment have shown that there are a sufficient amount of certified contractors that can place heating installations and apply insulation measures that are required for all heating strategies. However, as hydrogen gas is currently not used in hybrid heat pumps and the gas network, it remains uncertain if contractors would require additional training and certifications in order to install and maintain these installations.

Fourth, a survey has been conducted among the residents of the case study. The survey results showed that a majority of respondents feel that they do not have enough information to make a decisions on an alternative heating strategy. Additionally, the respondents indicate to be rather indifferent about the different heating strategies. Out of the current opinion of the respondents, it was not possible to identify which of the heating strategies the respondents currently prefer. What the survey results do show however, was which decision-making factors the residents consider as most and least important. These results show that the residents considered total costs as the most important factor, followed by CO2 emissions. Disruption during renovation was considered as the least important factor for the respondents of the survey.

Finally, by supplementing the survey results with additional literature, several sets of weights were designed and multi-criteria analysis calculations have been performed. Results of the multi-criteria analysis showed that depending on the applied weights, the all-electric and middle temperature district heating strategies performed the best for all types of dwellings. The middle temperature district heating strategy performed well under all applied sets of weights, as it performed relatively well on CO2-equivalent emissions, occupation space and reliability of experts. When the discount rate increased, middle temperature district heating also became more favorable in sets of weights where high weights were assigned to total costs.

The all-electric strategy performed well when high weights were assigned to total costs, as it has the lowest net present value out of all heating strategies. When the multi-criteria analysis accounted for a decreasing CO2 emission factor, the all-electric strategy also became the most preferable option for several representative dwellings when high weights were assigned to the CO2 emissions.

Sub question 4: What can we learn from this specific case study for the heat transition in other neighborhoods in The Netherlands?

We can conclude that the results of the performed multi-criteria analysis are specific for the case neighborhood. However, the results of the study show that the heating strategy that has the lowest total costs is not necessarily the best performing strategy when we also consider other decision-making factors than money. When we account for other decision-making factors than the ones that are currently used in decision support tools for the heat transition, other heating strategies may be preferred by the end-users of the heating strategies.

Main research question: *How to assess alternative heating strategies in neighbourhoods in The Netherlands while accounting for the life cycle of those heating strategies and for multiple household decision-making factors?*

This research has shown that multi-criteria analysis can be used to include different household decision-making factors in the assessment of alternative heating strategies from a life cycle perspective. With multi-criteria analysis, we can include different sets of weights, to gain insight in how alternative heating strategies compare with each other based on different household decision-making factors. We validated a selection of household decision-making factors and of alternative heating strategies with academic experts. By doing so, we tried to ensure that the opinions of households on the importance of the decision-making factors were accurately captured, and that heating strategies were assessed that are practically suitable to be eventually applied in the case neighborhood.

The multi-criteria analysis has demonstrated that there is no single most preferred outcome for the case neighborhood. This means that the heating strategy with the lowest total costs for the end-users, is not necessarily the most preferred alternative heating strategy. The multi-criteria analysis will show the preferred heating strategy for the applied set of weights. By assessing alternative heating strategies on different factors, while making use of weights based on the preferences of residents, insights can be gained in the heating strategies that are actually preferred by residents.

The multi-criteria analysis model provides information that can be used as a conversation starter within the neighborhood, and potentially with other stakeholders in the heat transition, to inform all residents about the differences in strategies, and the alternatives that shows preferable outcomes under specific circumstances. The combination of the multi-criteria analysis results with these conversations should provide the case with additional information which they can use in their plans to implement an alternative heating strategy.

9.2. Scientific contribution

This study aimed to contribute to the scientific literature on multi-criteria analysis by implementing a life cycle perspective to consider the emissions of heating strategies beyond the operation stage. In multi-criteria analysis studies, environmental criteria have been included, but these were merely limited to the direct energy consumption (Lizana et al., 2016; Seddiki et al., 2016; Yingkui Yang et al., 2018). This study has demonstrated that the operation phase is the overall highest contributor of CO_2-equivalent emissions, and that including the production and decommissioning stage in a life cycle assessment did not lead to any significant change in total emissions. However as this study only looked into one impact category, a recommendation was made to see how these results differ if other impact categories are considered in the life cycle assessment as well.

In this study, end-users were considered the stakeholder of main interest. Therefore, decision-making factors were selected for the multi-criteria analysis that are perceived as important by this specific group. By including the decision-making factors of the end-users, and considering their relative importance, alternative heating strategies were compared. In currently applied models and tools, generally only the cost component is considered in the assessment of different heating strategies. This study has demonstrated that when multiple factors other than costs are considered, other heating strategies than the ones with the lowest costs, can be considered as the most preferred alternatives. Future research should indicate if the current approach would show similar results for other neighborhoods in The Netherlands.

9.3. Societal contribution

The multi-criteria analysis results demonstrated that the individual preferences of the end-users can lead to different preferred heating alternatives. This means that the strategies that have the lowest overall costs may not be the most desired alternatives of the end-users. This is relevant information for municipalities, who are in the process of designing visions and preparing plans for the thermal energy transition in their municipalities.

Even though the life cycle perspective has shown that including product life cycle stages other than the operation phase does not significantly contribute to the overall CO_2-equivalent emissions, this underlines the importance of increasing the amount of renewables in the Dutch energy mix. The scenario analysis has shown that decreasing the CO2 emission factor of the electricity mix leads to significant changes in the overall CO2 emissions of the different heating strategies. Besides reducing the energy demand, moving away from fossil energy to fuel the energy demand has been shown once again to reduce the amount of emissions from the residential sector.

9.4. Recommendations

9.4.1. Recommendations for the case residents

In this study, it was shown that including more than one decision-making factor in an assessment of heating strategies can change the heating strategy that outperforms the rest. For example, if heating strategies are assessed only based on their financial costs, the heating strategy would the lowest costs would naturally rank best. In contrast, when including decision-making factors such as CO2 emissions, disruption during renovation, occupation space, and availability of experts, a different heating strategy might rank best.

However, there were two constants throughout this study. First, the identification and validation of heating strategies for representative dwellings indicates that, depending on the selected heating strategy, an energy label of D or B would be necessary. An energy label of D would be necessary for a connection to a potential middle temperature district heating network. Other heating strategies that do not consume natural gas would require an energy label of B. Second, under the assumptions of this study, we found that in all the scenarios that we tested, either the all-electric or the middle temperature district heating network outperformed the other strategies that did not use natural gas. Therefore, findings suggest that further exploring these two strategies could be promising.

The case residents are encouraged to use this work to discuss potential heating strategies in their neighborhood. They can identify a representative dwelling that is close to their own dwelling's situation, identify a set of weights that best represent their own preferences, and use the set of weights to compare how heating strategies would rank.

However, it must be noted that although representative dwellings have characteristics that are present in dwellings in the neighborhood, they are not necessarily an accurate representation of the actual dwellings. As this model was run for representative dwellings, the findings from the model are not to be interpreted to match individual dwellings in the neighborhood. After residents have received more specific information on their individual dwellings, they can compare if the model approximates the investment costs correctly. Therefore, results of this study are indicative of potential heating strategies and potential costs, but should at all times be validated with the corresponding experts for each specific situation. For example, additional information could be obtained from contractors since the investment costs that were used in this model can vary for specific individual houses.

Additionally, there is uncertainty about the project fee from district heating networks. Additional end-user costs in the form of project fees may significantly change the comparison of heating strategies based on what the number would be in reality. Therefore, extra information should be obtained on these costs to get a better picture of how these costs can potentially be charged to the end-users.

9.4.2. Recommendations for future research

Even though several recommendations for future research have been made in the discussion section, several other aspects for future research have been identified. Future research could look into the accuracy of the proposed model, by assessing the variables and assumptions that were made in this study, as these were not validated during the research. Additionally, research could be performed on the specific costs of district heating networks in the area of the case study. These findings could be used to improve the current multi-criteria analysis model, by providing a more accurate representation of district heating network costs.

As this research focused on thermal energy, or heat, primarily, individual energy generation options, such as solar panels were left out of the scope of the research. As the results of this research have shown that energy consumption has a high contribution in both the total costs and CO2-equivalent emissions, it would be interesting to see how the results of the multi-criteria analysis alter when individual, or collective, energy generation is considered.

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Appendix A. Survey summary

This appendix is an overview of questions and answers from the survey. After removing invalid responses and responses from homeowners whose dwellings use natural gas, the sample size was 32. Note that respondents were able to leave questions unanswered and that the percentages in each question are based on the number of responses received for that particular question. Therefore, not all percentages are representative of the entire sample.

Target population

The population of interest for the survey were the residents from the case study, that were at least 18 years old, and that could make decisions regarding renovation of their dwellings. By agreeing with the openingstatement of the survey, respondents confirmed that they were at least 18 years old and were able to make renovation decisions.

Sample size

The research sample consists of residents of the old area of the case neighborhood. These people are all homeowners and are thus able to make renovations to their dwellings. Note that since there are no respondents from the 'new' area of the neighborhood, results are not necessarily representative of the entire neighborhood.

Cleaning data

The survey had 35 responses. One of these responses was completely blank and was therefore marked as invalid and removed from the sample. The resulting 34 responses are equivalent to a response rate below 20%. Most of the respondents provided answers to all questions, but in some cases, some answers were left blank.

From the 34 respondents, two respondents indicated that they did not use natural gas to heat up their dwellings. The answers from these two respondents were excluded in the analysis of the survey, as this was not the group of interest for this research. This led to a sample size of 32.

Several answers were invalidated or had information removed. In some responses, question 14 and question 16 were incorrectly filled in. These responses either did not contain values within the required numerical range, or they identified the same factor as both the most important and the least important factor. A total of 16 responses were removed for this reason. Moreover, in question 6, one respondent filled in personal contact information. Following the data management plan, personal contact information was immediately deleted by the research team.

Q1 - Vraag 1. Bent u een deelnemer aan het project [NAME]? (N=32)

Approximately 71% of respondents from the survey are involved in the local sustainability project, while 29% of respondents are not involved in this project.

Q2 - Vraag 2. In wat voor type woning woont u? (N=32)

Results of this question show that most respondents live in terraced houses, followed by other types of semi-detached or detached houses.

Q3 - Vraag 3. Wordt uw woning momenteel verwarmd door middel van aardgas? (N=31)

Two non-natural gas dwellings were filtered out. Therefore, all respondents use natural gas to heat up their dwelling.

Q4 - Vraag 4. In welke mate bent u het eens met de volgende stellingen (N=32 and N=31):

- Ik heb me verdiept in verschillende alternatieve aardgas-loze warmtesystemen die mogelijk mijn huidige warmtesysteem (CV/HR-Ketel op aardgas) zouden kunnen vervangen
- Ik heb genoeg informatie om een keuze te maken voor een alternatief warmtesysteem

In the project group, 43% of respondents have indicated that they did not conduct any research on alternative heating systems. In the non-project group, 56% of respondents have indicated that they did not conduct research on alternative heating systems.

In the project group, 78% of the respondents stated that they do not think that they have enough information to make a decision, as opposed to 38% of the non-project group. Of the total respondent group, 68% stated that they do not have enough information to make a decision.

Q5 - Vraag 5. Ik heb via de volgende manieren onderzoek gedaan naar verschillende alternatieven om mijn warmtesysteem te vervangen (meerdere opties mogelijk) (N=32)
A wide variety of information sources are consulted. Governmental websites are consulted by 61% of respondents, while 31% of the respondents rely on conversations with neighbors and 28% of the respondents make use websites from commercial parties, or conversations with friends and family. The other options are selected by less than 16% of the respondents. From the respondents, 38% state that they have done no research at all.

Q6 - Vraag 6. Ik heb me verdiept in de volgende optie(s) om mijn huidige warmtesysteem te vervangen (meerdere opties mogelijk) (N=32)
About 65% of respondents from the project group indicate that they did not do research on any of the mentioned heating systems. For the non-project group, 55% indicate that they did not do research on any of these heating systems.

Q7 - Vraag 7. Ik heb mijn woning reeds geïsoleerd tot energielabel B of hoger (N=32)
Out of all respondents, 16% state that their dwelling has an energy label of B or higher. Half of the respondents state that their energy label is lower than B. Nearly 34% state that they do not know whether their energy label is higher than B or not.

Q8 - Vraag 8. In welke mate bent u het eens met de volgende stellingen: (N=27 and N=26)
- Ik heb me verdiept in verschillende alternatieven om mijn woning (verder) te isoleren
- Ik heb genoeg informatie om een keuze te maken voor verschillende (extra) isolatie-maatregelen die ik kan treffen in mijn woning

Approximately 30% of responses from the project group state that they did not conduct any research on insulation measures, compared to 14% of the responses of the non-project group.

From the project group, 50% of the respondents state that they do not have enough information to make a decision regarding insulation measures. Note than in the non-project group, none of the respondents indicated not having enough information.

Q9 - Vraag 9. Ik heb via de volgende manieren onderzoek gedaan naar verschillende alternatieven om mijn woning te isoleren (meerdere opties mogelijk) (N=29)
Similar to question 5, a variety of information sources are consulted. Of all respondents, 48% state that they make use of governmental websites to find information about insulation measures, 44% state that they make use of websites from commercial parties. Moreover, 40% of respondents have conversations

with their neighbors and 28% of the respondents state that they have not done any research into insulation measures.

Q10 - Vraag 10. Ik heb me verdiept in de volgende manieren om mijn woning te isoleren (meerdere opties mogelijk) (N=32)

From the project group, 30% of the respondents state that they have not done any research on any of the mentioned insulation measures. From the respondents of the non-project group, 11% state that they have not done any research on any of the mentioned insulation measures.

Q 11 - Vraag 11. Wat is uw mening ten opzichten van de volgende verschillende verwarmingsmogelijkheden voor woningen? (N=RANGE 29-32)

Een all-electric optie met een individuele warmtepomp
Een warmtenet met lage temperatuur bron via Warmte-Koude Opslag (WKO)
Een warmtenet met lage temperatuur bron via restwarmte
Een warmtenet gevoed door een hoge temperatuur bron via Geothermie
Een warmtenet gevoed door een hoge temperatuur bron via industriële restwarmte
Groen gas in combinatie met een hybride warmtepomp (HR-ketel met groen gas springt bij op heel koude dagen)
Waterstof gas in combinatie met een hybride warmtepomp (HR-ketel met waterstof springt bij op heel koude dagen)

Most respondents stated to have a neutral to positive opinion on most heating strategies. The respondents from the project group stated to have the most negative opinion about the all-electric strategy, as 25% of these respondents report to have a negative opinion towards this strategy. A share of 41% of the respondents of the project group reported not knowing what a hybrid strategy with hydrogen gas entails.

From the non-project group ,75% of the respondents stated to have a more positive opinion towards the hybrid strategy with hydrogen gas (opposed to 14% of the project group). For the other strategies, the percentual differences between the amount of positive opinions of these groups for other answers were less than 25%.

Overall: The all-electric strategy seems to be one of the least desired strategies, as 24% of respondents state that they have a negative opinion towards this strategy. For any strategy, approximately 20-25% of respondents do not know what they entail. This increase to approximately 35% for the hybrid-hydrogen strategy.

Q12 - Vraag 12. In hoeverre vindt u de volgende redenen belangrijk bij het nemen van een beslissing om te renoveren (N=30)

Totale kosten
Vermindering van CO2 productie
Ruimte die een warmtesysteem inneemt
Betrouwbare vaklui

Gedoe tijdens de renovatie

In both the project and non-project group, total costs are stated the most often as very important (50%). All factors are perceived as relatively important (over 50% in all cases). No extreme differences can be observed between the answers of the two demographic groups.

Q13 - Vraag 13. Welke van onderstaande redenen zou u het meest belangrijk vinden als u zou overstappen op een nieuw warmtesysteem? (N=31)
Total costs are identified as the most important factor (65% in total) for both the project group (68%) and the non-project group (56%). CO_2 emissions are mentioned in 19% of the responses (18% of the project group and 22% of the non-project group).

Occupation space is mentioned by 10% of respondents state as the most important factor (9% of the project group and 11% of the non-project group). Reliable experts and disruption during renovation are mentioned in 3% of responses.

Q14 - Vraag 14. Geef op een schaal van 1 tot 9 aan hoe veel minder belangrijk u de andere redenen vindt, ten opzichte van deze meest belangrijke reden: (N=16)
Several of the responses to this question were invalidated due to incorrectly filled in answers. These responses either did not contain values within the required numerical range, or they identified the same factor as both the most important and the least important factor. Therefore, no specific conclusions can be drawn from the received responses.

Q15 - Vraag 15. Welke van onderstaande redenen zou u het minst belangrijk vinden als u zou overstappen op een nieuw warmtesysteem? (N=31)
Disruption is perceived as the least important factor (48% in total) by the respondents of the project group (45%) and by the respondents of the non-project group (56%). Reliable experts are selected as least important in 16% of responses. Total costs and occupation space are selected in 13% of responses. 10% of respondents select CO_2-emissions as the least important factor.

Q16 - Vraag 16. Geef op een schaal van 1 tot 9 aan hoe veel belangrijker u de andere redenen vindt, ten opzichte van de minst belangrijke reden: (N=16)
Several of the responses to this question were invalidated due to incorrectly filled in answers. These responses either did not contain values within the required numerical range, or they identified the same factor as both the most important and the least important factor. Therefore, no specific conclusions can be drawn from the received responses.

Appendix B. Overview of heating strategies included in the analyzed calculation tools

This appendix presents an overview of the heating strategies and scenarios that are included in the earlier mentioned calculation tools. The information in this appendix is based on background reports and studies that have been performed with corresponding tools. For these models, it is described which heating strategies are considered and what the potential heat sources are for these strategies. This appendix describes which strategies there are for any neighborhood in general, and section 4.2 describes which of the defined strategies are relevant for the case study specifically.

In this appendix, an indication of costs for different technologies is presented in the description of the Vesta MAIS and Startanalyse models. This is presented to give an initial idea of the costs of different systems. Further elaboration on the costs of different heating strategies can be found in the LCC assessment.

B.1. Startanalyse and Vesta MAIS

The Startanalyse, is a techno-economic analysis built upon the Vesta MAIS model from PBL. Therefore, these models consider the same heating strategies. In this analysis, five renewable heating strategies are identified, which are integrated in the Vesta MAIS model. These five strategies are presented in a background report that is published by PBL (Hoogervorst et al., 2020). In the Vesta MAIS model several cost indicators are used to describe the different strategies. The values for these cost indicators have a lower and upper limit, but for calculations, the middle value is chosen. Any cost indicator that is mentioned in this appendix represents the middle value as described by Hoogervorst et al. (2020). The following five strategies are analyzed:

All-electric

This strategy uses individual (combi)heat pumps for space- and tap water heating, in combination with a local heat source. All dwellings need to be isolated up to energy label B, with an *Rc* (insulation-level) of approximately 2.5. Within dwellings, low temperature radiators are applied, as floor heating is costly and not always feasible (due to practical and technical limitations). The investment costs for these low temperature radiators are €1208 per dwelling Hoogervorst et al., 2020, p. 12. For this strategy, the electricity grid needs to be strengthened, as the capacity of the current grid is not high enough for this increase in electricity demand (Hoogervorst et al., 2020, p. 11). The costs for the reinforcement of the grid is considered in this model by taking the current length of the low voltage cables and multiplying it by a cost indicator for reinforcing the grid per meter (Schepers et al., 2019).

Either air-water heat pumps or water-water heat pumps can be used in this strategy. Air-water heat pumps have a seasonal performance factor (SPF) of 3.81 for a dwelling with an energy label of B. The water-water heat pump performs slightly better and has a SPF of 4.07. However, the investment costs of the water-water heat pump are higher than for the air-water heat pump (€6,544 and €4,998 respectively) (Hoogervorst et al., 2020, p. 12-14).

District heating with middle temperature (MT) source

In this strategy, the thermal energy demand is met through connecting with a heat network from a collective middle temperature-thermal source (70°C). Again, all dwellings are renovated/isolated until at least label B. There are four variants of this strategy:

1. Using a residual heat source. To meet the peak demand, a back-up green gas fired plant is required.
2. Geothermal heat. To meet the peak demand, a back-up green gas fired plant is required. This variant is for residential areas that do not have promising sources for geothermal energy and

thus have transport costs as they get the energy from areas that do have a promising geothermal source.
3. The same as variant 2. But here the area has a promising geothermal source.
4. Bio-CHP. The CHP is fed with green gas from a biomass fed green gas plant.

The costs that are considered in this scenario are costs for the construction of the heat network (805 €/m), connection costs (depending on the length of the connection pipe) and investment costs (Hoogervorst et al., 2020, p. 15). Investment costs for residual heat vary between 162.5 and 1300 €/kW. The investment costs for a geothermal installation are 1694.5 €/kW, and for Bio-CHP it is 415 €/kW.

District heating with low temperature (LT) source
In this strategy, the thermal energy demand is met through connection with a low temperature (30-50°C) heat source. As this is a too low temperature to be used as hot tap water or for space heating, collective or individual solutions should get the temperature to MT level. There are 5 variants available in this scenario. In all variants, dwellings should have isolation of at least label B.

1. (Industrial) residual heating from a 30°C source. In this variant, all dwellings get an individual combi heat pump for space heating and warm tap water, and LT-radiators are required. To ensure enough thermal energy during cold winter days, a buffer tank with seasonal storage is placed. In this variant the grid needs to be strengthened. Individual heat pumps in this scenario have a SPF of 6.1 at an energy label of B for space heating (Hoogervorst et al., 2020, p.21). The SPF for hot tap water is 2.5. The investment costs for an individual heat pump, including buffer tank and strengthened electricity connection are €4500 (Hoogervorst et al., 2020, p.21).
2. (Industrial) residual heating from a 30°C source. In this variant, a collective heat pump raises temperature to 70°C. Therefore no individual heat pumps are required and the grid does not need to be strengthened. The investment costs for this collective heat pump are 547.5 €/kW. There is also a buffer tank required which costs €1000 per dwelling (Hoogervorst et al., 2020, p.21).
3. (Industrial) residual heating from a 30°C source. In this variant, a collective heat pump raises temperature to 50°C. Dwellings need LT-radiators. For warm tap water, a booster heat pump is required in the houses. The investment costs for a booster heat pump, including buffer tank and strengthened electricity connection are €700 (Hoogervorst et al., 2020, p.21). No further grid changes are required in the neighborhood in this scenario.
4. Aquifer Thermal Energy Storage (ATES) – Aqua thermal energy, delivery at 50°C. A collective thermal energy storage with a dry cooler for regeneration is applied. The investment costs of an ATES-source is 115 €/kW (Hoogervorst et al., 2020, p.21). Furthermore, a collective heat pump is used and dwelling need LT-radiators. For warm tap water, a booster heat pump is required in the houses. No grid changes are required in the neighborhood.
5. ATES – Aqua thermal energy, delivery at 70°C. Low temperature heat from the ATES is collectively boosted to 70°C at the thermal energy storage with a heat pump. Therefore, current applied HT-radiators are sufficient for the dwellings. For regeneration of the ATES-source, heat is extracted from surface water. The investment costs for the heat exchanger is 220 €/kW (Hoogervorst et al., 2020, p.21).

Renewable gas with hybrid heat-pump
Hybrid heat pumps combines a small electric heat pump with HR boiler. The SPF of this hybrid heat pump is 4.4 (Hoogervorst et al., 2020, p.29). The investment costs for a hybrid heat pump are €3819.44. In cold days, the HR boiler makes up for the increase in demand. Due to lower power of the heat pump,

the grid does not need to be strengthened in most cases. This strategy assumes a biomass-fired plant that produces renewable gas.

Renewable gas with HR boiler
Space heating and warm tap water both come from HR boilers. The investment costs of an HR-boiler are €1775.80 per dwelling (Hoogervorst et al., 2020, p.27). As the supplied heat is 50°C, LT-radiators are needed in the dwellings. This strategy assumes a biomass-fired plant that produces renewable gas.

B.2. Caldomus
The Caldomus model differentiates a total of 15 different scenario's. These scenario's consist of three different renovation packages (Mans et al., 2017).

- In renovation package *R*, current dwellings are isolated with practical measures that do not require substantial modifications to the dwelling. Examples of applied technologies in this scenario are cavity wall insulation, insulating the inside of the roof and underneath the floor and replacing windows with HR++-glass.
- In renovation package *R+*, the outer layer of the dwelling is renovated to an insulation level (Rc) of 3.5 m^2K/W.
- Renovation package *R++* consists of renovations that take the dwelling to an insulation-value in line with the insulation requirements of newly built homes. For the roof, façade and floor this leads to Rc-values of 6, 4.5 and 3.5 m^2K/W respectively. Additionally, triple HR++ windows are applied in dwellings in this scenario.

Depending on dwelling characteristics (e.g. apartments, or ground-level dwellings) and the chosen heat supply system, the exact renovation measures are different per strategy. When it comes to the heat supply, in the Caldomus model, 5 different infrastructures are identified (Mans et al., 2017).

Gas
In this strategy, the current gas grid remains in use and biogas or hydrogen can be sed as energy carriers. Depending on the amount of PV in the renovation packages R+ and R++, the electricity grid needs to be strengthened.

Electricity

- *Hybrid*: In the hybrid strategy, the gas infrastructure remains unchanged. Due to the reduced heat demand by the implemented renovation packages and an electrical heat pump that takes care of the base load. The gas grid acts as a back-up in peak demand times.
- *All-electric*: In this strategy, the heat demand is fulfilled with electric heat pumps. Depending on the renovation package, the electricity grid needs to be strengthened.

High-temperature district heating
The heat demand is fulfilled with heat from a district heating network. Two variants are included in the model; one with a high temperature supply of 70°C that can also be used for tap water, and one with a low temperature supply (<50°C) for which a heat pump is required to heat up the tap water. Because of cooking on electricity and the required heat pump at low temperature supply, the electricity grid needs to be strengthened.

Low-temperature district heating
Caldomus does not specify the low temperature sources in their model as each neighborhood has different possibilities. Heat sources could be: Geothermal energy, ground coupled heat exchanger,

residual heat, the sewer or surface water. As the heat supply of these sources is lower than 50°C, a heat pump with a boiler is required to supply the dwellings with hot tap water.

B.3. CEGOIA

The CEGOIA model distinguishes several sustainable heating techniques to model the costs of the total heat chain in a neighborhood. An example of these techniques are the following, that have been used in a study by Leguijt, Schepers, Schuurbiers, and Blommerde (2016) to identify opportunities for the thermal energy transition in Haarlem:

- HR-boiler that runs on biogas
- Hybrid heat pump working with outside air
- Hybrid heat pump working with ventilation air
- Electric air-water heat pump
- Electric ground heat pump
- Wood pellet stove
- Residual heat
- Geothermal energy
- Neighborhood CHP
- Ground-coupled heat exchanger

These techniques, among others, can be categorized in seven main strategies that are further described in Schilling, Naber, and Schepers (2019). These strategies are also considered in the CEGOIA model.

Biogas

CEGOIA considers the use of biogas in combination with an HR-boiler or with a hybrid heat pump. CE Delft argues that the biggest problem of biogas is its availability. The potential of biogas for 2050 is 14% of the current gas consumption.

Hydrogen

Hydrogen can be produced by firing natural gas. When the CO2 emitted from this production process is captured through Carbon Capture & Storage (CCS), hydrogen can be produced ‘climate neutral’. This results in so called blue hydrogen. Hydrogen can also be produced with electricity from wind or PV, or through gasification of biogas. This leads to green hydrogen, which does not require CCS.
When dwellings are renovated to 100% hydrogen, an HR-boiler or hybrid heat pump is required. On the level of the dwelling, no further renovations are required. Though, some changes to the current gas grid are required, as the pipes need to be adjusted to be suitable for hydrogen transport. In recent reports, CE Delft does not take a 100% hydrogen scenario into consideration, as the technology is still in development (Schilling et al., 2019).

Electric heat pump

Electric heat pumps can be individually applied by homeowners. Though, implementing a heat pump requires a significant isolation level of at least energy label B. Further adaptations are switching to electric cooking systems and LT-radiators. When a large amount of dwellings and other buildings switch to an electric heat pump, it is possible that the electricity grid needs to be strengthened.

Wood pellet stove

A wood pellet stove is another individual solution that uses biomass (wooden pellets) as a heating source. A disadvantage of this technology is the amount of particulate matter that is emitted by burning these pellets. Large scale application on neighborhood level cannot be considered as a desirable solution.

High temperature district heating
According to Schilling et al. (2019), a high temperature district heating network requires new infrastructure to transport water of at least 80°C. This water is heated by means of a collective heating source, such as geothermal or residual heat. On a dwelling level, only HT-radiators and electric cooking systems are required. Extra insulation efforts are not required, but can be desirable considering thermal comfort levels.

Low temperature district heating
According to Schilling et al. (2019), low temperature district heating requires new infrastructure to transport water between 35°C and 55°C. This water is heated from low temperature heat sources (e.g. heat from water treatment plants and datacenters). For LT-district heating, the dwelling needs to be renovated to at least energy label B. Additionally, LT-radiators and a separate provider of hot tap water are required, and the cooking systems needs to become electric.

Middle temperature district heating
According to Schilling et al. (2019), middle temperature district heating requires new infrastructure to transport water between 55°C and 80°C. The heat source of this network comes from LT-sources(e.g. shallow geothermal and residual heat), and is brought to the right temperatures by means of a collective heat pump. Because a heat pump is used to heat up the water to temperatures up to 80°C, no extra steps have to be undertaken for hot tap water and current HT-radiators are sufficient. On a dwelling level, at least energy label E is required. Additionally, a switch to an electric cooking system is required.

B.4. Warmte Transitie Atlas
Over Morgen considers five main strategies for the heat transition in their model, these strategies are further explained in a report of a performed study to visualize the heat transition for the municipality of Nijmegen (Over Morgen, 2018c).

HT- district heating
Over Morgen (2018c) considers district heating from sources with a temperature of at least 70°C as high temperature district heating. These heating networks can have different heat sources, such as geothermal or residual heat from industry.

LT – district heating
According to Over Morgen (2018c), low temperature district heating networks have a source temperature lower than 70°C. An example of a heat source is surface water. In LT district heating, a (collective) heat pump is required to get the desired temperatures in dwellings.

All-electric
All-electric systems require individual heat pumps and electric cooking systems. Extensive renovation of the dwellings is also required.

Renewable gas
Renewable gas requires the least amount of adaptations to the infrastructure and to the dwellings. However, due to the limited availability of this type of has, it is not seen as a large-scale solution for the heat transition.

Future solutions
Besides the four main strategies that other models also consider, Overmorgen also mentions future solutions. Solutions they mention are heat storage in special heating batteries, storage through "power to heat" heating networks and infrared radiation panels. Nonetheless, these technologies are still in the development stage and they stress the importance of implementing the other mentioned heating strategies.

B.5. Aardgasvrije wijken - DWA
DWA distinguishes two main strategies which are already applied in certain areas: district heating and all-electric. Further elaboration on these two strategies is given in a study of DWA in the municipality of Woerden. This study investigates possibilities to transition away from natural gas in Woerden. (Waagmeester, 2018).

District heating
In the district heating strategy, the heat supply in dwellings comes from a district heating network and dwellings need to switch to electric cooking systems.

- For high temperature district heating, no additional insulation measures need to be undertaken, but it can lead to lower energy use and thus lower costs for the end-users. HT-radiators are required, similar to current natural gas situations. Additionally, electric cooking systems are required.
- For low temperature district heating, a heat source of approximately 40°C is used. This requires additional insulation to dwellings and the implementation of LT-radiators.

All-electric
In this strategy, the dwellings need to be renovated and a heat pumps are installed. Depending on the situation, the electricity grid needs to be strengthened. DWA considers far-reaching, or as good as possible insulation measures in dwellings.

B.6. Energy Transition Model - Quintel
ETM is an energy model that is not specifically focusing on the built environment. However in the model, several inputs for space heating and hot water can be modified. The inputs for heat sources of heating networks that are integrated in the model (de Haan, 2020) are the following:

- Condensing combi boiler
- District heating (with listed sources: Solar thermal, geothermal, residual heat, imported heat and (biogas) CHP.
- Heat pump (air)
- Heat pump (ground)
- Hybrid heat pump (gas)
- Hybrid heat pump (hydrogen)
- Wood pellet stove
- Electric heater
- Gas-fired heater

B.7. Conclusion of the overview
From this overview can be concluded that the heating strategies that are included in the calculation tools are relatively similar. When it comes to heating strategies, four main strategies are identified. These

strategies are: Middle or high temperature district heating, low temperature district heating, all-electric and renewable gas. For the district heating strategies, the heat source can be different, depending on the available heating sources in the area of the neighborhood in which the network is constructed. For the renewable gas strategy, biogas or hydrogen, or a mixture of these two can be used as energy carriers.

The examined models also highlight the need for insulation measures. Especially in strategies that include electric heat pumps or low temperature district heating, the need for insulation in dwellings is high. Most of these models do not go into detail about the type of insulation that is required. The Caldomus model actually distinguishes between three different renovation levels, which would lead to different renovation and insulation measures according to the dwelling characteristics and the chosen heating strategy (Mans et al., 2017). However, specific insulation materials that would lead to the desired Rc-values depending on the chosen renovation package are not mentioned.

Appendix C. Energy demand per heating strategy

This appendix shows how the energy demands were calculated for each heating strategy.

C.1. All-electric.

	Building type							
	TH_old	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**Unit**	**Source**	**Calculation**
Old electricity consumption (kWh)	3041	3570	3381	4000	2760	kWh	Liander (2020)	
Old gas consumption (m3)	1756	2180	1256	1637	1059	m3	Liander (2020)	
Energy demand for cooking on natural gas	37	37	37	37	37	m3	CE Delft (2018a)	
Energy demand for cooking with induction	175	175	175	175	175	kWh	CE Delft (2018a)	
Theoretical electricity consumption after insulation (kWh)	3041	3570	3381	4000	2760	kWh	-	Equal to old consumption
Theoretical gas consumption after insulation (m3)	626	753	1256	1637	1059	m3	Milieucentraal (2019)	
Actual gas consumption after insulation + cooking renovation	1267	1572	1219	1600	1022	m3	-	Calculation according to Equation 3 – demand for cooking on gas
Energy required for heating (MJ)	40099	49765	38592	50624	32350	MJ	-	Actual gas consumption * LHV natural gas
Energy required for heating (kWh)	11139	13824	10720	14062	8986	kWh	-	Energy (MJ) / 3.6
Electricity required accounted for SPF of heat pump (kWh)	2924	3628	2814	3691	2359	kWh	-	Energy required for heating / SPF heat pump
Total electricity required (kWh)	6140	7373	6369	7866	5293	kWh	-	Energy for heating (kWh) + old elec. consumption

C.1.1. Variables used for calculations All-electric.

Variable	Value	Unit	Source
SPF Heat pump	3.81	Factor	Hoogervorst et al. (2020)
LHV natural gas	31.65	MJ/m3	Schepers et al. (2019)

C.2. LT.

	Building type							
	TH_old	SD&TC_old	TH_new	SD&TC_new	AP_new	Unit	Source	Calculation
OLD electricity consumption (kWh)	3041	3570	3381	4000	2760	kWh	Liander (2020)	-
OLD gas consumption (m3)	1756	2180	1256	1637	1059	m3	Liander (2020)	-
Energy demand for cooking on natural gas	37	37	37	37	37	m3	CE Delft (2018a)	-
Energy demand for cooking with induction	175	175	175	175	175	kWh	CE Delft (2018a)	-
Theoretical electricity consumption after insulation (kWh)	3041	3570	3381	4000	2760	kWh	-	Equal to old consumption
Theoretical gas consumption after insulation (m3)	626	753	1256	1637	1059	m3	Milieucentraal (2019)	-
Actual gas demand after insulation + cooking renovation	1267	1572	1219	1600	1022	m3	-	Calculation according to Equation 3 – demand for cooking on gas
Energy required for heating (MJ)	40099	49765	38592	50624	32350	MJ	-	Actual gas consumption * LHV natural gas
Energy required for space heating	31657	39288	30467	39966	25540	MJ	-	Energy required * share space heating
Energy required for tap water	8442	10477	8125	10658	6811	MJ	-	Energy required * share tap water
Energy demand for space heating	26909	33395	25897	33971	21709	MJ	-	Energy required for space heating * share own energy consumption space heating
Energy demand for hot tap water	5909	7334	5687	7460	4767	MJ	-	Energy required for tap water * share own energy consumption tap water
Energy consumption of heat pump (accounted for SPF)	6775	8408	6520	8553	5466	MJ	-	Energy demand / SPF heat pump
Energy supplied by DH-network (GJ)	7	9	7	9	6	GJ	-	Energy consumption / 1000
Increased electricity consumption	1882	2336	1811	2376	1518	kWh	-	Energy consumption heat pump (MJ) / 3.6
Total electricity required (kWh)	5098	6080	5367	6551	4453	kWh	-	Increased consumption

								+ Theoretical elec. consumption

C.2.1. Variables used in calculations for LT.

Variable	Value	Unit	Source	Assumption
Ratio mean actual energy savings/theoretical savings	0.4	Factor	Filippidou et al. (2019)	-
Share energy demand (excl. cooking) for space heating	0.79	Factor	Energievergelijken (2020)	Based on the ratio between the demand for space heating and tap water from Energievergelijken (2020)
Share energy demand (excl. cooking) for hot tap water	0.21	Factor	Energievergelijken (2020)	-
LHV natural gas	31.65	MJ/m3	Schepers et al. (2019)	-
SPF Heat pump for space heating	6.1	Factor	Hoogervorst et al. (2020)	-
SPF Heat pump for hot tap water	2.5	Factor	Hoogervorst et al. (2020)	-
Share own energy consumption space heating	0.85	Factor	Hoogervorst et al. (2020)	Adapted from share of consumption at 30 degree delivery
Share own energy consumption for hot tap water	0.7	Factor	Hoogervorst et al. (2020)	Adapted from share of consumption at 30 degree delivery

C.3. MT.

	Building type							
	TH_old	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**Unit**	**Source**	**Calculations**
OLD electricity consumption (kWh)	3041	3570	3381	4000	2760	kWh	Liander (2020)	-
OLD gas consumption (m3)	1756	2180	1256	1637	1059	m3	Liander (2020)	-
Energy demand for cooking on natural gas	37	37	37	37	37	m3	CE Delft (2018a)	-
Energy demand for cooking with induction	175	175	175	175	175	kWh	CE Delft (2018a)	-
Theoretical electricity consumption after insulation (kWh)	3041	3570	3381	4000	2760	kWh	-	Equal to old consumption
Theoretical gas consumption after insulation (m3)	1048	907	1256	1637	1059	m3	Milieucentraal (2019)	-
Actual gas consumption after insulation + cooking renovation	1436	1634	1219	1600	1022	m3	-	Calculation according to Equation 3 – demand for

								cooking on gas
Energy required for heating (GJ)	45.44	51.72	38.59	50.62	32.35	GJ	-	Actual gas consumption * LHV natural gas /1000
Total electricity required (kWh)	3216	3745	3556	4175	2935	kWh	-	Theoretical consumption + induction cooking demand

C.4. Hybrid Green gas.

	Building type							
	TH_old	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**Unit**	**Source**	**Calculations**
OLD electricity consumption (kWh)	3041	3570	3381	4000	2760	kWh	Liander (2020)	-
OLD gas consumption (m3)	1756	2180	1256	1637	1059	m3	Liander (2020)	-
Energy demand for cooking on natural gas	37	37	37	37	37	m3	CE Delft (2018a)	-
Energy demand for cooking with induction	175	175	175	175	175	kWh	CE Delft (2018a)	-
Theoretical electricity consumption after insulation (kWh)	3041	3570	3381	4000	2760	kWh	-	Equal to old consumption
Theoretical gas consumption after insulation (m3)	626	753	1256	1637	1059	m3	Milieucentraal (2019)	-
Actual gas consumption after insulation + cooking renovation	1267	1572	1219	1600	1022	m3	-	Calculation according to Equation 3 – demand for cooking on gas
Energy demand fulfilled by hybrid heat pump (MJ)	22055	27371	21226	27843	17793	MJ	-	Share of heat fulfilled by hybrid heat pump * (actual gas consumption * LHV Natural gas)
Electricity demand for hybrid heat pump (kWh)	6126	7603	5896	7734	4942	kWh	-	Energy demand / 3.6
Electricity demand accounted for SPF of heat pump (kWh)	1392	1728	1340	1758	1123	kWh	-	Energy demand (kWh) / SPF hybrid heat pump
Total electricity demand (kWh)	4608	5473	4896	5932	4058	kWh	-	Theoretical elec. consumption + electricity demand of heat pump
Energy demand fulfilled by HE-boiler (MJ)	18045	22394	17366	22781	14558	MJ	-	Share of heat fulfilled by boiler * (actual gas consumption * LHV Natural gas)

Total natural/green gas demand (m3)	570	708	549	720	460	m3	-	Energy demand of boiler / LHV Natural gas

C.4.1. Variables used in calculations for Hybrid Green Gas.

Variable	Value	Unit	Source
SPF Hybrid heat pump	4.4	Factor	Hoogervorst et al. (2020)
LHV Natural gas & Green gas	31.65	MJ/m3	Schepers et al. (2019)
Ratio mean actual energy savings/theoretical savings	0.4	Rate	Filippidou et al. (2019)
Share of heat demand fulfilled by hybrid heat pump	0.55	Rate	Schepers et al. (2019)
Share of heat demand fulfilled by HE-boiler	0.45	Rate	Schepers et al. (2019)

C.5. Hybrid Hydrogen.

	Building type							
	TH_old	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**Unit**	**Source**	**Calculations**
OLD electricity consumption (kWh)	3041	3570	3381	4000	2760	kWh	Liander (2020)	-
OLD gas consumption (m3)	1756	2180	1256	1637	1059	m3	Liander (2020)	-
Energy demand for cooking on natural gas	37	37	37	37	37	m3	CE Delft (2018a)	-
Energy demand for cooking with induction	175	175	175	175	175	kWh	CE Delft (2018a)	-
Theoretical electricity consumption after insulation (kWh)	3041	3570	3381	4000	2760	kWh	-	Equal to old consumption
Theoretical gas consumption after insulation (m3)	626	753	1256	1637	1059	m3	Milieucentraal (2019)	-
Actual gas consumption after insulation + cooking renovation	1267	1572	1219	1600	1022	m3	-	Calculation according to Equation 3 – demand for cooking on gas
Energy demand fulfilled by hybrid heat pump (MJ)	22055	27371	21226	27843	17793	MJ	-	Share of heat fulfilled by hybrid heat pump * (actual gas consumption * LHV Natural gas)
Electricity demand for hybrid heat pump (kWh)	6126	7603	5896	7734	4942	kWh	-	Energy demand / 3.6
Electricity demand accounted for SPF of heat pump (kWh)	1392	1728	1340	1758	1123	kWh	-	Energy demand (kWh) / SPF hybrid heat pump
Total electricity demand (kWh)	4608	5473	4896	5932	4058	kWh	-	Theoretical elec. consumption + electricity demand of heat pump
Energy demand fulfilled by HE-boiler (MJ)	18045	22394	17366	22781	14558	MJ	-	Share of heat fulfilled by boiler *

								(actual gas consumption * LHV Natural gas)
Total natural gas demand (m3)	570	708	549	720	460	m3	-	Energy demand of boiler / LHV Natural gas
Total hydrogen demand	149	185	144	188	120	kg	-	Total natural gas demand / LHV hydrogen gas

C.5.1. Variables used in calculations for Hybrid Hydrogen.

Variable	Value	Unit	Source
SPF Hybrid heat pump	4.4	Factor	Hoogervorst et al. (2020)
LHV Natural gas & Green gas	31.65	MJ/m3	Schepers et al. (2019)
LHV Hydrogen gas	121	MJ/m3	van Wijk and Hellinga (2018)
Ratio mean actual energy savings/theoretical savings	0.4	Rate	Filippidou et al. (2019)
Share of heat demand fulfilled by hybrid heat pump	0.55	Rate	Schepers et al. (2019)
Share of heat demand fulfilled by HR-boiler	0.45	Rate	Schepers et al. (2019)

Appendix D. Changes in ranking of LCC scenarios

The Tables below show how the ranking of the baseline LCC (left part) change when each scenario (right part) is calculated. The tables give a ranking from 1 to 7, with 1 representing the highest NPV, and 7 representing the lowest NPV. Changes in the rankings due to the applied scenarios are indicated in bold.

D.1. Changes in ranking when a new discount rate is applied.

	Discount rate									
	3.05%					4.50%				
	TH_old	SD&TC_old	TH_new	SD&TC_new	AP_new	TH_old	SD&TC_old	TH_new	SD&TC_new	AP_new
Reference strategy	1	1	4	3	5	**2**	1	**6**	**5**	**6**
All-electric	7	7	7	7	7	7	7	7	7	7
LT - District heating	5	6	5	6	4	5	6	**4**	6	4
MT - District heating	2	3	2	2	1	**3**	**4**	**3**	**2**	**2**
Hybrid - Green gas	6	5	6	5	6	6	5	**5**	**4**	**5**
Hybrid - Hydrogen - C	4	4	3	4	3	4	**3**	**2**	**3**	3
Hybrid - Hydrogen - NC	3	2	1	1	2	**1**	2	1	1	**1**

D.2. Changes in ranking when a natural gas price growth rate is applied.

	Natural gas price growth rate									
	3.00%					5.00%				
	TH_old	SD&TC_old	TH_new	SD&TC_new	AP_new	TH_old	SD&TC_old	TH_new	SD&TC_new	AP_new
Reference strategy	1	1	4	3	5	1	1	**1**	**1**	**1**
All-electric	7	7	7	7	7	7	7	7	7	7
LT - District heating	5	6	5	6	4	**6**	6	**6**	6	**5**
MT - District heating	2	3	2	2	1	2	3	**3**	**3**	**2**
Hybrid - Green gas	6	5	6	5	6	**5**	5	**5**	5	6
Hybrid - Hydrogen - C	4	4	3	4	3	4	4	**4**	4	**4**
Hybrid - Hydrogen - NC	3	2	1	1	2	3	2	**2**	**2**	**3**

D.3. Changes in ranking when a new electricity price growth rate is applied.

	Electricity price growth rate									
	2.00%					0.00%				
	TH_old	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**TH_old**	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**
Reference strategy	1	1	4	3	5	1	1	**3**	**2**	**3**
All-electric	7	7	7	7	7	7	7	7	7	7
LT - District heating	5	6	5	6	4	**6**	6	**6**	6	**5**
MT - District heating	2	3	2	2	1	2	**2**	**1**	**1**	1
Hybrid - Green gas	6	5	6	5	6	**5**	5	**5**	5	6
Hybrid - Hydrogen - C	4	4	3	4	3	4	4	**4**	4	**4**
Hybrid - Hydrogen - NC	3	2	1	1	2	3	**3**	**2**	**3**	2

Appendix E. Changes in ranking of LCA scenario

The Table below shows how the rankings between the results from the baseline LCA change when the CO2 emission factor of the Dutch electricity mix is decreasing, due to the integration of a larger share of renewables in the electricity mix. The Table presents values from 1 to 6, with 6 representing the lowest overall emissions, and 1 the highest overall emissions. Changes in the rankings due to the applied scenario are indicated in bold.

E.1. The change in ranking results due to the LCA scenario.

	CO2 emission factor of the Dutch electricity mix									
	Current electricity mix					Renewable electricity mix				
	TH_old	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**	**TH_old**	**SD&TC_old**	**TH_new**	**SD&TC_new**	**AP_new**
Reference strategy	1	1	1	1	1	1	1	1	1	1
All-electric	2	2	2	2	2	**5**	**5**	**5**	**5**	**5**
LT-District heating	5	5	5	5	5	**6**	**6**	**6**	**6**	**6**
MT-District heating	6	6	6	6	6	**3**	**4**	**4**	**4**	**4**
Hybrid (Hydrogen gas)	4	4	4	4	4	4	**3**	**3**	**3**	**3**
Hybrid (Green gas)	3	3	3	3	3	**2**	**2**	**2**	**2**	**2**

Appendix F. Normalized individual assessments

This appendix shows the results of the normalization of the results of the individual assessments. The individual assessments were normalized according to Equation 1. For tables F.1. to F.4. the strategy that performs the best gets a score of 1. These strategies show the lowest results for the respective decision-making factor. The lower the number in these tables, the worse it performs. For Table F.5. a score of 1 represents that there are enough available experts, whereas a 0 indicates that there are not enough available experts.

F.1. Normalized results for total costs.

Total costs	REF	AE	LT	MT	H-GG	H-HY-C	H-HY-NC
TH_old	0.00000	1.00000	0.55128	0.19964	0.56143	0.50116	0.26614
SD&TC_old	0.00000	1.00000	0.70907	0.44174	0.64200	0.61111	0.40516
TH_new	0.32189	1.00000	0.36611	0.03500	0.40316	0.31549	0.00000
SD&TC_new	0.00000	1.00000	0.52397	0.09675	0.40245	0.35323	0.00768
AP_new	0.44017	1.00000	0.35788	0.00000	0.44754	0.34880	0.09419

F.2. Normalized results for CO2 emissions.

CO2 emissions	REF	AE	LT	MT	H-GG	H-HY
TH_old	0.00	0.75	1.00	0.96	0.86	0.80
SD&TC_old	0.00	0.73	1.00	0.93	0.84	0.78
TH_new	0.00	0.58	1.00	0.88	0.74	0.65
SD&TC_new	0.00	0.59	1.00	0.89	0.75	0.66
AP_new	0.00	0.57	1.00	0.88	0.74	0.64

F.3. Normalized results for disruption during renovation.

Disruption	REF	AE	LT	MT	H-GG	H-HY
TH_old	1	0	0	0.68	0	0
SD&TC_old	1	0	0	0.724138	0	0
TH_new	1	0.333333	0.333333	1	0	0
SD&TC_new	1	0.333333	0.333333	1	0	0
AP_new	1	0.333333	0.333333	1	0	0

F.4. Normalized results for occupation space.

Balancing design and space	REF	AE	LT	MT	H-GG	H-HY
	0.993074259	0	0.04925	1	0.753367	0.753367

F.5. Normalized results for availability of experts.

Availability of experts	REF	AE	LT	MT	H-GG	H-HY
	1	1	1	1	1	0

Appendix G. Relative comparison matrices for the MCA

This appendix presents the relative comparison matrices that were used to determine the weights for the MCA.

Table G.1. presents the best-others-matrix. In this table, the most important decision-making factor under each set of weights is given a value of 1. The other factors get a value that indicates the amount of relative preference of the most important factor, over this other factor.

Table G.2. Presents the others-to-worst matrix. In this table, the least important decision-making factor under each set of weights is given a value of 1. The other factors get a value that indicates the amount of relative preference of this other factor, over the least important factor.

G.1. Best-to-others matrix.

Best to others	Total costs	CO2 emissions	Occupation Space	Reliability of experts	Disruption
Set of weights 1 - Costs first	1	4	3	3	5
Set of weights 2 - Costs & Emissions	1	1	3	3	6
Set of weights 3 - Emissions & Experts	4	1	7	3	8
Set of weights 4 - Disruption & Space	5	3	2	3	1

G.2. Others-to-worst matrix.

Others to worst	Set of weights 1 [Disruption]	Set of weights 2 [Disruption]	Set of weights 3 [Disruption]	Set of weights 4 [Total costs]
Total costs	5	6	4	1
CO2 emissions	2	6	7	4
Occupation space	3	4	3	2
Reliability of experts	3	4	6	3
Disruption	1	1	1	5

Appendix H. Ranking of MCA scores

The Tables below show the ranking of the MCA scores for each scenario. For each scenario, rankings are presented for all of the representative dwellings, for all four sets of weights. The highest score is indicated with a 1, the lowest score is indicated with a 7. This means that for example in the baseline scenario (H.1.) for old terraced houses, the all-electric strategy performs the best.

H.1. Baseline scenario rankings.

Baseline							
Costs first	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	6	1	4	3	2	5	7
SD&TC_old	7	2	4	1	3	5	6
TH_new	4	1	5	3	2	6	7
SD&TC_new	5	1	4	2	3	6	7
AP_new	2	1	5	4	3	6	7
Costs & Emissions	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	1	4	2	3	5	6
SD&TC_old	7	2	4	1	3	5	6
TH_new	6	1	4	2	3	5	7
SD&TC_new	6	2	3	1	4	5	7
AP_new	6	1	4	2	3	5	7
Emissions & Experts	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	4	2	1	3	5	6
SD&TC_old	7	4	2	1	3	5	6
TH_new	7	4	2	1	3	5	6
SD&TC_new	7	4	2	1	3	5	6
AP_new	7	4	2	1	3	5	6
Disruption & Space	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	2	5	4	1	3	6	7
SD&TC_old	2	5	4	1	3	6	7
TH_new	2	5	4	1	3	6	7
SD&TC_new	2	5	4	1	3	6	7
AP_new	2	5	4	1	3	6	7

H.2. Scenario 1 rankings.

Scenario 1: Discount rate							
Costs first	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	5	1	4	3	2	6	7
SD&TC_old	5	2	4	1	3	6	7
TH_new	2	1	5	3	4	6	7
SD&TC_new	3	1	5	2	4	6	7
AP_new	1	2	5	4	3	6	7
Costs & Emissions	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	1	4	2	3	5	6
SD&TC_old	7	2	4	1	3	5	6
TH_new	5	2	4	1	3	6	7
SD&TC_new	5	2	3	1	4	6	7
AP_new	5	2	4	1	3	6	7
Emissions & Experts	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	4	2	1	3	5	6
SD&TC_old	7	4	2	1	3	5	6
TH_new	6	4	2	1	3	5	7
SD&TC_new	7	4	2	1	3	5	6
AP_new	6	4	2	1	3	5	7
Disruption & Space	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	2	5	4	1	3	6	7
SD&TC_old	2	5	4	1	3	6	7
TH_new	2	5	4	1	3	6	7
SD&TC_new	2	5	4	1	3	6	7
AP_new	2	5	4	1	3	6	7

H.3. Scenario 2 rankings.

Scenario 2: Emission Factor							
Costs first	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	6	1	4	3	2	5	7
SD&TC_old	7	1	4	2	3	5	6
TH_new	3	1	5	4	2	6	7
SD&TC_new	5	1	4	3	2	6	7
AP_new	2	1	5	4	3	6	7
Costs & Emissions	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**

TH_old	7	1	3	4	2	5	6
SD&TC_old	7	1	4	2	3	5	6
TH_new	6	1	4	3	2	5	7
SD&TC_new	7	1	2	3	4	5	6
AP_new	6	1	4	3	2	5	7
Emissions & Experts	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	1	2	3	4	5	6
SD&TC_old	7	2	3	1	4	5	6
TH_new	7	1	3	2	4	5	6
SD&TC_new	7	1	2	3	4	5	6
AP_new	7	1	3	2	4	5	6
Disruption & Space	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	2	4	5	1	3	6	7
SD&TC_old	2	5	4	1	3	6	7
TH_new	2	4	5	1	3	6	7
SD&TC_new	2	4	5	1	3	6	7
AP_new	2	4	5	1	3	6	7

H.4. Scenario 3 rankings.

Scenario 3: Discount rate & emission factor							
Costs first	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	5	1	4	3	2	6	7
SD&TC_old	5	1	4	2	3	6	7
TH_new	2	1	5	3	4	6	7
SD&TC_new	2	1	5	3	4	6	7
AP_new	2	1	5	4	3	6	7
Costs & Emissions	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	1	4	3	2	5	6
SD&TC_old	7	1	4	2	3	5	6
TH_new	5	1	4	2	3	6	7
SD&TC_new	5	1	3	2	4	6	7
AP_new	5	1	4	3	2	6	7
Emissions & Experts	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	7	1	3	2	4	5	6
SD&TC_old	7	2	3	1	4	5	6
TH_new	7	2	3	1	4	5	6

SD&TC_new	7	2	3	1	4	5	6
AP_new	7	1	3	2	4	5	6
Disruption & Space	**REF**	**AE**	**LT**	**MT**	**H-GG**	**H-HY-C**	**H-HY-NC**
TH_old	2	4	5	1	3	6	7
SD&TC_old	2	4	5	1	3	6	7
TH_new	2	4	5	1	3	6	7
SD&TC_new	2	4	5	1	3	6	7
AP_new	2	4	5	1	3	6	7