Eindhoven University of Technology

MASTER

Integrating the gain, hedonic and normative aspects in a cost-benefit analysis and decision support tool for transition to natural gas-free neighbourhoods

Nelissen, Diane C.S.

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This thesis is open to the public and has been carried out in accordance with the rules of the TU/e Code of Scientific Integrity

Diane Nelissen - 0949072

Thesis committee: Prof.dr. Theo Arentze, Dr. Ioulia V. Ossokina,
Prof.dr.ir. Bauke de Vries, and Dr.ir.-arch. Pieter Pauwels

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Date	18/10/2022
Author	D.C.S. Nelissen
ID Number	0949072
TUE email	d.c.s.nelissen@student.tue.nl
Institute	Eindhoven University of Technology
Faculty	Department of the Built Environment
Master program	Construction Management and Engineering (CME) & Urban Systems and Real Estate (USRE)
Adress	Den Dolech 2 5612 AZ Eindhoven
USRE:	
Chairman	Prof.dr. Theo Arentze
Graduation supervisor	Dr. Ioulia V. Ossokina
CME :	
Chairman	Prof.dr.ir. Bauke de Vries
Graduation supervisor	Dr.ir.-arch. Pieter Pauwels

In collaboration with the municipality of Eindhoven (Supervisor Ir. Eva van Enk)

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Abstract

To slow down the effects of climate change, CO_2 emissions must be reduced. It is a major challenge to transition the heating homes to natural gas free heating, since 85% of Dutch homes are still heated with natural gas, resulting in a very high CO_2 emission. This change has proven to be a challenge for existing housing stock since different techniques are available, but customization is essential for a successful implementation. This study aims to provide insight into the implementation of different heating techniques for a housing cluster while taking the gain, hedonic and normative aspects into account. The main stakeholder is the homeowner for whom the transformation can have a big impact. Homeowners often lack insight, which reduces their willingness to adopt energy-efficient heating techniques. To fill this gap, this thesis aims to work toward the development of a decision support tool that answers the question: *How can housing clusters be supported in their transition from natural gas towards a more sustainable heating technique optimizing the implementation and taking gain (financial), hedonic (comfort-related) and normative (environmental) aspects into account?* The research aims at developing a decision support tool to increase the insights into natural gas-free heating techniques and support the decision process of homeowners. The research consists of two main parts: in the first part, a limited cost-benefit analysis (LCBA), the costs and benefits have been determined for a reference housing cluster (located in neighbourhood 't Ven). The second part consists of the development of optimization models. The main advantage of the optimization models is that they provide quick insights into a wide variety of housing clusters, taking variables, preferences and cluster properties into account. A dashboard is created for these models, this dashboard provides the opportunity for the homeowner to interact with the optimization models. There are multiple factors influencing the decision of homeowners to implement natural gas-free renovations. When an alternative heating technique is implemented, it has multiple direct effects on the homeowner. A better understanding of the effects of each heating technique per housing cluster can be gained by optimizing the implementation of these techniques. By making these models accessible to homeowners, this group can be informed. There are multiple factors influencing the decision of homeowners to implement natural gas-free renovations. When an alternative heating technique is implemented, it has multiple direct effects on the homeowner. A better understanding of the effects of each heating technique per housing cluster can be gained by optimizing the implementation of these techniques and making these models accessible to homeowners.

Keywords: *natural gas-free heating, optimization, limited cost-benefit analysis, housing clusters*

Preface

This thesis is the research which concludes my master study at the TU/e. During the research, I experienced personal development and learned a lot, especially due to the input of the expects in the fields. Also, the possibility to be challenged and working with new methods in different fields was very

I am very grateful for the supervision and guidance of my two supervisors, Ioulia Ossokina and Pieter Pauwels. From whom I have learned a lot and helped guide me through the research. I would also like to thank the municipality of Eindhoven and especially my supervisor Eva van Enk and my temporary supervisor Roozbeh Nikdel. Their input provided fresh and very useful perspectives, which certainly contributed to a better final result of my research.

This project has been carried out with support from the MMIP 3 & 4 grant of the Dutch Ministry of Economic Affairs & Climate and the Dutch Ministry of the Interior & Kingdom Relations. Therefore, I would also like to give a thank you to the IEBB. I would also like to thank the different experts which provided me with very valuable advice during the research. Among others, the Regionaal energieloket, Woonbedrijf, Itho daalderop, Sjef Ollen, and Jorg van Waas. Their advice, data and insights contributed to the quality of the research.

This thesis also represents the end of my studies at Eindhoven University of Technology. I would like to thank everyone who has been part of my student life in Eindhoven.

Finally, I want to thank my family and friends who have supported me throughout this research.

I wish you happy reading and hope to provide new insights.

Diane Nelissen
Eindhoven, October 2022

Management summary

1) Motivation and research objective

Existing buildings are responsible for 30% of the CO_2 emissions worldwide and 16% in the Netherlands (CBS, 2020). This needs to be drastically reduced in the coming years, to make a planned shift towards a climate-neutral energy system by 2050. One of the major challenges here is upgrading the heating systems of owner-occupied homes. 84% of the Dutch housing stock is still heated with natural gas and 57,4% of the Dutch houses are owner-occupied (CBS, 2021a; CLO, 2020). The upgrade decision needs to be taken by home owners. The considerable costs of the alternative heating systems together with the lack of good insight into the benefits often reduce the willingness to upgrade. This study aims to provide a holistic insight into the financial, technical and social effects of heating system upgrades for individual home owners and clusters of home owners. The study is done for two main alternatives to natural gas heating: all-electric and district heating. More specifically, this thesis develops a decision support tool to facilitate home-owners in housing clusters in their transition from natural gas towards a more sustainable heating technique optimizing the implementation and taking the gain (financial), hedonic (comfort-related) and normative (environmental) aspects into account.

2) Methodology

The research goal is achieved in three steps. First, a limited Cost-Benefit Analysis (LCBA) is performed that evaluates and compares the costs and benefits of the alternative heating techniques for an individual home-owner over the time horizon 2020-2050. The LCBA follows the generally accepted CBA methodology (Romijn & Renes, 2013), but applied only to *individual home-owner* costs and benefits. The included effects are grouped into gain (financial), hedonic (comfort-related) and normative (environment-related) based on the Goal Framing Theory of Lindenberg & Steg (2007). The baseline scenario includes heating with natural gas and a switch to a hybrid heat pump in 2036. Two heating alternatives are: district heating at middle temperature (70°C heat and switch in 2023) and all-electric with an air-to-water heat pump (switch in 2023), see Figure 1. The LCBA is performed under two scenarios – high and low growth of energy prices. The development of energy prices is predicted based on research of the PBL. The low scenario involves the development of the variable natural gas price of +40% and variable electricity price of -34%. The high scenario involves the development of the variable natural gas price of +103% and variable electricity price of +17%. The net present value is calculated using a discount rate of 2.25%. The LCBA is done for a reference housing cluster inspired by homes in neighbourhood 't Ven in the city of Eindhoven. The main dwelling properties that are included in the LCBA model are dwelling size, construction year, type of dwelling, energy label, and distance to the district heating network.

	Baseline alternative	District heating 1	All-electric 1
Heating	*NG*	DH	AHP
Cooking	*NG*	ID	ID
Hybrid heat pump	*X*		
Air-to-water heat pump			X
Connection district heating network		X	
Insulation	*D->B*	B	B
Mechanical ventilation	*X*	X	
Mechanical ventilation with heat recovery			X
Solar panels		X	X
Replace fuse box		X	X
Shift to 3x 25 A electricity connection	*X*	X	X
Remove gas connection		X	X
Electric cooking		X	X
LT radiators			X

Figure 1: Interventions of the baseline and policy alternatives (NG: natural gas, DH: district heating, ID: induction, E: electricity, AHP: air-to-water heat pump, D: insulation label D, B: insulation label B)

Second, a multi-objective optimization model is developed that not only optimizes between pre-defined alternative heating options and the status quo as LCBA does, but also has additional decision support options. It can advise on (i) the most suitable moment of switching, (ii) whether additional dwelling upgrades (solar panels, insulation) should be implemented. Further, the user can indicate individual preferences for comfort, environmental and financial effects. Techniques of Mixed-Integer Linear Programming (MILP) are used to model the optimization solution, coded in Python (packages PULP and PYOMO).

Third, both the LCBA and the optimization are processed in a decision-supporting dashboard that can be used by home-owners as well as municipalities and other parties responsible for boosting the energy transition in homes. The dashboard was created using R Shiny while the interaction with the Python model had been established with Reticulate.

3) Findings

3.1.) Limited cost-benefit analysis

Figure 2 gives an overview of the individual costs and benefits that have been included in the LCBA. Based on the results of the LCBA the following can be concluded:

Gain/ Financial effects for homeowners

1. Based on the Net Present Value of financial effects, it is financially beneficial to switch to District heating or All-electric in the scenario of high growth in energy prices. Switching yields cost savings (NPV) of 7% for District heating and 12% for All-electric, compared to the baseline.
2. In case of low growth, All-electric generates small savings of 2% costs. District heating involves however 10% higher costs than the baseline alternative.
3. The distribution of the costs and benefits over time differs for All-electric and District heating. District heating requires lower initial investment (among other things it does not need adjusting the radiators or heat recovery ventilation) and generates lower yearly savings. All-electric reaches high yearly savings at the cost of a high upfront spending.
4. The properties of the houses have limited impact on the feasibility of District heating. In the high scenario, the cost savings for different studied houses range from 5% to 8%. For all-electric, the properties of the houses make much more difference. Depending on the housing type, the cost savings can be as low as 8% and as high as 18%.
5. A larger distance to the heating network makes district heating less attractive. In a high scenario, switching to district heating is profitable for houses located at a distance of up to 50-60 meters to the network.

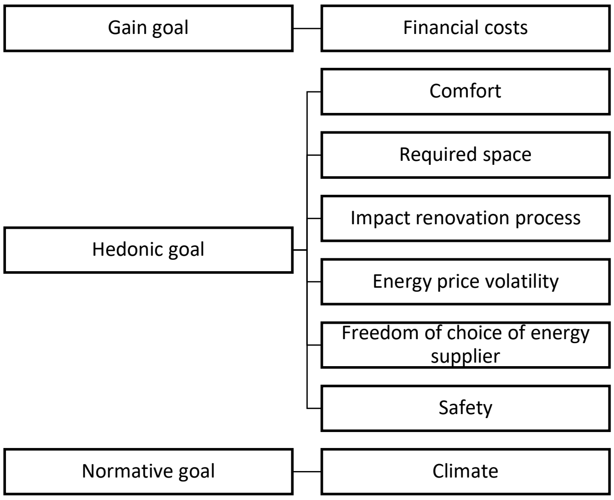

Figure 2: Overview of the effects

6. A larger size of the housing cluster results in a positive impact on the costs for district heating. The costs will result in 8% savings compared to the baseline alternative.

Hedonic/comfort and normative/environmental effects for individual homeowners

1. The total of hedonic/comfort effects is similar for both District heating and All electric and does not differ much from the baseline. The specific effects do differ though.
    a. Both alternative techniques offer an improvement in safety (smaller risk on and less accidents with the heating technique) as compared to natural gas.
    b. All-electric yields addition comfort due to the heat recovery ventilation. This comes at the cost of longer renovation works and larger required space.
    c. District heating has a negative effect connected to the risk of monopolistic behaviour of heat suppliers.
2. Both policy alternatives result in a major decrease in CO_2 emission compared to the baseline alternative. District heating saves 58% and All-electric 73%.

3.2.) Multi-objective dynamic optimization

The assumptions of LCBA concerning the concrete implementation of alternative techniques (year of switch, size of housing cluster, additional measures such as solar panels) do not need to be optimal. Using the optimization model improvements to this can be made:

1. Many different implementations of techniques can be compared quickly and efficiently,

searching for the best solution. Therefore, findings of these techniques can be collected quickly.
2. Housing types and characteristics, the size of the cluster, and location relative to the district heating can be easily adjusted.
3. User input is enabled. For example, in the current version, the user can compare techniques based on her individual-specific relative preferences for gain, hedonic and normative effects. For instance, for people who are mainly concerned about gain/financial effects, postponing the district heating in high scenario, until the moment that renovation is required in baseline (2036) may be attractive. This result does not hold however if environmental effects play an important role.

3.3) The dashboard

The dashboard provides the opportunity for the homeowner to use the optimization models. The municipality of Eindhoven indicated that the dashboard could contribute to informing homeowners about the heating techniques.

4) Conclusions

Overall, there are multiple factors influencing the decision of homeowners to implement natural gas-free renovations. When an alternative heating technique is implemented, it has multiple direct effects on the homeowner. By optimizing the implementation of the heating techniques, and taking the different variables and cluster into account, a better understanding of the effects is created. Making these models accessible to homeowners, will help to inform this group.

The research contributes to multiple fields of research. First of all, insight is generated into the factors influencing the decisions of homeowners for implementing natural gas-free renovations. In the field of CBA for sustainable heating techniques, a contribution is made to getting a better insight into the effects on the major stakeholder, the homeowner. By creating optimization models the gained insights can be optimized and the different objectives can be combined in finding the most suitable implementation. Furthermore, due to these models, an understanding of the effects of the different alternatives can be obtained very quickly per cluster. Via the dashboard, the model can also be made accessible to the stakeholder which makes it usefull for homeowners and municipality.

Limitations

1. The required high amount of assumptions;
   a. Subsidies have been included in the calculation of investment costs as is in 2022. Changes in subsidies will affect the results. It results in higher costs for the installation of insulation, heat pumps, solar panels, and the connection of district heating.
   b. The limitations of the electricity network have not been taken into account. Furthermore, for the connection costs of District heating, an existing network has been taken into account
   c. The relative preferences between gain, hedonic and normative effects have been based on a single study of social housing tenants.
   d. Per extra dwelling included in the cluster, the connection price is reduced by 5% (up to 50%).
   e. The heat price is disconnected from the natural gas price in 2024.
2. The dashboard needs to be further tested on a focus group before it can be widely used.

Further research:

1. Further research into the preferences of homeowners for natural gas-free heating techniques. The current research uses the weights of Wielders (2021) for the goals.
2. Expanding research into the effects of implementing heating techniques on large-scale housing clusters.
3. Further research on comfort levels of homeowners and their comfort preferences.
4. Further CBA research incorporates the indirect social effects of the heating techniques.
5. Expanding the optimization models and the created dashboard to increase usability. By improving the dashboard for the users the usability can be increased.

5) References

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Samenvatting

1) Motivatie en onderzoeksdoelstelling

Bestaande gebouwen zijn verantwoordelijk voor 30% van de CO_2-uitstoot wereldwijd en 16% in Nederland (CBS, 2020). Dit moet de komende jaren drastisch omlaag, om een geplande omslag te maken naar een klimaatneutrale energiehuishouding in 2050. Een van de grote uitdagingen hierbij is het verbeteren van de verwarmingssystemen van koopwoningen. 84% van de Nederlandse woningvoorraad wordt nog steeds verwarmd met aardgas en 57,4% van de Nederlandse woningen zijn koopwoningen (CBS, 2021a; CLO, 2020). De beslissing om te upgraden moet door de huiseigenaren worden genomen. De aanzienlijke kosten van de alternatieve verwarmingssystemen samen met het gebrek aan goed inzicht in de voordelen verminderen vaak de bereidheid om te upgraden. Deze studie wil een holistisch inzicht geven in de financiële, technische en sociale effecten van upgrades van verwarmingssystemen voor individuele huiseigenaren en clusters van huiseigenaren. De studie wordt uitgevoerd voor twee belangrijke alternatieven voor aardgasverwarming: all-electric en warmtenet. Meer specifiek wordt in dit onderzoek een beslissingsondersteunend instrument ontwikkeld om huiseigenaren in woonclusters te faciliteren in hun overgang van aardgas naar een duurzamere verwarmingstechniek, waarbij de uitvoering wordt geoptimaliseerd en rekening wordt gehouden met de winst (financieel), hedonische (comfortgerelateerde) en normatieve (milieu) aspecten.

2) Methodologie

Het onderzoeksdoel wordt in drie stappen bereikt. Eerst wordt een beperkte kosten-batenanalyse (BKBA) uitgevoerd die de kosten en baten van de alternatieve verwarmingstechnieken voor een individuele huiseigenaar over de tijdshorizon 2020-2050 evalueert en vergelijkt. De BKBA volgt de algemeen geaccepteerde KBA-methodiek (Romijn & Renes, 2013), maar dan alleen toegepast op de kosten en baten van de individuele woningeigenaar. De opgenomen effecten zijn gegroepeerd in baten (financieel), hedonische (comfort-gerelateerd) en normatieve (milieu-gerelateerd) op basis van de Goal Framing Theory van Lindenberg & Steg (2007). Het basisscenario omvat verwarming met aardgas en een overschakeling op een hybride warmtepomp in 2036. Twee verwarmingsalternatieven zijn: een warmtenet op midden temperatuur (70°C warmte en omschakeling in 2023) en all-electric met een lucht/water-warmtepomp (omschakeling in 2023), zie Figure 3. De BKBA wordt uitgevoerd onder twee scenario's - hoge en lage groei van de energieprijzen. De ontwikkeling van de energieprijzen wordt voorspeld op basis van onderzoek van het PBL. Het lage scenario omvat de ontwikkeling van de variabele aardgasprijs van +40% en de variabele elektriciteitsprijs van -34%. In het hoge scenario is de ontwikkeling van de variabele aardgasprijs +103% en de variabele elektriciteitsprijs +17%. De netto contante waarde wordt berekend aan de hand van een discontovoet van 2,25%. De BKBA is uitgevoerd voor een referentie wooncluster geïnspireerd op woningen in wijk 't Ven in de stad Eindhoven. De belangrijkste woningeigenschappen die in het BKBA-model zijn opgenomen zijn woninggrootte, bouwjaar, woningtype, energielabel en afstand tot het stadsverwarmingsnet.

	Nulalternatief	Warmtenet 1	All-electric 1
Verwarmen	*NG*	DH	AHP
Koken	*NG*	ID	ID
Hybride warmtepomp	*X*		
Lucht warmtepomp			X
Aansluiten aan warmtenet		X	
Isolatie	*D->B*	B	B
Mechanische ventilatie	*X*	X	
Mechanische ventilatie WTW			X
Zonnepanelen		X	X
Vervangen meterkast	*X*	X	X
Verbetering naar 3x 25 elektriciteit aansluiting	*X*	X	X
Verwijderen aardgas aansluiting		X	X
Elektrisch koken		X	X
LT radiatoren			X

Figure 3: Interventies van het nul alternatief en beleidsalternatieven (NG: aardgas, DH: stadsverwarming, ID: inductie, E: elektriciteit, AHP: luchtwarmtepomp, D: isolatielabel D, B: isolatielabel B).

Ten tweede wordt een multi-objectief optimalisatiemodel ontwikkeld dat niet alleen optimaliseert tussen vooraf gedefinieerde alternatieve verwarmingsopties en het nulalternatief zoals BKBA doet, maar dat ook aanvullende beslissingsondersteunende opties heeft. Het kan advies geven over (i) het meest geschikte moment van omschakeling, (ii) of aanvullende woningverbeteringen (zonnepanelen, isolatie) moeten worden uitgevoerd. Verder kan de gebruiker individuele voorkeuren aangeven voor comfort-, milieu- en financiële effecten. Technieken van Mixed-Integer Linear Programming (MILP) worden gebruikt om de optimalisatieoplossing te modelleren, gecodeerd in Python (pakketten PULP en PYOMO).

Ten derde worden zowel de BKBA als de optimalisatie verwerkt in een beslissingsondersteunend dashboard dat gebruikt kan worden door zowel huiseigenaren als gemeenten en andere partijen die verantwoordelijk zijn voor het stimuleren van de energietransitie in woningen. Het dashboard is gemaakt met R Shiny, terwijl de interactie met het Python-model tot stand is gebracht met Reticulate.

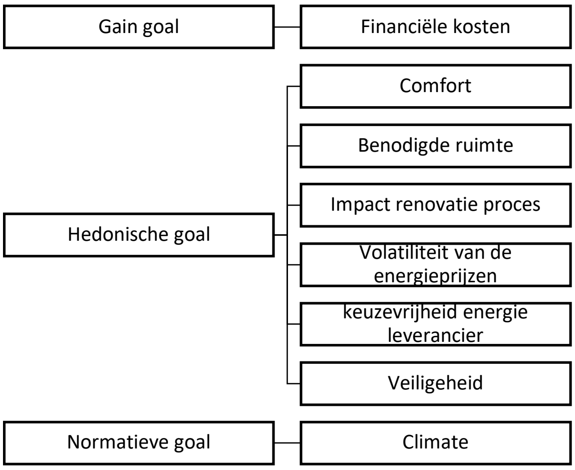

Figure 4: Overzicht van de effecten

3) Bevindingen

3.1.) Beperkte kosten-batenanalyse

Figure 4 geeft een overzicht van de afzonderlijke kosten en baten die in de kosten-batenanalyse zijn opgenomen. Op basis van de resultaten van de BKBA kan het volgende worden geconcludeerd:

Baten/ Financiële effecten voor huiseigenaren

1. Op basis van de Netto Contante Waarde van de financiële effecten is het financieel gunstig om over te stappen op een warmtenet of All-electric in het scenario van hoge groei van de energieprijzen. Overschakelen levert een kostenbesparing (NCW) op van 7% voor een warmtenet en 12% voor All-electric, vergeleken met het nulalternatief.
2. Bij lage groei levert All-electric een kleine besparing op van 2% kosten. Een warmtenet brengt echter 10% hogere kosten met zich mee dan het nulalternatief.
3. De verdeling van de kosten en baten in de tijd verschilt voor All-electric en een warmtenet. Een warmtenet vergt een lagere initiële investering (er is onder meer geen aanpassing van de radiatoren of ventilatie met warmteterugwinning nodig) en levert een lagere jaarlijkse besparing op. All-electric bereikt hoge jaarlijkse besparingen ten koste van hoge initiële uitgaven.
4. De eigenschappen van de woningen hebben een beperkte invloed op de haalbaarheid van een warmtenet. In het hoge scenario variëren de kostenbesparingen voor verschillende bestudeerde huizen van 5% tot 8%. Voor all-electric maken de eigenschappen van de woningen veel meer verschil. Afhankelijk van het woningtype kan de kostenbesparing zo laag zijn als 8% en zo hoog als 18%.
5. Een grotere afstand tot het warmtenet maakt verwarmen met een warmtenet minder aantrekkelijk. In een hoog scenario is overschakeling op een warmtenet rendabel voor huizen die op een afstand van maximaal 50-60 meter tot het netwerk liggen.
6. Een grotere omvang van het wooncluster heeft een positief effect op de kosten voor een warmtenet. De kosten leiden tot een besparing van 8% ten opzichte van het nulalternatief.

Hedonische/comfort- en normatieve/milieu-effecten voor huiseigenaren

1. Het totaal van de hedonische/comforteffecten is vergelijkbaar voor zowel een warmtenet als All electric en verschilt niet veel van het nulalternatief. De specifieke effecten verschillen echter wel.
   a. Beide alternatieve technieken bieden een verbetering van de veiligheid (kleiner risico op en minder ongevallen met de verwarmingstechniek) in vergelijking met aardgas.
   b. All-electric levert extra comfort op dankzij de warmteterugwinning. Dit gaat ten koste van langere renovatiewerkzaamheden en een grotere benodigde ruimte.

   c. Een warmtenet heeft een negatief effect in verband met het risico van monopolistisch gedrag van warmteleveranciers.
2. Beide beleidsalternatieven leiden tot een belangrijke daling van de CO_2-uitstoot in vergelijking met het nulalternatief. Een warmtenet bespaart 58% en all-electric 73%.

3.2.) Multi-objectieve dynamische optimalisatie

De aannames van BKBA over de concrete invulling van alternatieve technieken (jaar van omschakeling, omvang wooncluster, aanvullende maatregelen zoals zonnepanelen) hoeven niet optimaal te zijn. Met behulp van het optimalisatiemodel kunnen hierin verbeteringen worden aangebracht:

1. Veel verschillende implementaties van technieken kunnen snel en efficiënt met elkaar vergeleken worden, op zoek naar de beste oplossing. Daarom kunnen geoptimaliseerde bevindingen van deze technieken snel worden verzameld.
2. Woningtypen en kenmerken, de grootte van het cluster, en de locatie ten opzichte van het warmtenet kunnen eenvoudig worden aangepast.
3. Gebruikersinput is mogelijk. In de huidige versie kan de gebruiker bijvoorbeeld technieken vergelijken op basis van haar individu-specifieke relatieve voorkeuren voor winst, hedonische en normatieve effecten. Zo kan het voor mensen die zich vooral zorgen maken over winst/financiële effecten, aantrekkelijk zijn om het warmtenet in het hoge scenario uit te stellen tot het moment dat renovatie in het nulalternatief (2036) nodig is. Dit resultaat gaat echter niet op als milieueffecten een belangrijke rol spelen.

3.3) Het dashboard

Het dashboard biedt de huiseigenaar de mogelijkheid om de optimalisatiemodellen te gebruiken. De gemeente Eindhoven gaf aan dat het dashboard kan bijdragen aan het informeren van huiseigenaren over de verwarmingstechnieken.

4) Conclusies

In het algemeen zijn er meerdere factoren die de beslissing van huiseigenaren beïnvloeden om aardgasvrije renovaties uit te voeren. Wanneer een alternatieve verwarmingstechniek wordt toegepast, heeft dit meerdere directe effecten op de huiseigenaar. Door de implementatie van de verwarmingstechnieken te optimaliseren, en rekening te houden met de verschillende variabelen en het cluster, ontstaat een beter begrip van de effecten. Door deze modellen toegankelijk te maken voor huiseigenaren, wordt deze groep beter geïnformeerd.

Het onderzoek draagt bij aan meerdere onderzoeksgebieden. Allereerst wordt inzicht gegenereerd in de factoren die van invloed zijn op de beslissingen van huiseigenaren om aardgasvrije renovaties uit te voeren. Op het gebied van KBA voor duurzame verwarmingstechnieken wordt een bijdrage geleverd aan het verkrijgen van een beter inzicht in de effecten op de belangrijkste stakeholder, de huiseigenaar. Door optimalisatiemodellen te maken kunnen de verkregen inzichten worden geoptimaliseerd en de verschillende doelstellingen worden gecombineerd bij het vinden van de meest geschikte uitvoering. Bovendien kan door deze modellen zeer snel per cluster inzicht worden verkregen in de effecten van de verschillende alternatieven. Via het dashboard kan het model ook toegankelijk worden gemaakt voor de belanghebbenden waardoor het bruikbaar is voor huiseigenaren en gemeente.

Beperkingen:

1. De vereiste grote hoeveelheid aannames;
   a. Subsidies zijn meegenomen in de berekening van de investeringskosten zoals die in 2022 gelden. Veranderingen in subsidies zullen de resultaten beïnvloeden. Het leidt tot hogere kosten voor de installatie van isolatie, warmtepompen, zonnepanelen en de aansluiting van stadsverwarming.
   b. Er is geen rekening gehouden met de beperkingen van het elektriciteitsnet. Voorts is voor de aansluitingskosten aan het warmtenet rekening gehouden met een bestaand netwerk.
   c. De relatieve voorkeuren tussen winst, hedonische en normatieve effecten zijn

gebaseerd op één onderzoek onder huurders van sociale woningen.
    d. Per extra woning opgenomen in het cluster wordt de aansluitprijs verlaagd met 5% (tot 50%).
    e. De warmteprijs wordt in 2024 losgekoppeld van de aardgasprijs.
3. Het dashboard moet verder getest worden op een focusgroep voordat het breed gebruikt kan worden.

Verder onderzoek:

1. Nader onderzoek naar de voorkeuren van huiseigenaren voor aardgasvrije verwarmingstechnieken. Het huidige onderzoek gebruikt de gewichten van Wielders (2021) voor de doelen.
2. Uitbreiding van het onderzoek naar de effecten van de implementatie van verwarmingstechnieken op grootschalige woningclusters.
3. Verder onderzoek naar het comfortniveau van huiseigenaren en hun comfortvoorkeuren.
4. Verder KBA-onderzoek waarin de indirecte maatschappelijke effecten van de verwarmingstechnieken worden meegenomen.
5. Het uitbreiden van de optimalisatiemodellen en het gemaakte dashboard om de bruikbaarheid te vergroten. Door het dashboard voor de gebruikers te verbeteren kan de bruikbaarheid worden vergroot.

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Terminology & Abbreviations

CO_2	Carbon dioxide
Paris agreement	A legally binding international treaty on climate change
Climate neutral	No effect on the climate
Bcm	Billion cubic metres
IDE	Integrated development environment
Fossil fuels	Non-renewable energy sources, oil, coal and natural gas
MNL	Multinominal logit model
Renewable energy sources	Sources that regenerate and can replenish themselves indefinitely
PAW	Program Natural Gas-Free Neighbourhoods
CBS	Centraal Bureau voor de Statistiek
WTP	Willingness to pay
ERM	Energy renovation measures
LP	linear programming
QP	Quadratic programming
QCQP	Quadratically constrained quadratic programming
SOCP	Second-order cone programming
SDP	Semidefinite programming
ATES	Aquifer thermal energy storage
CBA	Cost-benefit analysis
LCBA	Limited cost-benefit analysis
KEV 2021	“Klimaat- en energieverkenning” 2021
WACC	Weighted average cost of capital

VAT	Value added tax
AHP	Analytic Hierarchy Process
MILP	Mixed integer linear programming
MOOP	Multi-objective optimization problem
CPI	Consumer price index
GIS	Geographic information system
DH1	District heating middle temperature
DH2	District heating low temperature
AL1	All-electric with an individual air-to-water heat pump
AL2	All-electric with a collective ground heat pump
Niet-Meer-Dan-Anders principle	no more than other principles (district heating should not costs more for the homeowner than heating with natural gas)
NN	Nearest neighbour algorithm
CME	Construction management and engineering
USRE	Urban systems and real estate

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1. Introduction

1.1. Background

One of the current main threats is climate change, which threatens health, economic prospects and water sources. Effects of climate change like extreme weather already occur worldwide (Pachauri et al., 2014). Global climate change is caused by the emission of greenhouse gases, of which CO_2 (carbon dioxide) is the most important. The emission of CO_2 grew from 2012 with an average annual growth rate of 1.1% to 52.4 gigatons in 2019 (Olivier & Peters, 2020). To decrease emissions and limit the consequences of climate change, the international community created the agreement of Paris. For the Netherlands to meet this agreement, CO_2 emission needs to be decreased by 95% in 2050 as compared to 1990 (Rijksoverheid, 2020b). To achieve this, a shift towards a climate-neutral energy system needs to be made. More than half of the final energy consumption in the Netherlands was used for heating in 2019, which means that by reducing the emission for heating a big impact can be made. Currently, natural gas is the main energy source used for heating in the Netherlands, the contribution of natural gas only decreased from 411 PJ in 2015 (total energy consumption for heating 465 PJ) to 389 PJ in 2019 (total 459 PJ). Natural gas is a non-renewable energy source, which is fossil fuel (oil, coal and natural gas) (Niessink et al., 2020). Renewable energy sources are defined as sources that regenerate and can replenish themselves indefinitely (biomass, hydropower, geothermal, wind and solar energy). Nuclear energy could be added to this list of renewable energy sources because it is possible to perform nuclear fusion. But currently, nuclear fusion requires more energy than it produced, which makes it inefficient and not costs effective (Energievergelijk, 2022). If only nuclear fission is performed, it produces harmful waste. Therefore, there has been chosen not to take nuclear energy into account for the current research (Chowdhury, 2012). The challenge for the shift toward a climate-neutral heating system for the built environment is to replace the use of natural gas with a sustainable energy source for the existing housing stock. The challenge for the shift toward a climate-neutral heating system for the built environment is to replace the use of natural gas with a sustainable energy source for the existing housing stock. This shift moves slow. Study results indicate that besides technical possibilities, there are barriers to homeowners' willingness to implement off-gas renovations. Which are caused by different preferences and lack of information. The decrease in the use of natural gas is necessary, besides reducing CO_2 emission, for the following three reasons:

1. The supply of natural gas from Dutch soil decreases considerably due to the decision of the Dutch government to stop drilling for natural gas in Groningen, as a result of the earthquakes in the area. Consequently, the Netherlands cannot supply its natural gas in the future anymore (Hier opgewekt, n.d.; Rijksoverheid, n.d.-a).
2. If natural gas is imported from other countries (like Norway and Russia), to meet the current demand, this will make the Netherlands dependent on other countries for energy supply which could be a risk. Natural gas from other countries is also more expensive and additional CO_2 is emitted with the transportation over long distances (Hier opgewekt, n.d.; Ministerie van Economische zaken, 2016; Rijksoverheid, n.d.-a).
3. As natural gas is not inexhaustible worldwide, in the future heating with natural gas will not be possible. It is estimated that the gas supply will be exhausted in 60 years (Milieu centraal, n.d.-a).

It is the Dutch government's goal to have 7 million dwellings and 1 million other buildings free of natural gas heating by 2050, although significant progress still needs to be made

(Rijksoverheid, 2020a). The goal, of eliminating the use of natural gas for heating the built environment, can only be reached if the energy demand can be supplied in another (sustainable) way. This means that the non-renewable sources, which are petroleum and natural gas, are not suitable. In *Appendix A: Share of heating technologies and total installed capacity by country*, the share of heating technologies per European country is shown. In this Appendix, it can be seen that the Netherlands has a relatively high natural gas use (due to the natural gas fields in the Netherlands) compared to the other European countries which also have a high use of other fossil fuels like oil and coal. Therefore, these countries also need to shift to alternative heating techniques to replace the use of fossil fuels and reduce their CO_2 emissions. To select which alternative heating techniques (which do not use fossil fuels) are suitable, the focus will be on techniques that are suitable in West Europe, since this area has a comparable climate to the Netherlands, see *Appendix B: European climate zones*. Therefore, the selected techniques which are suitable for the Netherlands can also be suitable alternative heating techniques in other West European countries. Furthermore, the heating techniques which are considered fitting alternatives in the European Union are taken into account (European Commission, n.d.; Fleiter et al., 2016).

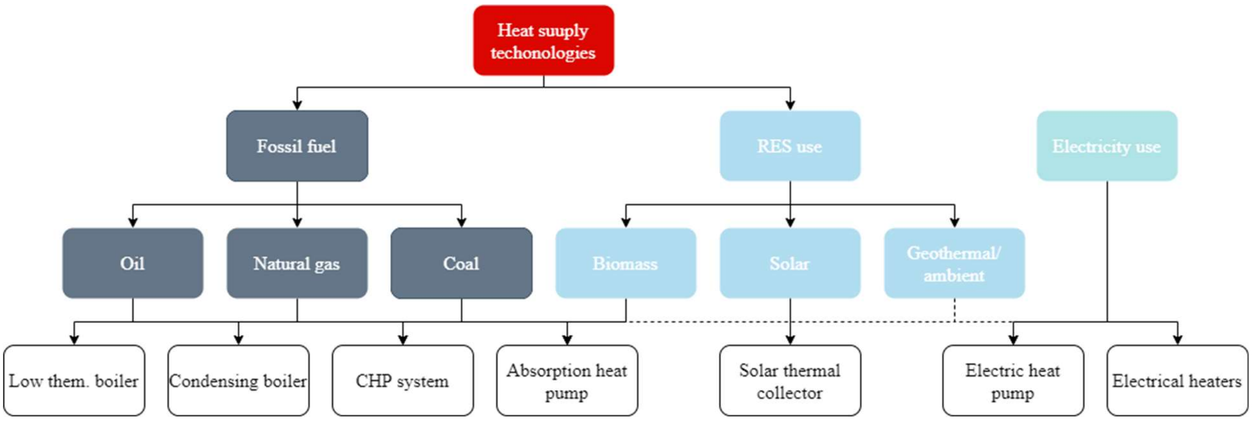


Figure 5: Structure of heat supply technologies (Fleiter et al., 2016)

One of the alternatives to fossil fuels is biomass, see Figure 5. The heat generated from burning biomass (like wood) can be applied to individuals and groups of dwellings (a cluster). This is not considered a suitable alternative, due to the negative consequences that it emits CO_2 and there is not enough local biomass (which is required to make this a sustainable alternative) to apply this heating method on a large scale. Furthermore, it results in high particulate matter emission, which can cause health risks for residents (Koppejan & De Bree, 2018). The heat source hydrogen can be burned as a gas, which only results in an emission of water vapour. This is seen as a promising heat source for the future but will not have a significant impact until 2030 since it is currently mostly produced with natural gas. Furthermore, it is not yet available on a large scale and when hydrogen is used this is only possible when the whole neighbourhood switches to hydrogen for heating since the gas network needs to be adapted for the transport of hydrogen (Essent, n.d.-c; Expertise Centrum Warmte, 2020d). Another alternative is heating using a solar thermal collector. This heating technique is suitable to reduce the use of natural gas. But for the Western European climate, it will not be feasible to meet the whole heat demand of a household through a solar thermal collector without the use of natural gas (Milieu centraal, n.d.-b). Other alternatives to heating with natural gas are purchased heat (district heating), electricity for heat, and green gas. Green gas is biogas that has been upgraded to the same quality as natural gas. Due to the low availability of green gas, this could mainly be beneficial for dwellings for which big renovations are not feasible (Hoogenvorst et al., 2020). The heat extracted from the environment, by heat pumps, can be extracted from the air, ground and water, from which heat from ground and air are most common on a small-scale level. Disadvantages of heat pumps are the high investment costs, and the dwellings need to have a high level of insulation. For purchased heat (district heating), a central heat source is used to heat the buildings (often housing) around them. This central heat source can be residual heat from industry, biomass and geothermal energy (Milieu Centraal, n.d.-e). District heating is suitable for high to medium-density areas with a high heat demand in a small area. Most of these techniques are already implemented in the Netherlands but only on a small part of the building stock. Table 1 shows that these alternative heating techniques supply only a small share of the total energy consumption. The table shows that besides natural gas most energy is generated with biomass and purchased heat. The contribution of biomass to the total energy consumption for the heating of Dutch housing is approximately 4% and mainly concerns the burning of wood of households in boilers and heaters. Purchased heat mainly consists of heat from district heating. The electricity consumption used for heating consists of electricity used for heat pumps, the pumps for central heating boilers and electric heating boilers (Niessink et al., 2020).

Table 1: Final energy use for heating of households 2019 (Niessink et al., 2020)

Energy source	PJ	%
Petroleum	2	1
Natural gas	274	87
Solar heat	1	0
Biomass	16	5
Purchased heat	12	4
Electricity for heat pumps	2	1
Electricity for electric heat boilers	3	1
Electricity for boiler pumps	4	1
Heat extracted from the environment by heat pumps	5	2
Hydrogen	0	0

All the described heating techniques have advantages and disadvantages, their feasibility is dependent on the properties of the dwellings. There is not one best alternative technique to replace heating with natural gas for all dwellings, which means that customization is required. Furthermore, the available heating techniques consist of individual techniques, which are techniques that only provide heat to one dwelling, and collective techniques, which supply heat to a group of dwellings. Therefore, the feasibility of these collective techniques is not only dependent on the properties of one dwelling but also the number of included dwellings and their properties. It is more complicated to assess the feasibility and impact of the techniques for groups of dwellings. Although the implementation of collective heating techniques can lead to extra challenges, these techniques must be included in the energy transition. The energy transition is currently moving too slow, therefore only transitioning individual dwellings will not be enough to reach the goal. In contrast, for collective techniques, big groups of dwellings can switch to a natural gas-free heating technique simultaneously. There already are researches that describe the benefit of clustering dwellings to accelerate the energy transition. Houses can be clustered based on location or based on building properties. An example of the latter is the research of Murder et al. (2021), in which dwellings are clustered in groups of a minimum of 15.000 dwellings. This research focused to reduce the energy demand and the clusters contain dwellings to which the same sustainability solution can be applied in the same way (G. Mulder et al., 2021). The current research there will be focused on the implementation of heating techniques, instead of merely the decrease of energy consumption. Therefore, the dwellings are grouped based on location, they need to be located close together and form relatively compact units. This clustering approach enables the assessment of the feasibility of the heating techniques. If customization per cluster is applied, the technical and financial aspects are relevant, which include the characteristics of the building and the combination of the housing cluster. The desired most fitting technical solution depends on a variety of aspects, as described above, including the properties of the clusters but also variables that can differ over time, like energy costs. It can be very time- and cost-consuming to determine the most suitable technology per housing cluster. Furthermore, the climate agreement states that the program for the energy transition of municipalities needs to be on a basis of the lowest financial and social costs (Tigchelaar et al., 2021). For the social aspects, the stakeholders are important; the most important stakeholders, in this case, will be the homeowners for whom the transformation can have a big impact on their way of living, also financially. Homeowners often lack insight, which reduces their willingness to adopt energy-efficient heating techniques. There are already models that provide information, but they mostly do not offer a holistic consideration of the relevant gain, hedonic and normative aspects to find the most fitting transformation of the housing cluster. To fill this information gap, this thesis aims to answers the question: *How can housing clusters be supported in their transition from natural gas towards a more sustainable heating technique optimizing the implementation and taking gain (financial), hedonic (comfort-related) and normative (environmental) aspects into account?*

The goal of the research is to create an insight into the most fitting implementation of the different heating techniques for a housing cluster, taking the gain, hedonic and normative aspects into account. To create insights into the impact of the heating techniques for housing clusters cost-benefit analysis (CBA) can be used. CBA is an effective tool for use in the ex-ante assessment of policy options. The CBA is a systematic information tool to provide an overview of the effects, risks and uncertainties of a measure and the resulting costs and benefits to society. If a CBA is performed, the most suitable implementation can be selected incorporating the gain, hedonic and normative aspects, but this can only be determined for the housing cluster the CBA is performed on. To increase the added value of the research for the energy transition the gained insights need to be multi-applicable. Therefore, a model will be created that can generate these insights based on the (input) properties of the cluster. An optimization model would be preferable for this since it can provide these results and allows for more variables to be assessed. The results will help the user in the decision-making process for the energy transition for heating and could increase the willingness of the homeowner to replace the use of natural gas with sustainable energy. To answer the research question, seven sub-research questions have been created, which are shown in Table 2.

Table 2: Sub-research questions

Research phase	Nr	Sub-research question
Literature review	1	Which techniques, to supply homes with sustainable heating, are feasible in West Europe and how are they implemented?
	2	What attributes influence people when making a shift to sustainable energy for their homes and how do people weigh them?
Cost-Benefit Analysis	3	Which variables impact the feasibility of the techniques until 2050 and how do they develop?
	4	What are the costs and benefits of each of the heating techniques for sustainable energy in the Netherlands?
	5	How can a model optimize the implementation of a heating technique for a housing cluster?

Data collection and model creation	6	How can the most suitable heating technique be selected for a housing cluster based on the preferences of homeowners?
	7	How can a dashboard be created that will make the model usable for the user?

1.2. Research design

In Table 2, the sub-questions for the research are shown, and the research is divided into 3 steps based on the sub-questions, see Figure 6. Sub-question 1 needs to be answered by creating an overview of the techniques which are feasible in West Europe. Sub-question 2 needs to be answered because for homeowners to engage in sustainable energy behaviour the result of the cost and benefits needs to be positive. To result in a positive outcome the energy interventions need to meet the preferences of the homeowners of which the attributes need to be known. The result of this sub-question is used for sub-question 4 and 6. By answering sub-question 3, it will be defined which external variables have an impact on the feasibility of the different techniques and how they develop. This information is required to answer the sub-questions 4, 5, and 6. For sub-question 4, all costs and benefits per technique need to be determined. For sub-question 5, an optimization model will be created that can predict the implementation and results of the different techniques. For sub-question 6, an optimization model will be created that determines the optimal solution based on the preferences of the homeowners. For sub-question 7, a dashboard will be created, using the outputs for sub-questions 5 and 6, that can be used, and the results can be interpreted by the users.

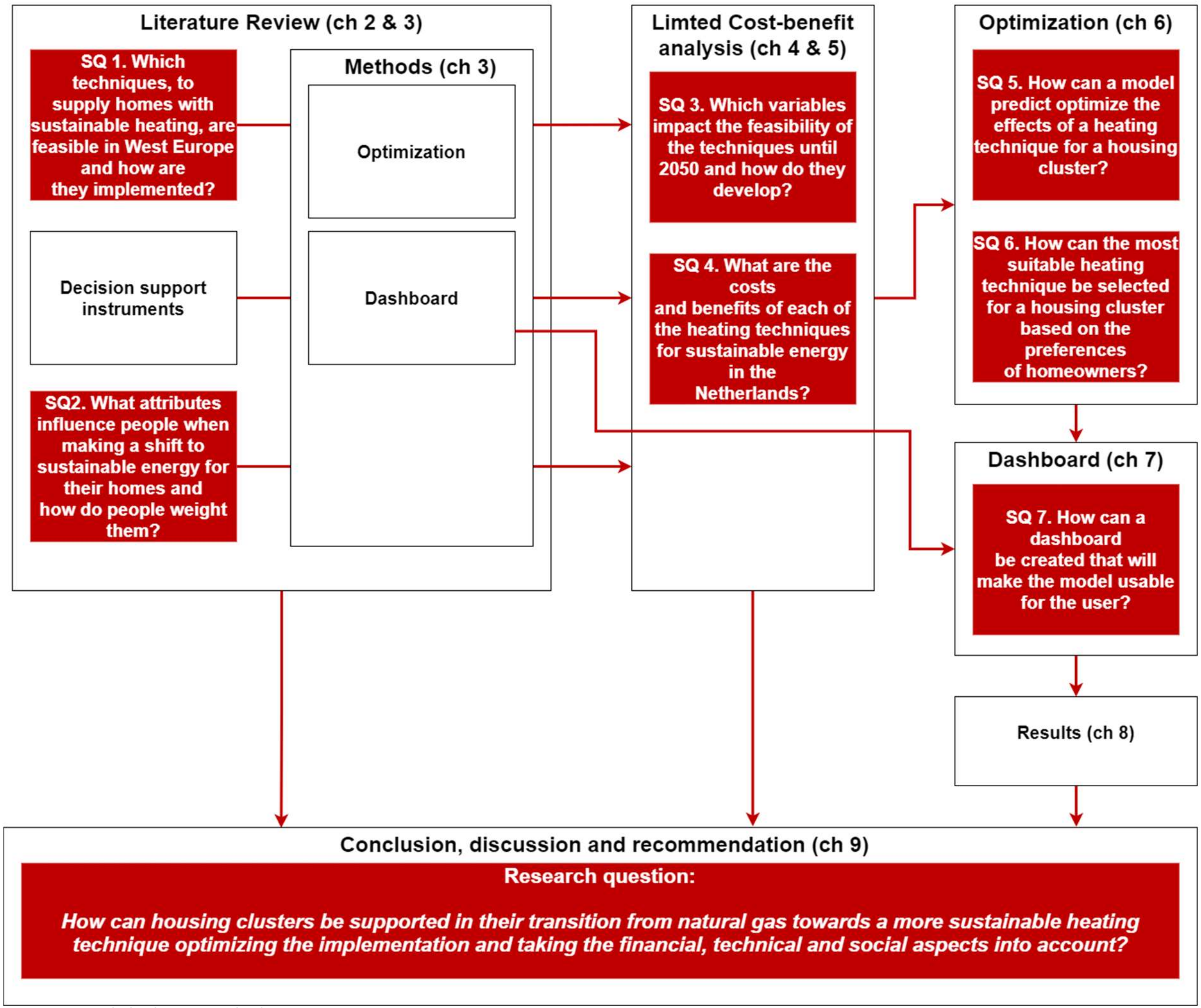


Figure 6: Global research design

1.3. Research scope, limitations and relevance

The scope of the research will be the Dutch housing stock and it is focused on the scale of a housing cluster. As described above, for the current research the housing clusters that will be taken into account are, clusters consisting of dwellings that are spatially clustered. These dwellings are grouped closely together and form relatively compact units. Although the energy transition is not only a problem in the Netherlands, it has been chosen to mainly focus on the Dutch housing stock because housing properties, costs and preferences might differentiate per country, which could make the results less reliable. Although the country-specific input like housing types and costs will be collected for the Netherlands, attributes that people focus on and heating techniques will be compared with other West European countries (which have many similarities to the Netherlands). Therefore, the final model could provide a good framework for developing similar models for other countries, in later research. The research will focus on owner-occupied homes since homeowners need to decide individually whether to invest in sustainable heating. This scope is selected because tenants will not invest and implement the home improvement measures themselves, but the homeowner (for example the housing corporation) will. Housing corporations often already have the required knowledge in their organisation and organise heating renovations in clusters to increase efficiency. Consequently, it is important to focus on the owner-occupied houses because this includes a bigger part of the housing stock (57%) and the results could be a bigger addition to the energy transition (StatLine, 2021). Furthermore, by creating an optimization model for the implementation of the heating technique, these results could also be useful for housing corporations. The research will also focus on dwellings and not on apartments or high-rises. This will be done because in an apartment building it is often not possible to change the technique for heating per apartment but only for the whole building, which often is a mix of owner-occupied and rental apartments. As a result, individual apartments cannot be included in a housing cluster with other types of dwellings. In this case, it would be better if the transition would be organised per apartment building. For an apartment building, fewer heating techniques are possible, and less customization is required (due to similarities of the apartment). Consequently, a bigger advantage can be reached by creating a model for the transition of the dwelling types that are not apartments (which include at least 64% of the housing stock and has a higher natural gas consumption than apartments, see *Appendix C: Relative importance of the MNL model* (StatLine, 2021)). The research will focus on the different techniques that will provide a sustainable energy supply for the housing stock and will replace natural gas. The research will focus on the cluster form of houses to enable the advantages of shared energy production. This means that the research will mainly focus on areas with a medium to high housing density (which are areas where shared energy production could be feasible). To conclude, the scope of the research is the Dutch housing stock on housing cluster scale, with owner-occupied homes, including the different dwelling types except for apartments and in medium to high-density areas.

The main output of the research is the insight into the costs and benefits for homeowners of alternative natural gas-free heating techniques. These insights are combined results of cost-benefit research and optimal implementation of the heating techniques based on the optimization models. The optimization models will be visualized by creating a dashboard, resulting in quick insights into the implementation of the techniques. The dashboard (using the optimization model) enables the user to optimize the implementation of the heating techniques based on their preferences. The main users of the dashboard will be homeowners, but it could also have added value for local authorities to inform homeowners. Furthermore, the insights gained from the Cost-Benefit Analysis can help municipalities to gain a better understanding of the effects of the heating techniques.

The research will also have some limitations. Many variables influence the results of the research but for some elements, assumptions need to be made. For example, to calculate the current energy use of a house many characteristics of the specific house need to be known, like the type of insulation, type of windows, window area and equipment. Many of these characteristics cannot be gathered from the user or open-source data and this needs to be done manually. This results in a very time-consuming and costly process. Therefore, the energy consumption will be predicted with information on the housing market, which will result in less accurate results. Second, a selection of techniques will be incorporated into the optimization model which will determine per heating technique the optimal implementation. The selected techniques are the currently most used heating techniques. However, since customization is required for housing clusters there will be cases where the best technique is one that is not incorporated in the research. Third, the stated choice experiment will mainly be executed in the city of Eindhoven. The goal is that there will be high variance in respondents but there could be some difference in results compared to preferences nationwide.

1.4. Academic relevance

This thesis contributes to the large literature on the residential energy efficiency gap, which discusses the factors that influence the willingness to invest in sustainability, and the motivators and barriers that influence the decision-making process. For the Netherlands, the main factors that were found are environmental concerns, investment costs, utilization costs, comfort and nuisance (Broers et al., 2019; Ebrahimigharehbaghi et al., 2019; Haas, 2020; Jansma et al., 2020; Wielders, 2021), see *Appendix D: Research natural gas-free neighbourhood initiatives*. Homeowners will make a shift in heating techniques if this will result in a higher perceived utility or if it is mandated by law (Banfi et al., 2008; Steg et al., 2015). When comparing these results with other European countries, there are some differences in preferences which could be caused by differences in cultures and heat demand (see *Appendix E: Overview of five European countries and their energy mixes*). Researchers find overall high satisfaction with the current natural gas use (Sovacool, Cabeza, et al., 2021; Sovacool, Demski, et al., 2021). Further, households can be less likely to switch to low-carbon heating due to uncertainty and lack of knowledge (Sovacool, Cabeza, et al., 2021; Sovacool, Demski, et al., 2021). Additionally, a high level of desired thermal comfort was found, which requires a different implementation of heating techniques due to differences in housing type and climate between the European countries. In terms of country variation, there is a difference in heating preferences, which indicates that there is a cultural element of heating (preferences) (Sovacool, Cabeza, et al., 2021; Sovacool, Demski, et al., 2021). These results imply that, when generalizing the preferences of techniques, this can be done best in an area with matching climate and cultures. The above-described results give an insight into the factors that influence the decision-making process towards sustainable natural gas-free heating in the Netherlands, but currently, an insight into the preferences of the homeowners comparing the different heating techniques is lacking.

Besides the differences in preferences of homeowners, one of the problems that were found in the literature is that lack of information can have a negative effect on a homeowner's decision to invest in energy renovation measures (ERM). The ERM industry is often seen by homeowners as unreliable and non-transparent (Bartiaux et al., 2014; Broers et al., 2019; Karvonen & Karvonen, 2013; Risholt & Berker, 2013; Wilde, 2020). Banfi et al. described that the willingness to pay (WTP) for energy-saving measures is generally higher than the costs of implementing them. But incomplete information and inattention can be important contributors to the energy efficiency gap in the residential sector (Banfi et al., 2008). The lack of information about the advantages of the efficiency measures but perhaps also the lack of methods to quantify the advantages in economic terms can decrease the willingness to adopt energy-efficient techniques (Palmer & Walls, 2021). This can be caused by the underestimation of the positive effects of the energy-efficient improvements for uninformed residents, even when the improvements are cost-effective. This lack of information is an important contributor to the current energy efficacy gap (Ossokina et al., 2021). Due to the consequences of the energy transition caused by this lack of information, policy instruments should aim at tackling these barriers. This should not only be done by providing reliable and tailormade information about the different possible solutions and their effects but also supporting them through the process (Ebrahimigharehbaghi et al., 2019).

The last main academic contribution of the research is that it will be investigated to what extent it is possible to calculate the long-term effects of applying certain energy renovations, while still making a reasonable suggestion that is useful for decision making. This will be done by creating optimization models that can optimize the implementation of the heating technique based on user preferences (comfort, CO_2 emission, and cost). These models will make several contributions, first of all, they will create insights into how multi-objective optimization can be used to optimize the implementation of heating techniques for the long-term effects incorporating the preferences of homeowners. Secondly, insights will be created into what information is needed and how reliable the results are using the assumptions. Furthermore, not only insights into the variables that influence the optimal implementation will be created, but also how they develop and their influence on the optimal implementation. The model itself can provide a framework for further development by using optimization for determining the implementation and long-term effects of heating techniques. This can result in more in-depth insights, but it can also serve as a framework for the creation of such optimization for other West European countries. Last of all, the model can add to cost-benefit research, to show how such a model can be used to quickly assess effects for a cluster instead of executing this assessment manually for every separate cluster.

1.5. Practical relevance

There already are policy instruments in the Netherlands that aim at supporting various types of users in their transition to non-natural-gas-based heating. First of all, there is the online energy desk (energieloket.nl) which, can provide tailor-made advice on how energy efficiency and comfort can be improved in a dwelling (Ebrahimigharehbaghi et al., 2019). Another model that provides information to the decision-maker about the end-user costs, is the Dashboard end-user cost of the TNO (Tigchelaar et al., 2021). The Dashboard is developed for municipalities, and it helps municipalities by giving an insight into the expected costs of end-users and other involved actors. But both policy instruments have shortcomings (see Section 2.2). This thesis will contribute to resolving these shortcomings. Research will be done on the development of a decision support tool to help homeowners in the decision-making process by providing custom insights into the consequences of the heating techniques. The homeowners need insight into how the different heating techniques can be implemented for their housing cluster. The main insight for homeowners is what the costs and CO_2 reduction will be per implementation of a heating technique compared to other techniques and heating with natural gas depending on multiple variables. Besides the homeowner, the decision support tool will also provide added value to local authorities like a municipality. The tool can support local authorities in informing homeowners about alternative heating techniques to speed up the energy transition. By providing these custom insights, the homeowners get an understanding of how the different techniques can be implemented in their situation and can compare the consequences of the different techniques. This can make the homeowner more willing to change their source of heating and can help them with making a better and more informed decision about the heating technique. This could speed up the energy transition, which is necessary to replace the use of natural gas with a sustainable energy source since a custom solution is required. The results of the optimization model will be useful for users who do not all have technical knowledge about heating techniques or programming. Therefore, the optimization model needs to be made easy to interact with. This is done by creating a dashboard, which is an instrument that is suitable for presenting data into an integrated visual display and initiating actions. The main benefits of a dashboard are related to creating an overview and enabling users to zoom in on details, which would be beneficial for comparing the different techniques for heating and providing more detail per technique (Matheus et al., 2020). For the dashboard to be usable, it needs to be online available.

1.6. Organisation of the research

The report describes the process of answering the research question. To answer the research question first the sub-questions will be answered following the above-described research design. The research starts with the literature review in Chapter 2, which needs to answer the first two research questions. The literature review consists of three main stages, which are literature research into alternative heating techniques (Section 2.1), the decision support instruments (Section 2.2) and the preferences of homeowners (Section 2.3). The literature review is followed by Chapter 3, Methods. In this Chapter, the optimization methods will be discussed, and there will be focussed on linear programming and multi-objective programming. In Chapter 4, the limited Cost-Benefit Analysis will be executed and described. For this analysis, the methodology of Romijn & Renes (2013) is followed. In Chapter 5, the results of the Cost-Benefit Analysis are presented, a conclusion is drawn, and a sensitivity analysis is executed. The second main research part is described in Chapter 6. This Chapter describes the creation of the optimization models. The Chapter starts with an explanation of the methodology of the Chapter. The first Section of the Chapter includes the description of the optimization models, which are optimized using linear programming and multi-objective optimization. In the second Section of the Chapter, the results of the optimization models are presented and validated. In Chapter 7, describes the creation of the dashboard which is an interface for the created optimization models. The dashboard is also validated in this Chapter using the user requirements and expert opinion. The results of the overall research are presented in Chapter 8 which combines the results of the Cost-Benefit Analysis and the optimization models. Lastly, the report concludes with a conclusion, discussion and recommendations in Chapter 9.

2. Literature review

In this Chapter, the literature review will be discussed. This review will answer the first and second sub-research questions. First, the alternatives to natural gas which are suitable in West Europe will be analysed. These alternative heating techniques will be described and compared. In the second Section, the existing decision support instruments will be analysed. In the third and last Section, the preferences of homeowners will be researched. The study will investigate which factors influence homeowners' decisions to switch to a gas-free heating system. This will be achieved by examining the goal framing theory. Additionally, the influence of socio-demographic characteristics, dwelling characteristics, and information provision will be examined.

2.1. Alternative heating techniques to natural gas

In this Section the first sub-research question will be answered: *Which techniques to supply homes with sustainable heating are feasible in West Europe and how are they implemented?* In Figure 7, it can be seen how this Section contributes to the research.

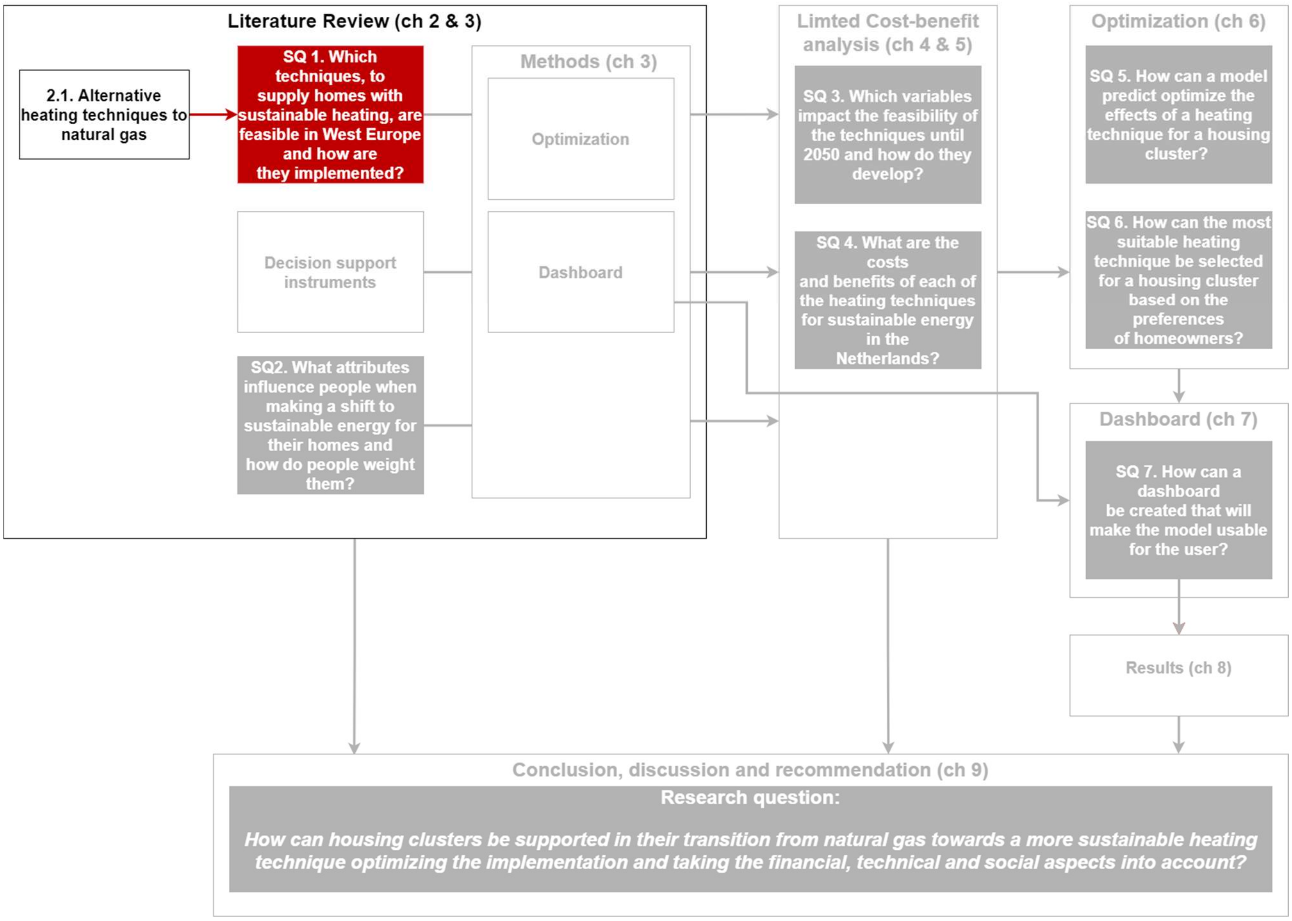


Figure 7: Literature review Section 2.1. within the overall research design

The goal is to replace heating using natural gas with a more sustainable source. This means that the non-renewable sources, which are petroleum and natural gas, are not suitable. In *Appendix A: Share of heating technologies and total installed capacity by country*, the share of heating technologies per European country is shown. In this figure, the Netherlands has a relatively high natural gas use (due to the natural gas fields in the Netherlands) compared to the other European countries which also have a high use of other fossil fuels like oil and coal.

To select which alternative heating techniques (which do not use fossil fuels) are suitable, there will be focussed on techniques that are suitable in West Europe. This will be done because this area has a comparable climate to the Netherlands, see *Appendix B: European climate zones*. Therefore, the selected techniques which are suitable for the Netherlands can also be suitable alternative heating techniques in other West European countries. Furthermore, the heating techniques which are considered fitting alternatives in the European Union are taken into account (European Commission, n.d.; Fleiter et al., 2016).

In the introduction, the main available natural gas-free heating techniques have been described. The alternatives that are suitable to replace natural gas are purchased heat (district heating), electricity for heat, and green gas. The selected heating techniques (see Table 3), are further elaborated below. In Table 5, the advantages and disadvantages of the techniques are listed. There is not one best technique, but customization is required. For the feasibility of a heating technique, not only the costs and consequences for the related homeowners are of importance, but also the construction of the required infrastructure. This infrastructure is required to facilitate the used techniques for heating. An extension of the infrastructure is often needed for a district heating network or the electricity network. An overview of some of the research on this subject to answer these problems is shown in *Appendix F: Cost of infrastructureAppendix F: Cost of infrastructure*.

Table 3: Suitable alternative heating techniques to natural gas

Code	Name of the technique	Heat source
NG1	Natural gas	Boiler with natural gas (current heating technique)
DH1	District heating	District heating middle temperature (MT)
DH2	District heating	District heating low temperature (LT)
AL1	All-electric	Air-to-water heat pump
AL2	All-electric	Collective ground heat pump
AL3	All-electric	Ground heat pump
GG1	Green gas	Hybrid air-to-water heat pump with green gas boiler

2.1.1. District heating

For district heating, a central heat source is used to heat the buildings (often housing) around them. This central heat source can be residual heat from industry, biomass and geothermal energy (Milieu Centraal, n.d.-e). District heating is suitable for areas with a high heat demand in a small area. For district heating, a pipe network, through which warm water flows, is used. This network connects heat producers with customers. This connection can be created in various ways. Which connection needs to be made, depends on elements like the distance between source and destination, the desired temperature and required capacity. Heat networks can be classified between transmission networks and distribution networks. Transmission networks have limited branching and transport heat over long distances to heat transfer stations. From these stations, heat is transmitted through usually highly branched distribution networks to the end-users (Hoogevorst, 2017). For district heating, there are always two pipes, one for the supply of the heat and the other to drain the cooled water back (Expertise Centrum Warmte, 2021b). By using heat networks, the heating of a house can be done by using residual heat. This means that overall, less energy is needed to heat a dwelling. Although heat networks reduce the total required amount of energy, the production method of the energy affects the level of sustainability of the heat networks (heat sources produced by fossil fuels have a higher CO_2 emission) (Hoogevorst, 2017). In the future, the heat for the network also needs to be produced from sustainable sources. There are multiple different types of heat networks. First of all, there is a difference in how the heat for the network is generated. The main heat sources of district heating networks are waste incineration plants, power stations, residual heat, geothermal, bioenergy, aqua thermal and heat from datacentres. These heat sources differ in sustainability, but the main difference for the homeowner is what temperature level the heat source delivers. The temperature level has three levels suitable for existing homes, which are high-temperature (HT) 90 °C (>75 °C), middle-temperature (MT) 55 °C -75 °C and low-temperature (LT) 30 °C - 55 °C. The advantage of a high-temperature network is that it is suitable for poorly insulated dwellings (label E/F/G) but at this temperature level there are less sustainable heat sources available, and it has higher heat losses than the other levels. Consequently, the HT level is less suitable than the other temperature levels (Expertise Centrum Warmte, 2021b).

2.1.1.1. District heating with middle temperature (DH1)

A district heating system with a middle temperature is the first heating technique. This is, like all district heating alternatives a collective technique which means that it is only feasible if it is widely adopted. If a district heating network is constructed it is most likely to be feasible in neighbourhoods with high density and high heat demand. To connect a home to a middle-temperature district heating network, some changes to the dwelling are required, see Figure 8. The heat network enters the home on the ground floor, which can be in contrast to homes, where the boiler is in the attic. Additionally, a delivery set is needed for the house to provide heat. If a middle temperature network is installed, the delivered temperature is only 10 °C lower than the heat supplied by a natural gas boiler. This means that in most cases the radiators do not have to be replaced and the insulation level needs to be at a minimum D+ to provide the household with a comfortable temperature in their home (Expertise Centrum Warmte, 2020a). Additionally, the natural gas connection must be disconnected, and electric cooking must be installed. Home adaptations like solar panels and ventilation are optional depending on the level of insulation.

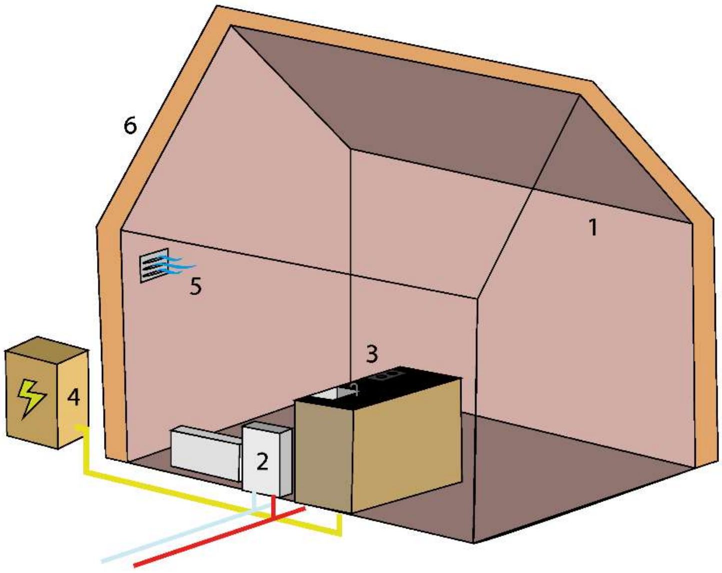


Figure 8: Infographic DH1, (1) Remove gas connection, (2) Connection to district heating with delivery set, (3) Electric cooking, (4) Electricity net reinforcement, (5) Ventilation system (optional), (6) Improve insulation to at least level D+, solar panels are also optional. Infographic inspired on (Expertise Centrum Warmte, n.d.).

2.1.1.2. *District heating with low temperature (DH2)*

The second heating technique is a district heating system with a low temperature. This is similar for the homeowner with the MT level but some extra alterations to the home are required because the supplied temperature is cooler, see Figure 9. Therefore, the level of insulation needs to be higher, at least insulation level B and the heat release system needs to be made fit for low temperatures which means that special low-temperature radiators or floor heating are necessary. Furthermore, a booster heat pump will be required to supply hot tap water and a boiler tank to store the hot tap water (Expertise Centrum Warmte, 2020b; Kirch et al., 2019; van Leeuwen et al., 2019).

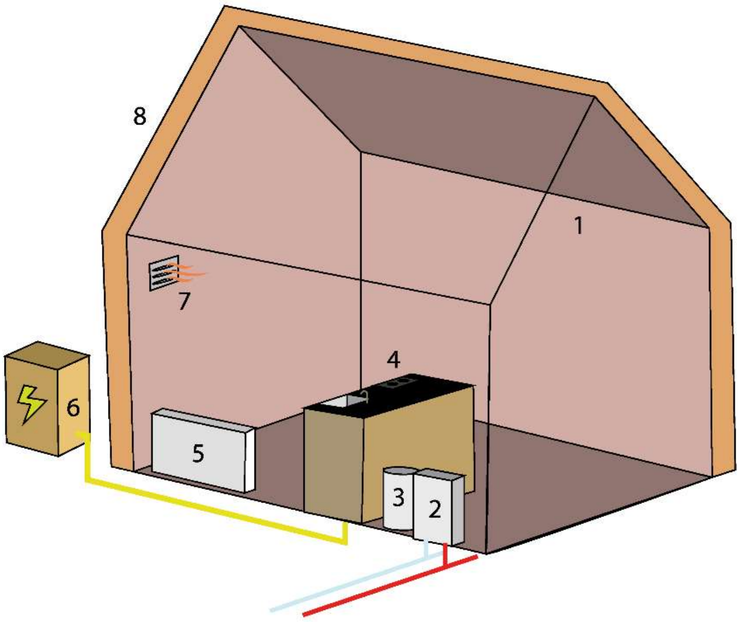


Figure 9: Infographic DH2, (1) Remove gas connection, (2) Connection to district heating with delivery set, (3) Booster heat pump, (4) Electric cooking, (5) Low-temperature radiators, (6) Electricity net reinforcement, (7) Ventilation system with heat recovery, (8) Improve insulation to at least level B, solar panels are also optional. Infographic inspired on (Expertise Centrum Warmte, n.d.).

2.1.2. All-electric

Another alternative, to replace the use of natural gas for the heating of homes, is the use of electricity. This alternative is often called all-electric because the whole energy need of the household is fulfilled by electricity. In 2019, 2% of Dutch houses are all-electric and are connected to a heat pump which fully provides for the heat supply of the household (van Polen, 2021). This share of all-electric houses is expected to rise to 6% in 2025 and 8% in 2030 (Hammingh et al., 2020). When a house is all-electric, a household cooks and heats the building using electricity. There are multiple options for the heating of a dwelling using electricity. These systems are electric floor heating, electric heater, electric radiator, electric boiler, infrared heating or a heat pump. Considering these different heating techniques, the heat pump is the most suitable heating technique for all-electric. The other all-electric techniques have a very high electricity consumption which makes them less sustainable compared to heat pumps. Techniques like infrared heating also provide less comfort than heat pumps (Klimaatexpert, 2018). There are multiple types of heat pumps. In Table 4 the different types of heat pumps have been described including their advantages and disadvantages. The most suitable heat pumps for all-electric are the air/water heat pump, ground/water heat pump and collective water/water heat pump. These are more suitable than the other heat pumps because an air/air heat pump has low efficiency and can cause a nuisance in the house. The hybrid heat pump is not suitable for all-electric systems since natural gas is still needed for the heating of homes (instead of only electricity).

Table 4: Types of heat pumps (Technische Unie, n.d.)

Type of heat pump	Explanation	Advantages	Disadvantages
Air/air heat pump	An air-air heat pump collects the heat for the heating of a home from the air and the outdoor air is the heat source. This type of heat pump can also be used as an air conditioner. The heat pump can be used throughout the year but has the disadvantage that the created airflow in the house can cause nuisance like the feeling of draught.	• Cheap (cheapest of the different heat pumps). • Can function as an air-conditioning. • Can quickly heat a room. • Easy to install.	• Low efficiency for cold weather (extra heating required). • Cannot be combined with existing radiators or floor heating. • Cause nuisance (draught).
Air/water heat pump	The air-water heat pump also collects the heat from the air but transits it to the refrigerant, which heats water or tap water. The air-water heat pump is the most used type in the Netherlands. The air heat collects approximately three-thirds of its energy from the air.	• Easy to install. • Cheaper than the ground heat pumps • Energy efficient	• The efficiency is dependent on the outdoor temperature. • Noise pollution
Water/water heat pump	This type of heat pump collects heat from groundwater. The groundwater is pumped up (from which the heat is collected) and the collected water is pumped back into the ground. The collected energy is used for the heating of the home and tap water. This is open-source and is called Aquifer thermal energy storage (ATES). Because these installations are costly it is often only applied for high capacity (multiple houses or utility).	• Highest energy efficiency level • Requires little space • Groundwater can be used for other purposes • Can cool the house if required	• High drilling and installation costs • A licence is required to pump groundwater.
Ground/water heat pump	Groundwater (or brine-water) heat pumps use energy in the ground for heating and hot water production. (horizontal) By ground collectors close to the surface, transfer the thermal energy to the heat pump. Or (vertical) with geothermal probes that are placed vertically in the ground and generate thermal energy at a depth of 40 to 100 meters. This type has a higher efficiency than the air-to-water heat pumps but they also require a high initial investment.	• Outside temperatures do not impact a groundwater heat pump. • Only a small outside area is required (vertical installation).	• Drilling is expensive.
Hybrid heat pump	A hybrid heat pump is a combination of a high-efficiency boiler (using natural gas or green gas) and a heat pump. The heat pump heats the home most time of the year and the high-efficiency boiler is used for the heating of tap water and during very cold days for the heating of the home.	• Easy to install • Cheaper than some of the other heat pumps	• The house is still dependent on natural gas. • Noise pollution

2.1.2.1. All-electric with air-to-water heat pump (AL1)

For the all-electric heating technique, the energy consumption of a dwelling is fully supplied by electricity which means that also the heat for room heating and hot water is produced using electricity. The technique, all-electric with an air-to-water heat pump (air/water heat pump), uses an air-to-water heat pump to produce heat. A heat pump is a very efficient technique to extract heat from the air or ground. An electric heat pump upgrades the heat from the source (which is in this case the air) to a usable temperature for the heating of a home and hot tap water, see Figure 10.

A heat pump delivers low-temperature heating (45-55 °C) which means that when applied, it needs to be combined with an improvement of insulation of the home (to at least a building envelope label of B). Other required alterations to the house are the addition of a boiler vessel (which is needed for the storage of tap water), a ventilation system (with heat recovery for some rooms), electric cooking and low-temperature radiators (or floor heating). Other required alterations to a home are the removal of the gas connection and extending the electricity connection (due to the high consumption) (Expertise Centrum Warmte, 2021a). The level of sustainability of this technique depends on how sustainable the used electricity is because the all-electric technique has a high electricity consumption. Therefore, it could be profitable to use solar panels for this technique to produce sustainable electricity. Furthermore, heat pumps can also cool a dwelling which means that the chance that an air conditioner is required will be smaller.

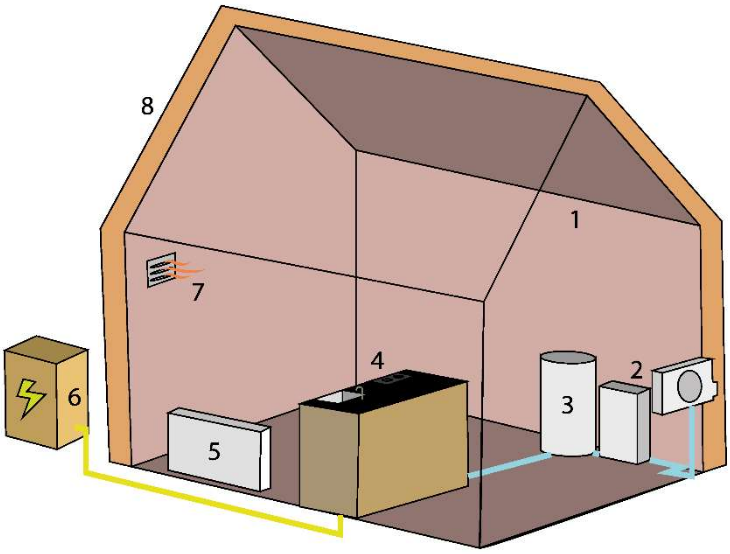


Figure 10: Infographic AL1, (1) Remove gas connection, (2) air-heat pump, (3) Boiler vessel, (4) Electric cooking, (5) Low-temperature radiators, (6) Electricity net reinforcement, (7) Ventilation system with heat recovery, (8) Improve insulation to at least level B, solar panels are also optional. Infographic inspired on (Expertise Centrum Warmte, n.d.).

2.1.2.2. All-electric with ground heat pump (AL3)

The all-electric with a ground heat pump heating technique is very similar to the above-described all-electric technique. The main difference is that in this case a ground heat pump (ground/water heat pump) is used instead of an air-to-water heat pump. A ground heat pump uses the ground as the heat source to heat a home (geothermic). This means that for the application of a ground heat pump enough space in the ground is required, see Figure 11. To place the network in the ground, drilling in the ground is necessary. In a high-density area, there is not always enough space available to install a ground heat pump. An advantage of the ground heat pump over the air-to-water heat pump is that it

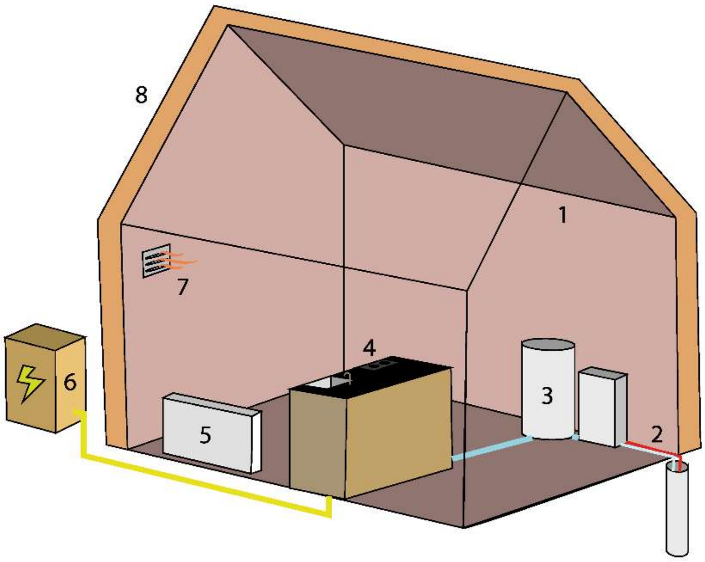


Figure 11: Infographic AL2 and AL3, (1) Remove gas connection, (2) ground-heat pump, (3) Boiler vessel, (4) Electric cooking, (5) Low-temperature radiators, (6) Electricity net reinforcement, (7) Ventilation system with heat recovery, (8) Improve insulation to at least level B, solar panels are also optional. Infographic inspired on (Expertise Centrum Warmte, n.d.).

often requires less energy and it does not produce noise pollution (Expertise Centrum Warmte, 2021a).

2.1.2.3. *All-electric with collective ground heat pump network (AL2)*

The third all-electric heating technique is all-electric with a collective ground heat pump network that uses a water/water heat pump, with a collective ground heat pump network. This technique does not require every dwelling to drill an individual shaft for the ground loop, but a single deep shaft must be drilled collectively, saving a lot of costs for each household. For this technique, every dwelling has an individual heat pump, and the home needs to be adapted for all-electric with a heat pump similar to the other described all-electric heating techniques.

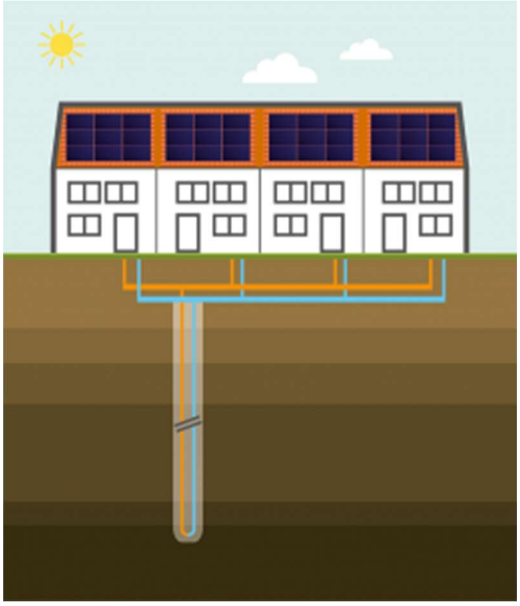


Figure 12: All-electric with collective heat pump network

2.1.3. Green gas

Green gas has similar properties to natural gas, which means that the gas network can be used to distribute it to the users. Currently, green gas is already added to the natural gas in the gas network, but this is a very small part of the gas in the network. Hoogevorst et al. predicted that the available amount of green gas for the built environment will rise to 1 bcm in 2030 and 2 bcm in 2050. The total predicted amount of green gas will be higher (10-12 bcm) but this is also required for other sectors like the industry and transport. Green gas can only contribute to the shift from natural gas to other energy sources and not completely replace natural gas consumption, since the estimated available amount of green gas is still less than the currently used natural gas (Hoogenvorst et al., 2020). The already existing gas network is suitable for the transport of green gas, which means that the connection cost will be low. However, some alterations to the gas network will be required to make it possible to inject green gas into the transport network (but it is estimated by Hoogevorst et al. that this will be less than 1% of the production cost of green gas in 2030). Another benefit of green gas is that alterations in the house, like the replacement of a boiler, stove, radiators and insulation are not necessary. This can be an advantage, especially for older dwellings in high-density areas for which the other techniques are not feasible (Groengas Nederland, n.d.; Hoogenvorst et al., 2020;

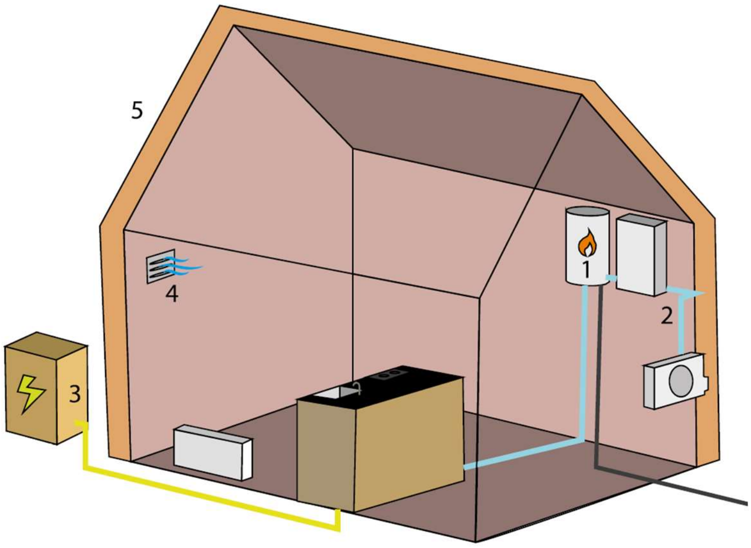


Figure 13: (1) Green gas, (2) hybrid heat pump, (3) Electricity net reinforcement, (4) Ventilation system (optional), (5) Improve insulation to at least level B, solar panels are also optional. Infographic inspired on (Expertise Centrum Warmte, n.d.).

Wiskerke, 2011). Two main heating techniques apply green gas for the heating of homes. The first option is to fully replace natural with green gas and the second technique is a hybrid heat pump. Due to the limited availability of green gas, a strategy where green gas fully replaces natural gas will not be suitable because in that case, only a very limited number of dwellings can shift to green gas. Since using green gas requires (compared to the other heating techniques) little alterations to the dwelling it is very suitable for old high-density dwellings (because these types of dwellings are more difficult and costly to make energy efficient) which makes it even more important to make the technique available for as many dwellings as possible. Consequently, there has been chosen to only focus on heating green gas with a hybrid heat pump.

2.1.3.1. Green gas with a hybrid heat pump (GG1)

The heating technique green gas with a hybrid heat pump heats the dwelling with a combination of a hybrid air-to-water heat pump and a high-efficiency boiler (that uses green gas), see Figure 13. The main required heat will be provided by an air-to-water heat pump. Only on days when a high amount of heat is required (for example during the winter), the high-efficiency boiler is used to replenish the heat demand. By applying this heating technique only, a limited amount of green gas and a small heat pump is required, an advantage of this is that the electricity network rarely needs to be reinforced. This heating technique delivers the heat at a temperature of 80°C which means that the radiators do not need to be replaced and only limited insulation measures are required. Green gas can be used for cooking which means that applying electric cooking is also not required. This heating technique can be applied to all types of dwellings, but it would be preferable to apply the technique to dwellings where it is difficult to apply the other techniques due to technical or financial limitations (Expertise Centrum Warmte, 2020c).

2.1.4. Comparison of the techniques

As described above, district heating, all-electric and green gas could be alternatives for natural gas. In Table 5, the advantages and disadvantages of the methods are listed. The table clearly shows that the methods show benefits compared to each other but especially compared to natural gas. Nevertheless, the table also shows that there are still some challenges that can make them less attractive to implement. When considering these advantages and disadvantages it can be concluded that there is not one best alternative heating technique to natural gas and that the feasibility of the different techniques differs per situation. Although the heating technique which uses green gas provides opportunities, especially for dwellings with technical and financial limitations, this technique is the least feasible due to the very limited availability of green gas for the housing stock.

Table 5: Advantages and disadvantages of district heating and all-electric (Bewonerscollectief Capelle aan den Ijssel, 2018; Enexis, n.d.; J. Jorna, 2017; Julia Jorna, 2018; Kassa, 2018; Regionaal energieloket, n.d.; UnitedConsumers, n.d.; Vereniging eigen Huis, n.d.)

	District heating	All-electric	Green gas
Advantages	District heating is a safer heating option than natural gas	The decrease in CO_2 emission, especially when a household generates its own electricity using solar panels	Green gas is generated from renewable sources
	The use of district heating can result in awareness of the user of where the energy comes from	When a household generates its own energy, it is less dependent on an energy supplier.	A decrease in CO_2 emission.

	For the use of district heating, relatively few adjustments to the house are required.	The energy heating cost can be lower, especially when the house is well insulated, and the household generates its own energy.	The current gas network can be used which makes it a suitable alternative when district heating and all-electric are not possible (like in dense city centres and monumental buildings)
	Reduces the CO_2 emission for heating (depending on the source)	There are possibilities to get subsidies for the purchase of a heat pump.	Could be used with the current boiler, stove and radiators, which results in low investment cost
	There is a possibility for heating and cooling a dwelling.	Some of the systems also can heat and cool a building.	Investment in isolation and ventilation is not necessary
Disadvantages	Heat networks are often owned by the same company that also supplies the heat. So, the user has no choice for a supplier.	When using a heat pump in many cases a large initial investment is needed because the house must be very good insulated	Green gas is currently more expensive than natural gas
	Currently, it is often as expensive or more expensive than natural gas. Also, the price will grow depending on the natural gas price.	Also, the heat pump can only heat water up to 55 degrees Celsius which requires an adjusted heating system.	There is a very limited green gas capacity for the building stock
	With a heat network at a low temperature, the user needs to get used to the fact that no quick small adjustments to the temperature are possible.	Due to the higher use of electricity, it can be possible that a more elaborated electricity connection is required.	The costs of producing green gases are higher than natural gas, electricity or heat from a heat network.
	In some cases, there can be some doubts about the environmental effects of the heat network, depending on how the heat was generated	A heat pump could cause noise pollution.	
	District heating can only be supplied if it is offered in the area.		
	District heating is only suitable in an urban area (due to high density)		

2.2. Decision support instruments

There currently already are policy instruments in the Netherlands that aim at supporting various types of users in their transition to non-natural-gas-based heating. They mostly do not offer a holistic consideration of the relevant gain, hedonic and normative aspects to find the most fitting transformation of the housing cluster. Therefore, an optimization model will be created for decision support. That can be used by the main stakeholder homeowners but will also provide information to the user: the local authority (municipality). To increase the added value of the model, insights are required into the existing instruments and their knowledge gap. First, the insights of decision support instruments for local authorities will be analysed, which contains the insights of cost-benefit analysis. Second, the decision support instruments for individuals (homeowners) will be analysed. In Figure 14, it can be seen how this Section contributes to the research.

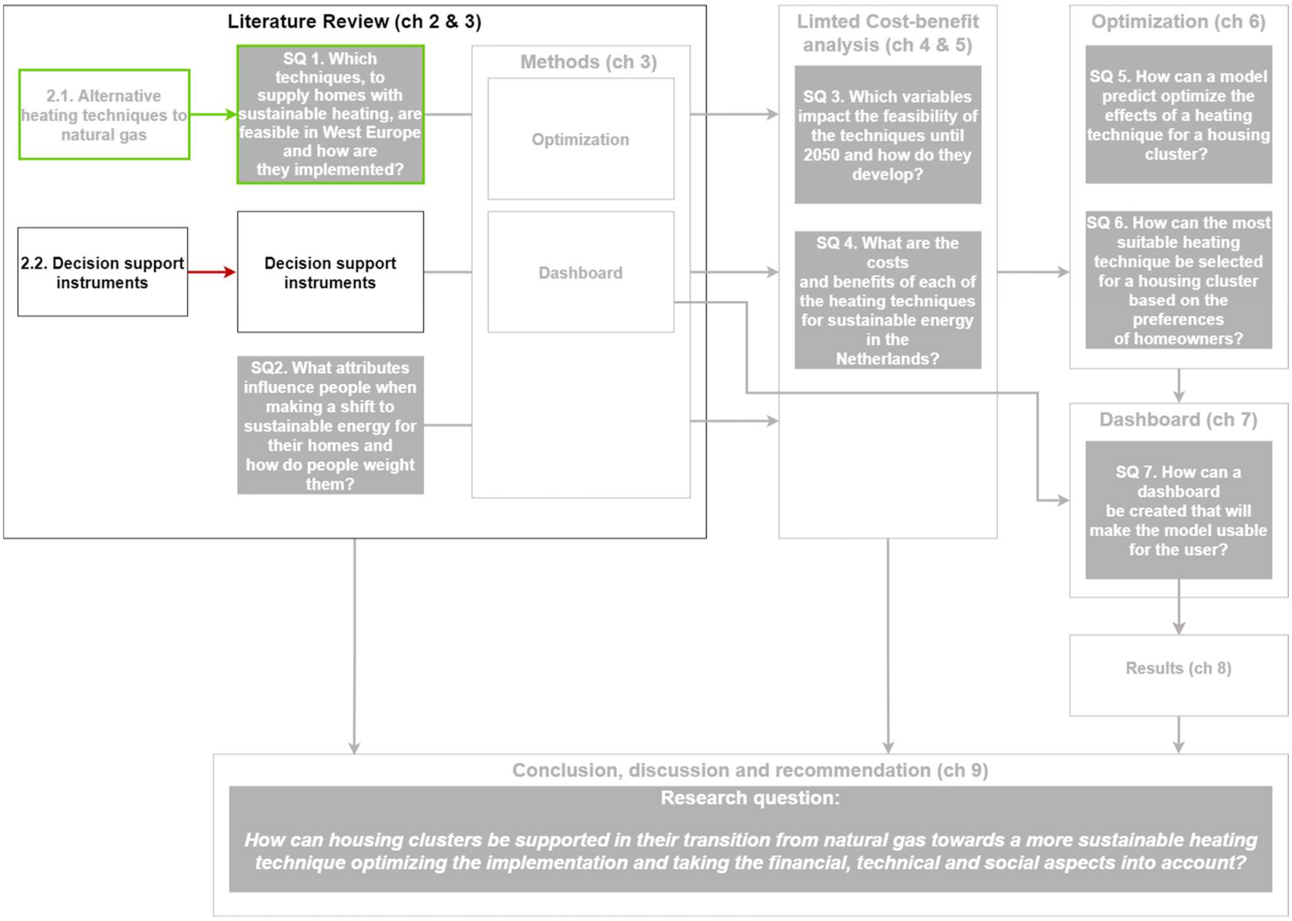


Figure 14: Literature review Section 2.2. within the overall research design

2.2.1. Decision support instruments for local authority (policy maker)

To be able to find the most suitable heating technique for each housing cluster, the above-mentioned heating techniques must be compared in the current research. To evaluate and compare the costs and benefits of the different heating techniques, a (social) cost-benefit analysis (S)CBA can be performed. Cost-benefit analysis (CBA) is an important tool for use in the ex-ante assessment of policy options. The CBA is a systematic information tool to provide an overview of the effects, risks and uncertainties of a measure and the resulting costs and benefits to society as a whole. The found advantages and disadvantages are quantified in a CBA and values are assigned to them (in Euros). A balance in Euros can be created of the benefits minus the costs (which also includes the effects on the aspects of social welfare for which there is no market price). Expressing the effects in monetary terms as much as possible, makes it possible to compare them and to weigh up the pros and cons of a measure. This will make it possible to answer the question of whether the economic and social costs of a measure outweigh the economic and social benefits (Romijn & Renes, 2013). Romijn & Renes (2013) have described the methodology of Cost-Benefit Analysis in the report General guidance for Cost-Benefit Analysis (of the CPB and PBL). The main steps of this analysis are

Figure 15: Steps of the CBA (Romijn & Renes, 2013)

shown in Figure 15. In the current Section, a literature review will be conducted on previous CBA research to understand the involved stakeholders and the effects identified in comparable studies. It is possible to determine the information gap if insight is gained into the existing research. Consequently, the current research can better be scoped to answer this information gap. The current Section will first present an overview of existing CBA research concerning sustainable heating techniques. Based on these researches, the gap in the CBA will be determined.

2.2.1.1. Existing research Cost-Benefit Analysis

An overview of CBAs focused on sustainable heating techniques for dwellings or research on the effects of these techniques has been created in Table 6. In this table, the goal per research has been described. From these researches, the involved stakeholders and the effects of the sustainable heating techniques will be identified.

Table 6: Overview of researches focussed on effects of sustainable heating techniques (CE Delft, 2018; Huygen, 2018; Huygen et al., 2019; Leurent et al., 2018; M. Mulder & Hulshof, 2021; RVO, 2018; Tieben et al., 2020; van Melle et al., 2015; van Steen, 2008)

Source	Goal
(RVO, 2018)	The goal of the study "is to investigate the potential of small-scale sustainable heating technologies in the rental sector and to what extent these techniques can contribute to the desired acceleration of the sustainability challenge in the short and long term" (RVO, 2018). Incorporated techniques: heat pump systems, solar boilers and biomass boilers.
(Tieben et al., 2020)	"The study calculates the social costs and benefits of various heat options aimed at making the heat supply in the built environment and greenhouse horticulture in West Brabant and Hart van Brabant more sustainable" (Tieben et al., 2020). Incorporated techniques: regional district heating, local district heating, green gas and all-electric.
(M. Mulder & Hulshof, 2021)	The objective of this policy paper is to show how a social cost-benefit analysis can be conducted for district-heating systems, which may help policymakers in their discussion of the social desirability of this policy option to reach their climate-policy objective (M. Mulder & Hulshof, 2021).
(van Steen, 2008)	In this study, a social cost-benefit analysis was made concerning making energy use more sustainable in existing office buildings. The analysis provides insight into the investment costs and savings of sustainable systems and measures in the field of energy and CO2 emissions (van Steen, 2008).
(CE Delft, 2018)	In this study, a social cost-benefit analysis (SCBA) is performed for a heat network in Zaandam-East, based on the concrete business cases drawn up by Alliander DGO and Engie (CE Delft, 2018).
(Leurent et al., 2018)	"This paper aims to evaluate and compare the potential cost savings and greenhouse gas reduction of district heating systems using heat from nuclear-combined heat and power plants in Europe" (Leurent et al., 2018).
(van Melle et al., 2015)	This study is focused on the question of what new technological developments will mean for the reliability and affordability of the energy system of the future. The report aims to contribute to discussion and decision-making about the energy transition (van Melle et al., 2015).
(Huygen et al., 2019)	The ambition is to make 1.5 million existing homes and buildings natural gas-free by 2030. The question the research aims to answer is, what role can heat networks play in this and what can the Netherlands learn from Denmark (Huygen et al., 2019)?
(Huygen, 2018)	This paper describes how we can ensure that attractive and affordable alternatives are available for consumers so that they can easily switch to natural gas-free living and working (Huygen, 2018).

Of the research described in Table 6, the researches of Tieben et al. (2020), Mulder & Hulshof (2021), and CE Delft (2018) have the closest resemblance to the current research. An overview of these researches has been created in Table 7 and they are further elaborated below. Most of the CBAs are focused on determining the social costs and benefits of the implementation of district heating networks. The focus on district heating networks instead of individual heating techniques for social cost-benefit analysis can be explained by the fact that district heating networks require a large initial investment and are only feasible if there are sufficient dwellings involved in the district heating network. This is in contrast with individual heating techniques which can be implemented (and decided for) per household. Although implementing individual heating techniques on a large scale can have a big societal and non-market impact. Due to this, the reference CBAs compare the scenarios with district heating with these alternative individual techniques.

Table 7: Overview of the selected CBAs (CE Delft, 2018; M. Mulder & Hulshof, 2021; Tieben et al., 2020)

	Tieben et al. (2020)	Mulder & Hulshof (2021)	CE Delft (2018)
Goal	The study calculates the social costs and benefits of various heat options aimed at making the heat supply in the built environment and greenhouse horticulture in West Brabant and Hart van Brabant more sustainable.	The objective of this policy paper is to show how a social cost-benefit analysis can be conducted for district-heating systems, which may help policymakers in their discussion of the social desirability of this policy option to reach their climate-policy objective.	In this study, a social cost-benefit analysis (SCBA) is performed for a heat network in Zaandam-East, based on the concrete business cases drawn up by Alliander DGO and Engie.
Region (population)	West-Brabant and Hart van Brabant	Neighbourhoods Vinkhuizen-Noord & -Midden, Paddepoel-Noord & Midden, and Selwerd-West. The area includes 3200 residential buildings.	Municipality Zaanstad
Household types	The averages of several housing types are used in the CBA.	12 types of buildings are used. The housing types are distinguished based on housing type, construction period, energy label and natural gas consumption.	Corporation homes, new-build homes and other buildings.
Horizon	2020-2050	2022-2080	2018-2068
Scenario's	The scenarios of the welfare and living environment of the planning offices, as prescribed in the SCBA guidelines, are used for the CO2 prices.	Three scenarios: S1: Modest climate policy S2: Intermediate climate policy S3: Intensive climate policy	Two scenarios: High: combines high population growth with high economic growth. Low: a more moderate demographic development and a more modest economic growth.
Baseline alternative	Natural gas will remain the primary fuel for heating homes. Some households will switch to heat pumps. By 2050 75% of the households depend on natural gas for heat supply. The energy-saving pace in the baseline alternative is 0.5% per year.	The households will continue to heat their home using natural gas.	The most likely situation without a heat network. 1) tenants of housing associations and public buildings in Zaandam continue to use gas-fired boilers, 2) new-build homes will be 'all-electric' or will have a high-efficiency gas boiler, and 3) the residential complexes will be renovated over time.
Policy alternatives	1) regional heat network (focussed on biomass, geothermy or a mixture), 2) local heating source (with or without the use of the existing regional heat network), 3) Individual heating technique (using solar thermal/green gas or all-electric)	The policy alternatives all include district heating but vary in the heat source for the network (which results in a different source temperature). The main difference for the homeowner is delivery temperatures (30°C, 50°C and 70°C)	All policy alternatives all include the same implementation of a district heating network but differ in the heat source of the network: 1. biomass power plant, with SDE subsidy 2. biomass power plant, without SDE subsidy, and 3. gas-fired peak boiler.
Findings	None of the policy alternatives has a positive balance. Project alternative 3A (in which green	Variant V1 (delivery temperature 50°C) has the most negative welfare effect	The CBA is positive for district heating with existing and new construction dwellings. The

	gas is used) provides relatively the most favourable balance. The most expensive alternative is 2B which focuses on local heat networks fed by local heat sources.	and V2 and V3 (both delivery temperature 70°C) do not differ strongly although V2 performs better.	CBA without new construction dwellings is negative but can be made positive if extra dwellings are added.

CBA timeframes differ among the studies. The analyses are conducted over a period of 30 to 60 years. That the minimum timeframe extends until 2050 can be expected because at this moment in time the housing stock needs to be heated with sustainable sources. Because the CBA aims to predict the effects over a long period, they have created scenarios to deal with the development uncertainties. Examples of these uncertain variables are energy costs and climate policies. The three analyses all analyse the costs and the benefits of a large research area. Tieben et al. (2020) execute the analysis for a transition toward sustainable heating in the RES regions “West-Brabant” and “Hart van Brabant”. The second CBA (of Mulder & Hulshof) focuses on the North-western part of the city of Groningen which includes 3200 residential buildings. For the research of CE Delft, a heat network in Zaandam-East (municipality of Zaanstad) is considered. With this network low-CO_2 heat will be used to heat housing association homes, new-build homes and other buildings.

Baseline alternative

Romijn and Renes (2013) describe the baseline alternative as “*The baseline alternative is the most likely situation that would develop in all the relevant markets for the CBA if the measure under consideration were not implemented.*”. The baseline alternative is essentially a benchmark against which all relevant policy alternatives are measured. Therefore, it is critical for reliable results of a CBA to determine a reliable baseline alternative.

Tieben et al. (2020) describe the baseline alternative in their research as the development of the heat supply between 2020 and 2050 if no additional investments are made to sustainable heat supply. While the use of natural gas is decreasing, it remains the primary fuel for heating homes. However, some households will switch to heat pumps. By 2050, 75% of households depend on natural gas for heat supply. The other dwellings will be heated using a heat pump. The energy-saving pace in the baseline alternative is 0.5% per year, which results in a heat demand of 6.3 TWh in 2050.

Mulder & Hulshof (2021) describe their baseline alternative as "*The situation in which no specific policy measures are taken, but where autonomous changes may occur*". As a result, it is expected that households will continue to heat their home using natural gas.

CE Delft defines the baseline alternative as the alternative which is the most likely situation without a heat network. This means that: 1) tenants of housing associations and public buildings in Zaandam continue to use gas-fired boilers, 2) newly-build homes will be 'all-electric' or will have a high-efficiency gas boiler, and 3) just as in the reference alternative, the residential complexes will be renovated over time (CE Delft, 2018).

These studies reveal that for the baseline alternative, it is assumed that most of the existing housing stock will be heated by natural gas. In the different baseline alternatives, it is also assumed that households will save energy due to natural interventions like renovation and insulation.

Policy alternatives

The policy alternatives described by Tieben et al. (2020) are 1) regional heat network (focussed on biomass, geothermy or a mixture), 2) local heating source (with or without the use of the existing regional heat network), and 3) Individual heating technique (using solar thermal/green gas or all-electric) (Tieben et al., 2020).

The policy alternatives described in the CBA of Mulder & Hulshof (2021) all include district heating but vary in the heat source for the network (which results in a different source temperature). For the homeowner, the main differences in the scenarios are the delivery temperatures. These are 30°C, 50°C and 70°C, this results in a different implementation and use of the district heating network.

The research of CE Delft describes three policy alternatives, which all include the same implementation of a district heating network but differ in the heat source of the network. The policy alternatives are 1) biomass power plant, with SDE subsidy, 2) biomass power plant, without SDE subsidy, and 3) gas-fired peak boiler.

For the policy alternatives that have been taken into account for the reviewed CBAs, it can be seen that the main focus lies on district heating alternatives. Only the research of Tieben et al. (2020) takes individual heating techniques into account.

Effects

The three CBAs identify the costs and benefits of the selected alternatives. These will be discussed per research.

The CBA of Tieben et al. (2020) first identifies the costs for the policy alternatives (and the baseline alternative) and secondly identifies the benefits, see Table 8. Included in the costs are the following elements: costs associated with the heat source, distribution, transport, and energy savings. The cost associated with the heat source consists of the investment and the operational costs for the different used heat sources. The costs for energy saving are the investment costs for the energy-saving measures. The benefits that are identified in the CBA are the avoided costs, which relate to both energy infrastructure and energy costs, climate and nature benefits, social-economic effects, and security of supply. The climate and nature benefits are the avoided costs of emissions from the use of fossil fuels. As a result of the investments in the heat transition, social-economic factors like employment are affected. This will mainly consist of a shift in employment, but this effect will disappear over the long term (Tieben et al., 2020).

Table 8: Effects of CBA of Tieben et al. (2020)

	Effect
Costs	
	Investment costs
	Operational costs
	Distribution cost
	Transport cost
	Energy reduction
Benefits	
	Avoided costs in energy infrastructure
	Avoided costs energy costs
	Climate and nature benefits
	Security of supply
	Emission costs
	Employment opportunities

In the CBA of Mulder & Hulshof (2021), the cost and benefits are identified for the various stakeholders and the external effects, which are shown in Table 9 and summarized below. For households, the investment costs per heating technique and needed alterations to the dwelling are included, which are investments in the improvement in insulation, low-temperature heat distributors, alternative appliances for cooking, and connection to district heating. The CBA showed that the height of the investment cost depends on the properties of the dwelling. Besides investment costs, energy costs are also included for households, which include the variable and fixed costs. The total welfare effects for the stakeholder households are investments, the fees they have to pay to the heat-transport operator, the costs of the heat supplied by the heat supplier, the costs for using electricity (for heat pump), the savings on expenditures for natural gas and fees for gas transport, and potential subsidies received from the government. For the district heating system, three stakeholders can be identified, which are the heat producer, heat-transport operator, and heat supplier. Currently, these three roles are often conducted by one player. For the welfare effects, the costs for these three roles are included. The indirect economic effects are the effects on the electricity network due to the change in demand, the natural gas network due to the change in demand and production and other infrastructures. Due to digging in the ground for the construction of a district heating network, other infrastructures are also affected. This includes electricity grid maintenance, replacing water pipelines or building a new fibre network for telecommunication. The external effects include the environmental effects, the societal value of reduced gas consumption, and the non-monetary costs of the required effort of households. Last of all, the economic effects on the government are the energy taxes and the change in the cash flow of the government.

Table 9: Effects of CBA Mulder & Hulshof (2021)

Stakeholder			Effect
Household		Costs	Investment costs
			Costs heat transport network
			Heat consumption
			Electricity consumption
		Benefits	Savings on natural gas
			Subsidy government
Heat supplier	Heat producers	Costs	CAPEX heat source
			OPEX heat source
			Electricity use
		Benefits	Revenues sales heat
	Transport operator	Costs	CAPEX infrastructure
			OPEX
		Benefits	Transport fees
	Heat supplier	Costs	Purchase of heat from heat source
			Retail cost
		Benefits	Sales of heat to households
Indirect economic effects		Costs	Investments in upgrading the electricity grid
			Change in profit of sales of gas
			Change in revenues for gas transport
			Reduced costs of other infrastructures
External effects		Costs	Societal costs of effort required by household
		Benefits	CO_2 emissions
			NO_x emissions
			SO_2 emissions
			Emission of small particles
			The societal value of reduced gas consumption
Government		Costs	Tax revenues on gas consumption households
			Subsidies
		Benefits	Tax revenues on electricity consumption households
			Tax revenues on electricity consumption heat system

The CBA for district heating in Zaanstad, created by CE Delft, identified the costs and effects of the policy alternatives, see Table 10. CE Delft identified the costs as investment costs, reinvestment costs, operational costs, and avoided maintenance and reinvestment costs. Several benefits have been identified, including energy costs avoided for homes and utility buildings, tax and subsidy reductions, environmental benefits, and employment opportunities. Eventually, CE Delft did not include employment opportunities due to staff shortages which means that additional investment mainly leads to higher wages.

Table 10: Effects of CBA of CE Delft (2018)

	Valuation expressed in	Scale level	Duration
Costs:			
Investment costs	€	Zaanstad and national	2018-2030
Reinvestment costs	€	Zaanstad and national	2018-2068
Operating costs	€	Zaanstad and national	2018-2068
Saved fuel costs	€	Zaanstad and national	2018-2068
Effects:			
SDE+ subsidy	€	Zaanstad	2018-2068
Employment opportunities	€	N/A	2018-2068
Climate benefits	€	Zaanstad and national	2018-2068
Income energy tax + ODE	€	National	2018-2068
Reduction other emissions	€	Zaanstad and national	2018-2068
Effects on the natural gas network	€	N/A	2018-2068

Results

The results of the CBA of Tieben et al. (2020), and Mulder & Hulshof (2021), are shown in *Appendix G: Results of reference CBA*. The results of the CBAs can be compared to find which policy alternatives provide the highest overall welfare effect. From the research of Tieben et al. (2020), it can be seen that none of the policy alternatives has a positive balance. Project alternative 3A (in which green gas is used) provides relatively the most favourable balance. The most expensive alternative is 2B which focuses on local heat networks fed by local heat sources. The overall welfare effect of Muller & Hulshof (2021) shows that variant V1 has the most negative welfare effect and V2 and V3 do not differ strongly although V2 performs better.

2.2.1.2. Current knowledge and gap

Based on existing CBAs, it is possible to determine which aspects of CBA for switching to sustainable heating technologies have been researched. In addition, it can be determined which areas need further study. Figure 16 provides an overview of the main effects of overall welfare, according to the above-described research. The Figure demonstrates that existing CBAs are predominantly focused on district heating (and scaled accordingly). This means that a large scale was used and the effects on the implementation and exploitation of these networks have been investigated in multiple situations. On the other hand, only limited effects on homeowners have been identified. This can be explained by the large scale of the analysis which results in the use of averages instead of determining the individual direct effects per household (based on the properties). Consequently, there is a gap in information since, as stated by TNO, consumers place more emphasis on the added value of convenience and comfort, circularity, durability, noise, and the lifespan of installations than only on cost and energy savings (Huygen, 2018). Due to the existing knowledge on district heating for different heat sources, the effects on the other stakeholders are already determined. This makes it an appropriate focus for the current research to investigate the costs and the benefits of the stakeholder households. This scope is shown in a light red colour in Figure 16. The research scope should be designed to create a CBA for the shift towards a sustainable heating technique on a household, or cluster level. The current approach allows researchers to determine which

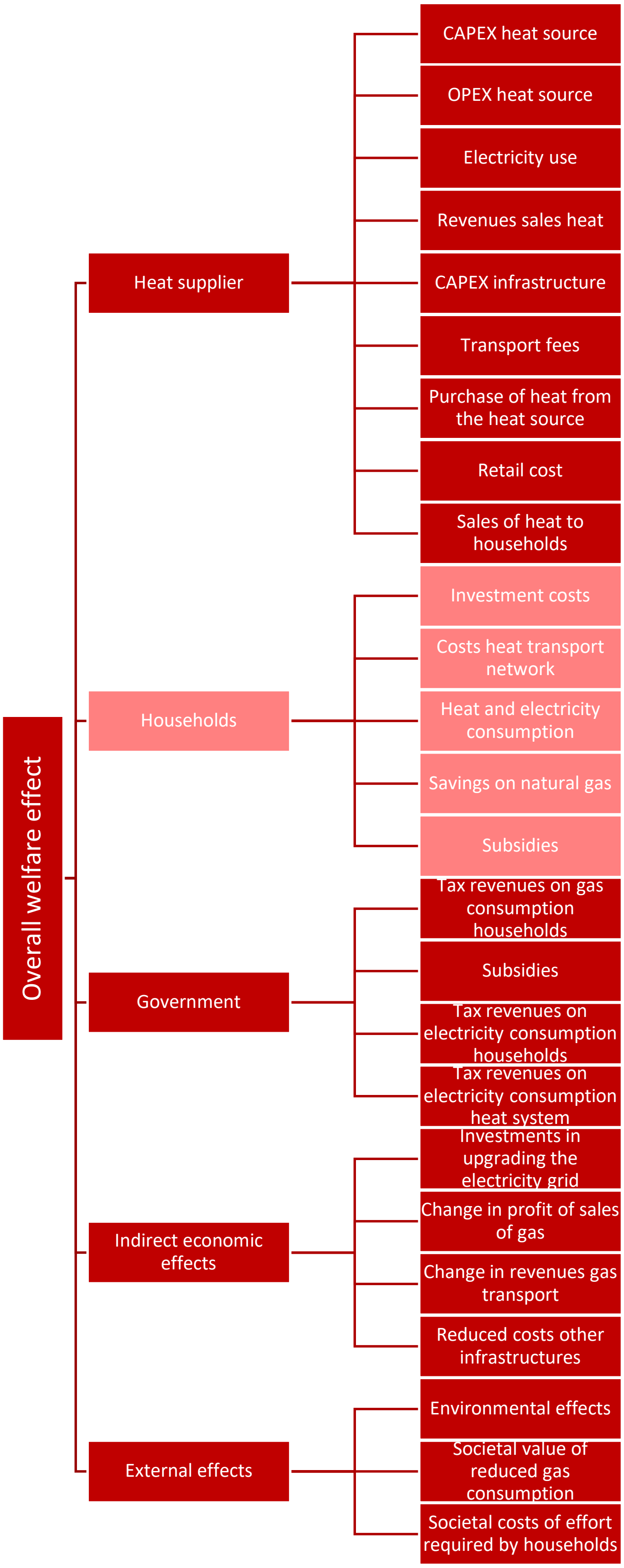


Figure 16: Overview of overall welfare effects based on existing CBA, the pink blocks indicate the proposed scope for the current research (CE Delft, 2018; M. Mulder & Hulshof, 2021; Tieben et al., 2020)

areas would benefit the most from alternatives. By choosing this scale, it will be possible to identify more effects for households, as well as investigate a more tailored effect of the techniques on the household. For these household effects there can be a focus on the “soft” benefits which are lacking in the existing research. The results of the CBA can be used to advise households on their heating choices, this can provide a household with more information than the current CBA. Because the CBA would be specified on their scale and situation. Furthermore, due to existing research, the "larger scale" effects are already determined, and the current research can elaborate on the stakeholder “household”. This will add to the current research by creating more insight into the effects of the heating techniques on this group.

2.2.2. Decision support instruments for an individual (end-user)

The lack of information about the advantages of energy efficiency measures but also the lack of methods to quantify the advantages in economic terms can decrease the willingness to adopt energy-efficient techniques (Palmer & Walls, 2021). If there is a lack of information provided to homeowners, homeowners are less likely to adopt a natural gas-free heating technique. Therefore, information provision is essential. The aim is to develop a tool to better understand the effects of heating techniques, incorporating external factors (such as the development of energy costs). Before this tool can be created it is important to gain insights into which tools are currently available, to determine their added value and shortcomings. This information can be used to create requirements for the tool. There are already websites and policy instruments in the Netherlands that aim at supporting various types of users in their transition to non-natural-gas-based heating. The main added value and shortcomings are listed in Table 11 and further explained below.

Table 11: Main added value and shortcomings of the tools Regionaal Energieloket and Dashboard Eindgebruikerkosten (Regionaal Energieloket, n.d.; TNO, 2022)

	Regionaal energieloket	Dashboard Eindgebruikerskosten
Added value	- Provides insight into the needed alterations to the home for natural gas-free renovation (including investment costs and cost savings). - Good information provision about the home alterations.	- Creates insight into the costs for the involved actors - Different types of outputs
Shortcomings	- No insights for housing clusters - The development of variables cannot be alternated - No insight into assumptions - Separate solutions - No insight into energy costs, maintenance costs, reinvestment costs and CO_2 emission.	- No insights for housing clusters - The development of variables cannot be alternated - Little insight into the required alterations to the house - No comparison of heating with natural gas - Insights only shown for the years 2020 and 2030

Regionaal Energieloket (regional energy desk)

The online energy desk (energieloket.nl) is used by more than 200 Dutch municipalities. The energy desk can provide tailor-made advice on how energy efficiency and comfort can be improved for houses. Furthermore, it provides information about the different improvements (Ebrahimigharehbaghi et al., 2019). Although the energy desk already offers insight into multiple available heating techniques and can generate custom advice for a homeowner, there are still some shortcomings. The desk does not take collective solutions into account. The variable scenarios that are used for the calculation cannot be changed. It is not clear which scenarios are used, which makes the results less transparent. Other shortcomings are that all improvements are shown separately and no total advice per technique has been created. Furthermore, there is not a complete overview of the costs and CO_2 emissions over the years which helps the homeowner to compare the techniques.

Dashboard Eindgebruikerskosten (Dashboard end-user cost)
The Dashboard provides information to the decision-maker about the end-user costs. The dashboard is from the TNO (Tigchelaar et al., 2021). The Dashboard is developed for municipalities and it helps municipalities by giving an insight into the expected costs of end-users and other involved actors (private/social landlord, grid operator, national government, private/social tenant). But the dashboard also has some shortcomings. It only functions per house (no cluster form) and only provides the expected investment costs, no information about variable scenarios, CO_2 reduction, required interventions or comparison with the current situation.

Based on the shortcomings of the existing tools, the goals of the current research tool can be established. To increase the added value of the tool. The main requirements that the tool should meet to improve the added value compared to current tools:

1. Incorporate housing clusters.
2. Incorporate the development of the variables to create results based on a scenario.
3. Create insights into the operating costs for homeowners.
4. Incorporate insights into the alterations for the house and the costs of the implementation.
5. Include a comparison of the natural gas-free heating technique with heating with natural gas.

2.3. Preferences of homeowners

To reach the aimed sustainable energy transition, a wide range of changes in energy behaviour are required. This will involve the adoption of sustainable natural gas-free energy sources and energy-efficient technology, and investments in energy efficiency measures in dwellings (Steg et al., 2015). Homeowners will make a shift in heating techniques if this will result in a higher perceived utility or if it is mandated by law (Banfi et al., 2008; Steg et al., 2015). To reach these changes, it is important to understand which factors affect the acceptability of energy policies, energy systems changes and what are the preferences of homeowners. In this Section, the second sub-research question will be answered: *What attributes influence people when making a shift to sustainable energy for their homes and how do people weigh them?* In Figure 17 it can be seen how this Section, contributes to the research.

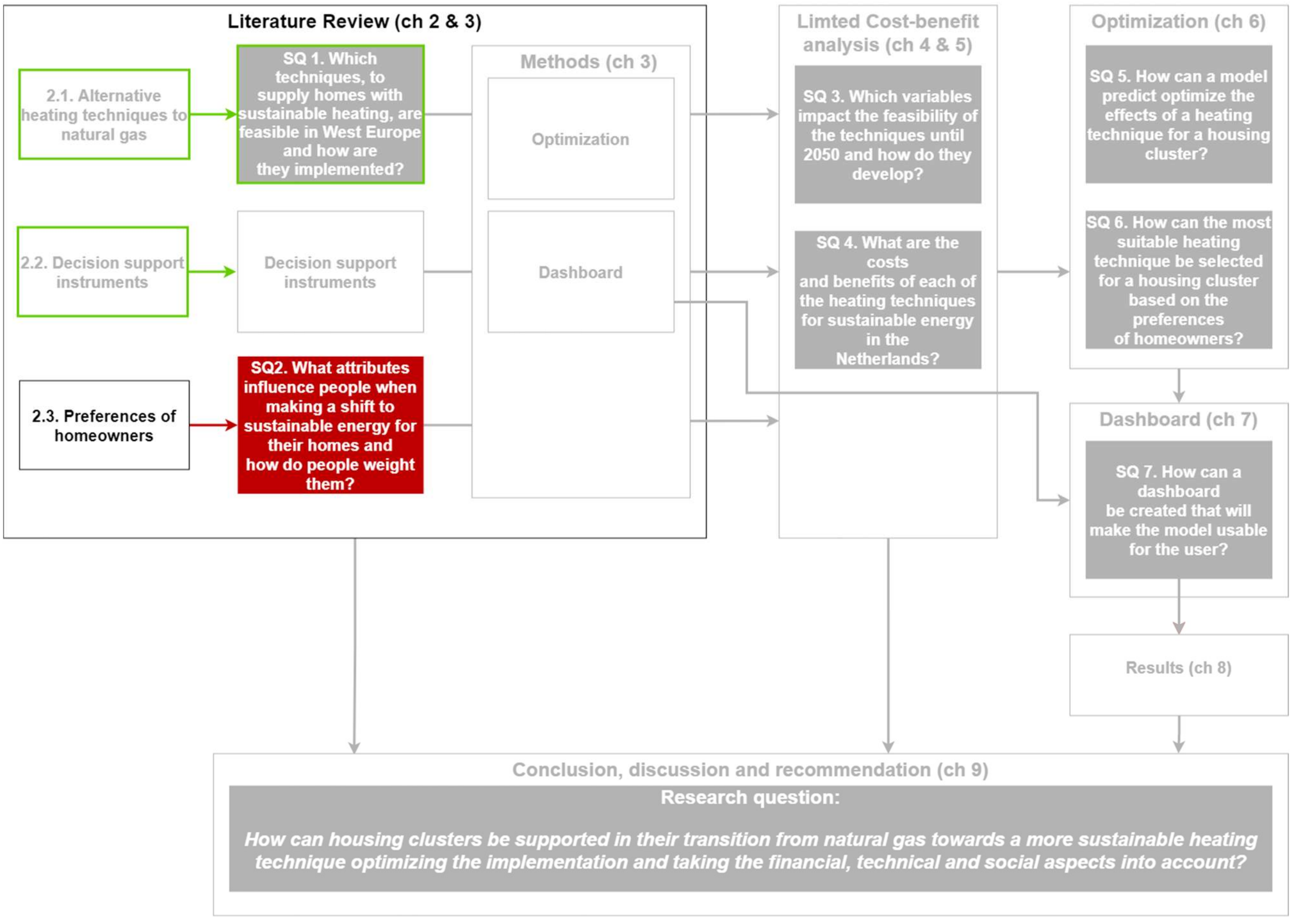


Figure 17: Literature review Section 2.3. within the overall research design

2.3.1. Goal framing theory

An understanding of the factors that influence pro-environmental behaviour is necessary to assist in driving a move toward a natural gas-free, more sustainable heating technique among homeowners. Shifting to a natural gas-free heating technique can be considered pro-environmental behaviour. Steg et al. (2014) describe that according to the goal framing theory (Lindenberg & Steg, 2007), there are three different goals (or motivations) that influence the behaviour of people. These goals are hedonic, gain and normative. Hedonic goals lead people to focus on actions that will improve their feelings in a particular situation. Examples of this can be avoiding effort, seeking direct pleasure or excitement. Gain goals, cause people to be sensitive to changes in their resources. Examples of this can be changes in money and status. The last goals are the normative goals, these goals drive people to focus on how appropriate their actions are. This will make them especially sensitive to what they think they are ought to do, examples of this can be contributing to a clean environment and showing exemplary behaviour. The different goals influence which information people detect, what knowledge is cognitively most accessible, what action alternatives are perceived and how people will act per situation. The strongest goal in a situation will also influence the cognitive processes and decision-making the most, while the other goals in the background increase or decrease (depending on whether they are compatible with the goal frame or not) (Steg, Bolderdijk, et al., 2014).

Steg et al. (2015) described three key factors that influence sustainable energy behaviour, which are; knowledge, motivations and contextual factors. Commonly, people are aware of the problems that are related to the energy use of a home and they are concerned about this (Abrahamse, 2007). But the knowledge is not always accurate. People have a limited understanding of the degree to which their behaviour contributes to climate change (Bord et al., 2000). They also have misinterpretations of the relative contribution of different processes are to global warming (Whitmarsh et al., 2011). Furthermore, their perception of the energy use of their own behaviour is often also not accurate. Steg et al. (2015) showed by reviewing the literature that knowledge may be a precondition for sustainable energy behaviour, but it is not enough to promote such behaviour. Knowledge will have an effect but it is only limited when people are not motivated to engage in sustainable energy behaviour, or when they do not feel like they can engage in such behaviour (Steg et al., 2015). Whether or not people engage in sustainable energy behaviour will depend on their motivation. Steg et al. 2015 found that people are more likely (or motivated) to participate in sustainable energy behaviour when the consequences are more favourable (higher benefits than costs). Furthermore, people do not only consider individual but also collective consequences (Steg, Perlaviciute, et al., 2014). People want to see themselves as morally right (which encourages sustainable energy behaviour) (Bolderdijk et al., 2013), which could imply that sustainable energy behaviour does not only come from individual considerations but also moral considerations. When considering to what extent the individual or collective considerations affect sustainable energy behaviour and which factors increase this likelihood, it can be seen that values appear an important factor. Values reflect life goals that define what is important for people and what consequences they strive for (Rokeach, 1973; Schwartz, 1992). Four different types of values are relevant for the evaluations and behaviour of people related to sustainable energy behaviour. These values are hedonic (make people focus on pleasure and comfort), egoistic values (make people focus on safeguarding and promoting their resources), altruistic values (make people focus on the well-being of other people and society), and biospheric (make people focus on consequences for nature and the environment) (de Groot & Steg, 2008; Steg,

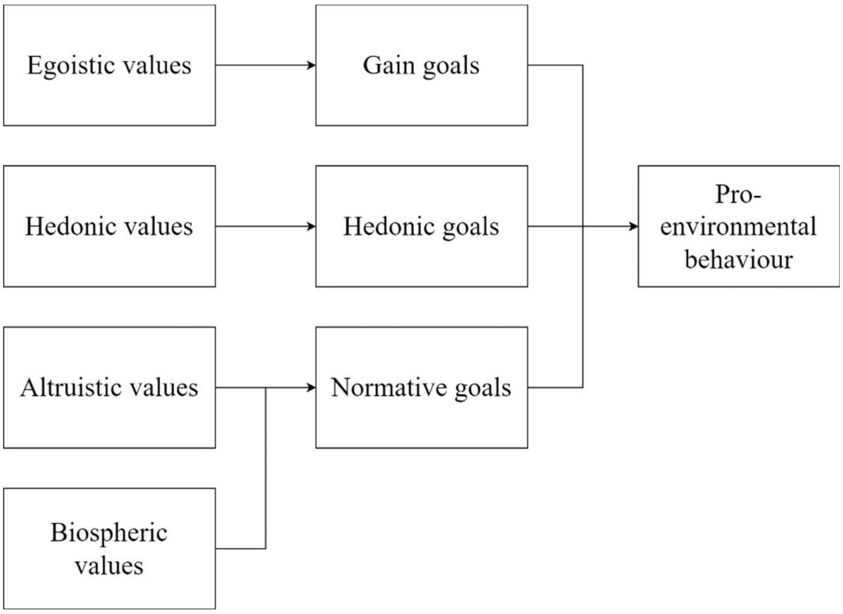


Figure 18: Relation between the values and the goals

Perlaviciute, et al., 2014; Steg & De Groot, 2012). People are more aware of environmental problems when they value the biospheric values higher or value the egoistic values lower. These four different values (egoistic, hedonic, altruistic and biospheric) determine the chronic accessibility of the three goals from the goal framing theory. Subsequently, it will affect the likelihood a certain goal will be important and steer attention, preferences and behaviour in a specific situation. Which value affect which goal is shown in Figure 18 (Steg, Bolderdijk, et al., 2014).

2.3.2. Drivers and barriers to natural gas-free renovations

In this Section a literature review is done on the drivers and barriers of homeowners to energy renovation measures for natural gas-free heating, an overview of the findings is shown in Table 12. Research by Haas (2020) showed that the majority of inhabitants are willing to invest in sustainability, if they have enough financial means or when the (local) government offers financial support (subsidies). The shift to a more sustainable home is mostly made because of environmental considerations, but cost savings and living comfort are also common drivers (Haas, 2020). Research by Wielders (2021) showed that the six main motivators and barriers which determine the decision-making process towards gas-free heating for tenants were heating type, housing costs, comfort, nuisance and house and neighbourhood improvements. Out of all these, the heating type was insignificant, and housing costs, comfort and nuisance were most influential in the decision-making process (from which cost was the most important) (Wielders, 2021). Research by Jansma et al. (2020) found the main benefits and concerns of renters and homeowners (compared) to shift from natural gas to a more sustainable energy source for their homes. The main benefit respondents in the research gave was the decrease in CO_2 emission, other benefits that were given by homeowners (but were less important) were the decrease of seismic activities in Groningen and it would make the Netherlands less dependent on other countries. The main concerns were costs and feasibility, but also sustainability, comfort, long-term viability and installation and utilization costs. The main sustainability concern was whether the technique was more sustainable than natural gas, which was particularly the case for district heating and biomass. Another main concern was that comfort of living could be negatively influenced if the alternative heating technique would be implemented. An example of this concern is that a heat pump would cause noise and would use too much space. Furthermore, it was a concern that it would be difficult to reach a comfortable temperature (heat pump and district heating). In the research, it was also found that in contrast to tenants, homeowners did not have a clear preference for a communal alternative technique to natural gas. The financial concerns are mainly about the question of whether the investment would pay off (increase the value of the house and decrease energy costs). Homeowners that saw a change in heating technique as a good investment and/or received a government loan or subsidy were more inclined to adopt that heating technique. While if homeowners did not see it as a good investment and/or received a government loan or subsidy it would prevent them from making this decision (Jansma et al., 2020). Ebrahimigharehbaghi et al. (2019) identified the drivers for the shift towards energy efficiency renovations to be gaining financial benefits (which include costs savings and increase in house value) and enhancing the quality of life (which includes increasing comfort, improving ventilation, boiler replacement and reducing noise). The main barriers that were identified were the costs of the energy-saving measures, lack of subsidies, the credibility of expert info (companies and government) and information barriers. Lack of financial support from public authorities was identified as essential for renovators. The categories that were found to be insignificant for drivers were technical benefits, environmental concerns and experience of other people. The barriers were past experiences and lack of support and help from family, friends and acquaintances (Ebrahimigharehbaghi et al., 2019). Broers et al. (2019) conducted an empirical analysis to identify the decision-making process of Dutch homeowners for energy renovation measures, which can be seen in *Appendix H: Overview of research towards motivators to shift towards sustainable heating*. The research showed that energy renovation decisions are not insulated but consist of multiple decision moments. In the research, the main motivator was saving energy (and money) but also environmental concern and improving comfort and the main barriers were financial or other priorities (Broers et al., 2019).

Table 12: Overview of drivers and barriers

Driver	Source	Barrier	Source
Environmental concerns	(Broers et al., 2019; Haas, 2020)	Costs	(Broers et al., 2019; Ebrahimigharehbaghi et al., 2019; Jansma et al., 2020; Wielders, 2021)
Costs savings	(Broers et al., 2019; Ebrahimigharehbaghi et al., 2019; Haas, 2020; Jansma et al., 2020; Wielders, 2021)	Feasibility	(Jansma et al., 2020)
Living comfort/quality of life	(Ebrahimigharehbaghi et al., 2019; Haas, 2020)	Comfort	(Jansma et al., 2020) (Wielders, 2021)
Comfort	(Broers et al., 2019; Ebrahimigharehbaghi et al., 2019; Wielders, 2021)	Long term viability	(Jansma et al., 2020)
Decrease in CO_2 emission	(Jansma et al., 2020)	sustainability	(Jansma et al., 2020)
decrease of seismic activities in Groningen	(Jansma et al., 2020)	lack of reliable experts/information	(Ebrahimigharehbaghi et al., 2019)
less dependent on other countries	(Jansma et al., 2020)	Lack of subsidies	(Ebrahimigharehbaghi et al., 2019)
Financial support	(Ebrahimigharehbaghi et al., 2019; Jansma et al., 2020)	Heating type	(Wielders, 2021)
Improving ventilation	(Ebrahimigharehbaghi et al., 2019)	Nuisance	(Wielders, 2021)
Increase house value	(Ebrahimigharehbaghi et al., 2019)	Other priorities	(Broers et al., 2019)
Energy savings	(Broers et al., 2019)		
House and neighbourhood improvements	(Wielders, 2021)		

The main drivers and barriers which influence the willingness of homeowners to shift from natural gas to a more sustainable natural gas-free heat source have been found. These main drivers and barriers have been combined with the goals of the goal framing theory, to understand the motives behind these drivers and barriers to homeowners. To find how these effects affect the willingness to shift towards natural gas-free heating techniques. The weights of the goals need to be determined. Research has been done (i) to the weather providing information about the consequences of residential energy retrofitting encourages public housing tenants to agree with retrofitting, and how this differs by type of information offered (Ossokina et al., 2021). (ii) The preferences of social tenants regarding the willingness to participate in the transition towards natural gas-free heating systems (Wielders, 2021). (iii) Investigating the preferred choices of Dutch homeowners between insulation material packages (Kaltenegger, 2021). The research of Wielders (2021) combined the attributes with the Goal-Framing theory and determined the relative importance of the attributes. Therefore the weights of the goals could be determined and it has been decided to incorporate the weights of this research in the current research. The downside of using these results is the focus of Wielders (2021) on Dutch social tenants, which could differentiate of the weights of Dutch homeowners. The relative importance of the goals, hedonic, gain and normative have been determined based on the relative importance shown in *Appendix C: Relative importance of the MNL model*. In Figure 19 an overview is shown of the goals and the weights. In this figure, it can be seen that the gain goals have the highest weight and the normative goals have the least importance.

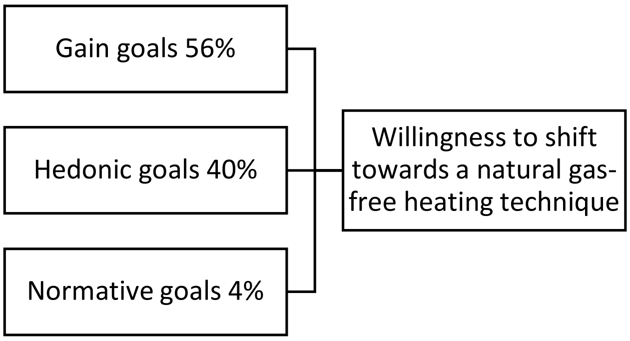


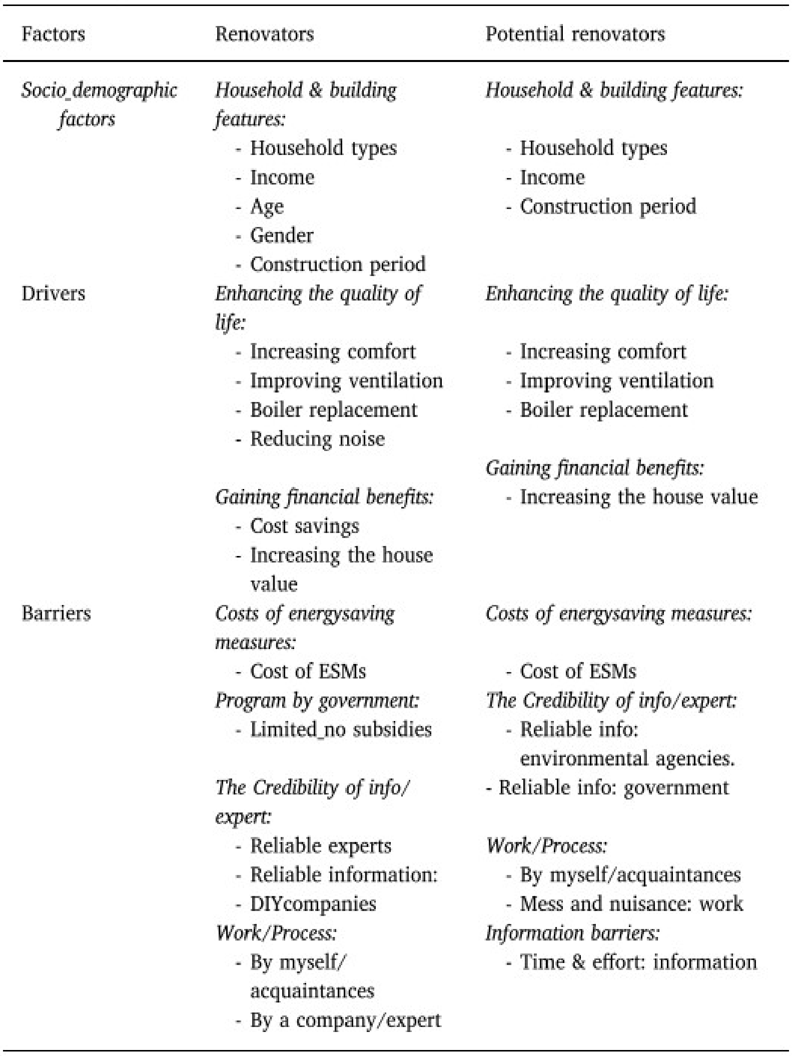
Figure 19: Main attributes combined with the goals of the goal framing theory

2.3.3. Comparison of preferences in Europe

When comparing the preferences with other European countries, it can be seen that there are some differences in preferences which could be caused by differences in cultures and heat demand (see *Appendix A: Share of heating technologies and total installed capacity by country*). When comparing the preferences of low carbon heat between European countries, it can be seen that there is overall high satisfaction with the current natural gas use. The researchers also found that households were less likely to switch to low-carbon heating due to uncertainty and lack of knowledge. Furthermore, a high level of desired thermal comfort was found, which requires a different implementation of techniques due to housing type and climate. In terms of country variation, a difference in heating preference was found, which could underscore the cultural element of heat (Sovacool, Cabeza, et al., 2021; Sovacool, Demski, et al., 2021). These results imply that, when generalizing the preferences of techniques, this can be done best in an area with matching climate and cultures.

2.3.4. Socio-demographic and dwelling characteristics

Socio-demographics and dwelling characteristics also influence the willingness to perform energy renovations. Mortensen et al. (2016) determined whether all homeowners can be assumed as one homogeneous group (in terms of motivation factors). The research was conducted using the data of a survey of 883 homeowners in Denmark. The research concluded that homeowners cannot be assumed as one group, because the key parameters for determining the motivation factors are related to the homeowner's current position in life (age, presence and age of children, time of ownership, occupation and income) (Mortensen et al., 2016). In the research of Nair et al. (2010) survey data of 3000 homeowners in Sweden in 2008 has been researched to analyse the factors that influence the adoption of investment measures to improve the energy efficiency of their buildings. Socio-demographic characteristics that were found significant were age, income and education level. It was found that respondents that were younger and were higher educated were more likely to adopt an investment measure. Contextual factors that were found were the age of the house, thermal discomfort, past investment and perceived energy costs (Nair et al., 2010). The research of Ebrahimigharehbaghi et al. (2019) aimed to understand the barriers and drivers towards energy efficiency renovations among Dutch homeowners. The researchers executed a regression analysis on the Dutch national survey for renovators and potential renovators. The significant factors regarding the decision-making for renovators are shown in Figure 20. It can be seen, that the significant sociodemographic factors for renovators and potential renovators are household type, income and construction period. The socio-demographic factors that are only significant for renovators are age and gender (Ebrahimigharehbaghi et al., 2019). The main socio-demographic and dwelling characteristics that were found have been added to the model in Figure 19 and a conceptual model has been created in Figure 21.



Factors	Renovators	Potential renovators
Socio_demographic factors	*Household & building features:* - Household types - Income - Age - Gender - Construction period	*Household & building features:* - Household types - Income - Construction period
Drivers	*Enhancing the quality of life:* - Increasing comfort - Improving ventilation - Boiler replacement - Reducing noise *Gaining financial benefits:* - Cost savings - Increasing the house value	*Enhancing the quality of life:* - Increasing comfort - Improving ventilation - Boiler replacement *Gaining financial benefits:* - Increasing the house value
Barriers	*Costs of energysaving measures:* - Cost of ESMs *Program by government:* - Limited_no subsidies *The Credibility of info/ expert:* - Reliable experts - Reliable information: - DIYcompanies *Work/Process:* - By myself/ acquaintances - By a company/expert	*Costs of energysaving measures:* - Cost of ESMs *The Credibility of info/expert:* - Reliable info: environmental agencies. - Reliable info: government *Work/Process:* - By myself/acquaintances - Mess and nuisance: work *Information barriers:* - Time & effort: information

Figure 20: Results of research of Ebrahimigharehbaghi et al. (2010) significant factors for renovators and potential renovators regarding the decision-making for renovators

2.3.5. Influence of information provision

Besides the differences in preferences of homeowners, one of the problems that were found in the literature is that lack of information can have a negative effect on a homeowner's decision to invest in energy renovation measures (ERM). Information provision and the way of approaching and collaborating with homeowners during the process are of importance for the willingness to shift from natural gas to a more sustainable source of energy (Broers et al., 2019; Dignum et al., 2021; Ebrahimigharehbaghi et al., 2019; Koning et al., 2020; Kort et al., 2020; Tigchelaar et al., 2019). This information provision and communication can be an obstacle. Research by Kanne et al. (2020) showed that 78% of the Dutch inhabitants did not receive any information about how the heat transition could impact them, while 65% indicates that they need this. Only 24% of the Dutch inhabitants, which consist mainly of people with a high education level, understand what the heat transition means for houses (Kanne et al., 2020). The ERM industry is often seen by homeowners as unreliable and non-transparent (Bartiaux et al., 2014; Broers et al., 2019; Karvonen & Karvonen, 2013; Risholt & Berker, 2013; Wilde, 2020). Banfi et al. described that the willingness to pay (WTP) for energy-saving measures is generally higher than the costs of implementing them. But incomplete information and inattention can be important contributors to the energy efficiency gap in the residential sector (Banfi et al., 2008). The lack of information about the advantages of the efficiency measures but perhaps also the lack of methods to quantify the advantages in economic terms can decrease the willingness to adopt energy-efficient techniques (Palmer & Walls, 2021). This can be caused by the underestimation of the positive effects of the energy-efficient improvements for uninformed residents, even when the improvements are cost-effective. This lack of information is an important contributor to the current energy efficacy gap (Ossokina et al., 2021). Due to the consequences for the energy transition of this lack of information policy instruments should aim at tackling these barriers. This should not only be done by providing reliable and tailormade information about the different possible solutions and their effects but also supporting them through the process (Ebrahimigharehbaghi et al., 2019).

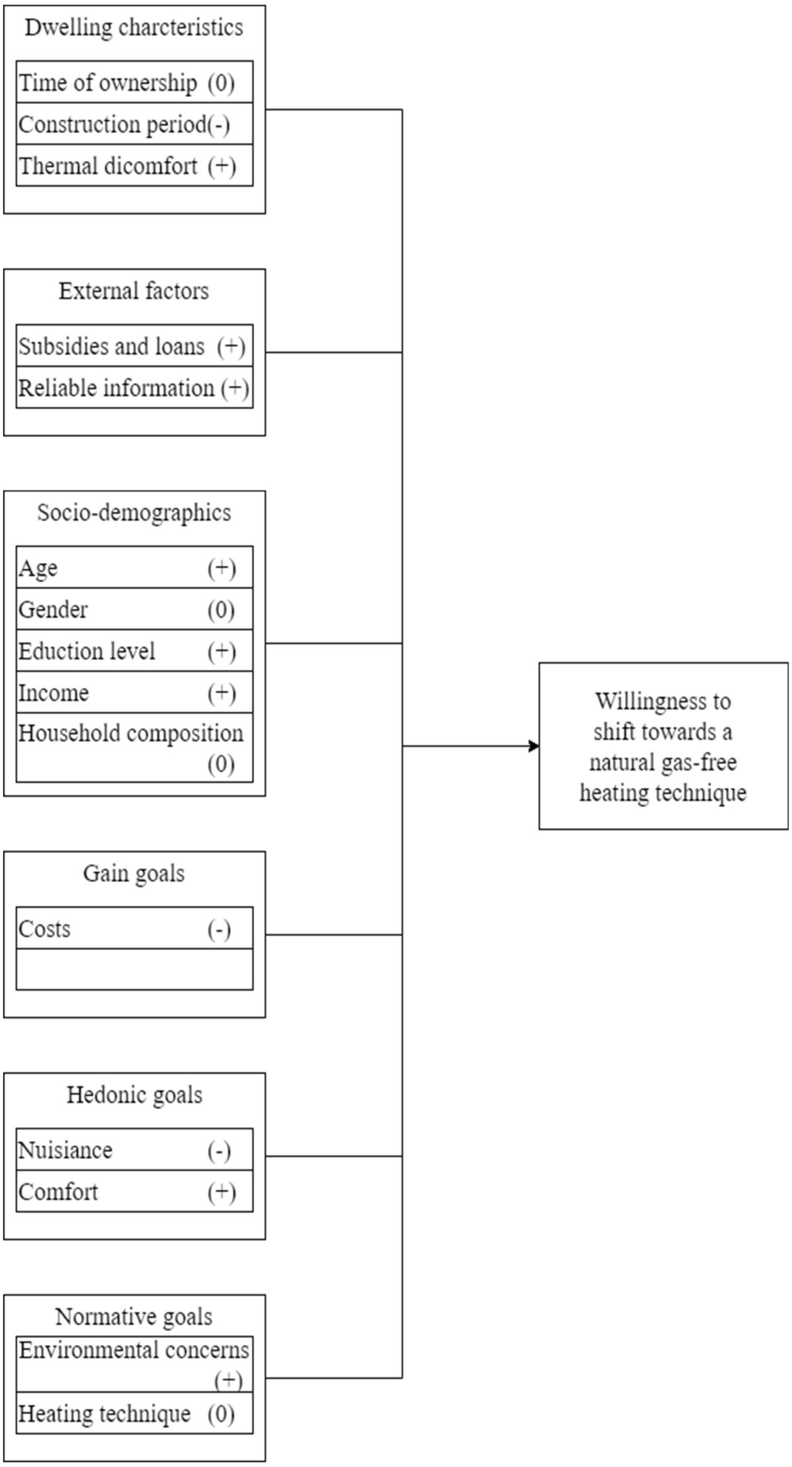


Figure 21: Conceptual model

2.4. Conclusion

In the first Section (2.1) of the Chapter, the alternative heating techniques to heating with natural gas have been discussed. In this analysis, it became clear that there is no single alternative heating technique that is capable of replacing all natural gas heating. Six potential alternative heating techniques, which include district heating techniques, all-electric heating techniques and green gas heating techniques have been analysed, see Table 3. From these six techniques, there will be focused on four techniques, which can be seen in Table 13. It can be seen that both middle and low-temperature district heating techniques will be included because these are suitable techniques but have different implementations for the homeowner. Furthermore, the individual ground heat pump is not taken into account since the collective ground heat pump could offer advantages over the individual alternative (less investment costs). The goal of the current research is to take the effects of heating of a housing cluster into which makes the collective ground heat pump also more interesting for the research. The individual heating technique air-to-water heat pump is included since it is a suitable and highly used all-electric technique. The green gas technique is also not included due to the lack of available green gas for the housing stock in the Netherlands.

Table 13: Suitable alternative heating techniques to natural gas

Code	Name of the technique	Heat source
NG1	*Natural gas*	*Boiler with natural gas*
DH1	District heating	District heating middle temperature (MT)
DH2	District heating	District heating low temperature (LT)
AL1	All-electric	Air-to-water heat pump
AL2	All-electric	Collective ground heat pump

In the second Section (2.2), the decision support instruments of local authorities and individuals have been analysed. Current CBA research and decision support tools have been analysed and their knowledge gab has been identified. In the third Section (2.3), the preferences of the homeowners have been discussed. In this Section, the main drivers and barriers to natural gas-free renovation have been identified and weighted. The preferences have been compared with European countries, which implied that, when generalizing the preferences of techniques, this can be done best in an area with matching climate and cultures.

3. Methods

To create a model to determine the optimal implementation of the selected heating techniques, optimization can be used. In the current Chapter, optimization methods will be discussed. In the first Section, the basic concept of optimization and methods will be discussed. The most fitting optimization method for the current research will be selected and explained in the second and third Sections. The second Section described linear optimization and the third Section explained multi-objective optimization. Last of all, an analysis will be done on methods and packages for creating a dashboard. In Figure 22 it can be seen how this Section, contributes to the research.

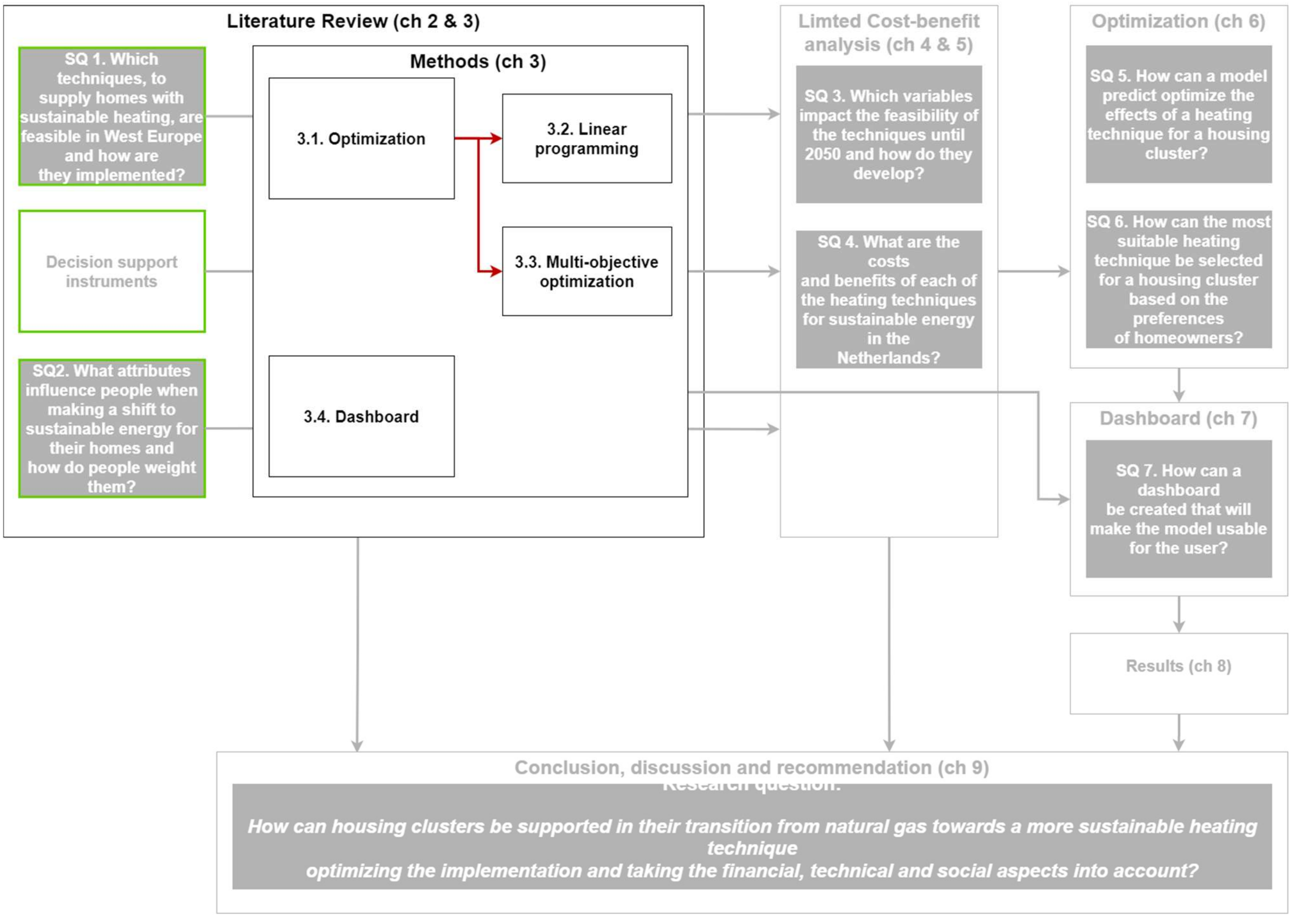


Figure 22: Methods Section 3.1. – 3.4. within the overall research design

3.1. Optimization

As described in Chapter 1, it needs to be determined what the best implementation of a heating technique is per housing cluster. The "best" or optimal implementation of the different heating techniques can be found using optimization methods. There are many different methods to find optimal solutions. In this Section, the different methods will be analysed.

3.1.1. Heuristics vs. optimization

There are multiple methods to solve optimization problems. Between these methods, there are significant variations in the characterization of the objective function (single or multi-objective). The optimization methods can be divided into two main categories: 1. Soft computing (Heuristic and Metaheuristic algorithms) and 2. Mathematical Optimization methods (Silveira et al., 2021). The categories are shown in Figure 23. To find which method is suitable for the current research these optimization methods will be further discussed below.

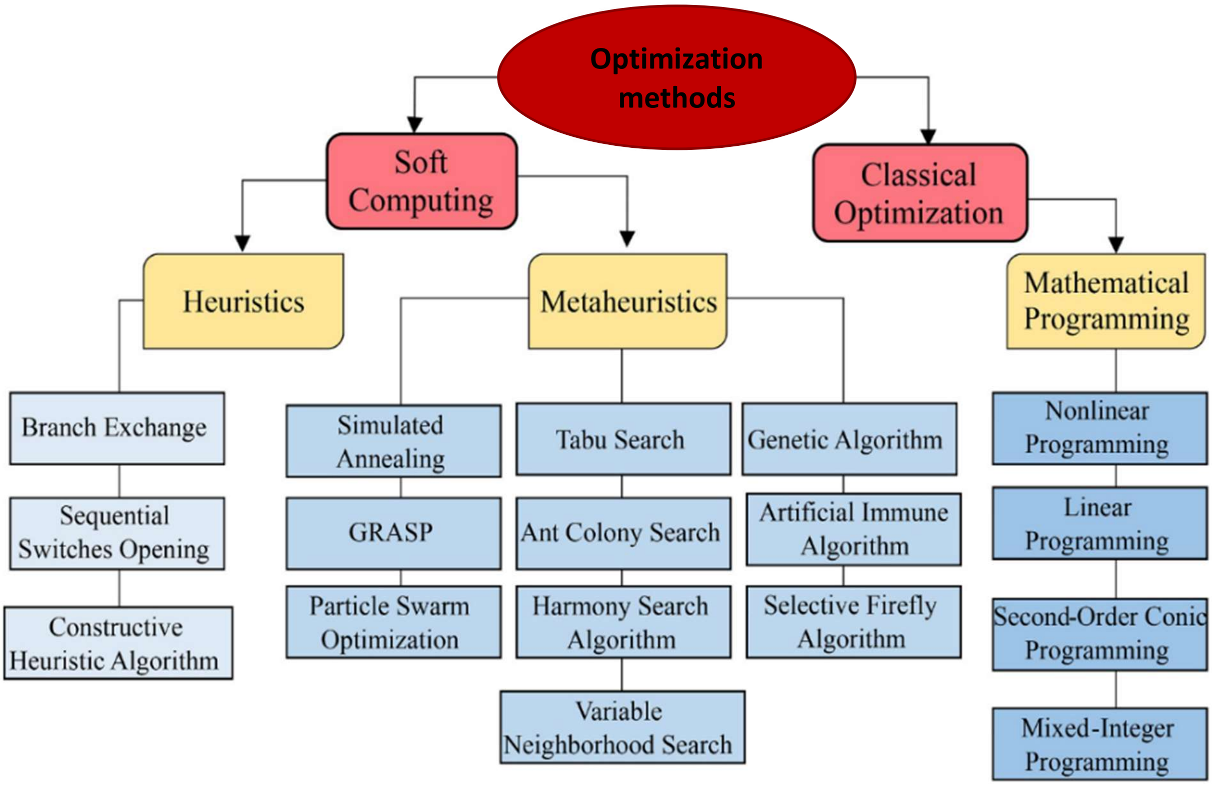


Figure 23: Optimization methods (Silveira et al., 2021)

3.1.1.1. *Soft computing*

Heuristics

Heuristic algorithms, in contrast with classical optimization methods, are algorithms designed to solve optimization problems in a suboptimal way to increase speed (Vanderkam et al., 2007). A heuristic is a problem-solving approach, which uses practical processes ("rules of thumb") to create a feasible solution to the problem. For a heuristic problem-solving approach, the optimal solution is not necessarily found, but the solution needs to be good enough to solve the problem. The main advantages of using heuristic algorithms are that they provide results quickly and require low computational effort (Silveira et al., 2021). An example of a heuristic algorithm used to solve the well-known Traveling Salesmen Problem is the nearest neighbour (NN) algorithm. The algorithm finds the shortest route by repeatedly finding the closest city.

Metaheuristics

Metaheuristics are "higher level" heuristics and often perform better than simple heuristics. Heuristics are often problem-dependent. In contrast, metaheuristics are problem-independent. This means that metaheuristic algorithms can be applied to a wide range of problems. Metaheuristics can produce solutions using trial and error. There is aimed to find a good feasible solution in an acceptable amount of time, though this solution does not guarantee to be the best (Gandomi et al., 2013).

3.1.1.2. Classical optimization

In contrast to the (meta)heuristic algorithms, classical optimization methods can find the global optimum. This capability is the main benefit of using classical optimization methods over heuristics. Another benefit is that these optimization models are highly flexible. In these mathematical optimization methods, an objective function (or multiple) is optimized under a set of constraints that should be satisfied. One of the main disadvantages of mathematical optimization methods is that they are more complicated. Mathematical optimization methods require a high computational effort compared to soft computing (Caner Taşkın, 2018; Silveira et al., 2021). These classical methods are further explained in the following Sections of this Chapter.

When comparing the different methods, the classical mathematical optimization methods are most appropriate to use in the current research, because it is able to find the global optimum. This optimum needs to be found to determine the optimal implementation of a heating technique based on the assumptions. For long-term planning mathematical optimization methods are more suitable since they can, in contrast with heuristics, find the best results. Heuristics often stop with a solution, even though there are better solutions to the same problem (Caner Taşkın, 2018; InSync, 2019; Silveira et al., 2021). For short term planning problem heuristics are often used to get a quick insight into a suitable strategy. For long term planning problems optimization is often used to increase the reliability of the predictions.

3.1.2. Optimization Methods

The implementation of the heating techniques needs to be optimized for an objective. In the literature review, it was found that multiple goals influence pro-environmental behaviour. Therefore, multiple objectives can be optimized. To optimize on one goal a single objective optimization can be used, and to find the optimal implementation for a combination of these goals a multi-objective optimization can be used. There are many different categories of optimization, in Figure 24 an overview is given of the main optimization categories. The different categories are further explained in

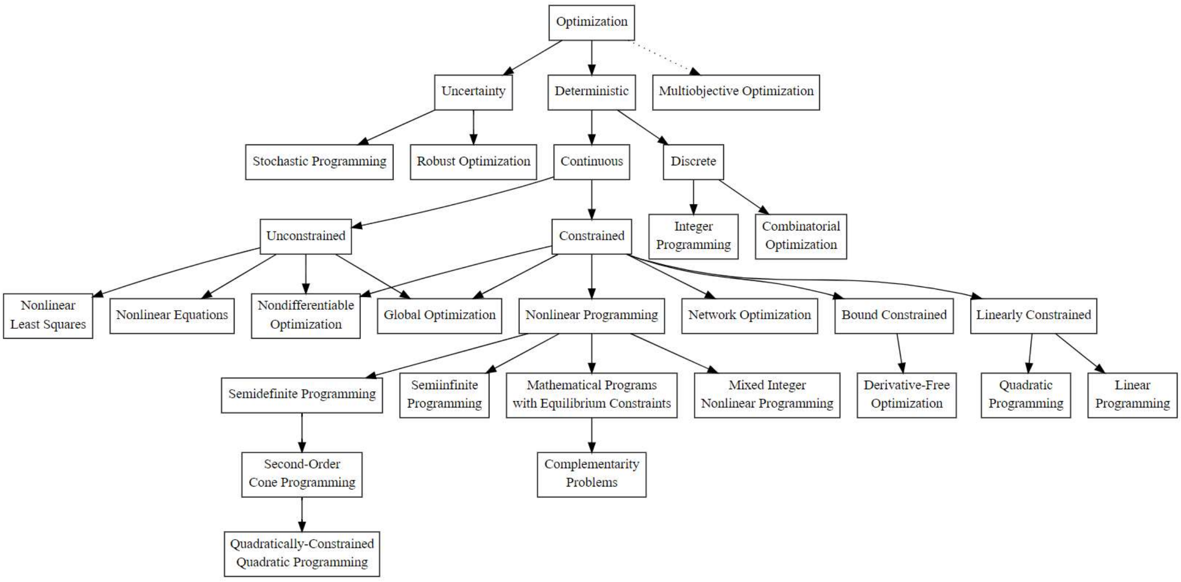


Figure 24: Taxonomy of optimization fields (NEOS, 2013n)

Appendix I: Optimization *methods*. The models that will be created need to be able to find the optimal implementation of the heating technique based on the separate single objectives (gain, hedonic, normative). The optimization method that is most suitable for the creation of these models (from the methods described in

Appendix I: Optimization methods) is linear programming. This method is selected because it optimizes a single objective, which is the described optimization problem, and the problem can be expressed linearly. Furthermore, linear programming is an accessible optimization technique which makes it likely to reach the goal of the research. Also, the research must be highly interpretable for stakeholders. This means that the model should be as white box as possible, resulting in a model that is assessable to use and interpret. With a linear optimization model, this is more likely to be achieved (Hulstaert, 2019). Linear programming is further explained below. To find the optimal implementation of the heating techniques based on the homeowner preferences, these separated single objective models need to be combined in one model. To achieve this, the multi-objective optimization will be applied. Multi-objective optimization is further explained below.

3.2. Linear programming

In this Section linear programming is explained. This is done in three main steps, first, the basic concept is described, second the solution techniques, and last the software resources.

3.2.1. Basic concept

Linear programming is the process of minimizing or maximizing the objective function which is subject to a number of constraints. In Information box 1 below, an example of a linear programming optimization model is shown. The objective function is a function that defines some quantity that should be minimized or maximized. In the example, the profit is maximized based on the number of produced cars A and B times their profit. The variables that are used in the objective function are the same as the variables that have been used in the constraints. In the example, there are two variables: the number of cars A and B. The objective function needs to be linear (Hayes et al., 2022). The constraints can be linear equality and inequality requirement (Karloff, 1991). A constraint is an (in)equality that defines how the values of the

Information box 1: Linear programming example

Linear programming example:
Resourcing problem for a car manufacturer
The factory runs on one month (30 days) cycles. There is one robot, 2 engineers and one detailer in the factory. The detailer has some holiday off, so only has 21 days available. The 2 cars need different time with each resource:

- Robot time: Car A – 3 days; Car B – 4 days.
- Engineer time: Car A – 5 days; Car B – 6 days.
- Detailer time: Car A – 1.5 days; Car B – 3 days.

Car A provides €30,000 profit, whilst Car B offers €45,000 profit. The profit can be maximized for a cycle, using linear optimization, which can be modelled as follows:

Maximise:
$Profit=30{,}000A+45{,}000B$

Objective function: maximize the profit using the function number of car A times profit of car A plus number of car B times profit of car B.

Subject to:
$A \geq 0$
$B \geq 0$
$3A+4B \leq 30$
$5A+6B \leq 60$
$1.5A+3B \leq 21$

Constrains: the requirements the optimization needs to meet.
First two constrain describe that the number of cars A and B need to be equal or bigger than 0. The rest of the constrains describe the time with each resource.

variables in the optimization problem are defined. The constraints define the feasible region, which represents the possible values of the variables that satisfy the constraints. In the example, the constraint describes that the number of cars A and B needs to be equal to or bigger than zero and the time with each resource.

As described above, a feasible solution is a solution that meets all constraints, and the optimal solution is the solution with the smallest value of the objective function (minimizing problem) or the largest value (maximizing problem). A linear problem can have one optimal solution, multiple solutions or no solutions. Linear problems with no feasible solutions or constraint conditions with unbounded objective functions have no optimal solutions. A value of a variable can only take on any continuous value between its upper and lower bound in a linear program (NEOS, 2013h).

3.2.2. Solution techniques

Linear programming is often used due to its many applications and its effective general-purpose techniques for finding the optimal solution. A linear program can find the optimal solution without needing a reference to extra information about the problem. Simplex methods and barrier/interior point methods are two families of solution techniques that are commonly used. Each of these techniques produces a progression of increasing trial solutions until an optimal solution is found based on the conditions for an optimal solution.

- Simplex methods: the simplex methods were introduced by Gearge Dantzing (the 1940s). The simplex method works by starting at the basic vertex of the feasible region. Finding a basic feasible solution and testing whether it is an optimal solution. This is followed by repeatably improving the solution until the optimal solution is obtained (Hayes et al., 2022; Neos, 2020).
- Barrier/interior-point methods: the interior-point method starts at an interior point and moves along the central path to get to the solution (Tibshirani, 2015). Interior points methods are most suitable for large-scale problems with many degrees of freedom (Design optimization, 2020).

A mixed-integer linear programming (MILP) problem performs minimization and maximization problems that have a linear objective but have an extra constraint, which is that at least one variable needs to be an integer. Therefore MILP problems have variables that are constrained to be only integers while other variables are allowed to be non-integers (in contrast to integer programming) (Kumar & Mageshvaran, 2020). Mixed-integer problems are quite similar but provide advantages compared to linear programming. For example, mixed-integer problems can use binary variables, which can be used to mimic logical constraints (for example a yes or no decision) (Stojiljkovic, n.d.). Mixed-integer problems are solved with more complex algorithms than linear problems, like Branch and Bound algorithm, Branch and Cut algorithm, and Branch and Price algorithm.

3.2.3. Software resources

Over the past decades, advances have been made in optimization software. Often the commercial solvers are somewhat more robust and faster compared to the free alternatives. An overview of MILP optimization software packages is shown in *Appendix J: MILP optimization software packages*. Due to the costs of commercial solvers and because the freely available solvers are useful for many optimization problems, a free solver will be used for linear optimisation.

Table 14: Algorithmic features of solvers (Linderoth & Ralphs, 2005)

	Preproc	Built-in Cut Generation	Column Generation	Primal Heuristic	Branching Rules	Search Strategy
ABACUS	No	No	Yes	No	f,h,s	b,r,d,2(d,b)
BCP	No	No	Yes	No	f,h,s	h(d,b)
bonsaiG	No	No	No	No	p	h(d,b)
CBC	Yes	Yes	No	Yes	e,f,g,h,s,x	2(d,p)
GLPK	No	No	No	No	i,p	b,d,p
Lp_solve	No	No	No	No	e,f,i,x	d,r,e,2(d,r)
MINTO	Yes	Yes	Yes	Yes	e,f,g,p,s	b,d,e,h(d,e)
SYMPHOY	No	Yes	Yes	No	e,f,h,p,s	b,r,d,h(d,b)

Table 14 indicates the algorithmic features of each solver. The table includes per solver whether it has a pre-processor, if it can dynamically generate valid inequalities, if it is can perform column generation, if it includes primal heuristics, and what are the branching rules and search strategies that can be used (Linderoth & Ralphs, 2005). The letters in the columns “branching rules” and “search strategy” in the table are explained in Table 15.

Table 15: The letters in Table 14 are explained (Linderoth & Ralphs, 2005)

The letters of the column available branching methods, stand for the methods:	The letters of the column available search strategies, stand for:
- e: pseudo cost branching - f: branching on the variables with the largest fractional part - h: branching on hyperplanes - g: GUB branching - i: branching on first or last fractional variable (by index) - p: penalty method - s: strong branching - x: SOS(2) branching and branching on semi-continuous variables	- b: best-first - d: depth-first - e: best-estimate - p: best-projection - r: breadth-first - h(x,z): a hybrid method switching from strategy ’x’ to strategy ’z’ - 2(x,z): a two-phase method switching from strategy ’x’ to strategy ’z’

Several free Python libraries are specialized to interact with linear or mixed-integer linear programming solvers. Often used open-source optimization libraries are SciPy, PuLP, and Pyomo. When these three optimization libraries are compared it can be seen that the SciPy is the most supported optimization library, has the most capabilities and uses plain Python syntax. A disadvantage of SciPy is that it does not support binary optimization problems very well (Shvab, 2020). Binary optimization can be useful in optimizations to indicate whether something is “used” or not. An example of the current research could be whether a heating technique is used. PuLP and Pyomo have a more similar syntax structure. But compared to the other libraries, PuLP is the most accessible library of the three. A disadvantage of PuLP is that it can only be used for linear optimization problems. Pyomo has support for nonlinear optimization problems and can do multi-objective optimization (Shvab, 2020). If the goal is to create merely a linear optimization problem the PuLP would be the most preferable library due to the high accessibility and the high amount of available information.

3.3. Multi-objective optimization

A multi-objective optimization problem (also called MOOP) deals with more than one objective function, which is in contrast to the above described single-objective optimization problems. There are some fundamental differences between single and multi-objective optimization techniques (Deb, 2014). Deb (2014) describes the following properties of multi-objective optimization:

- The cardinality of the optimal set is usually more than one,
- There are two distinct goals of optimization, instead of one, and
- They possess two different search spaces.

Multi-objective optimization results with conflicting objective results in a number of Pareto-optimal solutions. This is in contrast with the single-objective optimization problems where there usually is one optimal solution. Another difference with single-objective optimization is that the objective functions of a multi-objective optimization constitute a multidimensional space. This space is called the solution space (*Z)* and it is in addition to the decision variable space which is common to all optimization problems. For every solution *x* there is a point in the solution space which is denoted by:

$$f(x) = z = (z_1, z_2, \dots , z_m)^T$$

The mapping takes place between an n-dimensional solution vector and an M-dimensional objective vector. In the following Sections, multi-objective optimization will be further explained. First, the Pareto and the concept of dominance will be discussed, next preference-based multi-objective optimization, and last of all the software resources are analysed.

3.3.1. Pareto

The fundamental difference between single and multi-objective optimization lies in the cardinality of the optimal set. Most of the time, a user of an optimization model only wants one optimal solution. This is the problem in the case of multi-objective optimization, since there are multiple objectives, there exist multiple solutions. To solve the optimization problem one optimal solution needs to be selected. This decision often needs to be made using higher-level information. The information is often non-technical, qualitative and experience-driven. The optimal solution can be selected based on user preference and weighting. The ideal multi-objective procedure as described by Deb (2014) follows the following principle:

Step 1 Find multiple trade-off optimal solutions with a wide range of values for objectives.

Step 2 Choose one of the obtained solutions using higher-level information.

If the objectives are optimized simutanisly in a multi-objective optimization problem conflicts can arise. If one objective is improved, this will be at the expense of one (or more) other objective(s). This principle of dominance is used for this problem: two solutions are compared to each other and it is determined whether one dominates the other. If solutions *X* and *Y* are compared, *X* dominates *Y* if *X* is not worse than *Y* in all objectives and *X* is better than *Y* in at least one objective. A solution is not included in the set of optimal solutions unless there is no

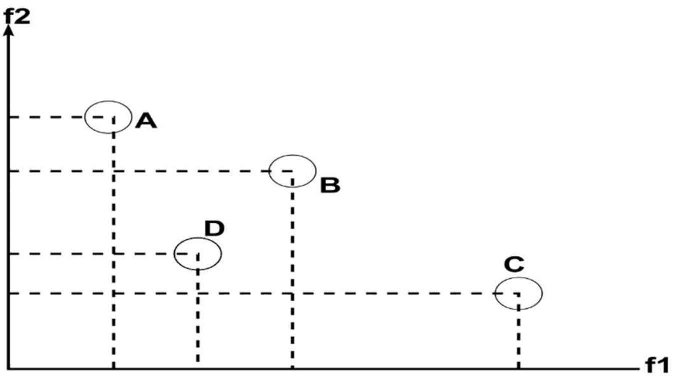


Figure 25: The concept of dominance in multi-objective optimization (Abbass, 2003)

solution better measured on all objectives. A non–dominated solution is called Pareto (Abbass, 2003). An example can be seen in Figure 25. In this Figure, a two-objective problem is shown which contains four solutions. In this problem, function 1 (f1) and function 2 (f2) need to be minimized. Solution B is dominated by solution D because solution D is better than B on all objectives. Solutions A, C and D are non-dominated, none of these solutions perform better than each other on all objectives. If this pair-wise comparison is executed on a fixed set of solutions a set of solutions will remain, which dominate the other solutions, this set is called the non-dominated set or the Pareto front. Ngatchou et al. (2005) describe the non-dominated set as: “*A solution belongs to the Pareto set if there is no other solution that can improve at least one of the objectives without degradation any other objective*” (Ngatchou et al., 2005).

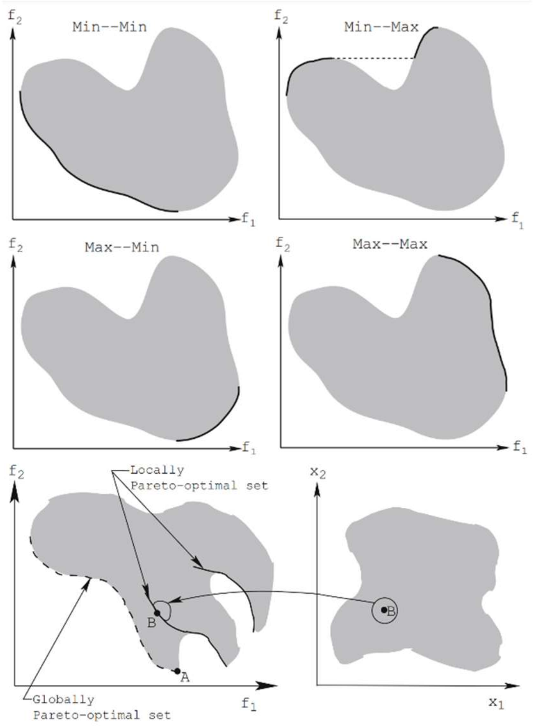


Figure 26: Chart 1-4: Pareto-optimal solutions are marked with continuous curves for four combinations of two types of objectives. Chart 5-6: Locally and globally Pareto-optimal solutions (Deb, 2014)

The set of solutions is P (contains all solutions) and the Pareto front is P’. P’ for the example shown in Figure 25, contains solutions A, C and D. In Figure 26, an example is given of the Pareto front with continuous curves for four different scenarios. There can be global and local Pareto front, for which the global front contains the non-dominated set over the whole search space (Deb, 2014). An example of the global and local Pareto front can be seen in Figure 26.

3.3.2. Preference-based multi-objective optimization

For the current research, the optimal implementation of a heating technique needs to be found based on the preferences of homeowners. As described above, to find the optimal solution between the solutions of multiple objectives, trade-offs need to be made. Because many multi-objective optimization problems can result in a large objective space. Extensive population size and extensive computing effort are required to find a well-distributed set of solutions on the Pareto front (Wang, 2021). To select one of these solutions a different level of importance can be assigned to one of these objectives. An example of this can be the relative importance between an objective of the level of comfort (maximize) and the objective of the level of costs (minimize). To be able to assign this relative importance between these two objectives, a relative preference factor among the objectives needs to be known. If this relative preference factor is known a composite objective function can be used as the weighted sum of the objectives. The weighted-sum approach is probably the most used classical multi-objective optimization approach. In this method, the set of objectives is scalarized into single objectives. In this method, multiple objectives are combined into a single objective function by multiplying each objective by a weighting factor and then adding all weighted objective functions (Kim & De Weck, 2006). Equation 1 displays an example of a combined objective function, where w_i (i=1,…,m).

Equation 1: Weighted-sum approach

$$J_{weighted\ sum} = w_1 J_1 + w_2 J_2 + \cdots + w_m J_m$$

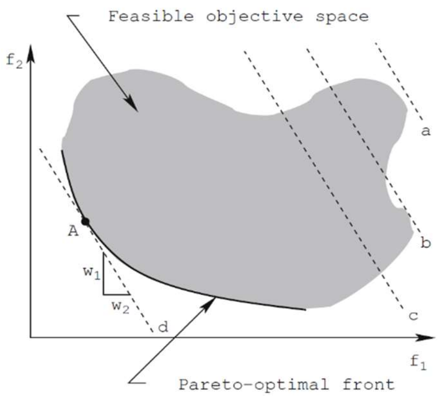


Figure 27: Illustration of the weighted-sum approach on a convex Pareto-optimal front (Deb, 2014)

How the weighed-sum approach can find the Pareto-optimal solution is illustrated in Figure 27. In this example, a problem is illustrated with two objectives, and two weights w_1 and w_2 (only one is independent). By changing the weight vector, a different Pareto-optimal point can be obtained. Well-known drawbacks of the weighted sum method, which are discussed in multiple studies (Das & Dennis, 1997; Kim & De Weck, 2006; Messac & Mattson, 2002), are:

1. The optimal solution distribution is often not uniform
2. The optimal solutions in the non-convex part of the Pareto-optimal front are not detected. Therefore the approach can miss the point on the Pareto-optimal front and could potentially miss the optimal solution.

The weights used for this weighted sum are equal to the preference factors. By using and optimizing such composite objective function it is possible to find one particular trade-off solution. This procedure (although not often used in this way) can also find multiple trade-off solutions by using different preference vectors and comparing the corresponding solutions (Deb, 2014). An important note to preference-based (weighted-sum) multi-objective optimization is that the solution is largely sensitive to the relative preference vector used. If the relative preference (the weight) is changed, this will result in a different solution. Consequently, unless a reliable preference vector is known the results could be highly subjective to the user (Deb, 2014).

3.3.3. Software resources

For the current research, preference-based multi-objective optimization is the most suitable approach for solving multi-objective problems. These multi-objective models will be, like the single objective model, created in the programming language Python. When creating these multi-objective optimization models, a suitable package and solver need to be selected. Multiple packages can be used for multi-objective optimization. The Pyomo package is very suitable for the weighted sum approach, because this package allows the user to interact with most of the suitable solvers, like Gurobi, CPLEX, CLPK, CBC, Mosek, and Baron.

3.4. Dashboard

As described before, incomplete information and inattention can be important contributors to the energy efficiency gap in the residential sector (Banfi et al., 2008). The lack of information about the advantages of efficiency measures but perhaps also the lack of methods to quantify the advantages in economic terms can decrease the willingness to adopt energy-efficient techniques (Palmer & Walls, 2021). This can be caused by the underestimation of the positive effects of the energy-efficient improvements for uninformed residents, even when the improvements are cost-effective. This lack of information is an influential contributor to the current energy efficacy gap (Ossokina et al., 2021). Therefore, the model that will be created in the current research should be used and interpreted by the target group, which are homeowners. For this group, it is unlikely that they can understand and interpret Python optimization models. Hence, it is critical that the inputs and outputs can be created for the homeowner in a way that is clear for them. A dashboard can be used to reach this goal. A dashboard can be built to inform users about the consequences of different heating techniques for heating homes. The goal of the dashboard is to be an interactive dashboard that can, using different optimization models, provide an overview and advice about the different techniques for a housing cluster, based on user input. There are multiple techniques/packages for the creation of dashboards. Dash of Plotly[1] and Rstudio Shiny[2] are two tools that are often used and free. Dash is a Python framework which can be used to create web applications. Dash is written in Flask, Plotly.js, and React.js. R Shiny is an open-source package in R, which provides a framework for the creation of any sort of app. When comparing the two technologies it can be seen that Dash requires more boilerplate code than Shiny. Shiny is more user-friendly and uses less code than Dash to create a better-looking dashboard. On the other hand, Shiny takes more work to create custom styling for the app (instead of the default styling) compared to Dash. Furthermore, the Bootstrap is much cleaner in Dash than Shiny. For the deployment of the dashboard, it does not matter whether Shiny or Dash is used, they both have many deployment possibilities. Comparing both packages, it can be concluded that both are very useful when creating a dashboard (Skrzydło, 2022). In this case, the Shiny package is preferred over Dash due to its user-friendliness. As described before, the optimization model will be created using Python and the dashboard can be made using R shiny. When these two languages are combined, the benefits of both languages can be utilized in the creation of a dashboard. Shiny provides an automatic reactive binding between input and outputs and provides extensive pre-built widgets. These widgets make it possible to create more elegant and powerful applications without a considerable amount of required prior knowledge compared to the common alternatives.

The RStudio package Reticulate[3] will be used for weaving Python directly into RStudio. Reticulate is an RStudio package that works by embedding a Python session within an R session. This helps to provide a seamless interface between Python and RStudio. The library of the Reticulate package supports the translation between RStudio and Python objects. Furthermore, it allows calling Python scripts/modules from R in numerous settings. One of the benefits is that Python can be used within RStudio in the same way R would be used, leveraging the console for a combined Python + R REPL (Hickey, 2019).

3.5. Conclusion

In this Chapter, the optimization methods have been analysed. It has been found that optimization models need to be created to find the most fitting implementation of the heating techniques. The single-objective MILP (for costs, comfort and CO_2 emission) and multi-objective weighted sum models are the most suitable methods for the research. The optimization models will be made usable for the homeowner by creating a dashboard interface using RStudio Shiny with the package Reticulate.

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[1] https://dash.plotly.com/

[2] https://shiny.rstudio.com/

[3] https://solutions.rstudio.com/r/reticulate/

4. Limited Cost-benefit analysis

In the previous Chapter, the scope of the cost-benefit analysis has been determined. The focus of the analysis will be the costs and benefits of households. In the analysis, only the direct effects on the homeowners will be taken into account, because previous research already takes indirect effects into account. Therefore, a limited costs benefit analysis will be executed. In this Chapter the third and fourth sub-research questions will be answered, which are:

3. *Which variables impact the feasibility of the techniques until 2050 and how do they develop?*
4. *What are the costs and benefits of each of the techniques for sustainable energy in the Netherlands?*

In Figure 28, it can be seen how this Chapter contributes to the research.

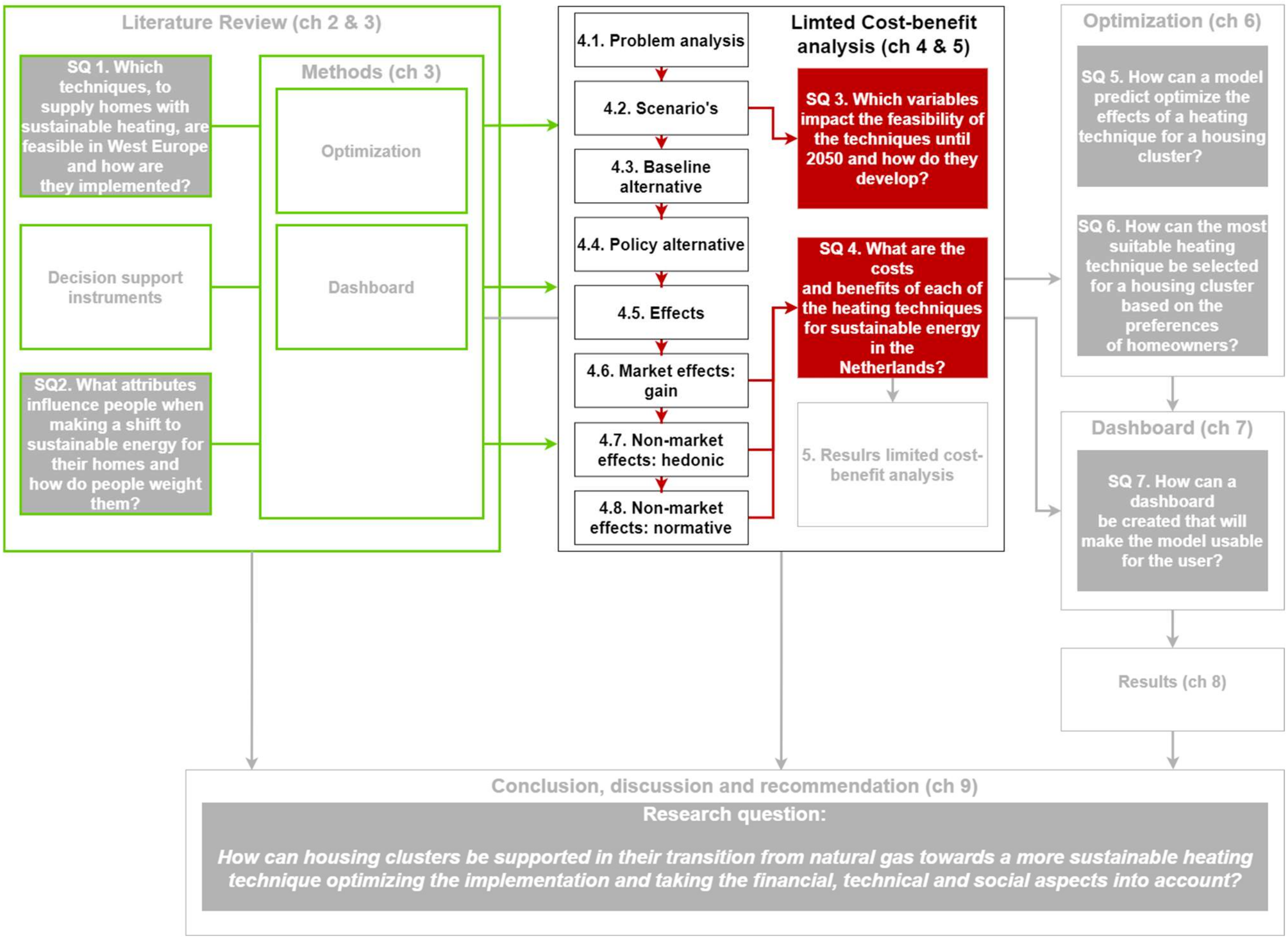


Figure 28: Limited Cost-Benefit Analysis within the overall research design

Although a limited cost-benefit analysis (LCBA) will be performed for the current research, the CBA methodology that Romijn & Renes (2013) have described in the report General guidance for Cost-benefit analysis (of the CPB and PBL) will be used. The steps that will be followed in this analysis are shown in Figure 28 and Figure 29. Some CBA steps have already been executed and are described in the previous Chapters. Which will be briefly discussed in this Chapter. During this analysis, the effects will be determined for the different heating

Figure 29: Steps of the CBA (Romijn & Renes, 2013)

techniques selected in the previous Chapter, and the results will be compared for a reference housing cluster. By doing this insight can be given by the LCBA into the advantages and disadvantages and what will be the most appropriate heating technique for a reference cluster. The results will be discussed in the flowing Chapter and a sensitivity analysis will be performed.

4.1. Problem analysis

As described in the introduction climate change is one of the current main threats, which is caused by the emission of greenhouse gasses. To limit the consequences of climate change, CO_2 emissions need to be decreased. Currently, natural gas is the main energy source used for heating in the Netherlands. The challenge for the shift toward a climate-neutral heating system for the built environment is to replace the use of natural gas with a sustainable energy source for existing housing stock. The most beneficial heating techniques to replace heating with natural gas depends on the properties of a housing cluster. Additionally, despite the technical possibilities, research shows a lack of willingness among homeowners to do off-gas renovations due to different preferences and a lack of information. The goal of the LCBA is to find the most beneficial alternative heating technique to heating with natural gas. Therefore, the effects, costs and benefits need to be determined to be able to compare the different techniques and select the most beneficial technique. Even though heating techniques have a variety of stakeholders, described in previous CBA research, the selected main stakeholder is the homeowner, on whom the change of heating technique can have a major impact due to direct consequences such as costs, comfort, and nuisance. The LCBA will focus on the direct effects on homeowner.

The costs and benefits of different heating techniques are highly dependent on the properties of the dwellings and cluster of dwellings, but it is impossible to perform a Cost-Benefit Analysis on all Dutch housing clusters. Therefore, a reference housing cluster is created that is representative of the Dutch owner-occupied housing stock. The cluster is based on the houses of neighbourhood ‘t Ven (Haren, 2021). These dwellings will be further introduced later in the research and used for validation (see Section 6.2.3). This cluster is used because it is comparable with the most common energy supply profiles, see *Appendix K: 10 most common housing profiles of homes heated with natural gas*. The energy supply profiles are the most common profiles of homes heated with natural gas, created by the CBS (CBS, 2021d). Dwelling 3 and 5 of the reference cluster of ‘t Ven are very similar. These differences would not have a significant impact on the results therefore the properties of dwelling 3 are also used for dwelling 5. The housing cluster is shown in Table 16. The current energy consumption of the dwellings is unknown. Additionally, it is assumed that the age of the central heating boiler is 10 years. Boilers can last up to 15 years, it is assumed the average age is 10 years. Since more people replace their old boilers with alternative heating techniques, the number of boilers for central heating has decreased (CBS, 2021b). This LCBA incorporates the properties of the dwellings/cluster as independent variable and not the type of users. The dwelling and cluster are used because they have a direct impact on whether and how the various heating techniques can be implemented, which determines how beneficial they are. The behaviour and type of use also impact the effects of the heating technique, but this effect is smaller and often unknown.

Table 16: Housing clusters

Housing type	Construction year	Floor size	Household size	Energy label	Type of roof	Current energy	Age of central heating boiler
Corner house	Before 1946	109	2	D	Slanted roof	Unknown	10 years
Terraced house	Before 1946	155	2	D	Slanted roof	Unknown	10 years
Terraced house	Before 1946	127	2	E	Slanted roof	Unknown	10 years
Corner house	Before 1946	71	2	F	Slanted roof	Unknown	10 years
Terraced house	Before 1946	127	2	E	Slanted roof	Unknown	10 years

In the climate agreement, it is stated that the heat transition needs to take place at the lowest social cost. Therefore, the alternative with the lowest financial costs will not automatically be the most suitable alternative. The benefits of the different alternatives have a big impact. This means that the most suitable heating technique has the highest results as a result of both the costs and the benefits of the technique. This means that all costs and all benefits should be taken into account, not only the material ones but also the intangible ones (Huygen & Diran, 2020). The most beneficial heating technique needs to meet some conditions:

- It needs to meet the current energy demand;
- The CO_2 emission needs to decrease compared to the current situation;
- The heating technique needs to be a Dutch commonly implemented alternative heating technique (see Section 2.1).

Timeframe

For the LCBA a timeframe of 30 years has been selected. Some CBAs have a longer timeframe. This has not been deemed necessary for the current research, because the effects after 2050 have little impact on the results if a discount rate is. Furthermore timeframes of 25-30 years are not usual for energy focused CBAs, after this timeframe the uncertainty of the scenario's increase often becomes too high (Tieben et al., 2020). The timeframe used for the LCBA is 2020-2050.

4.2. Scenario's

Before the costs and benefits can be determined the circumstances under which the alternatives will be implemented need to be defined. These variables are exogenous, and their development is uncertain over the set timeframe. The main variables for the LCBA are identified using current CBA research. The variable that is identified are the energy costs (M. Mulder & Hulshof, 2021; Tieben et al., 2020; van der Molen et al., 2021). In the current Section, these variables will be described, and their development will be predicted. Furthermore, the use of a discount rate also impacts the results of the LCBA. The current Section consist of; (1) the prediction of the energy consumption; (2) the prediction of the natural gas expenditures; (3) the prediction of the electricity expenditures; (4) the prediction of the district heating expenditures; (5) the discount rate. Last of all, two scenarios will be created which will be researched using these variables for the LCBA.

4.2.1. Prediction of energy consumption of dwellings

To be able to predict the energy costs for the different heating techniques, besides information on the energy price, also the current energy consumption (natural gas and electricity) needs to be known. If this information is not available, which is the case for the reference cluster. The energy consumption needs to be predicted based on a limited set of available properties. Research by Wyatt (2013) showed that energy consumption is associated with the type of dwelling. Therefore, a model is created that can predict the energy consumption based on the type of house (Wyatt, 2013). The analysis method that is used is a regression analysis using RStudio. For the determination of the housing types, the data from the “Woononderzoek Nederland 2018” also called “WoON 2018” is be used. The results of the WoON research contain statistical information about the housing situation of the Dutch population and their wishes, needs and terms for housing (CBS, n.d.).

The regression analysis is described in *Appendix L: Prediction of energy consumption of dwellings*. With the regression results, the energy consumption of dwellings can be predicted using the input variables construction year, housing type, floor space and household size. With these results, Equation 2 and Equation 3 are created. Using these independent variables as an input for these equations the energy consumption per housing type can be predicted. The equations will be used during the research to predict the natural gas and electricity consumption when it is not known. Note here that the variables construction year, household size and housing type are using dummy coding.

Equation 2: Prediction of natural gas consumption

EXP(*Natural gas consumption*) = 5,022 -0,043 * *Construction year 1965-1974* -0,174 * *Construction year 1975-1991* -0,352 * *Construction year 1992-2004* -0,483 * *Construction year 2005-2018* + 0,481 * LN(*Floor space)* + 0,080 * *2 persons* + 0,136 * *3 persons* + 0,158 * 4 *persons* + 0,173 * *5 persons or more* -0,421 * *Terraced house* + 1,278 * *Detached house* + 1,278 * *Semi-detached house* -0,253 * LN(*Floor space*) * *Semi-detached house* -0.253 * LN(*Floor space*) * *Detached house*

Equation 3: Prediction of electricity consumption

EXP(*Electricity consumption*) = 6,310 + 0,060 * *Construction year 1975-1991* + 0,066 * *Construction year 1992-2004* + 0,284 * LN(*Floor space)* + 0,305 * *2 persons* + 0,433 * *3 persons* + 0,503 * 4 *persons* + 0,541 * *5 persons or more* + 0,516 * *Detached house* + 0,516 * *Semi-detached house* -0,102 * LN(*Floor space*) * *Detached house* -0,102 * LN(*Floor space*) * *Semi-detached house*

4.2.2. Prediction of natural gas expenditures

For the use of natural gas, a household has gas expenditures. The natural gas bill includes two types of costs, fixed costs and variable costs. The fixed costs are independent of the natural gas consumption and the variable costs are dependent on the amount of natural gas used by the household (Luteijn et al., 2021).

The fixed costs, consist of two sub-costs:

1. Network management costs: the costs that the consumer pays to the network operator. These are the costs for the connection, the fuse box and the transportation of the natural gas. The network management costs consist of the standing charge, the capacity rate, the periodic connection fee and the meter rent.
2. Fixed delivery costs: These are the costs that the consumer pays to the energy supplier for the delivery of natural gas.

Variable costs consist of three types of costs:

1. Variable delivery costs: These are the costs that are paid to the energy supplier per cubic meter of natural gas.
2. Energy tax: This is the tax that needs to be paid to the Dutch government.
3. “Opslag duurzame energie” (ODE) (Renewable energy storage): This is an extra tax of the Dutch government on energy. The income of this extra tax is used to stimulate the production of renewable energy.

Table 17: Fixed and variable natural gas prices 2018-2021 and 2030 (excluding VAT) (Luteijn et al., 2021; van Polen, 2021)

Fixed	Unit	2018	2019	2020	2021	2030 Lower-end	2030 Middle	2030 Upper-end
Network management costs	€/year	146	147	153	152	133	152	171
Delivery costs	€/year	46	55	56	57	57	57	57
Variable								
Delivery costs	€/m^3	0,28	0,29	0,23	0,25	0,26	0,33	0,42
Energy tax	€/m^3	0,26	0,29	0,33	0,34	0,39	0,39	0,39
Opslag duurzame energie	€/m^3	0,03	0,05	0,08	0,08	0,09	0,09	0,09

Table 17 shows which costs need to be paid for natural gas and the amount of these costs. The costs for 2018-2021 are known, and the costs for 2030 have been predicted by Luteijn et al. (2021). The costs are forecast for 2030 with a price range since development is highly uncertain. This range provides an impression of possible developments in the natural gas price under influenced by a variety of external factors. The ‘delivery costs’, ‘Energy tax’, and ‘ODE’ do not have the range for 2030, since there is not enough available information on the development of these costs. For the tax in 2030, the tax developments as described in the “Wet fiscale maatregelen Klimaatakkoord” have been used (Rijksoverheid, 2019a), for which a range is not necessary.

The development of network management costs is highly uncertain. Current networks will be maintained but fewer new networks will be constructed in the coming years (due to the abolition of the connection duty for newly constructed dwellings in 2018). The assumption is made that the number of natural gas connections remain at the current level (Luteijn et al., 2021). The variable ‘delivery costs’ consist of the wholesale prices and overhead costs. The price range for the wholesale prices is based on the KEV 2021 (Klimaat- en energieverkenning 2021). For the overhead costs and fixed supply costs of natural gas, Luteijn et al. assumed that these would remain at the same level as for 2021 (as presented in (CBS, 2021c)).
The accounting and tax consultancy firm PricewaterhouseCoopers (PWC) investigated the development of network management costs commissioned by Netbeheer Nederland (Strategy & PWC, 2021). The middle and lower-end natural gas price development scenarios are based on this report. As Strategy & WPC did not predict a high scenario, Luteijn et al. (2021) assumed that the high scenario would develop with the same steepness as the low scenario.

The delivery costs of natural gas have been highly variable in the past years, see Figure 40. Besides the price peak of 2019, the natural gas price is rapidly increasing since 2021. This is caused by multiple factors including the high dependency of the Netherlands on international natural gas, high international demand for natural gas and limited natural gas supply. The predicted variable delivery costs are a weighted average of the different types of energy contracts. Half of the Dutch households have a variable contract, in which price fluctuation is instantly visible compared to fixed contracts (Luteijn et al., 2021).

Examples of the cost development

It is assumed that the cost development as described above will continue to 2050. The described cost development is shown in the figures below for a house with a natural gas consumption of 1500 m^3. In the figures below, the yearly costs are shown for the predicted lower-end and upper-end natural gas price development scenarios. In Figure 30 (low) and Figure 31 (high), the expenditures are broken down to the sub-costs, and in Figure 32 the lower-end and upper-end scenarios are shown cumulatively.

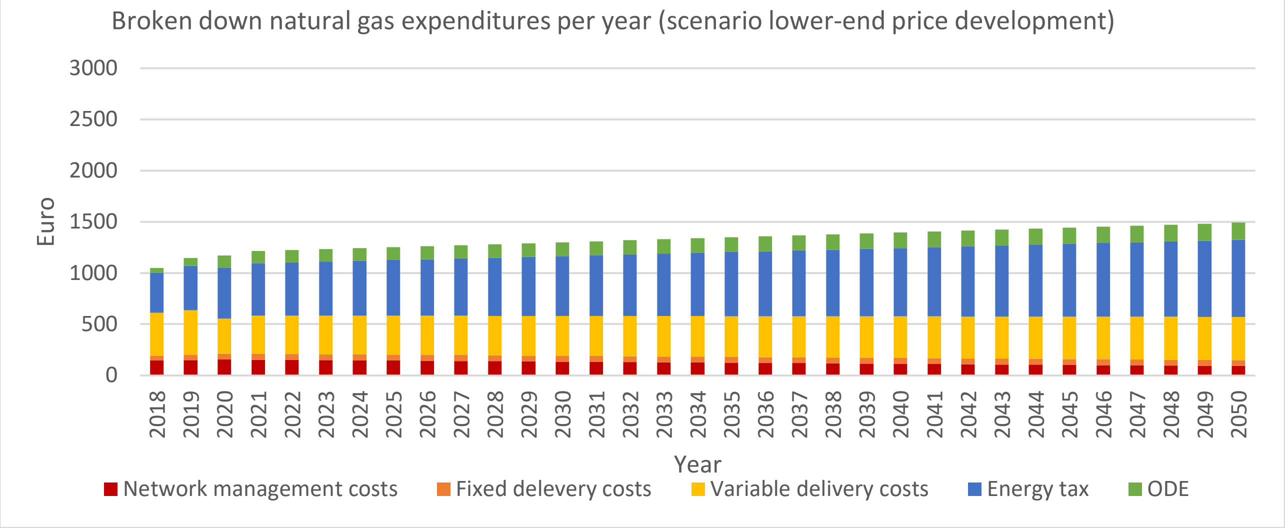


Figure 30: Broken down natural gas costs per year for reference household (scenario lower-end natural gas price development)

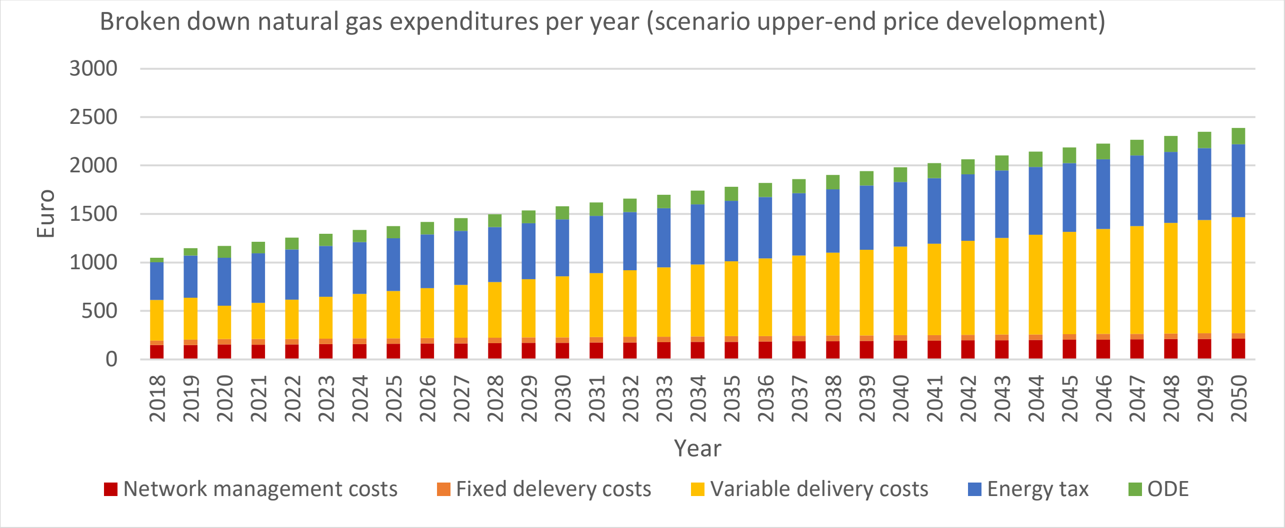


Figure 31: Broken down natural gas costs per year for reference household (scenario upper-end natural gas price development)

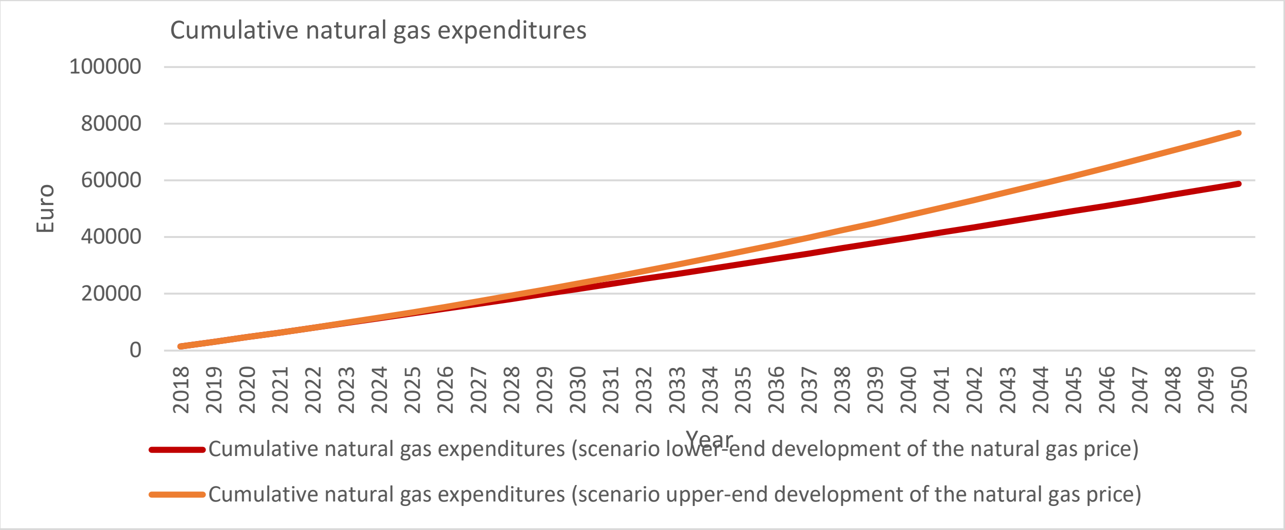


Figure 32: Yearly natural gas expenditures cumulative, scenario lower-end and upper-end natural gas price development

4.2.3. Prediction electricity expenditures

For the use of electricity, a household has electricity expenditures, the electricity bill exists of two types of costs, fixed costs and variable costs. The fixed costs consist of the 'network management costs' and the 'fixed delivery costs' of a 'tax reduction'. Per electricity connection, a tax reduction is paid to compensate for the variable energy tax ODE.

Table 18: Fixed and variable electricity prices 2018-2021 and 2030 (excluding VAT) (Luteijn et al., 2021; van Polen, 2021)

Fixed	Unit	2018	2019	2020	2021	2030 Lower-end	2030 Middle	2030 Upper-end
Network management costs	€/year	195	198	200	209	209	255	295
Delivery costs	€/year	45	55	57	58	58	58	58
Tax reduction	€/year	313	258	436	453	447	447	447
Variable								
Delivery costs	€/kWh	0,06	0,07	0,06	0,07	0,07	0,08	0,1
Energy tax	€/kWh	0,11	0,10	0,10	0,09	0,07	0,07	0,07
Opslag duurzame energie	€/kWh	0,01	0,02	0,03	0,03	0,03	0,03	0,03

Table 18 shows the different costs that need to be paid for electricity and the amount of these costs. The costs for 2018-2021 are known but the costs for 2030 have been predicted by Luteijn et al. (2021) and the price range is provided. For the tax reduction, the Dutch Ministry of Finance does not provide information on the development until 2030, it is assumed that it will remain at the same level. In the case the tax reduction is higher than the costs, it is assumed that the costs will be zero.

The price range for the wholesale prices is based on the KEV 2021. For the electricity overhead costs, Luteijn et al. assumed a small increase compared to 2021 based on the report of Hoogervorst about the cost of climate-neutral electricity in 2030 (Hoogervorst, 2020). The fixed delivery costs are assumed to remain at the same level as in 2021 (CBS, 2021c). The development of network management costs is highly uncertain. It is expected that high investments in the electricity network are required due to an increased demand for the electricity network (Luteijn et al., 2021). In the case of the upper-end price development scenario, it is assumed that the investments in the electricity network will be required at an earlier stage than described by Strategy & PWC. If the investments are needed 5 years earlier than described in the report of Strategy & PWC, the network management costs will rise with 25% of the anticipated costs increase between 2030 and 2050. This scenario is selected as the upper-end price development scenario for 2030 by (Luteijn et al., 2021).

Examples of the cost development

It is assumed that the cost development as described above will continue to 2050. The described cost development is shown for a house with an electricity consumption of 3500 kWh. In the figures below, the yearly costs are shown for the predicted lower-end and upper-end price development scenarios. In Figure 33 (lower-end) and Figure 34 (upper-end) the expenditures are broken down to the sub-costs, and in Figure 35 the lower-end and upper-end scenarios are shown cumulatively.

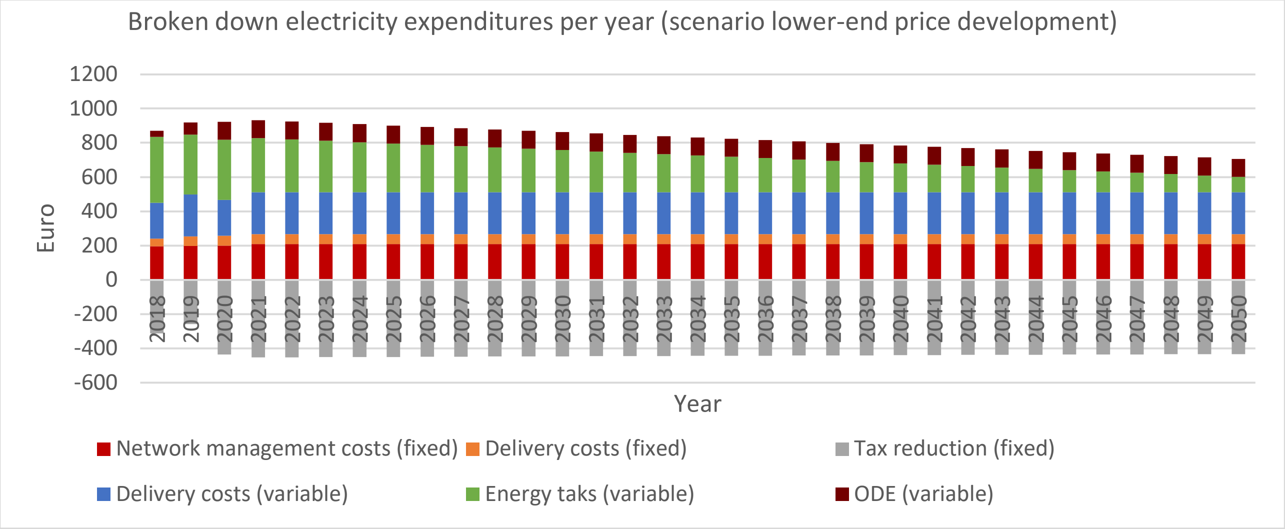


Figure 33: Broken down electricity costs per year for reference household (scenario lower-end electricity price development)

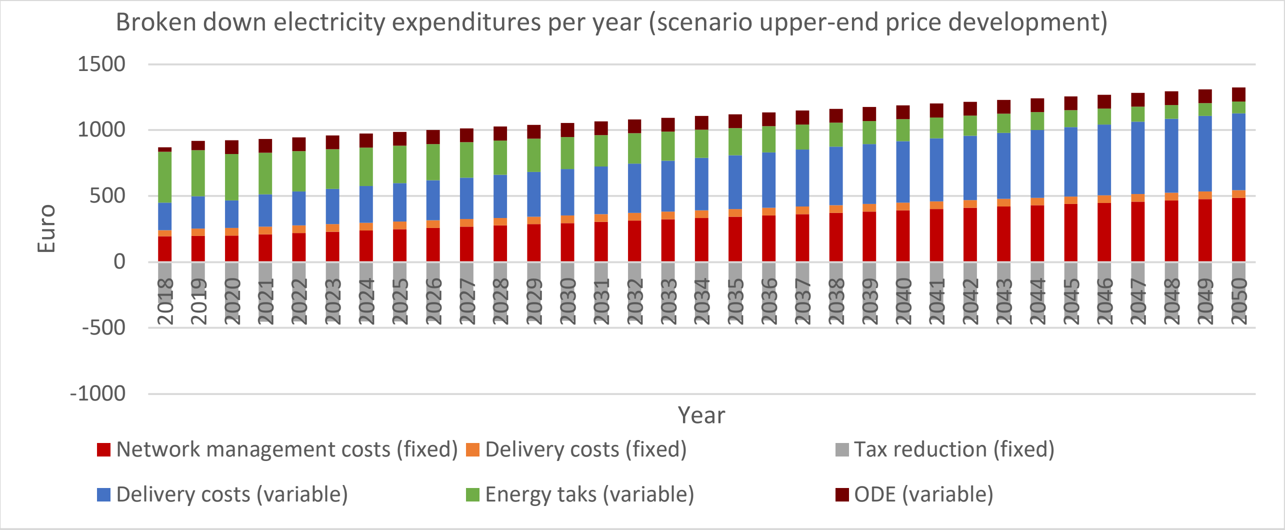


Figure 34: Broken down electricity costs per year for reference household (scenario upper-end electricity price development)

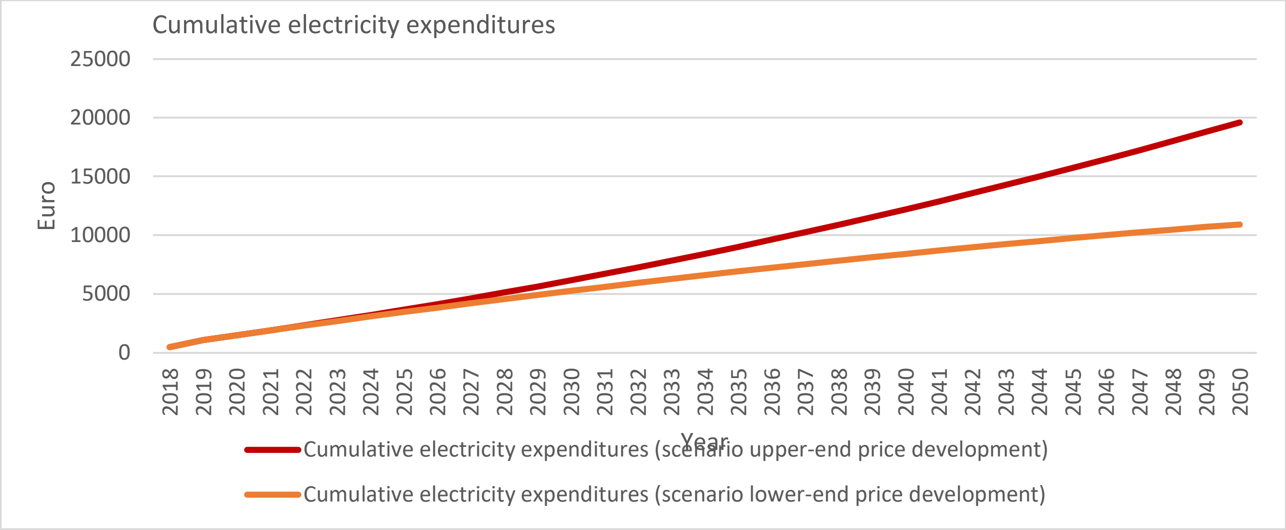


Figure 35: Yearly electricity expenditures cumulative (scenario lower-end and upper end electricity price development)

4.2.4. Prediction district heating expenditures

When district heating is used to heat a house, the homeowner needs to pay connection costs and fixed costs. The maximum costs are determined per year by the authority consumer and market (ACM). The different costs are shown in Table 19 for the years 2019-2022, for a dwelling that uses the heat from the district heating network for heating and tap water, based on the information of ACM (ACM ConsuWijzer, 2022; Autoriteit Consument en Markt, 2021).

Table 19: Maximum costs district heating (ACM ConsuWijzer, 2022; Autoriteit Consument & Markt, 2021)

		2019	2020	2021	2022
Fixed costs	Per year		€ 469,17	€ 478,60	€ 494,58
Prices per GJ	Per GJ	€ 28,47	€ 26,06	€ 25,51	€ 53,95
Measurement costs	Per year	€ 25,89	€ 26,63	€ 26,83	€ 27,47
Rent delivery set	Per year		€ 126,19	€ 125,50	€ 131,16
Connection costs =< 25m	Per connection	€ 1.038,89	€ 4.510,73	€ 4.878,04	€ 4.959,14
Connection costs >25 m per m	Per connection (per m)	€ 33,91	€ 180,74	€ 219,69	€ 224,49

Table 20: Development of the yearly costs for heat (Tigchelaar et al., 2019)

Type of costs		2020	2030
Fixed costs	Per year (fixed)	€469,17	€469,17
Variable costs	Per GJ (variable)	€26,06	€36,76

The costs for heating, as can be seen in the tables above (Table 19 and Table 20) consist of the following costs:

1. Fixed costs – For heating and hot tap water
2. Measuring costs – the costs for measuring the consumption of heat.
3. Price per GJ – Variable costs that the consumer pays per GJ of heat that is used.
4. Rent delivery set – The district heating network is connected to a dwelling using a delivery set, which can be rented per dwelling.

Besides the yearly costs, there are investment costs for a dwelling to be connected to a district heating network, which are:

- Connection costs ≤25 meter – These are the connection costs to be connected to the network in all cases.
- Connection costs >25 meter per extra meter – These are the extra connection costs to be connected to the network if the network is located more than 25 meters away per extra meter.

Tigchelaar et al. (2019) predicted the cost for the end-user in 2030 which can be seen in Table 20. For this prediction, only the fixed costs and the variable costs (price per GJ) have been considered. For the current research, the development of the costs for heat needs to be predicted until 2050. Furthermore, the development of all sub-costs for heat needs to be considered. The development of the costs is described below and shown in Figure 36, Figure 37, and Figure 38.

The fixed costs have increased quite rapidly from 2020 to 2022. If these costs would keep rising with the same steepness the fixed costs could be around €850 in 2050, which would make district heating too expensive to implement and therefore the prediction unreliable. Tigchelaar et al. (2019) predicted in their research that the fixed costs would stay at the same level as in 2020. Because there is no further formation on how these costs will likely develop until 2050, it has been chosen to assume the fixed costs remain at the same level as the most recent data (2022).

The maximum amounts of the variable costs are dependent on the height of the natural gas prices. The methodology that is used for this is the “Niet-Meer-Dan-Anders” principle (no more than other principles), which means that the costs of natural gas are used as a reference to determine the maximum delivery rate of heat. Therefore, the maximum delivery rate of heat cannot be higher than the costs an average user would have for the same heating using natural gas (Autoriteit Consument en Markt, 2021). Three scenarios have been created for the variable costs, based on the development of the natural gas price. In the research, the development of the heat price is depending on the used natural gas price scenario. As described above the price of heat is currently linked to the price of natural gas. In the coming years, natural gas will decrease to be the main energy source. Therefore the natural gas price will lose its value as a reference and the heat price will need to detach from the natural gas price (Harmelink, 2020). It is expected that this will happen in 2024, but since this date is not certain, is a variable, when the price is detached, the heat price will remain at a constant level and not keep growing with the same steepness as the natural gas price. These assumptions are shown for a household with a current gas consumption of 1500 m^3 in Figure 36, Figure 37 and Figure 38. It is assumed that the heat costs will detach from the natural gas costs in 2024, which can be seen in the figures. The costs predicted by Tigchelaar et al. (2019) are comparable with the high heat price scenario.

The rent of the delivery set has shown a small increase from 2020 to 2021 and a big increase in 2022, which makes it difficult to make reliable predictions for the rent development of the delivery set. Furthermore, no further information is available on the cost development of the rent of the delivery set. Therefore, the rent of the delivery set is assumed to remain at the level of 2022. The same strategy is used for the prediction of the development of the connection costs. The rent of the delivery set and the measuring costs are included in the maintenance costs at a later stage of the LCBA.

An example of the costs of district heating for one household (2021) is shown in Table 21 and Table 22. Not in all cases the maximum costs needed to be paid by this household. But for the research, the maximum amounts will be used in order not to underestimate the costs of district heating.

Table 21: Example of connection costs for district heating (Duurzaamheidspact Eindhoven, 2020)

	Capacity	BAK	BAK extra distance (>25m/m)	Project contribution	Total connection costs
Individual	Up to 100 KW	€3.727,88	€149,37	€2.272,12	€6.000,00

Table 22: Example of yearly costs for district heating (Duurzaamheidspact Eindhoven, 2020)

Cost type		Amount (incl. VAT)	
Fixed costs		€365,34	Per year (fixed)
Delivery set		€126,19	Per year (fixed)
Measuring costs		€26,63	Per year (fixed)
Total		€518,16	Per year (fixed)
Variable cost	€25,77	Per GJ (variable)	

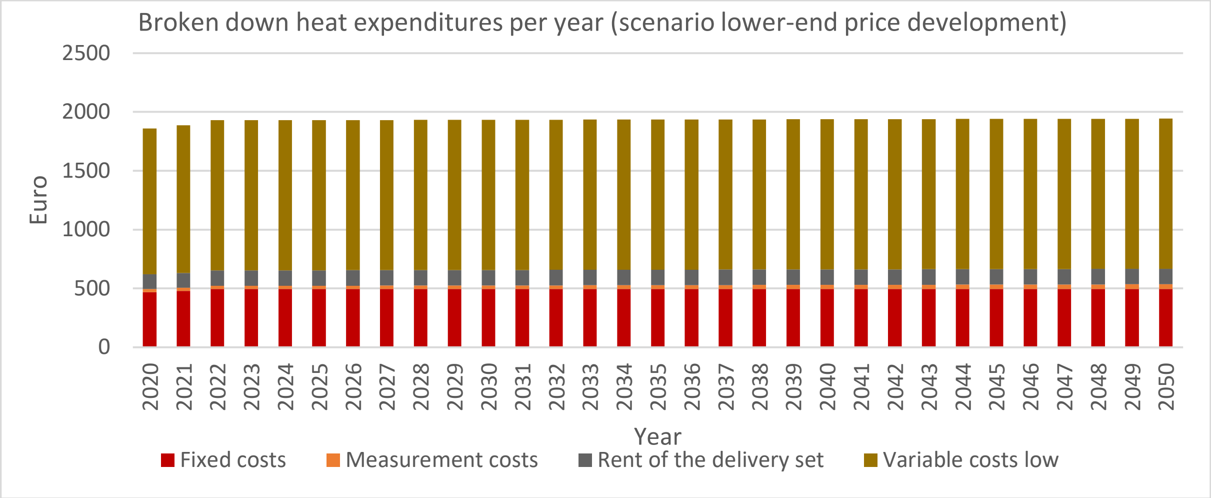


Figure 36: Broken down heat expenditures per year (scenario lower-end heat price development)

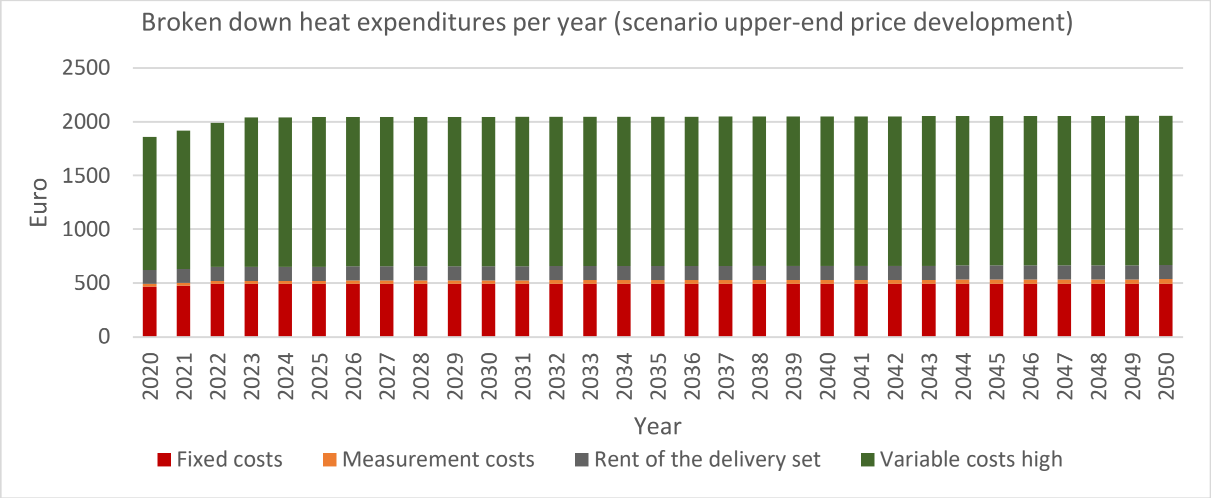


Figure 37: Broken down heat expenditures per year (scenario upper-end heat price development)

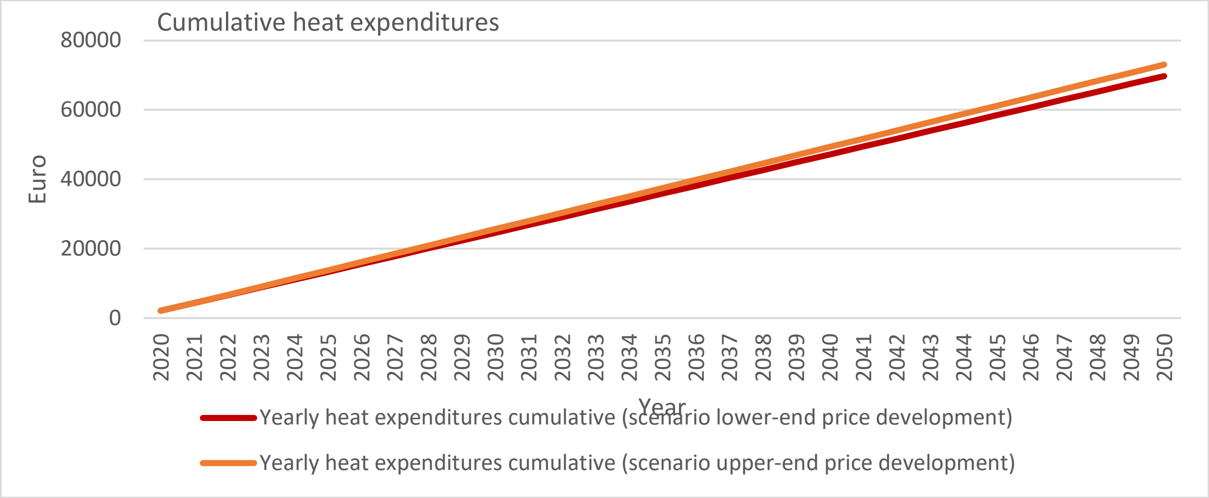


Figure 38: Yearly heat expenditures cumulative (scenario lower-end and upper-end price development

4.2.5. Development of investment cost

The investment costs of the techniques may increase or decrease over time. The development of the investment costs is called “learning factors” in the Vesta Mais model. These learning factors indicate the relative change in the development of the investment costs in a year, compared to the starting year (which is 2020). The development of these learning factors is uncertain (van der Molen et al., 2021). Therefore, a development range is used to deal with this uncertainty. In the research, an optimistic learning curve and a pessimistic learning curve are indicated. The optimistic learning curve predicts that the investment costs will decrease over time, due to technical developments of the techniques. For the pessimistic learning curve, it is assumed that the investment cost will remain at the same level compared to the starting year of 2020. The developments of the investment costs based on the Vesta Mais model are shown in Table 23.

Table 23: Development of the learning curve of the investment costs (van der Molen et al., 2021)

Technique	Learning curve	2020	2030	2040	2050
Insulation label improvement	Optimistic	100%	82%	69%	59%
	Pessimistic	100%	100%	100%	100%
HE boiler	Optimistic	100%	81%	65%	55%
	Pessimistic	100%	100%	100%	100%

Hybrid heat pump	Optimistic	100%	55%	44%	37%
	Pessimistic	100%	100%	100%	100%
Heat pump air	Optimistic	100%	62%	55%	42%
	Pessimistic	100%	100%	100%	100%
Heat pump ground	Optimistic	100%	62%	50%	42%
	Pessimistic	100%	100%	100%	100%
Low-temperature heat release systems	Optimistic	100%	88%	71%	60%
	Pessimistic	100%	100%	100%	100%
Connection costs district heating	Optimistic	100%	80%	70%	64%
	Pessimistic	100%	100%	100%	100%

4.2.6. Discount rate

When a Cost-Benefit Analysis is created with benefits in the far future, the discount rate needs to be considered. In these cases, the discount rate is one of the most important variables. The discount rate is a percentage that can be used to calculate the expected costs and benefits in the future back to the base year of the project (net present value) (Centraal Planburau, 2015; Rijkswaterstaat, 2020). The discount rate can be seen as the minimum required return from a social perspective. Social welfare will increase if the expected return of an investment project exceeds the discount rate, and, if it is lower, welfare will decrease. To be able to make a correct assessment of prosperity in the present compared to the future, a discount rate is required. If the value of the discount rate is higher, the future weight of the costs and benefits will be lower (Ministerie van Financiën, 2020). If a discount rate is used, the impact of the benefits in the far future reduces dramatically. The importance of the discount rate increases with the time horizon. To illustrate the importance of the right discount rate, the example in Figure 39 can be used. The figure shows the discount rates of 5.5%, 4% and 1%, on the vertical axis the present value is expressed as a percentage of €100. In this example, it can be seen that when a project would yield a €100 in 100 years, it would have a present value of only €0,47 (with a discount rate of 5.5%) (Centraal Planburau, 2015).

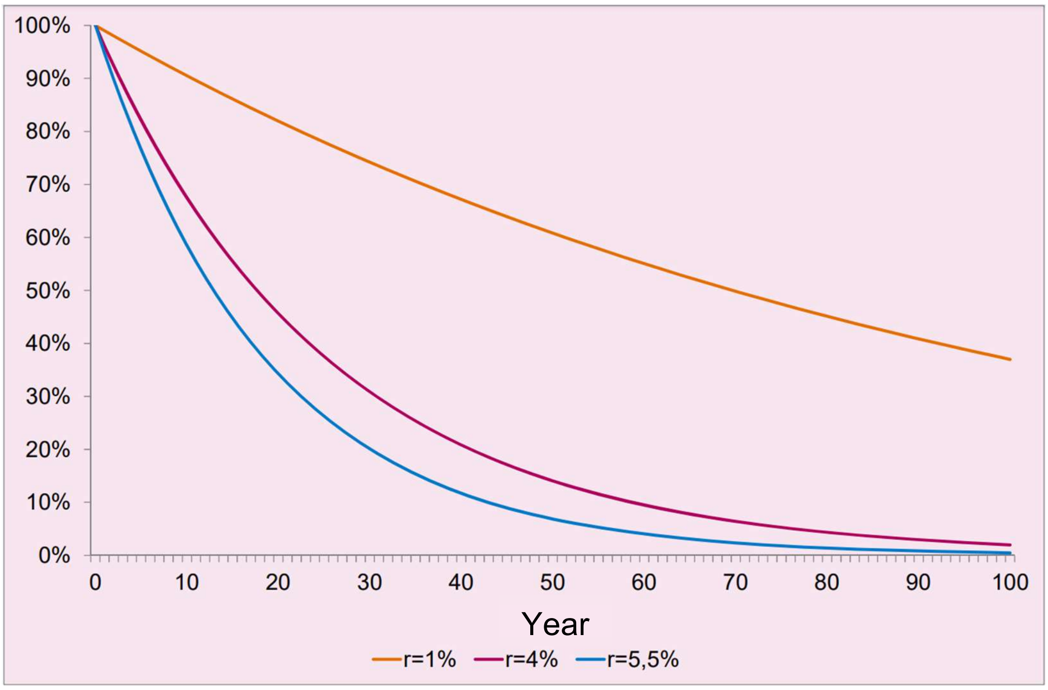


Figure 39: Present value of proceeds of €100 (Centraal Planburau, 2015)

To determine the social discount rate, the wealth theory can be used as a conceptual framework. When there is a high time preference, this will result in a rise in the discount factor and thus the discount rate. This means that the discount rate rises when people are more impatient and when the growth rate of the macro consumption was already high during the lifetime of the project. This is explained by the Ramsey-rule, which is shown in Equation 4 (Centraal Planburau, 2015).

Equation 4: Ramsey-rule

$$d_t = \delta + \gamma g_t$$

In this equation, d_t is the discount rate between the current time and period t. δ is the time preference rate, which can be explained as the degree of impatience. g_t is the average growth rate of consumption between the current time and period t. γ is the degree to which the marginal utility of consumption over a period decreases with its level (Centraal Planburau, 2015). The Ramsey-rule is derived from a theoretical setting in which the government (as a representative of all citizens) maximize Social welfare. According to this rule, the risk-weighted standard discount rate can be broken down into four components which are shown in Equation 5 and explained below.

Equation 5: Risk-weighted discount rate (Ministerie van Financiën, 2020)

$$\begin{aligned} &Risk\ weighted\ discount\ rate \\ &\qquad = time\ preference + wealth\ effect + precautionary\ effect \\ &\qquad + standard\ risk\ premium \end{aligned}$$

Time preference: Reflects how impatient society is in choosing between prosperity now or later in time (only because of the time difference). This component can have a zero or a positive value, if the value is positive this means that the costs and the benefits are weighted less heavily when they ley further in the future. If the value is zero all generations are weighted equally.

Wealth effect: describes how society deals with differences that are associated with trends in welfare growth.

Precautionary effect: describes how society deals with the uncertainty of the future level of welfare. This effect is always negative. The magnitude of this effect depends on the aversion to difference or risks, the tendency to be prudent the size of the macroeconomic volatility.

Standard risk premium: This effect is always positive and regards the required compensation for the project risks of an average investment project. If the macroeconomic volatility or the aversion to differences or risks is larger, the higher the risk premium (Ministerie van Financiën, 2020).

The Ministry of Finance of the Netherlands created updated advice for the discount rate in 2020. This advice is based on market information, of average values over a longer period to reduce the influence of fluctuations in financial prices. The main recommendations on the level of the discount rates that should be applied in social cost-benefit analyses are shown in Table 24 (Ministerie van Financiën, 2020).

Table 24: Recommendations discount rate (Ministerie van Financiën, 2020)

	Height discount rate	Explanation

Standard discount rate	2,25%	Applicable to all types of policy changes and all types of costs and benefits barring the two exceptions below.
Discount rate for fixed, sunk costs	1,6%	Applicable only to costs that are largely or wholly independent of usage and are typically sunk.
Discount rate for highly non-linear benefits	2,9%	Only applies to benefits that are in strong degree non-linear with the Applicable only to benefits that are highly non-linear relative to usage, where usage, moreover, depends on the state of the economy

In the Table, it can be seen that besides the standard discount rate, there are two exceptions (Ministerie van Financiën, 2020).

- The *discount rate for fixed, sunk costs*, relates to the costs that are largely independent of usage (i.e., fixed costs) or when there are no alternative uses for investments (i.e., sunk costs).
- The *discount rate for highly non-linear benefits* relates to benefits that are highly non-linear relative to usage. For which the usage depends on the state of the economy.

For the current Cost-Benefit Analysis, for most costs and benefits the standard discount rate will be used (2.25%). For the fixed costs, the discount rate for fixed, sunk costs will be used (1.6%), these fixed costs include the fixed energy costs and the maintenance costs. To determine the net present value for the costs and benefits of the Cost-Benefit Analysis Equation 6 will be used. In this equation, the net present value will be determined, by the sum of the net present value per year minus the initial investment.

Equation 6: Net present value

$$NPV = \sum_{t=1}^{t} \frac{C_t}{(\,1 + r\,)^t} - C_0$$

NPV = Net present value
C = cash flow
r = Discount rate
t = Time
C_0 = Initial investment

4.2.7. Scenarios for the LCBA

In the previous Sections the analysis and the prediction of the development of the variable have been described. In the current LCBA, two scenarios will be considered which are shown in Table 25. Contrasting scenarios have been selected to see how these variables affect the outcome of the LCBA. The selected “extreme” scenarios are created based on what would be realistic scenarios in the case of high or low costs.

Table 25: Scenario’s to test the optimization models

	Natural gas price development	Electricity price development	Development investment cost
Scenario low	Lower-end	Lower-end	Pessimistic
Scenario high	Upper-end	Upper-end	Pessimistic

In Figure 40, it can be seen that, except for some outliers, there is a correlation between the consumer price index (CPI) of natural gas and electricity over the last 25 years. Therefore, it is deemed likely that if the natural gas price is high this will also be the case for electricity, which makes the selected scenarios probable. The "high" and "low" scenarios for energy will be further explained later in this Chapter.

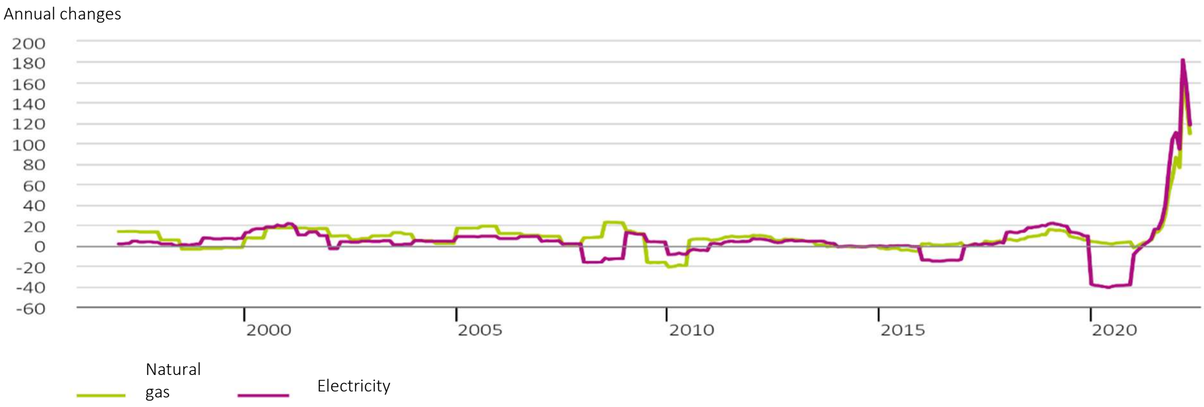


Figure 40: Consumer price index of natural gas and electricity in the Netherlands (CBS, 2022)

4.3. Baseline alternative

In the LCBA, the different heating techniques (policy alternatives) are compared with the baseline alternative. In this Section, the baseline alternative will be described. The baseline alternative is the development that would occur in the absence of the policy alternatives. Romijn and Renes (2013) describe the baseline alternative as "*the most likely situation that would develop in all the relevant markets for the CBA if the measure under consideration were not implemented.".* The baseline alternative is essentially a benchmark against which all relevant policy alternatives are measured. The baseline alternative should contain:

- The existing policy, including the measures that are already agreed on but not yet implemented;
- Planned measures;
- Small interventions that partly resolve or mitigate the problem;
- No doom scenario.

In the baseline alternative, it is assumed that the dwellings of the housing cluster will initially remain heated using natural gas. Since heating with natural gas does meet the heating criteria of homeowners and, as found by Jansma et al. (2020), most tenants and homeowners do prefer the current heating technique (which is natural gas). But for the baseline alternative, it will be very likely that the homeowner will shift to a hybrid heat pump if the boiler needs to be replaced after 2026. This is assumed because the Dutch government obliges homeowners to replace their old boiler with a heat pump after 2026 (or another natural gas-free heating technique) (Rijksoverheid, 2022). Compared to the current situation, more changes will occur. For the baseline alternative, the insulation of homes will likely be increased. Due to the increase in the price of natural gas, which is described and predicted in Section 4.2.2, homeowners are likely to invest in measures that will decrease their energy use. A very effective measure is an increase in insulation. Steenbekkers et al. (2021) researched homeowners' motivations and perceived barriers to achieving sustainable living in their homes. They found that almost a quarter improved the insulation of their homes in the previous 5 years. They also found that 26% did not want to improve the isolation of their home (Steenbekkers et al., 2021). These percentages make it likely that homeowners in the baseline alternative improve their isolation level.

Assumptions for the baseline alternative
Some assumptions must be made for the baseline alternative. First, when no policy alternative will be applied, it is likely, as described above, that homeowners will apply some home improvements, which will be an improvement of insulation. For the insulation level, the insulation labels are used (from the Vesta MAIS 5.0 model), which is an indication of the building envelope. The insulation label is comparable with the energy label but the heating installations are not taken into account (van der Molen et al., 2021). For the baseline alternative the insulation label of a dwelling should be at least to level D at first and at least level B (Rc 2,5) at a later stage in time. This will happen at a natural moment in time, which will most likely be the moment when the HE boiler needs to be replaced. When the boiler needs to be replaced the homeowner will be actively involved with the energy use in their home. A HE boiler needs to be replaced after 13 years (Essent, n.d.-b). This means that the homeowner will be likely to improve his house's insulation level once every 13 years.

To create an insight into the interventions that will be probable for the baseline alternative, an overview is shown in Table 26. For the reference house, it is assumed that the house has a 10-year-old HE boiler. This means that the boiler needs to be replaced after three years and an insulation improvement will be made at this moment in time (so it will have at least level D). The next moment in time that the HR boiler needs to be replaced (in 2036), a hybrid heat pump will be installed. At this moment in time, the insulation level will also be improved to its final level of insulation level B. If the insulation is improved to level B, a ventilation system needs to be installed. The energy costs of the baseline alternative for scenario low and high are shown in Table 27. More information about the assumptions for these interventions can be found in Section 4.6.1.

Table 26: Likely intervention baseline alternative (X is placed in the years the intervention is installed/used)

	Replacement	Year	Baseline alternative
Heating		2020-2035	Natural gas
		2036-2050	Hybrid heat pump
Tap water		2020-2050	Natural gas
Cooking		2020-2050	Natural gas
Insulation		2020	Current energy label
		2023	D
		2036	B
Ventilation mechanical	18 years	2020-2036	
		2036-2050	X
Replace fuse box	25 years	2020-2036	
		2036-2050	X
Shift to 3x 25A electricity connection	15 years	2020-2023	
		2023-2036	
		2036-2050	X

Table 27: Energy costs of the baseline alternative

		Baseline alternative				
		Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Scenario low	Natural gas	€ 20.703	€ 17.316	€ 15.787	€ 17.144	€ 15.787
	Electricity	€ 11.974	€ 12.732	€ 11.500	€ 9.530	€ 11.500

	Heat	€	-	€	-	€	-	€	-	€	-
	Total	€	32.677	€	30.048	€	27.286	€	26.674	€	27.286
Scenario high	Natural gas	€	26.340	€	22.103	€	20.199	€	21.903	€	20.199
	Electricity	€	22.061	€	22.882	€	21.201	€	18.706	€	21.201
	Heat	€	-	€	-	€	-	€	-	€	-
	Total	*€*	*48.401*	*€*	*44.985*	*€*	*41.400*	*€*	*40.609*	*€*	*41.400*

4.4. Policy alternatives

The policy alternative is described by Romijn & Renes (2013) as: *"A policy alternative is the smallest possible package of complementary measures that is expected to be technically and legally possible, economically feasible and have a credible relation with the problem identified in the problem analysis".* Furthermore, Romijn & Renes describe four criteria that a policy alternative needs to meet, which are:

1. The policy alternative must be irreducible
2. The policy alternative must seek to meet the policy objective
3. The policy alternative must be technically and legally practicable
4. The policy alternative must be economically feasible.

In Section 2.1 four main alternatives to heating using natural gas have been identified. These alternatives will be the policy alternatives, and, in this Section, these policy alternatives will be further defined. The project alternatives are summarized below. Table 28 shows which interventions are needed per policy alternatives and when these interventions need to be implemented.

District heating 1: Middle temperature district heating

District heating 1 is the policy alternative that shifts the heating of the housing cluster from natural gas to middle-temperature district heating. When the homes of a cluster are connected to a middle-temperature district heating network, a minimum insulation level of D is required. Although the insulation label needs to be D at a minimum, over the period until 2050 the insulation level will likely be improved to level B (which is the same level as is implemented in the baseline alternative). Other alterations that are needed for this alternative are a shift to electric cooking, an increase in electricity connection, disconnection from the natural gas network and the connection to the district heating network and the placement of the heat delivery set.

District heating 2: Low-temperature district heating

The policy alternative district heating 2 involves switching the heating of the housing cluster from natural gas to low-temperature district heating. For this alternative, the district heating network will supply the home with lower-temperature water than a middle district heating network. Therefore, extra interventions are required for the implementation of this policy alternative. It is necessary to have at least level B insulation, a booster heat pump to heat tap water, low-temperature radiators, a switch to electric cooking, a bump in the electricity connection, disconnection from the natural gas network, and connection to the district heating system, as well as the placement of the heat delivery system.

All-electric 1: Individual heat pump
The policy alternative all-electric 1 is the alternative for which the heating of the housing cluster is shifted from natural gas to all-electric with an individual heat pump. For this alternative, each dwelling of the cluster will have an individual heat pump to generate the heat. At the moment the air-to-water heat pump is installed, also the natural gas connection can be disconnected. Other required alterations are the implementation of low-temperature radiators, a shift to electric cooking, an increase in electricity connection and an insulation increase to at least level B.

All-electric 2: Collective heat pump
The policy alternative all-electric 2 is the alternative for which the heating of the housing cluster is shifted from natural gas to all-electric with a ground heat pump. For this alternative, each dwelling of the cluster will have an individual ground heat pump to generate the heat but with a collective ground shaft for the u-loop. Because the shaft is collective, the drilling costs will be reduced per household. When the all-electric ground heat pump is installed the natural gas connection can be disconnected. Other required alterations are the implementation of low-temperature radiators, a shift to electric cooking, an increase in electricity connection and an insulation increase to at least level B.

To increase the report's readability, it has been decided to focus on two policy alternatives during the limited Cost-Benefit Analysis. By doing this, these two policy alternatives can be explained in more detail. The policy alternatives on which will be focused are district heating 1 and all-electric 1. These alternatives have been selected because these two alternatives are both opposite to each other, which could create interesting insights for the analysis. But most of all, these two alternatives are the most commonly used heating techniques.

Table 28: Interventions of the policy alternatives and the baseline alternative (NG: natural gas, DH: district heating, ID: induction, E: electricity, BHP: booster heat pump, AHP: air-to-water heat pump, GHP: ground heat pump, CL: current insulation label, D: insulation label D, B: insulation label B)

	Replacement		*Baseline alternative*	District heating 1	District heating 2	All-electric 1	All-electric 2
Heating		2020-2023	*NG*	NG	NG	NG	NG
		2023-2050	*NG*	DH	DH	E	E
Tap water		2020-2023	*NG*	*NG*	NG	NG	NG
		2023-2050	*NG*	DH	DH + BHP	AHP	GHP
Cooking		2020-2023	*NG*	DH	NG	NG	NG
		2023-2050	*NG*	ID	ID	ID	ID
Insulation		2020-2023	*CL*	CL	CL	CL	CL
		2023-2036	*D*	B	B	B	B
		2036-2050	*B*	B	B	B	B
Ventilation mechanical	18y	2020-2023					
		2023-2036		X			
		2036-2050	*X*	X			
Ventilation Heat recovery	18y	2020-2023					
		2023-2050			X	X	X
Solar panels	13y	2020-2023					
		2023-2050		X	X	X	X
Replace fuse box	25y	2020-2023	*X*	X	X	X	X
		2023-2048					
		2048-2050	*X*	X	X	X	X

Shift to 3x 25 A electricity connection		2023-2036		X	X	X	X
		2036-2050	*X*				
Connection district heating		2020-2023					
		2023-2050		X	X		
Remove gas connection		2020-2023					
		2023-2050		X	X	X	X
Electric cooking	15y	2020-2023					
		2023-2050		X	X	X	X
LT radiators	50y	2020-2023					
		2023-2050			X	X	X
Booster heat pump	15y	2020-2023					
		2023-2050			X		
Hybrid heat pump	18y	2020-2036					
		2036-2041	*X*				
Air-to-water heat pump	18y	2020-2023					
		2023-2050				X	
Ground heat pump	18y	2020-2023					
		2023-2050					X

4.5. Effects

To identify the effects of the alternatives the goal framing theory is used (Lindenberg & Steg, 2007), described in Section 2.3. Based on the goals (or motivations) that influence the behaviour of people pro-environmental behaviour the direct effects on homeowners are determined. The effects are identified based on the literature review. An overview of the identified direct effects can be seen in Table 29. The weights of the goals, which have been determined in Section 2.3, are included in the Table. The effects will be valued in the following Sections. In the results of the LCBA, the effects will be added using the weights to determine the overall welfare effect.

Table 29: Identified effects

Type effect	Effect	Private or public	Measure
Gain (56%)	Costs	Private	€
Hedonic (40%)	Comfort	Private	Comfort level
	Required space	Private	m^3
	Impact renovation process	Private	Months
	Energy price volatility	Private	Hight of sensitivity of the energy price per energy source
	Freedom of choice of energy supplier	Private	Level of freedom of choice of energy supplier
	Safety	Private	Hight of safety
Normative (4%)	Climate	Public	Emission in kg CO_2

4.6. Market effects: gain

The Cost-Benefit Analysis will research the costs and benefits of alternative sustainable heating techniques to heating with natural gas. The analysis will focus on the costs and benefits of owner-occupied households. In this Section, two main types of costs can be identified. First, there are the costs that are required to implement the policy alternative. Which are the investment costs. Secondly, there are costs associated with maintaining the heating system. Included in these costs are maintenance costs, reinvestment costs, and energy costs. The costs are determined by the net present value for 2020. The Section costs out of: Section 4.6.1 Adaptation to the house, explains which adaptations to the house are required for the implementation of a heating technique. In Section 4.6.2 Investment costs, the investment costs for implementing the policy alternative are described. In 4.6.3 Maintenance costs, the maintenance costs per policy alternative will be defined. In Section 4.6.4 Replacement costs, the costs for the required replacements for the policy alternatives will be described. In Section 4.6.5, Energy costs, the prediction and energy costs will be presented, according to the scenarios selected.

4.6.1. Adaptation to the house

For the implementation of the different techniques, the costs need to be considered. In the current Section per required adaptation, for the alternatives, to the house are described. This includes the costs of the technique. In the following Sections, an overview will be provided of the investment costs, maintenance costs, reinvestment costs and energy costs.

4.6.1.1. Boiler

For the baseline alternative, it will be assumed that the dwellings will first be heated with the current technique which is natural gas and will shift to a hybrid heat pump in 2036. To be able to compare the different alternatives, the cost of replacing the current boiler will be incorporated into the model. These will be high-efficiency boilers that have greater efficiency in the amount of usable heat that is extracted from the natural gas compared to other older types of boilers. Because the high-efficiency boiler reuses the heat of the gasses that are released during the combustion of the natural gas (Essent, 2019). The high-efficiency boiler is a combination boiler that provides both heat and warm water. Not all dwellings need the same type of high-efficiency boiler because the required size of the boiler depends on the size of the house and the size of the household (on their needs). A boiler has a CW value, which is the comfort class of hot water. The CW value shows the tap water performance of the boiler, which means that the higher the CW value the more capacity of warm water the boiler has. The CW value starts from CW1 which is very small. Nowadays boilers start at CW3 which can be used for small households but not for all sanitation. Due to this, it has been chosen for the model to start with CW4 which is suitable for all small and medium-size dwellings (apartments and terraced houses). The boiler can supply a minimum of 7.5 litres of 60°C hot water per minute. At 40 °C, the boiler supplies at least 12.5 litres of hot water per minute. A boiler with a CW value of 5 is suitable for medium houses (semi-detached). This boiler can supply a minimum of 9 litres of hot water at 60 °C per minute and 15 litres per minute of hot water at 40 °C. The CW value of 6 is suitable for large and detached houses. This boiler can supply a minimum of 11 litres of hot water at 60 °C per minute and 22 litres per minute of hot water at 40 °C (infobron, n.d.). A HE boiler needs to be replaced after 13 years (Essent, n.d.-b). In the table below the average investment costs of the different types of high-efficiency boilers are shown, see Table 30.

Table 30: Average investment costs of a high-efficiency boiler per type

Type of high-efficiency boiler	Costs (2020)
CW4	€1800
CW5	€2100
CW6	€2550

The investment costs of the boilers will develop over time. This can be caused by developments in material prices, labour costs, productivity and innovations in the production process. Van der Molen et al. (2021) predicted two scenarios for the development of the investment costs of a HE boiler, see Section 4.2.5. For the optimistic scenario, it is assumed that the costs will go down to 55% of the costs of 2020 in 2030 and for the pessimistic scenario, it is assumed that the investment costs will not go down until 2050. Besides the change in investment costs, the efficiency of a natural gas boiler will increase. The efficiency of a HE boiler is on average 104% for the heating of the home (HH) and 72% for the heating of tap water (TWH) (CE Delft, n.d.-b). The last set of costs that need to be considered for a boiler is the maintenance costs. A HE boiler needs maintenance every 2 years. Many households have a contract for this. An all-in contract (which includes 2 yearly maintenance, 1-day service, call-out costs and material costs) costs between €130-€175 per year (the average of €153 is assumed for this research) (CV-kosten.nl, 2021). An overview of the costs for the reference cluster can be seen in Table 31.

Table 31: Overview of costs for the implementation of a HE boiler per dwelling of the reference cluster (development pessimistic)

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 2.100	€ 1.800	€ 1.800	€ 2.100	€ 1.800
Energy costs (Efficiency)	HH (104%) TWH (72%)	HH (104%) TWH (72%)	HH (104%) TWH (72%)	HH (104%) TWH (72%)	HH (104%) TWH (72%)
Maintenance costs	€ 153 p/y	€ 153 p/y	€ 153 p/y	€ 153 p/y	€ 153 p/y
Replacement costs	€ 2.100	€ 1.800	€ 1.800	€ 2.100	€ 1.800

4.6.1.2. Heat pump

For the baseline alternative and the all-electric policy alternatives, the dwellings will be heated using a heat pump. Three types of heat pumps are included in the research, which are a hybrid heat pump, an air-water heat pump and a collective ground-water heat pump. The hybrid heat pump heats a home using a combination of electricity and natural gas.

Hybrid heat pump

A hybrid heat pump will heat the dwelling in combination with a HE boiler. The heat pump provides 85% of the heat in the dwelling and the HE boiler for the other 15%. In addition, the HE boiler also heats the tap water (Werkspot, 2019). When a hybrid heat pump is installed, the current "central heating installation" needs to be replaced by a hybrid air-water heat pump and a new individual HE combi boiler. Besides the placement of these installations, new water pipes need to be constructed. Research by Arcadis (2021) showed that the average investment cost for the implementation of this heating technique is € 8.386 (Peppelman et al., 2021). Besides the investment costs, there are maintenance costs. These costs are estimated by assuming a maintenance subscription for the heat pump will be used. In Table 32 the costs are shown per. The heat pump lifespan is often between 15 and 20 years but can increase to 30 years (Warmtepomp-info, 2022). The heat pump does not need to be replaced for the baseline alternative.

Table 32: Overview of costs of a hybrid heat pump (baseline alternative) per dwelling of the reference cluster (Energiewacht, 2022b)

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 8.386	€ 8.386	€ 8.386	€ 8.386	€ 8.386
Energy costs (efficiency)	350 %	350 %	350 %	350 %	350 %
Maintenance costs	€ 175,68 p/y	€ 175,68 p/y	€ 175,68 p/y	€ 175,68 p/y	€ 175,68 p/y
Replacement costs	-	-	-	-	-

Air-to-water heat pump

If an air-heat pump is installed, the current 'central heating installation' will have to be replaced by an electric air-to-water heat pump with a heating controller and a 'storage' boiler (200ltr). Aside from the installation of the heating system, the piping will need to be rerouted and the water pipes will need to be insulated. Research by Arcadis (2021) showed that the average investment cost for the implementation of this heating technique is € 10.381 (Peppelman et al., 2021). Air-to-water heat pumps have a high energy efficiency because in addition to electricity they use the energy from the air-to-water the heat the home. The efficiency and the costs are shown in Table 33 (CE Delft, n.d.-f). The heat pump lifespan is often between 15 and 20 years but can increase to 30 years (Warmtepomp-info, 2022). It is assumed that the heat pump needs to be replaced every 18 years. The reinvestment costs are calculated based on the average costs for air-to-water heat pumps, Equation is shown in *Appendix M: Calculation investment costs and energy consumption air-to-water and ground heat pump*.

Table 33: Overview of costs of an air-to-water heat pump (baseline alternative) per dwelling of the reference cluster (Energiewacht, 2022b)

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 10.381	€ 10.381	€ 10.381	€ 10.381	€ 10.381
Energy costs (Efficiency)	HH (450%) TWH (260%)	HH (450%) TWH (260%)	HH (450%) TWH (260%)	HH (450%) TWH (260%)	HH (450%) TWH (260%)
Maintenance costs	€ 119,88 p/y	€ 119,88 p/y	€ 119,88 p/y	€ 119,88 p/y	€ 119,88 p/y
Replacement costs	€ 4.597,31	€ 5.736,54	€ 5.043,10	€ 3.656,20	€ 5.043,10

Ground heat pump

When a collective ground heat pump is installed, every dwelling needs an individual ground heat pump. The shaft in the ground for the loop can be installed and used collectively, which reduces investment and installation costs per household. Research by Arcadis (2021) showed that the average investment cost for the implementation of a ground heat pump including ground shaft and installation is € 20.025 (Peppelman et al., 2021). The investment costs calculated by Arcadis includes a ground shaft per dwelling, the cost will be lower if this is installed collectively. In the case of a housing cluster, the difference in investment costs needs to be calculated. This is done using the calculation method of the WKO-bodemtool of the RVO is used (Rijksdienst voor ondernemend Nederland, n.d.), which can be seen in *Appendix M: Calculation investment costs and energy consumption air-to-water and ground heat pump*. When multiple dwellings are connected to one ground loop the total meters of the depth of the shaft can be smaller than when every dwelling would have an individual shaft. The reduction of the needed meters of depth of the shaft will be based on the standardized situations of Ithodaalderop, which is a company that installs this type of ground heat pump network (ithodaalderop, n.d.). An overview of costs and the efficiency per dwelling is shown in Table 34. Based on the average lifetime it is assumed that the ground heat pump needs to be replaced every 18 years (Warmtepomp-info, 2022).

Table 34: Overview of costs of a ground heat pump (baseline alternative) per dwelling of the reference cluster (CE Delft, n.d.-a; Energiewacht, 2022a)

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 13.905	€ 13.275	€ 13.275	€ 13.275	€ 13.275
Energy costs (Efficiency)	HH (550%) TWH (375%)	HH (550%) TWH (375%)	HH (550%) TWH (375%)	HH (550%) TWH (375%)	HH (550%) TWH (375%)
Maintenance costs	€ 100 p/y	€ 100 p/y	€ 100 p/y	€ 100 p/y	€ 100 p/y

Replacement costs	€ 3.300	€ 3.300	€ 3.300	€ 3.300	€ 3.300

4.6.1.3. Insulation

In this Section, the cost and energy savings associated with improved insulation will be described. Investment costs for the improvement of the insulation of the shell of the house will be determined according to the type of house, the construction year, the energy label and the energy label to which the insulation shell will be upgraded. See *Appendix N: Investment costs insulation*. The investment costs are based on the investment costs calculated by van der Polen et al. (2021) of the "Functioneel ontwerp Vesta MAIS 5.0". The key figures of the investment costs, that were determined in this research, are floor space dependent. These key figures are based on regression analysis done with the data from the "Variatietool" of the TNO. The data in the "Variatietool" for the costs indicators for the insulation shell are from Arcadis and are based on the laws and regulations which apply from October 2019. The "Variatie tool" uses the insulation characteristics and geometry of homes based on the WoON 2018 (energy module). This is fitting for this research because for the determination of the current energy consumption of the houses (Section 4.2) also the WoON database of 2018 is used which means that the key figures are based on the same dwelling datasets. For the current research, the investment costs for insulation are based on the "Vesta MAIS", in this research a linear regression was used to express the investment costs of the insulation shell of a home as a function of the floor area (for all the possible jumps in energy label). Accordingly, the label jump cost for investment is expressed either in terms of a natural moment (minimum costs) or in terms of an independent moment (maximum costs). As the result of the regression, a linear equation can be created to determine the investment costs (y) as a function of the floor area. This formula is ($y = a * x + b$).

Many types of housing are used in the linear regression, for which the linear equation needed to be determined. In the research of van der Molen et al. (2021), some housing types did not have enough cases to create a reliable regression line. It has been decided to combine multiple years of construction in these cases (van der Molen et al., 2021). A dwelling's energy consumption will decrease as its insulation level increases. In the research of Wijngaart & Polen (2020) the change in energy use due to insulation is researched. The results are shown in Table 35 (Wijngaart & Polen, 2020).

Table 35: Average measured energy saving for insulation label increase (Wijngaart & Polen, 2020)

Current label	New label	Energy saving
G	D	11%
F	D	11%
E	D	8%
G	B	25%
F	B	27%
E	B	25%
D	B	19%
C	B	12%

Table 36: Overview of costs for improvement of insulation from the current insulation label X and the energy saving per dwelling of the reference cluster

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment from label X to D	€ -	€ -	€ 2.521	€ 4.042	€ 2.521
Investment from label D to B	€ 15.190	€ 11.700	€ 10.841	€ 11.847	€ 10.841

Investment from label X to B	€ 15.190	€ 11.700	€ 10.958	€ 13.359	€ 10.958
Energy saving label X to D	- %	- %	8%	11%	8%
Energy saving label X to B	19%	19%	25%	19%	15%

4.6.1.4. Ventilation system

When the insulation of a dwelling is improved to at least insulation label B, this can result in a lack of natural ventilation in the dwelling. A mechanical ventilation system is necessary for these situations. For some alternatives (baseline alternative and district heating 1), a simple mechanical ventilation system will be sufficient. But for the other alternatives, mechanical ventilation with heat recovery is required. In new construction dwellings, the required channels for mechanical ventilation with a heat recovery system can be installed during construction. But for the existing housing stock, it is often impossible/not viable to install these channels. An alternative to mechanical ventilation with heat recovery is decentral mechanical ventilation with heat recovery. In the current research, only existing houses are considered, due to this only decentral mechanical ventilation with heat recovery will be included. When decentral mechanical ventilation is implemented, a ventilation box, air ducts, a control panel, a roof terminal, and a fan radiator with Heat recovery need to be installed instead of the current natural ventilation. A disadvantage is that the piping can be visible.

For dwellings that do not require ventilation with heat recovery, a mechanical ventilation system will be used. This ventilation system has a natural air exhaust and a mechanical air supply, see *Appendix O: Operation mechanical ventilation system*. When mechanical ventilation is implemented, a ventilation box, air ducts, a control panel, a roof terminal, and ventilation grilles in glazing need to be installed instead of the current natural ventilation. *Appendix P: Investment costs ventilation system* includes the cost of decentralized mechanical ventilation with heat recovery as well as the mechanical ventilation system. It is assumed, based on "Functioneel ontwerp Vesta", that dwellings for which the insulation is upgraded to a level B or higher, a ventilation system needs to be installed. Most of the houses that were constructed before 1975 do not have a ventilation system (they have natural ventilation), which means a system has to be installed. The building decree after 1975 stated that homes needed to have a ventilation system. Houses built after 2000 are more likely to have an automatic ventilation system (Kosten-ventillatie, 2021). Table 37 shows the costs of the ventilation systems per dwelling, including labour, VAT, and placement. For the research, it will be assumed that houses built from 2000 or with an energy label B do not need to replace their ventilation system.

Table 37: Costs of ventilation per dwelling of the reference cluster (based on Appendix P: Investment costs ventilation system)

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
	Mechanical ventilation				
Investment costs	€ 2.745	€ 2.745	€ 2.745	€ 2.745	€ 2.745
Energy costs (saving)	- %	- %	- %	- %	- %
Maintenance costs	€ 48	€ 48	€ 48	€ 48	€ 48
Replacement costs (per 18y)	€ 350	€ 350	€ 350	€ 350	€ 350
	Ventilation with heat recovery				
Investment costs	€ 4.645	€ 4.645	€ 4.645	€ 4.645	€ 4.645
Energy costs (saving)	10 %	10 %	10 %	10 %	10 %
Maintenance costs	€ 66	€ 66	€ 66	€ 66	€ 66
Replacement costs (per 18y)	€ 600	€ 600	€ 600	€ 600	€ 600

4.6.1.5. *Home adaptation for cooking*

In the case of a policy alternative that does not use natural gas for heating, the natural gas network will be disconnected. This means that it will not be possible to cook using gas. Due to this, additional investment is required to shift from cooking with gas to cooking with electricity. The costs that are required for this shift are the replacement of the gas stove with an induction cooker, an extra power wire to the kitchen + extra group(s) in the meter cupboard, installation costs of the induction and the reinforcement of the main electricity connection to 3x25A, which is described in 4.6.1.6 (Milieu Centraal, n.d.-b; Natuur & Milieu, n.d.). Furthermore, in some cases, a new pan set (usable for cooking on induction), needs to be purchased. The average initial investment cost for an electric cooking adaptation in the home is €1.045. The induction stove needs to be replaced every 15 years, which costs on average €600. The costs are based on references collected from the sources shown in *Appendix Q: Investment costs induction cooker*. When a gas stove is replaced by an induction cooker this does not only affect the investment costs but also the yearly energy costs. By not using a gas stove anymore, on average the gas consumption of a household is reduced by 5% (Energievergelijken, n.d.). The induction cooker uses on average 175 kWh per year, which is added to the total energy consumption of the household (Milieu Centraal, n.d.-b). An overview of the costs of the home adaptation for cooking can be seen in Table 38

Table 38: Costs of home adaptation for cooking per dwelling of the reference cluster

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 1.045	€ 1.045	€ 1.045	€ 1.045	€ 1.045
Natural gas reduction (p/y)	-48 m^3	-37 m^3	-34 m^3	-39 m^3	-34 m^3
Electricity increase (p/y)	+175 kWh	+175 kWh	+175 kWh	+175 kWh	+175 kWh
Maintenance costs	€ -	€ -	€ -	€ -	€ -
Replacement costs (per 15y)	€ 600	€ 600	€ 600	€ 600	€ 600

4.6.1.6. *Increase electricity connection*

For some of the alternatives, the electricity connection needs to be reinforced because more electricity is required, for example, induction cooking, solar panels and a heat pump. In the Netherlands, most houses have a 1 x 35-ampere electricity connection. This connection is suitable for households with standard appliances (like a washing machine, oven or lighting) and a small number of solar panels. If more electricity is required, the electricity connection must be reinforced to 3 x 25 ampere. Which is suitable for dwellings with standard appliances but also solar panels, induction cookers, heat pumps and charging an electric car (Enexis Netbeheer, n.d.). It is assumed that the dwellings of the reference cluster currently have a 3 x 25-ampere connection. The cost of changing the electricity connection from 1 x 35 Ampere to 3 x 25 Ampere is €314.79 (Liander, 2021). Besides upgrading the electricity connection, it is also necessary to update the fuse box and add additional groups to connect all appliances. To replace the current fuse box with a fuse box with 10 groups the average cost will be around € 900 (Electra-Gigant, 2021). If the homeowner adds electrical appliances that use electricity for heating, it is presumed that the electric connection will be reinforced, and the fuse box will be replaced. Since the fuse box can be assumed to be still usable in newly constructed homes, it only needs to be replaced when the home was constructed over 25 years ago. Furthermore, the fuse box needs to be replaced every 25 years. An overview of the costs of the increase of the electricity connection can be seen in Table 39.

Table 39: Costs of increase electricity connection per dwelling of the reference cluster

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 1.045	€ 1.045	€ 1.045	€ 1.045	€ 1.045
Replacement costs (per 15y)	€ 900	€ 900	€ 900	€ 900	€ 900

4.6.1.7. Remove gas connection

For some of the alternatives, the dwelling will be heated without using natural gas (or green gas). In these cases, the gas connection can be permanently removed, due to which the homeowner does not need to pay yearly connection costs anymore. The grid operator did charge €757,81 for this service (Enexis netbeheer, 2021). Considering the current importance of the energy transition in the Netherlands, Economic Affairs and Climate Minister Wiebes has stated in a letter that the permanent removal of the gas connection will be fully compensated as of March 1, 2021. This decision was made because when the homeowner permanently removes the gas connection the homeowner contributes to the energy transition and should not be penalized for this. This arrangement will be applied until there is an alternative in the upcoming Energy law (Wiebes, 2021).

4.6.1.8. Solar panels

Electricity will be the energy source for all the selected alternatives. Solar panels could be a viable solution for producing the used electricity more sustainably. Solar panels can differ in size and efficiency. The efficiency of a solar panel can be indicated by Watt peak (Wp) which shows how much electricity the solar panel can generate in the most optimal situation. In reality, this production will be a bit lower, in the Netherlands on average 1-watt peak will generate 0,9 kWh. Equation 7 shows how the annual yield of solar panels in kWh can be calculated. The amount of energy solar panels can produce reduces over time. Manufacturers guarantee that after 10 years a minimum of 90% of the expected energy will be produced and after 25 years this will be 80% (Kemkens, 2020).

Equation 7: Calculating the annual yield of a solar panel (van der Wilt, 2021)

$$0{,}9 * number\ of\ solar\ panels * Wp\ (of\ one\ panel) \\ = Annual\ yield\ of\ solar\ panels\ in\ kWh$$

Groessens (2022) created an overview of the costs of solar panels (of different brands), this overview includes the costs of the converter, which is shown in *Appendix R: Size and investment costs of solar panels*
(Groessens, 2022). Using this data, rounded averages of the Wp and costs for solar panels can be calculated, the averages are shown in Table 40. In Table 41, the maintenance and replacement costs are shown.

Table 40: Average characteristics of solar panels (Groessens, 2022)

Characteristics of solar panels	
Average Wp per solar panel	345
Average €/Wp	1,26
The average area of a solar panel	1,64 m^2

Table 41: Maintenance costs of solar panels (Essent, n.d.-a; Homedeal, n.d.; Hultink, 2021)

Maintenance solar panels	Average costs
Cleaning of solar panels, per solar panel pr 5 years	€10
Solar panel inspection per year	€80-€100
Lifespan solar panels	25-40
Replacement converter (after 15 years)	€1000-€1200

To determine the maximum number of solar panels that can be implemented on the roof of a dwelling, some assumptions need to be made. The number of solar panels that can be placed on a flat roof is different from the number of panels that can be placed on a slanted roof differ. Due to this different calculation rules will be used for the different types of roofs.

Flat roof: On a flat roof, a 1-meter distance from the edge of the roof will be applied. On a flat roof, solar panels are placed using a mounting system to position them at the best angle. Due to this system, the panels need to be placed at a distance of 70 cm between them to prevent them from forming a shadow on each other (Zelfstroom, n.d.).

Slanted roof: On average more solar panels can be placed on a slanted roof than on a flat roof. Due to this difference, a slated roof variant will be used. For the assumptions of a slanted roof, first, the area of the roof needs to be calculated, which will be done using Equation 8 and Equation 9. On a slanted roof, solar panels need to be placed at 0,5 meters from the edge of the roof. Furthermore, the solar panels will be placed flat on the roof, which means that no distance between the panels is required (Zelfstroom, n.d.).

Equation 8: Calculate roof area slanted roof

$$\left(Length\ of\ the\ roof - 0{,}5 * \sqrt{\left(\frac{1}{2} * width\ of\ the\ roof - 0{,}5\right)^2 + (height\ of\ the\ roof)^2}\right) * 2 = Roof\ area$$

Equation 9: Calculate roof area slanted roof

$$\left(\sqrt{\left(\frac{1}{2} * width\ of\ the\ dwelling\right)^2 + (height\ of\ the\ roof)^2}\right) = Width\ of\ on\ side\ of\ the\ roof$$

When solar panels produce more electricity than used by the household this can be returned to the electricity network. There currently is a “salderings” regulation in place, which means that the excess of produced power can be returned to the energy supplier for €0,22 per kWh, with a maximum of the amount of kWh consumed by the household. Extra kWh can be returned for a lower rate (between €0,03-€0,012 per kWh). The Dutch government plans to reduce the “salderings” regulation from 2023 until it doesn’t exist in 2031. Compensation will be paid for every kWh that is returned to the network without “salderen” for which the rate of €0,06 per kWh is generally assumed. The maximum amount of kWh a household can return to the network using the “salderings” regulation is reduced from 2023 on by 9% per year until it is 0% in 2031 (Milieu Centraal, n.d.-a, 2022; Rijksoverheid, 2019b). Because the “salderings” regulation is reduced to 0% in 2031 it is assumed that the household only purchases the number of panels which are needed to produce electricity for their consumption. An overview of the costs of solar panels can be seen in Table 42.

Table 42: Costs of increase electricity connection per dwelling of the reference cluster

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
	District heating				
Number of panels	10	9	9	9	9
Investment costs	€ 4.347	€ 3.912	€ 3.912	€ 3.912	€ 3.912
Maintenance costs	110	108	108	108	108
Reinvestment costs	1100	1100	1100	1100	1100
	All-electric				
Number of panels	14	9	9	9	9
Investment costs	€ 6.086	€ 3.912	€ 3.912	€ 3.912	€ 3.912
Maintenance costs	118	108	108	108	108
Reinvestment costs	1100	1100	1100	1100	1100

4.6.1.9. Radiator

A radiator adaptation will be required for the policy alternatives, district heating 2 and all-electric (with an air-to-water heat pump and collective heat pump). This is needed because the heat pumps provide a lower temperature (35°C - 55°C) of warm water than a boiler heated with natural gas (70°C - 80°C). For the heat pumps to heat the dwelling to a comfortable temperature the radiators need to be able to provide enough heat. This can be done if the radiators have a big enough surface. Most of the current radiators are not suited for this but there are low-temperature radiators that can be used for low-temperature heat. Other heat release systems are floor or wall heating (Milieu Centraal, n.d.-c). For the current research, only the application of low heat radiators will be considered because they can be implemented in all dwelling types while the feasibility of the other types of low-temperature heating release systems is more dependent on the building properties. The investment costs of low-temperature radiators can be calculated by using the average price (€1.100) of low-temperature radiators times the number of rooms in the dwelling. The number of rooms will be determined dependent on the kind of house and is based on the average amount of rooms per kind of house from WoON 2018 database, see *Appendix S: Average number of rooms per type of dwelling*. A low-temperature radiator needs to be replaced after 50 years. An overview of the costs of LT radiators can be seen in Table 43.

Table 43: Costs of LT radiator per dwelling of the reference cluster

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Investment costs	€ 5.500	€ 5.500	€ 5.500	€ 5.500	€ 5.500

4.6.1.10. Subsidies

The Dutch government aims to stimulate the energy transition by providing subsidies. Below is a summary of the different adaptations and the application subsidies. When a home adaptation is not included in the overview below, there is no subsidy regulation for the adaptation. Due to the lack of information about the development of these subsidies, it will be assumed they will remain the same. An overview of the subsidies per dwelling can be seen in Table 44.

District heating:

For district heating the subsidy “Investeringssubsidie duurzame energie en energiebesparing” (ISDE) can be used. This subsidy can be used to reduce the investment in the connection to a district heating network. The height is €3325 but to qualify for this subsidy the following requirements need to be met (RVO, 2021):

- The dwelling needs to be an owner-occupied home and it is the main residence or will be after the renovation of the owner.
- The connection was made by a heat supplier.
- The connection to the heat network has been completed before the application can be submitted, but not before January 1, 2021.
- It can be proven that the home is disconnected from natural gas.
- It can be proven that the home is connected to a heat network through an agreement with a heat supplier.
- There can be applied for a subsidy up to a maximum of 12 months after the connection to a heat network.
- No subsidy has yet been provided for the connection of the house to a heat network.

Heat pump:

A heat pump is one of the appliances that are covered by the ISDE. Per January 2022 the ISDE-subsidy for (hybrid) heat pumps (bigger than 1 kW) are increased from 20% to 30% of the total investment costs. Which can be combined with the isolation investment. The requirements for this subsidy are shown below (Rijksoverheid, n.d.-b; RVO, 2022b):

- The dwelling needs to be an owner-occupied home and it is the main residence or will be after the renovation of the owner.
- The heat pump is a new product and is therefore not a second-hand/used product.
- The heat pump is installed in a home for which the environmental permit has been applied before or on 30 June 2018.
- The heat pump is installed before the application can be submitted.
- The installation was done by a construction installation company.
- The owner must have an invoice and proof of payment for the purchase and installation of the heat pump.

Insulation:

For insulation the ISDE-subsidy can also be used, to qualify for this subsidy at least two different insulation measurements need to be applied or at least one insulation measurement needs to be combined with the installation of a heat pump/solar water heater/district heating. When the requirements are met, approximately 30% of the investment can be subsidized by the ISDE. For the research, it will be assumed that a household is eligible for the subsidy when the insulation level will improve to at least level B or an insulation improvement combined with an alternative heating technique. The requirements for this subsidy are shown below (Milieu Centraal, n.d.-d; RVO, 2022a).

- When applying for a subsidy for an insulation measure, at least 1 other measure must be taken. This can be a different type of insulation measure and/or the implementation of a heat pump, solar boiler or connection to a heat network.

- If HR++ glass and Triple glass are combined, the total number of m2 of glass to be replaced must always be at least 8m2. A subsidy for a maximum of 45m2 will be given out.
- For HR++ glass a U-value of at most 1.2 W/m2K applies, for Triple glass a U-value of at most 0.7 W/m2K applies.
- When HR++ glass or Triple glass is used, this must be to replace the existing glass.
- When using Triple glass, it is also mandatory to replace the frames with insulating frames with a U-value of at most 1.5 W/m2K.
- All insulation measures must be carried out in the existing thermal envelope.
- For the type of insulation measure, when floor or ground insulation, cavity wall insulation or roof insulation, the insulation material is chosen that is locally sprayed PIR or PUR. Then this must be applied with an HFC-free blowing agent.
- The construction was done by a construction installation company.

Remove natural gas connection:
As described in Chapter 4.6.1.7 the permanent removal of the gas connection will be fully compensated (Wiebes, 2021).

Solar panels:
There is no subsidy for the investment in solar panels. But it is possible to get a refund on the VAT of the purchase and installation from the Dutch tax authorities (Rijksoverheid, n.d.-c). This regulation will also be applied in the current research.

Table 44: Subsidies per dwelling of the reference cluster

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Connection district heating	€ 3.325	€ 3.325	€ 3.325	€ 3.325	€ 3.325
Air-to-water heat pump	€ 3.114	€ 3.114	€ 3.114	€ 3.114	€ 3.114
Insulation	€ 4.557	€ 3.510	€ 3.287	€ 4.007	€ 3.287

4.6.2. Investment costs

The investment costs have been determined for the reference cluster, based on the above-described information. The investment costs for each alteration per dwelling per alternative are displayed in Table 45. As can be seen, the amount of the investment is not only determined by which alternative is implemented, but also by the properties of the dwelling. As an example, consider the cost of improving the insulation label. This depends on the type of dwelling, the construction year and the size of the dwelling. The Table shows that the alternative all-electric 1 has the highest investment costs and the alternative district heating 1 has the lowest investment cost.

Table 45: Overview of the investment cost for the reference housing cluster

	Baseline alternative				
	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Heating technique	€ 8.386	€ 8.386	€ 8.386	€ 8.386	€ 8.386
Insulation	€ 15.190	€ 11.700	€ 13.362	€ 15.889	€ 13.362
Ventilation system	€ 2.745	€ 2.745	€ 2.745	€ 2.745	€ 2.745

Home adaptation for cooking	€ -	€ -	€ -	€ -	€ -
Increase electricity connection	€ 1.215	€ 1.215	€ 1.215	€ 1.215	€ 1.215
Remove gas connection	€ -	€ -	€ -	€ -	€ -
Solar panels	€ -	€ -	€ -	€ -	€ -
Radiator	€ -	€ -	€ -	€ -	€ -
Subsidies	€ 2.516	€ 2.516	€ 3.272	€ 3.728	€ 3.272
Total	*€ 25.020*	*€ 21.530*	*€ 22.436*	*€ 24.506*	*€ 22.436*
		Policy alternative district heating 1			
Heating technique	€ 5.801	€ 5.801	€ 5.801	€ 5.801	€ 5.801
Insulation	€ 15.190	€ 11.700	€ 10.958	€ 13.359	€ 10.958
Ventilation system	€ 2.745	€ 2.745	€ 2.745	€ 2.745	€ 2.745
Home adaptation for cooking	€ 1.045	€ 1.045	€ 1.045	€ 1.045	€ 1.045
Increase electricity connection	€ 1.215	€ 1.215	€ 1.215	€ 1.215	€ 1.215
Remove gas connection	€ -	€ -	€ -	€ -	€ -
Solar panels	€ 4.347	€ 3.912	€ 3.912	€ 3.912	€ 3.912
Radiator	€ -	€ -	€ -	€ -	€ -
Subsidies	€ 7.882	€ 6.835	€ 6.612	€ 7.333	€ 6.612
Total	*€ 22.461*	*€ 19.583*	*€ 19.064*	*€ 20.744*	*€ 19.064*
		Policy alternative all-electric 1			
Heating technique	€ 10.381	€ 10.381	€ 10.381	€ 10.381	€ 10.381
Insulation	€ 15.190	€ 11.700	€ 10.958	€ 13.359	€ 10.958
Ventilation system	€ 4.645	€ 4.645	€ 4.645	€ 4.645	€ 4.645
Home adaptation for cooking	€ 1.045	€ 1.045	€ 1.045	€ 1.045	€ 1.045
Increase electricity connection	€ 1.215	€ 1.215	€ 1.215	€ 1.215	€ 1.215
Remove gas connection	€ -	€ -	€ -	€ -	€ -
Solar panels	€ 6.086	€ 3.912	€ 3.912	€ 3.912	€ 3.912
Radiator	€ 5.500	€ 5.500	€ 5.500	€ 5.500	€ 5.500
Subsidies	€ 7.671	€ 6.624	€ 6.402	€ 7.122	€ 6.402
Total	*€ 36.390*	*€ 31.774*	*€ 31.254*	*€ 32.935*	*€ 31.254*

4.6.3. Maintenance costs

For the reference housing cluster, the maintenance costs have been determined as described in Section 4.6.2. In Table 46 the maintenance costs are shown. As for the investment cost, the alternative district heating 1 requires the most expensive maintenance, whereas the baseline alternative is the least expensive. The high maintenance cost for district heating can be explained because the measurement costs for district heating and the rent of the delivery set are included in these costs.

Table 46: Overview of the maintenance cost for the reference housing cluster

	Baseline alternative				
	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Boiler	€ 153	€ 153	€ 153	€ 153	€ 153
Heating technique	€ 176	€ 176	€ 176	€ 176	€ 176
Ventilation system	€ 48	€ 48	€ 48	€ 48	€ 48
Solar panels	€ -	€ -	€ -	€ -	€ -
Total	*€ 8.098*	*€ 8.098*	*€ 8.098*	*€ 8.098*	*€ 8.098*
	Policy alternative district heating 1				
Boiler	€ 153	€ 153	€ 153	€ 153	€ 153
Heating technique	€ 152	€ 152	€ 152	€ 152	€ 152
Ventilation system	€ 48	€ 49	€ 50	€ 51	€ 50
Solar panels	€ 110	€ 108	€ 108	€ 108	€ 108
Total	*€ 9.139*	*€ 9.111*	*€ 9.139*	*€ 9.167*	*€ 9.139*
	Policy alternative all-electric 1				
Boiler	€ 153	€ 153	€ 153	€ 153	€ 153
Heating technique	€ 120	€ 120	€ 120	€ 120	€ 120
Ventilation system	€ 66	€ 66	€ 66	€ 66	€ 66
Solar panels	€ 118	€ 108	€ 108	€ 108	€ 108
Total	*€ 8.968*	*€ 8.688*	*€ 8.688*	*€ 8.688*	*€ 8.688*

4.6.4. Replacement costs

For the reference housing cluster, the reinvestment costs have been determined as described in Section 4.6.2. the reinvestment costs are the cost the homeowner needs to make to (partly) replace the technique after a period of use to keep it functioning. In Table 47 the reinvestment cost can be seen. The alternative all-electric 1 has the highest reinvestment technique, whereas the alternative district heating 1 is the least expensive. The baseline alternative and the all-electric alternative both use heat pumps, but the reinvestment for the baseline alternative is lower since the heat pump won't need to be replaced before 2050 since it was installed later.

Table 47: Overview of the reinvestment cost for the reference housing cluster

	Baseline alternative				
	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Heating technique	€ 5.160	€ 4.320	€ 4.320	€ 5.160	€ 4.320
Ventilation system	€ -	€ -	€ -	€ -	€ -
Home adaptation cooking	€ -	€ -	€ -	€ -	€ -
Increase electricity connection	€ -	€ -	€ -	€ -	€ -
Solar panels	€ -	€ -	€ -	€ -	€ -
Total	*€ 5.160*	*€ 4.320*	*€ 4.320*	*€ 5.160*	*€ 4.320*
	Policy alternative district heating 1				
Heating technique	€ -	€ -	€ -	€ -	€ -
Ventilation system	€ 450	€ 450	€ 450	€ 450	€ 450
Home adaptation cooking	€ 600	€ 600	€ 600	€ 600	€ 600
Increase electricity connection	€ 900	€ 900	€ 900	€ 900	€ 900
Solar panels	€ 1.100	€ 1.100	€ 1.100	€ 1.100	€ 1.100
Total	*€ 3.050*	*€ 3.050*	*€ 3.050*	*€ 3.050*	*€ 3.050*
	Policy alternative all-electric 1				
Heating technique	€ 4.597	€ 5.737	€ 5.043	€ 3.656	€ 5.043
Ventilation system	€ 600	€ 600	€ 600	€ 600	€ 600
Home adaptation cooking	€ 600	€ 600	€ 600	€ 600	€ 600
Increase electricity connection	€ 900	€ 900	€ 900	€ 900	€ 900
Solar panels	€ 1.100	€ 1.100	€ 1.100	€ 1.100	€ 1.100
Total	*€ 7.797*	*€ 8.937*	*€ 8.243*	*€ 6.856*	*€ 8.243*

4.6.5. Energy costs

The implementation of the baseline alternative or policy alternative impacts the energy costs due to two effects:

1. When one of the different heating techniques is implemented, a reduction in energy consumption can occur due to the higher effectiveness of a technique or a reduction in energy losses (an example is the implementation of insulation).
2. The policy alternatives use different sources of energy. These energy sources have different costs and scenarios for their development up to 2050.

For the reference housing cluster, the energy costs have been determined based on the predicted energy prices as described in Section 4.2 and the effect on energy consumption described in Section 4.6.1. In Table 48 the energy cost can be seen. As opposed to the other types of costs, all-electric 1 is the least expensive option since it relies on electricity, which can be produced by solar panels.

Table 48: Overview of the total energy cost for the reference housing cluster

		Baseline alternative				
		Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Scenario low	Natural gas	€ 20.703	€ 17.316	€ 15.787	€ 17.144	€ 15.787
	Electricity	€ 11.974	€ 12.732	€ 11.500	€ 9.530	€ 11.500
	Heat	€ -	€ -	€ -	€ -	€ -
	Total	€ 32.677	€ 30.048	€ 27.286	€ 26.674	€ 27.286
Scenario high	Natural gas	€ 26.340	€ 22.103	€ 20.199	€ 21.903	€ 20.199
	Electricity	€ 22.061	€ 22.882	€ 21.201	€ 18.706	€ 21.201
	Heat	€ -	€ -	€ -	€ -	€ -
	Total	*€ 48.401*	*€ 44.985*	*€ 41.400*	*€ 40.609*	*€ 41.400*
		Policy alternative district heating 1				
Scenario low	Natural gas	€ 2.571	€ 2.142	€ 2.007	€ 2.211	€ 2.007
	Electricity	€ 1.055	€ 1.224	€ 1.126	€ 871	€ 1.126
	Heat	€ 31.386	€ 27.567	€ 26.039	€ 26.803	€ 26.039
	Total	€ 35.013	€ 30.933	€ 29.172	€ 29.885	€ 29.172
Scenario high	Natural gas	€ 2.654	€ 2.209	€ 2.069	€ 2.281	€ 2.069
	Electricity	€ 1.729	€ 5.322	€ 4.308	€ 2.158	€ 4.308
	Heat	€ 32.647	€ 28.554	€ 26.917	€ 27.735	€ 26.917
	Total	*€ 37.030*	*€ 36.085*	*€ 33.293*	*€ 32.174*	*€ 33.293*
		Policy alternative all-electric 1				
Scenario low	Natural gas	€ 2.571	€ 2.142	€ 2.007	€ 2.211	€ 2.007
	Electricity	€ 1.055	€ 5.104	€ 3.442	€ 1.889	€ 3.442
	Heat	€ -	€ -	€ -	€ -	€ -
	Total	€ 3.627	€ 7.245	€ 5.449	€ 4.100	€ 5.449
Scenario high	Natural gas	€ 2.654	€ 2.209	€ 2.069	€ 2.281	€ 2.069
	Electricity	€ 4.161	€ 12.193	€ 10.012	€ 8.026	€ 10.012
	Heat	€ -	€ -	€ -	€ -	€ -
	Total	*€ 6.815*	*€ 14.402*	*€ 12.080*	*€ 10.307*	*€ 12.080*

4.6.6. Overview of costs

In the Sections above the costs for the different alternatives have been described. These costs include the investment cost, maintenance cost, replacement cost and energy cost. Table 49 shows the cost per alternative per scenario.

Table 49: Overview of the cost for the reference housing cluster

	Baseline alternative	**District heating 1**	**All-electric 1**
	Scenario low		
Investment cost	€ 115.927	€ 100.915	€ 163.607
Maintenance cost	€ 40.491	€ 45.695	€ 43.662
Replacement cost	€ 23.280	€ 15.250	€ 40.076
Energy cost	€ 143.971	€ 154.174	€ 25.869
Total	*€ 323.670*	*€ 316.035*	*€ 273.216*
	Scenario high		
Investment cost	€ 115.927	€ 100.915	€ 163.607
Maintenance cost	€ 40.491	€ 45.695	€ 43.662
Replacement cost	€ 23.280	€ 15.250	€ 40.076
Energy cost	€ 216.794	€ 171.876	€ 55.684
Total	*€ 396.493*	*€ 333.736*	*€ 303.030*

Depending on the scenario (low or high), the total costs will vary depending on the energy costs, since the energy prices are the only difference between the scenarios. It is remarkable that although the alternatives are different in implementation and heat supply, the total costs are not highly differentiated between the alternatives. In contrast with the total costs, the sub-costs differ widely between the alternatives. When comparing alternative district heating 1 with all-electric 1, the initial investment for all-electric 1 is 62% more expensive than the investment for district heating 1. However, district heating 1 has higher annual costs due to the high energy costs. When comparing the results of the two scenarios, for the low scenario, the total costs of the policy alternatives are quite comparable. For this scenario, the alternative district heating 1 has the lowest total costs. The baseline alternative has the highest costs. Due to the high energy prices in the second scenario (high), the total costs are greater. Furthermore, the differences between the alternatives are larger. Specifically, the difference between the baseline alternative and the policy alternatives. As for the baseline alternative, the higher costs are due to its higher energy consumption compared to the policy alternatives. The baseline alternative only gets an insulation label of B from the year 2036 and no solar panels. Furthermore, the baseline alternative is the only alternative that remains heating with natural gas, which has high prices in this scenario. In this scenario (high), the alternative district heating 1 has the lowest total costs and the baseline alternative has the highest costs (like scenario low).

4.7. Non-market effects: hedonic

The hedonic non-market effects that have been identified are comfort, required space, the impact of the renovation process, energy price volatility, safety and freedom of choice of energy supplier. These effects will be described and valued in this Section.

4.7.1. Comfort

The comfort level in a house is influenced by multiple factors. Comfort is influenced by many factors, and the current research focuses on physical comfort as this is the type of comfort that will be influenced by the implementation of the different policy alternatives. To judge the effect of comfort, the comfort level of the dwelling per alternative needs to be estimated. There is much research done on the thermal comfort level, but these methods often require a large of information and details about a dwelling. This information is not available about the reference clusters. Therefore, an assessment method needs to be selected that can give an indication of the comfort level using standard dwelling characteristics. To do so, the comfort level assessment model for existing housing of Brandenburg and Vroom's (2013) is used. In this model, three comfort categories are defined, which are heat, sound and air quality. These categories can change depending on which policy alternative is implemented (Brandenburg & Vroom, 2013a). The assessment model for comfort is visualized in Figure 41.

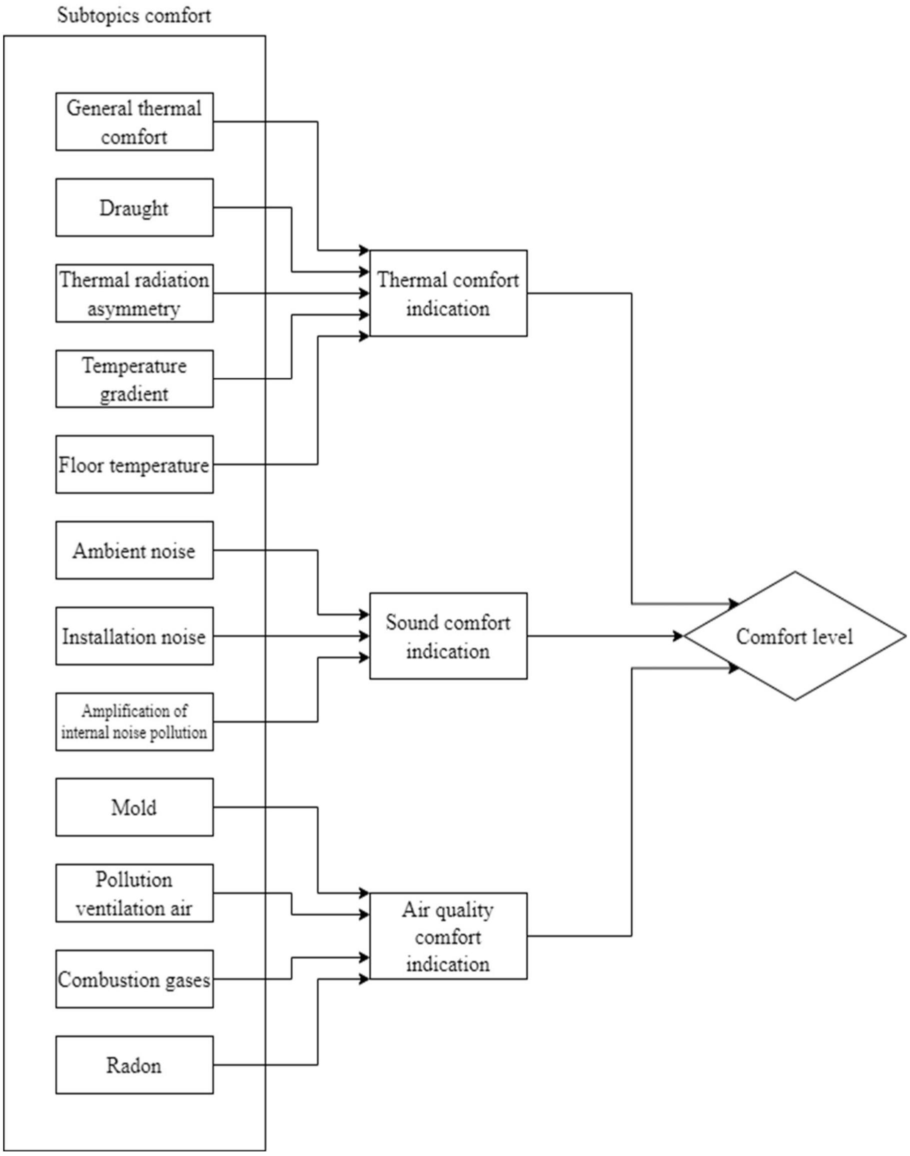


Figure 41: Overview of the comfort level assessment model

4.7.1.1. Thermal comfort indication

Thermal comfort

Thermal comfort is defined “*as state in which there are no driving impulses to correct the environment by the behaviour*” (Djongyang et al., 2010). Thermal comfort consists of two types: general thermal comfort and local thermal comfort (Peeters et al., 2007). Overall, thermal comfort is determined by the comfort of the entire room. Local thermal comfort is determined by four phenomena that can locally affect thermal comfort. These phenomena are draft, temperature gradient, thermal radiation asymmetry and floor temperature (Brandenburg & Vroom, 2013a).

General thermal comfort

To assess the general thermal comfort, the adaptive thermal comfort model (ATC-model) is used. In Appendix T: Assessment models subtopics comfort, the model for general thermal comfort is shown. In this model, the inside temperature for the dwelling needs to be calculated, using Equation 10. In this equation, data on the outside temperature over the past days needs to be known. This data is not available for the dwellings in the clusters. Therefore, it is assumed that the heating system can heat the dwelling to the desired temperature.

Equation 10: Calculate the inside temperature for the ATC-model

$$T_{e;ref} = \frac{T_v + 0{,}8 * T_g + 0{,}4 * T_{eg} + 0{,}2 * T_{eeg}}{2{,}4}$$

$T_{e;ref}$: Reference outside temperature day
T_v: Average daytime temperature outside of today
T_g: Average daytime temperature outside of yesterday
T_{eg}: Average daytime temperature outside of the day before yesterday
T_{eeg}: Average daytime temperature outside of three days ago

Draught

Draught is one of the most common aspects of local discomfort. The body can cool down significantly due to a too high airflow velocity. Draught can be caused by openings in the building envelope. These openings can be present due to poor insulation but also due to ventilation grilles (Brandenburg & Vroom, 2013a). For the assessment of the subtopic draught, the model shown in Appendix T: Assessment models subtopics comfort is used. In this model, the assessment of the subtopic draught depends on the ventilation used in the alternatives.

Thermal radiation asymmetry

The thermal radiation asymmetry can cause discomfort when the temperature difference between the indoor temperature and the surface temperature is too high. For the assessment of the subtopic thermal radiation asymmetry, the model shown in the first thermal radiation asymmetry model in Appendix T: Assessment models subtopics comfort is used. In this model, the level of comfort is determined by the temperature difference between the indoor temperature and the surface temperature. The surface temperature of a dwelling is not known in the current research. But the surface temperature is influenced by the level of insulation of a dwelling. Due to this, the three levels are divided by the level of insulation. This is shown in the second thermal radiation asymmetry model in the Appendix.

Thermal gradient

The temperature level can differentiate inside a dwelling. Because warm air rises, the air temperature is higher at the ceiling than at the floor level, which is the gradient. If the temperature difference is high, this can negatively affect the comfort level. Another reason for a high thermal gradient is when the temperature difference is disturbed. A disruption can appear at a window or exterior wall with a low insulation value because the air at these cool surfaces will cool down and move down towards the floor (Brandenburg & Vroom, 2013b). The assessment of the subtopic thermal gradient is done using the model which can be seen in Appendix T: Assessment models subtopics comfort. In a dwelling with single glazing, there is a greater likelihood of increased cold airflow, as opposed to HR++ glazing. Furthermore, a cold airflow can be prevented when radiators are placed below windows, which is a common practice in dwellings. The only exception is when underfloor heating is the main heat release system because this release system does not prevent cold air flows (Brandenburg & Vroom, 2013a).

Floor temperature

If a floor has a low temperature this will extract heat from the body through the feet. This will result in a decreased comfort level for the homeowner. Furthermore, when a floor temperature is too high, this will also result in discomfort and decreased hygiene. In general, a minimum floor temperature of 19˚C and a maximum temperature of 29˚C is recommended. The insulation of a floor and the implementation of underfloor heating positively impact the floor temperature. The assessment of the subtopic floor temperature is done using the model which can be seen in Appendix T: Assessment models subtopics comfort (Brandenburg & Vroom, 2013a, 2013b).

4.7.1.2. Sound comfort indication

Ambient noise

If too much ambient noise can enter a dwelling this will create discomfort for the homeowner. The amount of ambient noise that can enter the dwelling depends on the noise pollution on the façade of the dwelling and the sound-insulating effect of the façade. To determine the noise pollution on the façade, the default values of the ISSO 82.4 are used, which are shown in Table 50.

Table 50: Default values (ISSO 82.4.) (Brandenburg & Vroom, 2013a)

Location	Village	Suburb	City centre
Noise pollution	40 dB	50 dB	60 dB

The impact of ambient noise on comfort is assessed using the model in Appendix T: Assessment models subtopics comfort. In this model, the noise exposure is determined using Table 50. The criteria that the dwelling needs to meet are 1. Minimal double glazing, 2. The cracks in the dwelling are sealed and 3. There are no ventilation grilles installed in the dwelling.

Installation noise

Different installations produce sound. If this reaches high levels, this can decrease the comfort of the homeowner. Another consequence can be a misuse of the installations. Installations that produce higher sound levels than conventional heating installations are an air/water heat pump, HEe boiler and mechanical installation. The assessment of the subtopic installation noise is done using the model shown in Appendix T: Assessment models subtopics comfort.

Amplification of internal noise pollution

If the average level of noise decreases in a home, there is an increased risk of noise pollution from neighbours, adjacent rooms or installations in the home. This is described as internal noise pollution. The perception of internal noise nuisance depends on the soundproofing of the external façade. This is influenced by the type of glazing and the presence of facade grilles for ventilation. With single glazing and facade grilles, a lot of ambient noise penetrates the house, which reduces internal noise pollution. The assessment of the subtopic amplification of internal noise pollution is done using the model shown in Appendix T: Assessment models subtopics comfort (Brandenburg & Vroom, 2013a, 2013b).

4.7.1.3. Air quality comfort indication

Mold

Mold can be caused by moisture problems in a dwelling. This can be prevented by increasing the insulation level and the ventilation in a dwelling. The assessment of the subtopic mold is done using the model shown in Appendix T: Assessment models subtopics comfort.

Pollution ventilation air

If the air quality around a dwelling is polluted, this can result in the pollution of the ventilation air inside the dwelling. If the air quality outside the dwelling is unknown an approximation needs to be made of the pollution of ventilation. This approximation is made by assuming a relation between noise and air pollution since a high amount of traffic and industry will lead to a high sound and air pollution. Therefore, noise pollution is used to judge this subtopic (see Table 50). The assessment of the subtopic pollution ventilation air is done using the model shown in Appendix T: Assessment models subtopics comfort.

Combustion gases

The risk of combustion gases in the main heating system is determined by how the gases are discharged. An open heating system has an increased risk of combustion gases in the dwelling. Furthermore, the ventilation system also influences the risk of combustion gases in the dwelling. Mechanical ventilation ensures good drainage of the combustion gases. Furthermore, when the dwelling has a high level of insulation, the combustion gases have poorer drainage. Therefore, a dwelling with low airtightness has a better score on the subtopic combustion gases. The level of airtightness can be determined using Table 51. The assessment of the subtopic combustion gases is done using the model shown in Appendix T: Assessment models subtopics comfort.

Table 51: The level of airtightness

Negative factor	Score	Positive factor	Score
Construction year <= 1980	-1	Construction year > 1980	+1
Pitched roof	-1	Flat roof	+2
Façade not insulated	-2	Façade insulated	+2
Detached/corner/semi-detached dwelling	-2	Terraced dwelling	+2
Single glazing	-1	No single glass	+1

Radon

Radon is a radioactive gas that can occur in every dwelling, and it can enter the home mainly from the ground. The subtopic radon is assessed using the model in Appendix T: Assessment models subtopics comfort. In this model, the subtopic is firstly judged by whether floor insulation is present in the dwelling and secondly whether mechanical ventilation is used. If there is no floor insulation in the dwelling, mechanical ventilation can be used to drain the radon gases.

4.7.1.4. Assessment of the comfort level

Above, the assessment of all subtopics for the comfort model is described. The model shows how the topics of heat, sound and air quality impact the comfort level due to the properties of the heating techniques. In this network, the dependencies are shown but the weights of the different criteria are missing. These weights are important for the determination of the comfort level because it is very unlikely that every subtopic is equally important. The weights of these criteria cannot be obtained from literature, because they need to be determined relative to each other.

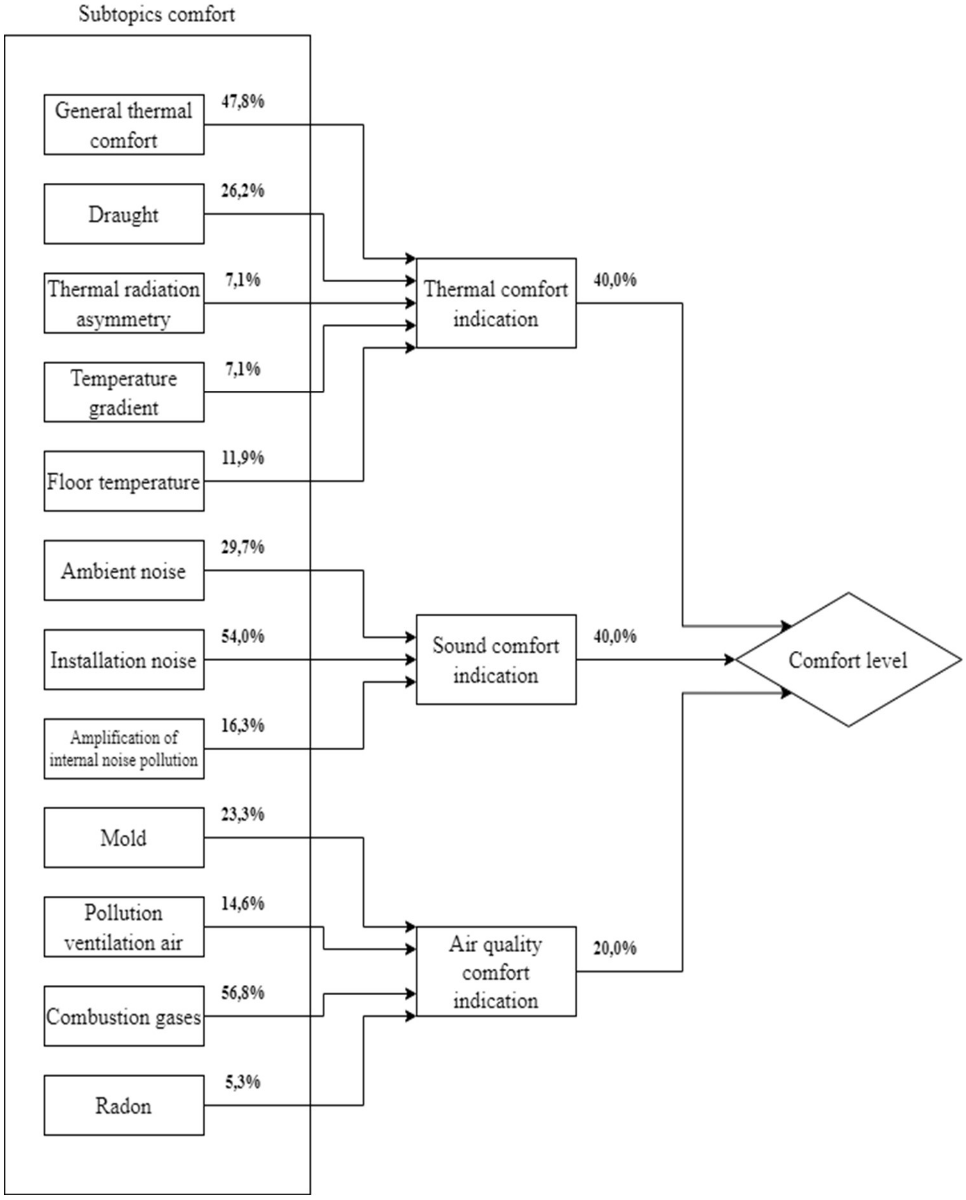


Figure 42: Comfort level assessment model including weight of the topics

The weight factor is based on the preferences in comfort. Preferences differentiate between people; a limited sample of preferences will not provide a reliable result and an extensive experiment on these preferences is not within the scope of the current research. Therefore, personal preferences are used to determine the weight of these different topics on the comfort level. To translate the preferences in weights per topic, the Analytic Hierarchy Process (AHP) is used. AHP uses pairwise comparison, for each pair of (sub)topics a judgement is made; which (sub)topic is more important for the goal (a high comfort level), and how much more important this (sub)topic is for the goal. To determine the level of importance, the labels of Saaty are used: 1. Equal importance, 3. Moderate importance, 5. Strong importance, 7. Very strong importance and 9. Extreme importance (2, 4, 6, and 8 can be used as intermediate values). The subtopics per topic have been compared to each other and the main topics have been compared, to weigh both the subtopic groups and the main topics. The results of this pairwise comparison are shown in Appendix U: Analytic hierarchy process. The weights, which result from the AHP, are shown in Figure 42.

Using the above-described method, the scores for the different alternatives have been calculated. In the model of Brandenburg and Vroom (2013) the subtopics have been scored based on a colour scale (green/orange/red). To make this scale usable for the determination of comfort level with the weights, it has been translated to a numerical scale (green = 1, orange = 0,5 and red = 0). Using this scale and the above-determined weights, the comfort levels have been determined, which are shown in Table 52.

Table 52: Assessment of the comfort level

Topic	Baseline alternative	District heating (MT)	All-electric 1
General thermal comfort	1	1	1
Draught	0,5	0,5	1
Thermal radiation asymmetry	1	1	1
Temperature gradient	1	1	1
Floor temperature	1	1	1
Thermal comfort indication	*0,87*	*0,87*	*1*
Ambient noise	0	0	0,5
Installation noise	0	0	0
Amplification of internal noise pollution	0,5	0,5	0,5
Sound comfort indication	*0,0815*	*0,0815*	*0,23*
Mold	1	1	1
Pollution ventilation air	1	1	1
Combustion gases	1	1	1
Radon	0,5	0,5	0,5
Air quality comfort indication	*0,9735*	*0,9735*	*0,9735*
Comfort level per year after renovation	**0,5753**	**0,5753**	**0,6871**
Difference with baseline alternative		**0**	**+0,1118**
Total comfort level over 30 years	**0,65**	**0,58**	**0,68**
Difference with baseline alternative		**-0,06**	**+0,04**

The Table shows that all techniques have a high score on thermal comfort. The all-electric 1 policy alternative has the highest score. Heat recovery ventilation is the main factor influencing this. The total comfort level is calculated using the above-determined weights per (sub)topic. The comfort level of the baseline alternative is comparable with the policy alternative district heating 1 after the renovation is completed. The change in heating technique is implemented in 2036 for the baseline alternative, instead of 2023, therefore the total comfort level of the baseline alternative is different from the comfort level of district heating 1. The total comfort level is calculated for the alternatives over the time period 2020-2050, which is a score between 1 and 0. The total comfort level is the sum of the yearly comfort level based on the implemented technique divided by the maximum value (31). The last two rows of Table 52 show the total comfort level and the difference from the baseline alternative. In this case, the all-electric 1 alternative results in the highest level of comfort. But the baseline alternative has a higher comfort level than the alternative district heating 1. This higher value for the baseline alternative is caused by the increased insulation level (label D) between 2023-2036 but no mechanical ventilation or heat pump (increase thermal comfort but no noise pollution).

4.7.2. Required space

The different policy alternatives require different installations as described in Sections 2.1 and 4.4. If the installations take up a high amount of space, this negatively affects the homeowner. The effect of the amount of space that is needed is relative to the baseline alternative, see Table 53. The district heating 1 alternative does not require extra space compared to the baseline alternative because the delivery set replaces the boiler. The alternative all-electric 1 takes up more space than the baseline alternative. As described above, the alternative all-electric 1 will heat the dwelling using an all-electric air-water heat pump. The element of the all-electric 1 technique that requires the most space, compared to the baseline alternative, is the boiler vessel. For alterations like cooking or solar panels, approximately the same amount of space is needed for the policy alternatives and the baseline alternative, which is why these alternations are not incorporated in Table 53.

Table 53: Required space per heating technique (CE Delft, n.d.-c, n.d.-e, n.d.-d, n.d.-f, n.d.-a; Vereniging eigen huis, n.d.)

		Baseline alternative	District heating 1	All-electric 1
Hr boiler		0,7 m x 0,4 m x 0,3 m = 0,084 m^3		
Delivery set			0,6 m x 0,2 m x 0,4 m = 0,048 m^3	
Hybrid heat pump	Inside unit	1,0 m x 0,6 m x 0,4 m		
	Outside unit	0,8 m x 0,8 m x 0,4 m = 0,496 m^3		
Air-to-water heat pump	Inside unit			1,0 m x 0,6 m x 0,4 m
	Outside unit			0,8 m x 0,8 m x 0,4 m = 0,496 m^3
Booster heat pump				
Boiler vessel				1,0 m x 1,0 m x 2,0 m = 2 m^3
Total required space		*0,58 m^3*	*0,048 m^3*	*2,496 m^3*
Total relative to baseline alternative			*-0,532 m^3*	*+1,916 m^3*

4.7.3. Impact renovation process

It will be necessary to renovate the home when the heating techniques are installed. This renovation has a negative effect on the homeowner due to the nuisance of the renovation process. If a more extensive renovation needs to be done, a homeowner is more negatively affected. The expected renovation time is determined based on an expert interview. When a dwelling switches to one of the heating techniques, the renovation can be done in one renovation, but some adaptations can also be implemented separately. Therefore, different phases have been created of adaptations to the dwelling that can be implemented separately. The renovation phases are shown in *Appendix V: Installation renovation phases*. With expert advice, the redevelopment time of each of the phases has been determined. The renovation time per phase is shown in Table 54. The increase in insulation has the biggest impact on the renovation time (approximately 2 weeks from label G to label B). Renovation time also decreases if the label jump is smaller (for label jump D to B, it takes one week). Furthermore, the table shows that district heating 1 takes the least time, mainly because it only requires a small improvement of the insulation label.

Table 54: Required time for the renovation process

	Baseline alternative	District heating 1	All-electric 1
Phase 1	2 weeks	2 weeks	2 weeks
Phase 2	3,5 days	3.5 days	5.5 days
Phase 3	0.5 day	0.5 day	0.5 day
Phase 4		1 day	1 day
Total	*14 days*	*15 days*	*17 days*
Difference with baseline alternative		*1 days*	*3 days*

4.7.4. Energy price volatility

Due to the obligation of delivery of energy (electricity, natural gas and heat) in the Netherlands, security of supply is not a risk for the homeowner. Although the energy should always be delivered by the energy supplier, due to fluctuations in availability the energy price can fluctuate. When the price of an energy source is highly sensitive, there is a high risk for high fluctuations (mostly increases) in the price for the homeowner. The risk of a high energy price volatility reduces the utility of risk-averse people. This means the higher the risk of volatility the lower the utility.

The Dutch natural gas production has rapidly reduced during the last decennium. Therefore, the Netherlands is currently highly dependent on foreign countries. This already showed to be problematic during the years 2021-2022 and resulted in a major increase in the natural gas price. Van de Beukel & van Geuns (2021) predicted that the security of supply will remain a risk. Because the Netherlands is dependent on other countries for the natural gas supply a reduction in supply will directly impact the price and make the natural gas price high.

The report of Tennet (2021) concluded that the security of the supply of electricity will be within the norm in the short term (until 2025). In long term, a reduction in the security of the supply of electricity is expected, but also in this case it is expected to remain within the security of supply norms (TenneT TSO B.V., 2021; van Beukel & van Geuns, 2021). Because electricity can be produced from different energy sources and within the Netherlands, the chance of high fluctuations in the price reduces. Nevertheless, one of the main challenges for the electricity supply in the Netherlands in the coming years will be the reinforcement of the electricity network, which may negatively impact the electricity price. In Figure 40, a correlation between natural gas and electricity price can be seen. When taking the correlation and expected network reinforcement costs, the electricity price volatility will be comparable to the volatility of natural gas even though homeowners can produce their own electricity using solar panels.

Research of the RVO predicted the security of supply of district heating at a similar level as the security of supply of natural gas (Bakker & Ruijg, 2012). The heat price is currently linked to the natural gas price which results in a similar volatility as natural gas. This dependency is expected to be reduced due to the disconnection of district heating from natural gas. District heating networks can have different energy sources which means that the volatility of the price could vary between networks. Because it is the goal of the Dutch government to disconnect the heat price from the natural gas price in 2024, it is assumed that the volatility of the heat price is similar to the natural gas volatility.

4.7.5. Safety

The different alternatives have different safety levels. When a safety risk is higher, this has a negative effect on the homeowner. When comparing the safety risks of the policy alternatives to the baseline alternative it can be concluded that all policy alternatives have a lower risk than heating with natural gas. Heating with natural gas results in the risk of carbon monoxide poisoning or natural gas leaks. The safety risk of the policy alternatives of district heating is the risk of leaks (warm water). Tests by Royal Haskoning DHV found that the leaks occur at 3,5% of a medium-size heat supplier. Personal injury of the user only occurs in a very limited number of cases. There are only three known cases of heavy personal injury due to a major leak. Research of Radar showed that 3% of the owners of heat pumps had an unsafe installation, the risk of unsafe heat pump installations are risks of fire or legionella infection. These results suggest that a leak of a district heating alternative can occur more often than an unsafe heat pump installation but an unsafe heat pump installation can create a bigger safety risk (Margadant, n.d.; NIBE, n.d.; Radar, 2019; Royal Haskoning DHV, 2016).

4.7.6. Freedom of choice of energy supplier

The alternatives use different energy sources for the heating of a home. For the use of the energy, the homeowner concludes a contract with an energy supplier. The included costs for the different types of energy are described in Section 4.2. The energy sources natural gas and electricity have many different suppliers in the Netherlands which are all connected to the same network. This makes it easy for the homeowner to switch energy supplier, depending on their current contract (ACM ConsuWijzer, n.d.). In the case of this high availability of suppliers, this reduces the risk of monopolistic behaviour of the energy supplier. The policy alternatives that are dependent on electricity have higher flexibility than natural gas because the consumer can be supplied by electricity from the electricity network but also by own production from solar panels. This is in contrast with district heating where a network in most cases is supplied with heat from one supplier. This means that the heat supplier has a monopoly position since the consumers cannot switch to another heating company without moving. Besides this there is also an information asymmetry, it is difficult for consumers to check whether the quantity and quality of the heat for which they are paying corresponds to the heat they receive (Autoriteit Consument & Markt, 2021).

4.8. Non-market effects: normative

The normative non-market effect that has been identified is climate. This effect will be described and valued in this Section.

4.8.1. Climate

The policy alternatives result in a change in CO_2 emissions. This change is caused by a reduction in energy consumption and by a change in energy sources. When the CO_2 emission is reduced this will result in a positive effect on the homeowner, due to a reduced effect on climate change. The costs of CO_2 emission are calculated using data from the RVO and the KEV (van der Molen et al., 2021). The CO_2 emission per dwelling per alternative is shown in Table 55. The baseline alternative has the highest CO_2 emission. The alternative all-electric 1 has the lowest emission. The difference between all-electric 1 and district heating 1 is because alternative all-electric 1 can produce electricity using solar panels (no CO_2 emission in production) which can be used for heating.

Table 55: The CO_2 emission in tonnes per dwelling over the period 2020-2050

	Baseline alternative				
	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Natural gas	39,96	31,02	26,98	30,55	26,98
Electricity	13,65	14,42	13,49	11,81	13,49
Heat	0,00	0,00	0,00	0,00	0,00
Total	*53,61*	*45,44*	*40,46*	*42,36*	*40,46*
	Policy alternative district heating1				
Natural gas	5,80	4,52	4,11	4,73	4,11
Electricity	2,40	5,33	4,63	2,81	4,63
Heat	12,76	10,00	8,90	9,45	8,90
Total	*20,96*	*19,85*	*17,65*	*16,98*	*17,65*
Difference with baseline alternative	*-32,65*	*-25,59*	*-22,82*	*-25,38*	*-22,82*
	Policy alternative all-electric 1				
Natural gas	5,80	4,52	4,11	4,73	4,11
Electricity	4,48	9,14	7,84	6,50	7,84
Heat	0,00	0,00	0,00	0,00	0,00
Total	*10,28*	*13,65*	*11,95*	*11,22*	*11,95*
Difference with baseline alternative	*-43,33*	*-31,79*	*-28,51*	*-31,14*	*-28,51*

4.9. Conclusion

In this Chapter the steps of the LCBA have been executed. The methodology was based on the CBA methodology of Romijn & Renes (2013). In the LCBA, the effects have been determined for the baseline alternative (heating with natural gas and a hybrid heat pump in 2036), and the policy alternatives district heating 1 and all-electric 1. The identified effects include, financial costs, comfort, required space, impact renovation process, energy price volatility, safety, freedom of choice, and climate. In the following Chapter the results of the current Chapter will be compared for a reference housing cluster. By doing this insight can be given by the LCBA into the advantages and disadvantages and what will be the most appropriate heating technique for a reference cluster.

5. Results limited cost-benefit analysis

In the previous Chapter, the effects of the limited cost-benefit analysis have been described. In the current Chapter, an overview will be provided of these costs and benefits and the overall welfare effects per alternative. The effects and main assumptions of the LCBA will be discussed in this Chapter, followed by the expected results. Next, the results of the LCBA can be created and discussed. These LCBA results can be assessed using the expected results. Conclusions and recommendations will be made based on the results of the LCBA. Lastly, a sensitivity analysis will be conducted to assess the results of the LCBA. In Figure 43, it can be seen how this Chapter contributes to the research.

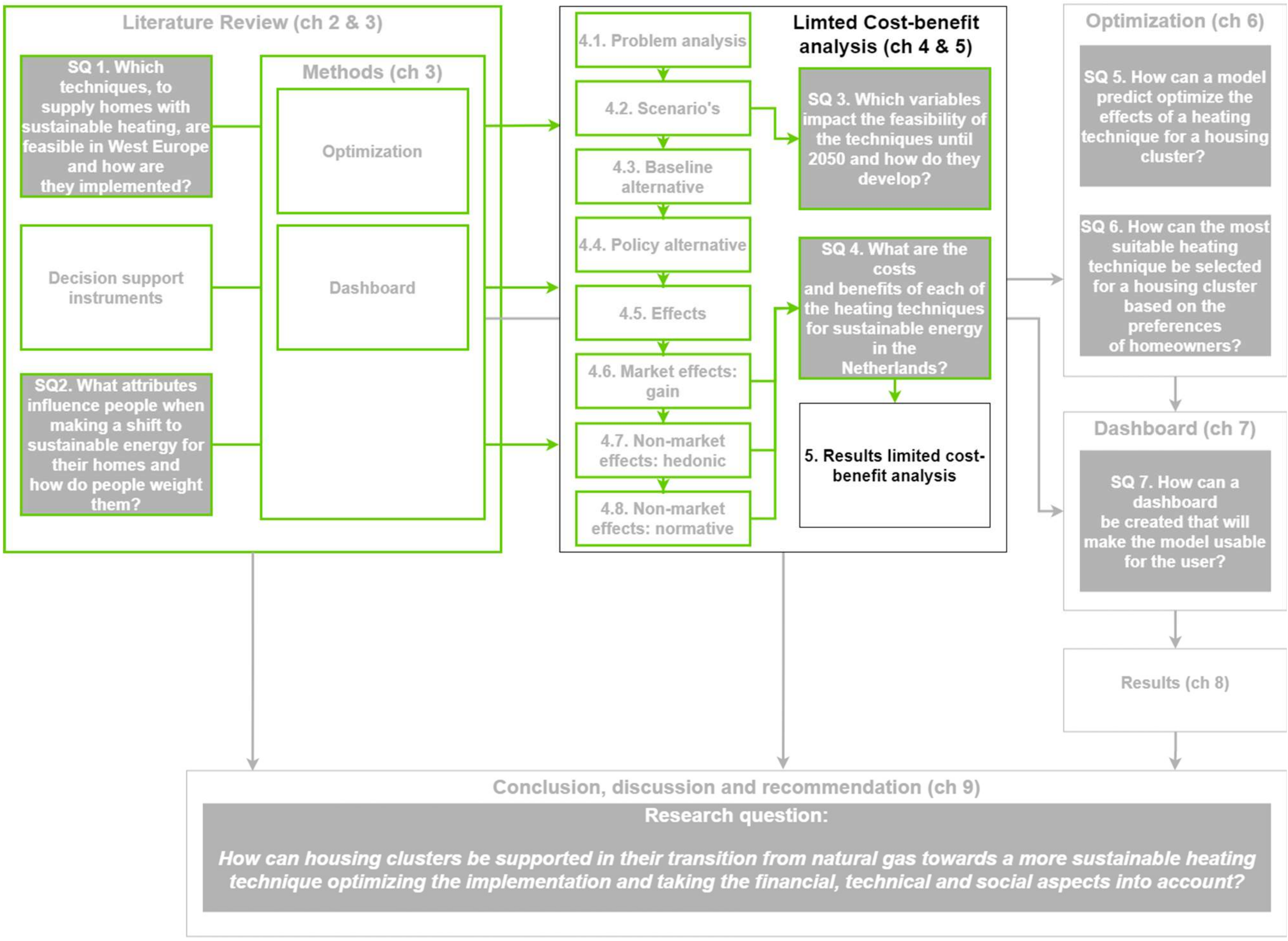


Figure 43: Results limited Cost-Benefit Analysis within the overall research design

The LCBA has been executed over a period of 2020-2050 for the reference housing cluster from the neighbourhood ‘t Ven (see Table 16). With the results of the effects of the LCBA, the overall welfare effect of two policy alternatives will be calculated. The policy alternatives are district heating 1 (middle temperature) and all-electric 1 (with an individual air-to-water heat pump), which will be compared to the baseline alternative. The alternatives differ in heating techniques and required adjustments to the home. The objective of the LCBA is to calculate the overall welfare effects for the stakeholder, who is the homeowner.

The goal framing theory was used in the selection of the effects of the LCBA on homeowners. The incorporated effects per goal for the stakeholder homeowner are shown in Figure 44. The LCBA compares the costs of the baseline alternative with the policy alternatives. When the effects of a policy alternative are higher than the baseline alternative, this results in costs.

When they are lower, this results in benefits. With this comparison for all effects, a balance can be created per project alternative.

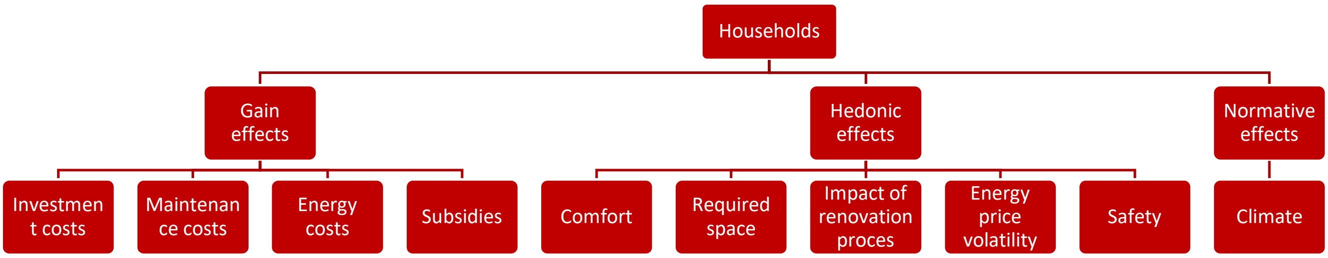


Figure 44: Overview of the identified effects on the stakeholder homeowner.

5.1. Main assumptions and expected results

In the LCBA described in the previous Chapter, many assumptions were made. The most relevant assumptions are listed below. Based on the assumptions, the expected results for each alternative are described and augmented. The results of the LCBA can be examined in the next Section based on these insights.

5.1.1. Main assumptions

The main assumptions used for the conclusions are:

1. The reference housing cluster for which the LCBA has been executed consists of 5 dwellings with the properties described in Table 16;
2. If a dwelling is connected to a district heating network, it is assumed that the dwelling is connected to an existing network;
3. The existing district heating network is located at an average of 30 meters from the front door;
4. Per extra dwelling included in the cluster, the connection price is reduced by 5% (up to 50%);
5. The heat price is disconnected from the natural gas price in 2024.

5.1.2. Expected results

Before reviewing the LCBA results, the expected results will be discussed. This will help to assess whether the results are plausible and reduce the risk of mistakes in the results and conclusions. The expected results are described in Table 56. This table presents the expected effect compared to the baseline alternative. If the effects are lower compared to the baseline alternative, this is indicated by an arrow pointing down and if the effect is higher the arrow will point upwards. If the effect results in a benefit the arrow is coloured green and if it results in a costs it is coloured red. Only for the effects that are caused by the change in scenario, scenario low and high are included.

Table 56: Expected results

	District heating 1		**All-electric 1**	
Effect	***Scenario low (variable natural gas price +40%, electricity price -34%)***			
Investment costs	▼	Due to smaller alterations to the dwelling (no hybrid heat pump and low-temperature radiator) investment costs are expected to be lower.	▲	More expensive alterations to the dwelling are required (air-to-water heat pump, ventilation with heat recovery and solar panels). Resulting in higher expected investment costs.

Maintenance costs		▼	Fewer in-house appliances that need maintenance, resulting in lower costs.	▲	More in-house appliances for a longer period, resulting in higher costs.
Replacement cost		▼	The replacement costs are expected to be lower because the technique does not include a heat pump which needs replacement.	▲	More installations are included which require replacement and are implemented at an earlier moment in time resulting in replacements in the timeframe.
Energy costs	Scenario low	▲	The costs are expected to be higher since the fixed heat price is higher than the fixed natural gas price.	▼	The costs are expected to be lower, only electricity is used which results in only fixed costs for electricity. Electricity fixed costs are lower than natural gas and the variable costs are higher. The used kWh is reduced due to solar panels.
	Scenario high	▼	Due to the high increase in natural gas prices and the use of solar panels the energy costs are expected to be lower.	▼	The costs are expected to be lower, only electricity is used which results in only fixed costs for electricity. Electricity fixed costs are lower than natural gas and the variable costs are higher. The used kWh is reduced due to solar panels.
Total costs	Scenario low	▲	*Due to the high energy costs and the discounted investment costs for the baseline alternative, it can be expected that the total costs are higher.*	▼	*Due to the low energy costs compared to the baseline alternative, it can be expected that the total costs are lower.*
	Scenario high	▼	*All sub-costs are lower than the baseline alternative, which results in lower expected total costs.*	▼	*Due to the low energy costs compared to the baseline alternative, it can be expected that the total costs are lower.*
Comfort		▼	The total comfort level over the period of 30 years is lower than the baseline alternative, mainly due to ventilation implemented in 2023 compared to 2036 in the baseline alternative.	▲	The total comfort level over the period of 30 years is higher than the baseline alternative, mainly due to ventilation with heat recovery.
Required space		▼	District heating 1 requires less space (no space for a boiler and hybrid heat pump are required).	▲	The all-electric 1 requires more space than the baseline alternative (Due to the boiler tank).
Impact renovation process		▲	The renovation to implement district heating 1 is longer, due to the installation of solar panels.	▲	The renovation to implement all-electric 1 is longer, due to the installation of solar panels and ventilation with heat recovery.
Energy price volatility		▼	Risk-averse people have a lower utility with for a higher energy price volatility.	▼	Risk-averse people have a lower utility with for a higher energy price volatility.
Freedom of choice of energy supplier		▼	Higher probability of monopolistic behaviour of energy supplier.	▲	Lower probability of monopolistic behaviour of energy supplier and self-production with solar panels
Safety		▼	Risk of using natural gas excluded.	▼	Risk of using natural gas excluded.
Climate (in kg CO_2 emission)		▼	The home is heated with a natural gas-free heating technique.	▼	The home is heated with a natural gas-free heating technique.

5.2. Results

The results of the LCBA can be seen in Table 57. The effects described in the previous Chapter have different measures (besides €). For some of these effects, it has been chosen to translate these measures to a qualitative scale of -- lowest to ++ highest. The results of the costs over the period 2020-2050 have been discounted, using the discount rate described in Section 4.2.6. In the results, it can be seen that there is a substantial reduction in CO_2 emission for the policy alternatives which is the goal of the energy transition. Consequently, reducing CO_2 emissions results in a benefit for the project alternatives. In addition to the benefits of reducing CO_2 emissions, the project alternatives also involve high costs. For scenario low (lower-end energy price development), the project alternatives have higher costs compared to the baseline alternative. Furthermore the investment for the baseline alternative has been made in 2036, which results in a lower weight of these discounted costs. Scenario high (high energy price), has an impact on the results of the LCBA through the energy costs. In the case of a high energy price, the policy alternatives are more beneficial. The baseline alternative is most negatively impacted by this scenario due to the high natural gas consumption.

Table 57: Overview of the average effects compared to the baseline alternative with the discount rate

	Baseline alternative *Absolute*	**District heating 1** Relative to baseline alternative	**All-electric 1** Relative to baseline alternative
Effect	***Scenario low (variable natural gas price +40%, electricity price -34%)***		
Investment costs (in € k)	*€ 16,54*	€ 2,34	€ 14,07
Maintenance costs (in € k)	*€ 6,11*	€ 1,04	€ 0,77
Replacement cost (in € k)	*€ 3,81*	€ -1,90	€ 1,21
Energy costs (in € k)	*€ 21,54*	€ 1,96	€ -17,20
Total costs (in € k)	*€ 48,00*	€ 3,44	€ -1,15
Comfort (index 0-31)	*0,65*	-0,06	+0,04
Required space (in m^3)	*0,58*	-0,53	1,91
Impact renovation process (in days)	*14*	1	3
Energy price volatility (index --/++)	*0*	+	+
Freedom of choice of energy supplier (index --/++)	*0*	--	+
Safety (index --/++)	*0*	++	+
Climate (in tonnes CO_2 emission)	*0,42 tonnes*	-0,22 tonnes	-0,30 tonnes
	Scenario high (variable natural gas price +103%, var electricity price 17%)		
Investment costs (in € k)	*€ 16,54*	€ 2,34	€ 14,07
Maintenance costs (in € k)	*€ 6,11*	€ 1,04	€ 0,77
Replacement cost (in € k)	*€ 3,81*	€ -1,90	€ 1,21
Energy costs (in € k)	*€ 31,43*	€ -5,62	€ -23,01
Total costs (in € k)	*€ 57,89*	€ -4,14	€ -6,96
Comfort (index 0-31)	*0,65*	-0,06	+0,04
Required space (in m^3)	*0,58*	-0,53	1,91
Impact renovation process (in days)	*14*	1	3
Energy price volatility (index --/++)	*0*	+	+
Freedom of choice of energy supplier (index --/++)	*0*	--	+
Safety (index --/++)	*0*	++	+
Climate (in tonnes CO_2 emission)	0,42 *tonnes*	-0,22 tonnes	-0,30 tonnes

In Figure 45 the total costs per project alternative are visualized. All project alternatives have lower total costs compared to the baseline alternative except scenario low with a discount rate. It is noteworthy that the total costs of the project alternatives do not have major differences in most cases. For scenario high without discount rate, there is a big difference between the policy alternatives and the baseline alternatives (+/- €15.000) which is mainly caused by the high natural gas cost and the lack of solar panels for the baseline alternative.

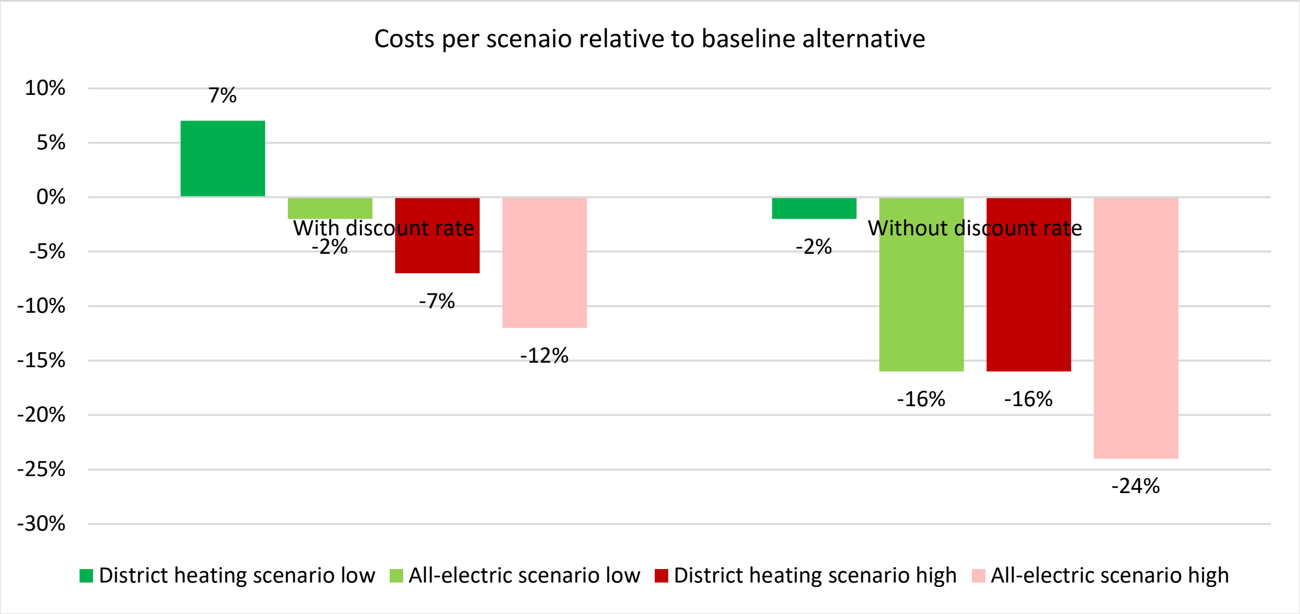


Figure 45: Distribution of costs per alternative

Distribution of costs

Figure 46 shows the percentage distribution of the costs per alternative. In the distribution of all-electric, the main cost item is the investment costs. Resulting in a low-cost distribution for the homeowner. In contrast to all-electric 1, the energy costs are the main cost item of the alternative district heating 1, which results in a high cost distribution.

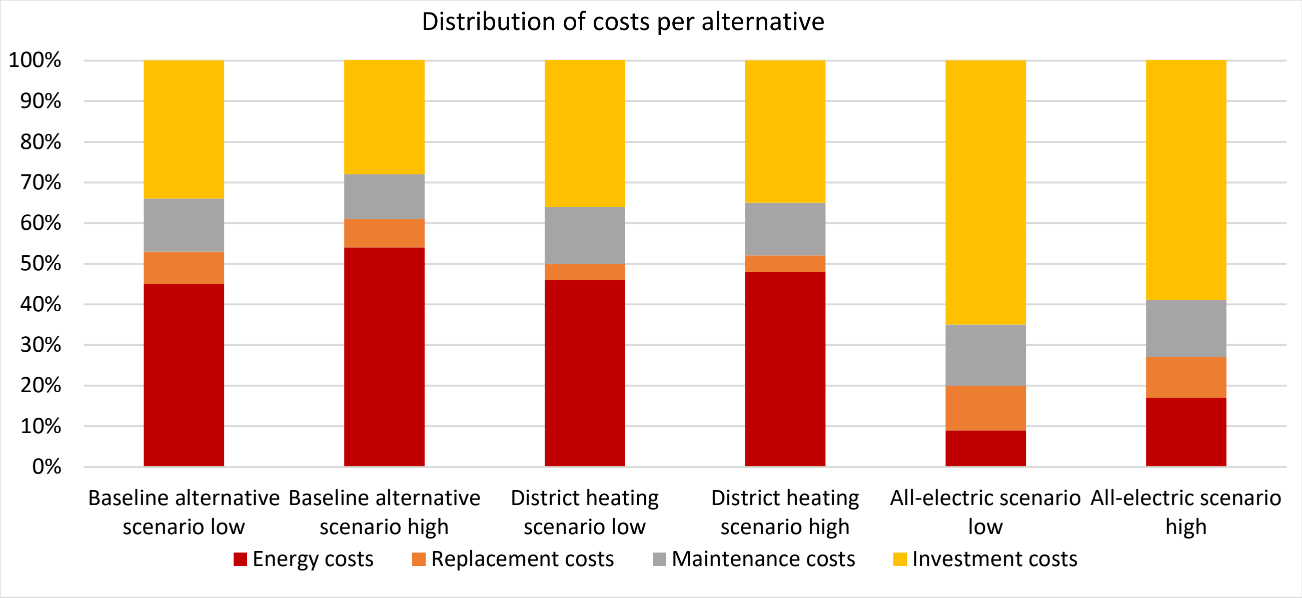


Figure 46: Distribution of costs per alternative

Moment of investment

For the LCBA, a timeframe of 30 years has been used, some CBAs have a longer timeframe. This has not been deemed necessary for the current research, since the effects after 2050 have little impact on the results due to the discount rate. Furthermore, timeframes of 25-30 years are not usual for energy-focused CBAs. After this timeframe, the uncertainty of the scenario's increase often becomes too high (Tieben et al., 2020). Due to the difference in cost distribution, the moment of investment of the alternatives can be compared. The cumulative costs of the policy alternatives compared to the baseline alternative are shown in Figure 47. In these charts, the majority of the costs (due to investment costs) for all-electric 1 are in the year 2023. District heating 1 has a clear investment moment in the year 2023 but the main share of costs are distributed over the years, due to high energy costs. The baseline alternative also has a major jump in costs (due to investment costs) in the year 2036.

The results of the LCBA are compared to the expected results to test the accuracy of the LCBA. In *Appendix X: Comparison of expected results and the results of the LCBA* the expected results are compared to the results of the LCBA. It can be seen that the LCBA meets the expected results. In *Appendix W: Comparison with the selected CBAs* the LCBA is compared to the reference CBAs.

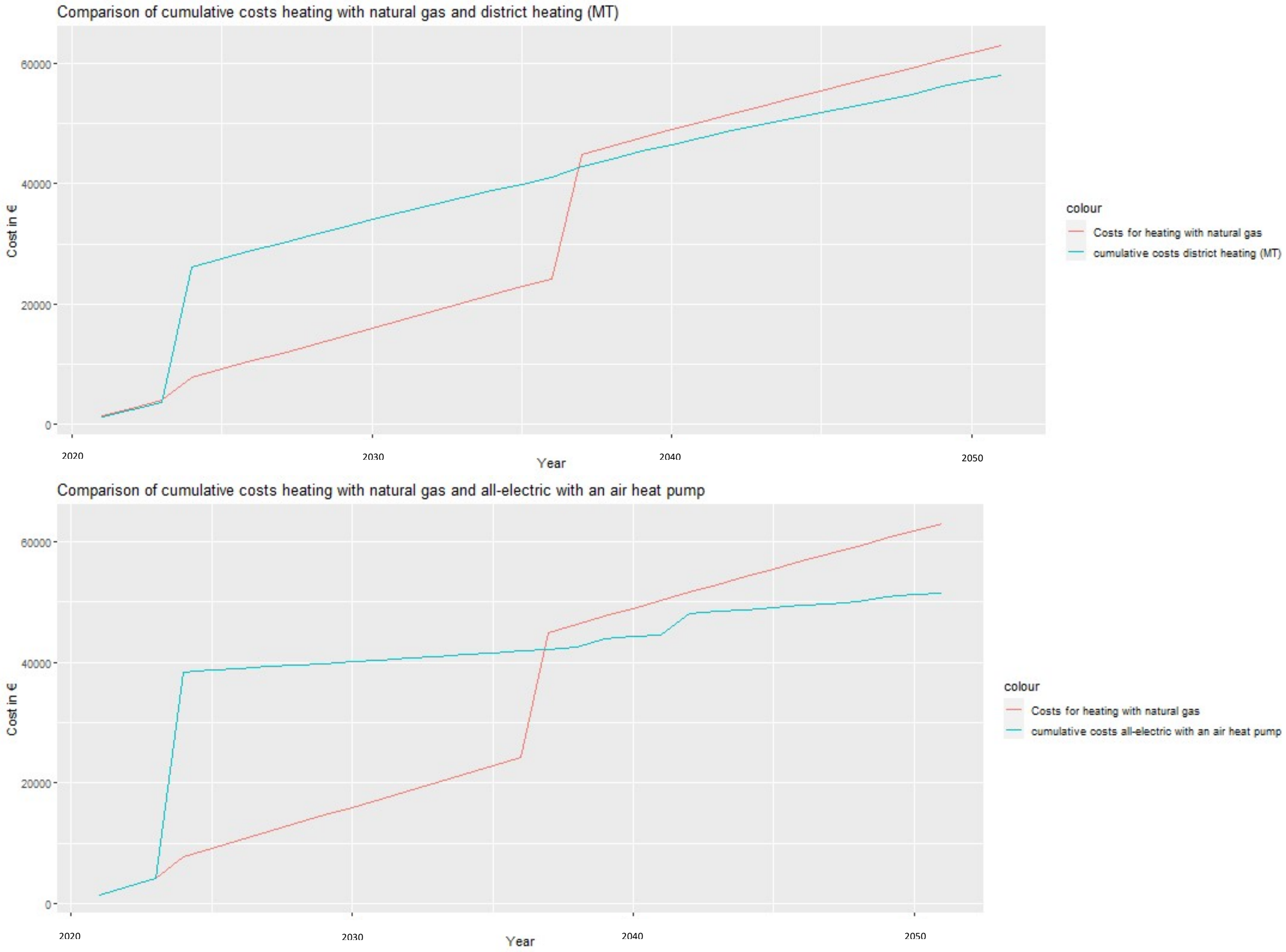


Figure 47: Moment of investment of the alternatives district heating 1 and all-electric 1 compared to baseline alternative (for dwelling 1, scenario high)

5.3. Overall welfare effects

The policy alternatives influence the gain, hedonic and normative effects. These effects have been identified in the LCBA and are summarized in Table 57. It can be seen that these effects have different measures which make it impossible to compare and draw a conclusion on which alternative is most beneficial. On some effects, a qualitative scale has been used. To compare the effects, this scale has been implemented on all effects. In Table 58 the results of this interpretation are shown. In this interpretation of the results, the value of costs is based on the total costs.

Table 58: Overview of the costs and benefits

Type of effect	Effect	*Baseline alternative*	District heating 1	All-electric 1	District heating 1	All-electric 1
			Scenario low (variable natural gas price +40%, electricity price -34%)		*Scenario high (variable natural gas price +103%, var electricity price 17%)*	
Gain effects	Costs	*0*	-	0	+	++
Hedonic effects	Comfort	*0*	-	+	-	+
	Required space	*0*	+	-	+	-
	Impact renovation process	*0*	-	-	-	-
	Energy price volatility	*0*	+	0	+	0
	Freedom of choice of energy supplier	*0*	--	+	--	+
	Safety	*0*	++	+	++	+
Normative effects	Climate	*0*	++	++	++	++
Total	*Added up*	*0*	*1*	*3*	*3*	*5*
	With weight	*0*	*-0,10*	*0,10*	*0,13*	*0,33*

The results of the gain effects are described above. For the Hedonic effects, the overall hedonic effects of district heating are comparable to the baseline alternative. The overall hedonic effect of all-electric is somewhat higher than the baseline alternative (+1). The normative effects include the effect of climate which is determined by the CO_2 reduction. Both policy alternatives have a major decrease in CO_2 emission, which results in a benefit for the homeowner.

The effects are added up and the results are shown in Table 58. Policy alternatives have higher benefits than the baseline alternative for high and low energy costs. However, the results show higher benefits for the policy alternatives in the case of a high scenario. Although this addition of effects results in an overall welfare effect, the overall welfare effects are likely different in reality. When effects are simply added up, all effects have a similar weight, although homeowners are likely to evaluate them differently. Therefore, the weights for gain effects, hedonic effects and normative effects have been used, see Section 2.3.2. Using this weight, the overall welfare can be determined (e.g. using the gain weight for the gain effects). The weighted scores have been normalized (using the maximum possible results). Therefore the weighted scores can have a value between -1 (minimum) and 1 (maximum), with 0 being equal to the baseline alternative. For the low scenario (lower-end energy price development), the all-electric alternative is most beneficial for the homeowner (weighted score +0,10). For the high scenario, both policy alternatives are more beneficial than the baseline alternative. In this case, all-electric (+0,33) is more beneficial than heating with district heating (+0,13). This is mainly due to the higher financial benefits of all-electric.

5.4. Sensitivity analysis

The results of the LCBA are based on information and calculations from many different sources. Furthermore many assumptions have been made which makes the results sensitive to the assumptions. The sensitivity of the results is tested by calculating the effects of higher and lower costs on the total costs. The results of the sensitivity analysis are shown in Table 59. In this Table, the financial benefits are shown for district heating and all-electric. Per policy alternative, the relative difference compares the total average costs relative to the baseline alternative per assumption.

Table 59: Sensitivity analysis for the baseline alternative, district heating 1 and all-electric 1. For the policy alternatives the total average costs relative to the baseline alternative are shown per assumption.

Sensitivity analysis	**Baseline alternative** *Absolute*	**District heating 1** *Relative to baseline alternative*	**All-electric 1** *Relative to baseline alternative*
	Scenario low (variable natural gas price +40%, electricity price -34%)		
Basis analysis	€ 48,00	€ 3,44	€ -1,15
Investment costs -30%	€ 43,03	€ 2,74	€ -5,37
Investment costs +30%	€ 52,96	€ 4,14	€ 3,07
Yearly cost -30%	€ 39,70	€ 2,54	€ 3,78
Yearly costs +30%	€ 56,29	€ 4,34	€ -6,08
District heating 20 m	€ 48,00	€ 2,65	€ -1,15
District heating 40 m	€ 48,00	€ 5,01	€ -1,15
District heating costs -10%	€ 48,00	€ 1,48	€ -1,15
District heating costs +10%	€ 48,00	€ 5,40	€ -1,15
Cluster size 15	€ 48,00	€ 4,69	€ -1,15
5 most beneficial dwellings All-electric1	€ 52,29	€ 4,35	€ -2,78
5 least beneficial dwellings All-electric1	€ 47,20	€ 3,76	€ 0,73
5 most beneficial dwellings District heating 1	€ 48,11	€ 3,12	€ -2,66
5 least beneficial dwellings District heating 1	€ 47,20	€ 3,76	€ 0,73
	Scenario high (variable natural gas price +103%, var electricity price 17%)		
Basis analysis	€ 57,89	€ -4,14	€ -6,96
Investment costs -30%	€ 52,93	€ -4,84	€ -11,18
Investment costs +30%	€ 62,85	€ -3,44	€ -2,74
Yearly cost -30%	€ 46,63	€ -2,77	€ -0,29
Yearly costs +30%	€ 69,16	€ -5,51	€ -13,63
District heating 20 m	€ 57,89	€ -4,93	€ -6,96
District heating 40 m	€ 57,89	€ -2,57	€ -6,96
District heating costs -10%	€ 57,89	€ -6,17	€ -6,96
District heating costs +10%	€ 57,89	€ -2,11	€ -6,96
Cluster size 15	€ 57,89	€ -4,40	€ -6,96
5 most beneficial dwellings All-electric1	€ 62,96	€ -4,90	€ -11,44
5 least beneficial dwellings All-electric1	€ 57,33	€ -3,03	€ -4,46
5 most beneficial dwellings District heating 1	€ 57,61	€ -4,85	€ -7,88
5 least beneficial dwellings District heating 1	€ 57,33	€ -3,03	€ -4,46

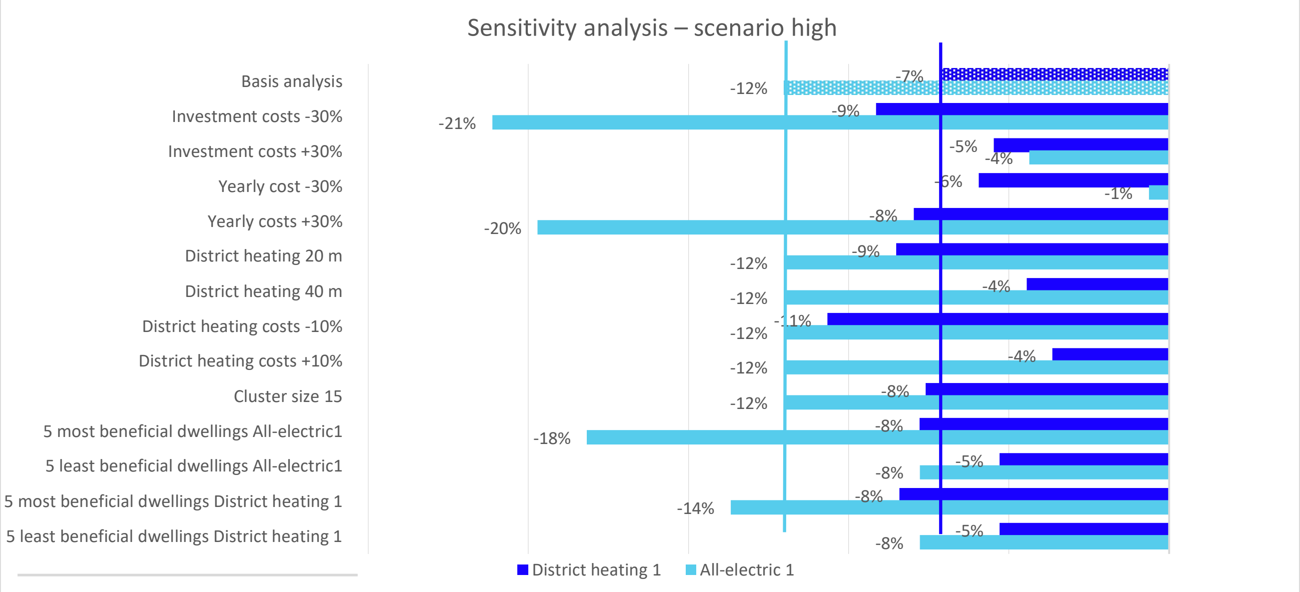


Figure 49: Sensitivity analysis, scenario high. The percentage difference from the two alternatives to the baseline alternative. The basis analysis (line one) shows the relative results based on the above described assumptions. In the lines below the one assumption is adjusted and the percentage difference in costs relative to the baseline alternative is shown.

In Figure 49 and Figure 48 the percentage difference for the relative costs per alternative to the baseline alternative are shown. The results of the sensitivity analysis show that the LCBA reacts as expected to the change of assumptions. The policy alternative all-electric is mostly sensitive to the change in investment costs (-21% and -5%, scenario high) and yearly costs (-20% and -1%, scenario high) difference, which can be explained by the high investment costs and the low yearly costs (due to energy costs) of all-electric. The all-electric alternative does not react to the changes of assumptions for clusters or district heating (lines 6-10 in Figure 49 and Figure 48), since the tables show that the percentage difference does not change compared to the bases analysis. This is an expected result since the baseline alternative and all-electric do not use district heating or collective heating.

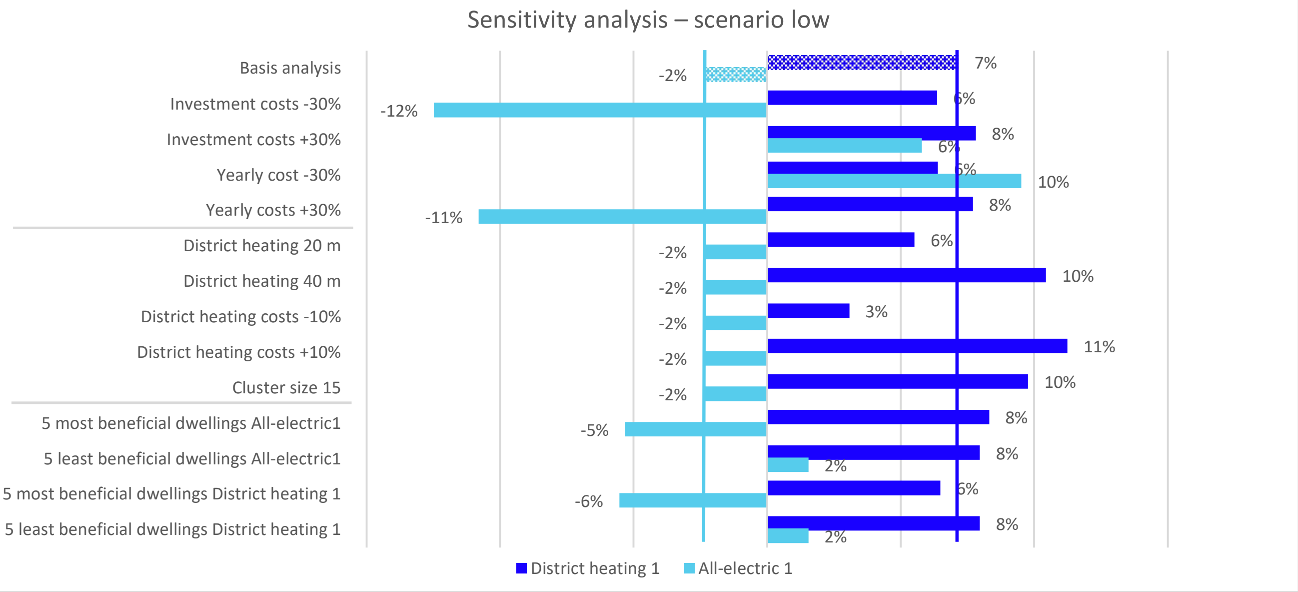


Figure 48: Sensitivity analysis, scenario low. The percentage difference from the two alternatives to the baseline alternative. The basis analysis (line one) shows the relative results based on the above described assumptions. In the lines below the one assumption is adjusted and the percentage difference in costs relative to the baseline alternative is shown.

For the policy alternative district heating 1, the district heating-related assumptions have a clear impact on the financial benefits. For district heating, the changes in distance to the district heating network (-9% and -4%, scenario high) and the district heating costs (-11% and -4%, scenario high) have clear effects on the financial benefits. Furthermore the results show that it is financially more beneficial if a cluster contains more dwellings, is closer to the district heating network and in the case of a change in the district heating price. By testing the most and least beneficial dwellings it can be seen that the dwelling properties have a clear impact on the financial benefits of a cluster.

5.5. Conclusions

Based on the above-described results of the LCBA, the conclusions that can be drawn for the reference housing cluster are:

1. Over 30 years the two policy alternatives – district heating and all-electric – generate similar financial benefits as compared to natural gas heating;
2. In the scenario with high growth of energy prices, it is financially attractive to switch to district heating or all-electric, in the scenario with low growth it is financially attractive to switch to all-electric;
3. On average the costs are very similar for similar housing types. There can be specific differences but these are not very large;
4. In contrast to the alternative all-electric, district heating requires less investment costs, but has higher yearly costs.

Based on the conclusions, the following recommendations can be given:

1. The financial benefits of heating with district heating differ per house, larger clusters with close proximity to the network benefit the most;
2. Dwelling one of the reference cluster has the greatest financial benefit from switching to natural gas-free heating for the alternative all-electric 1. The main properties are; a corner house, built before 1946, a small dwelling (109 m^2) and a current energy label of D;
3. Dwelling four of the reference cluster has the greatest financial benefit from switching to natural gas-free heating for the alternative district heating 1. The main properties are; a corner house, built before 1946, a small dwelling (71 m^2) and a current energy label of F;
4. Dwelling two of the reference cluster has the greatest financial costs from switching to natural gas free-heating. The main properties are; a terraced house, built before 1946, a small dwelling (71 m^2) and a current energy label of F;
5. Although the financial benefits of the alternatives district heating and all-electric are quite similar, district heating is more feasible for homeowners due to the higher distribution of costs.

While the limited cost-benefit analysis approaches the homeowner's overall welfare effects, it is important to keep in mind that the limitations of the electricity network (and the related costs for the homeowner) have not been taken into account. Furthermore, assumptions have been made about the district heating network to make a reasoned estimation of the costs. But if the network needs to be newly constructed, this could also have a big impact on the costs for the homeowner.

In the current Chapter, a LCBA has been conducted for a housing cluster of 5 dwellings. Based on these insights, an advice has been developed for the housing cluster. But there are two main limitations to this approach:

1. The policy alternatives used in the LCBA are based on an extensive set of assumptions. Therefore, the used implementation of a technique is not necessarily the optimal implementation.
2. The sensitivity analysis showed that the properties of the dwellings in a cluster impact the financial benefits per alternative. Therefore, the results are only applicable to the cluster that was studied.

6. Model description

In this Chapter, the creation of the optimization model will be described. The model will optimize the implementation of the heating techniques based on minimizing the costs for the homeowner over a period of 30 years. As described before, the optimization model is created using Python. The choice of using Python to create the optimization model with the PuLP and Pyomo packages is explained in Section 3.1.

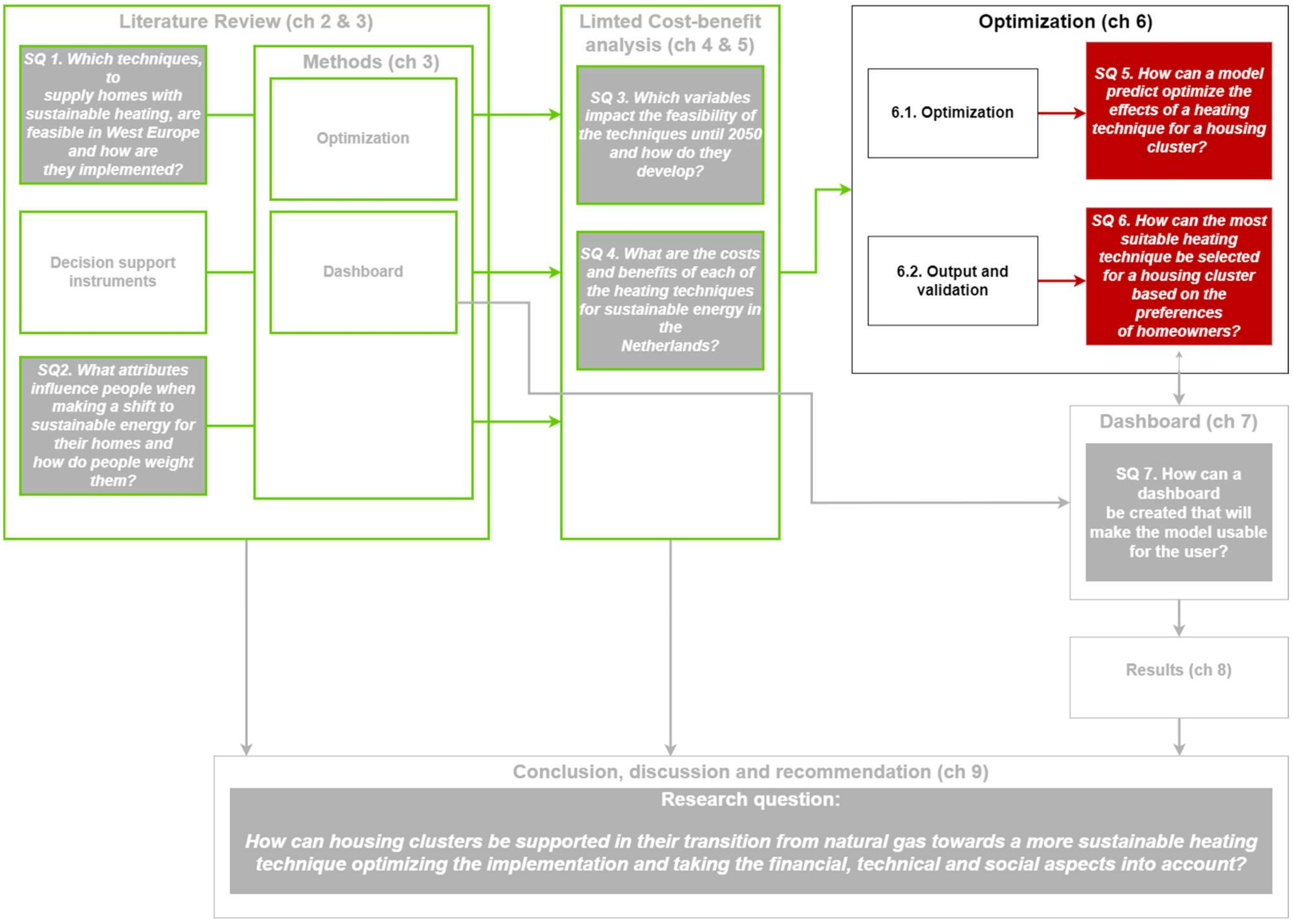


Figure 50: Creation of the optimization models within the overall research design

The optimisation models will be described in the first Section (6.1) of this Chapter. In the second Section (6.2), the output and validation will be discussed. Figure 50 displays how the Chapter contribute to the research.

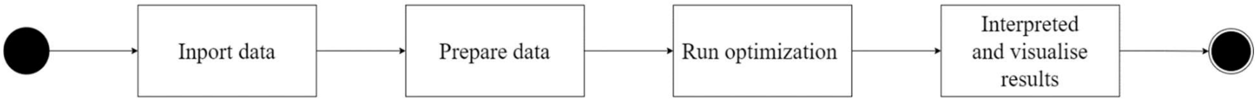


Figure 51: Simplified UML activity diagram of finding the optimal implementation of a heating technique

6.1. Optimization

This Section describes the creation of multiple optimization models. The Preference-based multi-objective optimization incorporates multiple objectives. To select which objectives need to be taken into account to incorporate the preferences of homeowners the goal-framing theory is used combined with the selected effects of the LCBA. Using the goal-framing theory allows for the use of a similar setup as the LCBA and use the weights described in Section 2.3.2. For the gain and normative goals, only one effect was identified in the LCBA but for the hedonic goal, six effects were identified. To decrease the risk of faulty results the effect comfort is selected as the optimization objective for the hedonic goal. This effect has been selected since it is the effect that has the highest relative importance in influencing the willingness to shift to a more sustainable natural gas-free heat source and it is measurable. For the gain goal, this effect is costs, for the hedonic goal this is comfort and for the normative goal, this is climate which will be expressed as CO_2 emission. For these objectives, first single-objective models will be created, which are combined in a multi-objective optimization model in a later stage, see Figure 52. The optimization of the implementation per heating technique for a dwelling is shown in Figure 51 in a simplified UML activity diagram. In the figure, it can be seen that before the actual optimization is executed, the first data preparation needs to be done. During this phase, the imported data, which includes multiple datasets and input parameters, is used. To perform the optimization (for the selected dwelling), it is necessary to determine the current state and consumption of the dwelling and to prepare the data for the optimization. After the optimization is run, the result needs to be interpreted and visualised, which eventually will be done by the RStudio Shiny dashboard, see Section 6.3. The more elaborated UML activity diagram is shown in Figure 54.

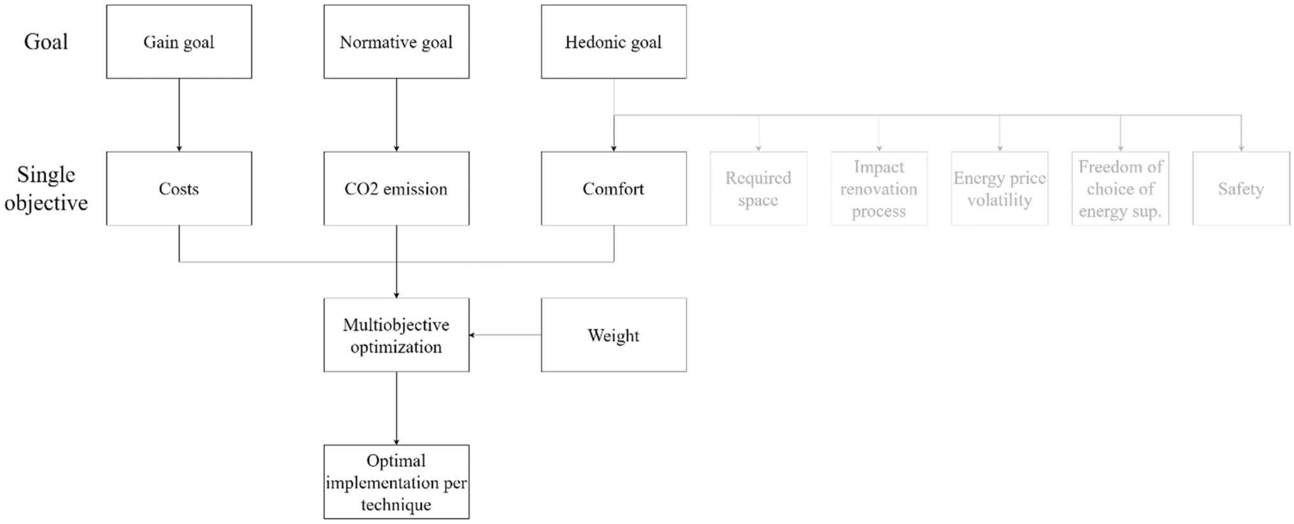


Figure 52: Overview of the needed optimization models

6.1.1. Parameters and variables

An optimization model consists of parameters, variables and constants. Variables represent a value of a quantity whose magnitude varies within a situation. Parameters represent a value of a quantity that is constant in a particular situation. Constants represent a value of a quantity that is the same in all situations (Mathematics for Teaching, n.d.). Below, the parameters and variables that are used in the optimization model are elaborated.

6.1.1.1. Parameters

An overview of the main parameters is shown in Table 60 and the values of the parameters are based on the input values of the user (see Section 6.1.2.2) and the data collected in Chapter 4.

Table 60: Main parameters

Parameters		Parameters	
Housing type	Housing_type	Development of the gas price scenario	G_price
Construction year	Constr_year	Development of the electricity price scenario	E_price

Household size	Household_size	Development of the investment costs scenario	Dev_cost
Floor size	Floor_size	Variables natural gas price	V_G_price
Energy label	Energy_label	Variable electricity price	V_E_price
Current natural gas consumption	G	Fixed natural gas price	F_G_price
Current electricity consumption	E	Fixed electricity price	F_E_price
Number of dwellings in the housing cluster	Nr_dwellings	Investment in the all-electric technique	Invest_AL
Length of the roof of the dwelling	Length_roof	Energy reduction due to change in insulation label	Energy_reduct_LB
Width of the roof of the dwelling	Width_roof	Natural gas consumption with improved insulation level	G2
Height of the roof of the dwelling	Height_roof	Electricity consumption with improved insulation level and alternative heating technique	E2
Investment costs electric cooking	Inv_elec_cooking	Investment costs LT radiator	Inv_lt_radiator
Investment costs heat pump	Inv_heat_pump	Investment costs WTW	Inv_vent_WTW
Type of roof of the dwelling	Type_roof	Investment costs solar panels	Inv_solar
Investment costs increase electricity connection	Inv_elec_connect	Number of rooms	Nr_of_rooms
Investment in insulation	Inv_insu	Number of solar panels	Nr_panel
Electricity produced by solar panels	E_solar	Electricity ground heat pump	E_ground_HP
Energy reduction due to shift to insulation label B	Energy_reduct_B	Energy reduction due to shift to insulation label D	Energy_reduct_D
Electricity for electric cooking	E_cooking	Electricity for mechanical ventilation	E_vent
Electricity for booster heat pump	E_boost_HP	Electricity for ventilation with heat recovery	E_WTW
Electricity for hybrid heat pump	E_hybrid_HP	Electricity for air-to-water heat pump	E_air_HP

6.1.1.2. Variables

The variables that are used in the optimization model are shown in Table 61. These variables are the variables that are used in the objective function of the optimization. These variables can change value depending on the values of the parameters to minimize the objective function. These variables are created per selected dwelling in the housing cluster for a collective heating technique, which will enable the model to determine the specific values per dwelling of the cluster. Below the table, the functions of the variables in the optimization are described.

Table 61: Variables of the optimization model

Variable	Variable name
Installation natural gas	In_g
Installation electricity	In_e
Heating status	H_status
Insulation status	I_status
Switch technique	S_tech
Switch insulation level	S_insu

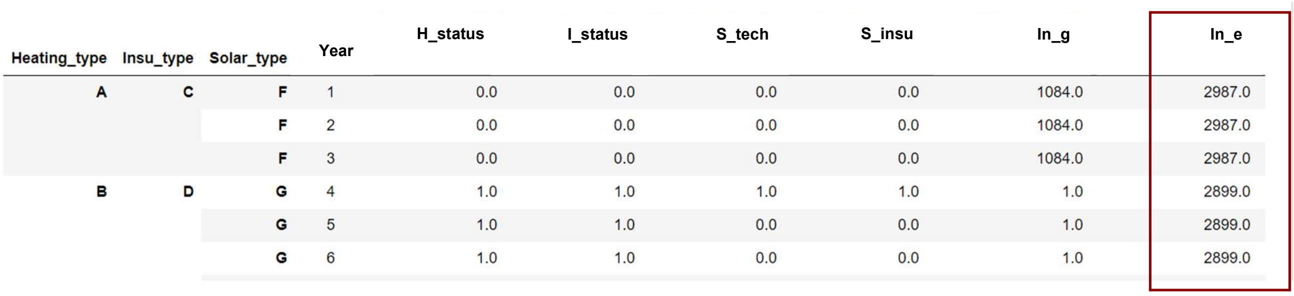
Installation natural gas (*In_g)*

When the dwelling is heated using natural gas, the dwelling has a yearly natural gas consumption. This natural gas consumption is described by the variable *In_g*. It describes the natural gas consumption in m^3 per year, depending on the parameter current natural gas consumption (*G)*, which heating technique is used and the level of insulation of the dwelling. The description of the optimization model provides information on how the value of the variable is computed. The variable is an integer with a low bound of 0. The maximum value of the natural gas consumption is the value of the parameter current natural gas consumption *(G).* This parameter is determined by the input (if known) of the user. If the value of the parameter is not known, the value is determined by the predicting equation (see Section 6.1.2.3). The value of the variable *In_g* can decrease over time (years) based on the implemented modifications (increase insulation and heating type). An example of the output of this variable can be seen in Figure 53. In this example, it can be seen that the value for the variable *In_g* decreases over time when a different heating technique and insulation level are implemented.

Installation electricity (*In_e)*

This variable describes the electricity consumption in kWh of a dwelling per year. A dwelling already consumes electricity for the use of daily appliances. But the value of the variable per year is influenced by the parameter current electricity consumption (*E)*, which heating technique is used and the level of insulation of the dwelling. The description of the optimization model provides information on how the value of the variable is computed.

The variable is an integer with a low bound of 0, which means the value cannot be negative. The variable has a starting value of the parameter current electricity consumption (*E)* which is the amount of electricity that is used for (non-heating) electrical appliances. If electrical heating techniques are implemented, the value of the variable can increase due to an increase in needed electricity that is consumed by the electricity network. If solar panels and/or increased insulation for electric heating are implemented, the value of the variable can decrease, due to the decrease of needed electricity that is consumed by the electricity network. An example of the output of this variable can be seen in Figure 53. In this example, it can be seen that the value for the variable *In_e* decreases over time due to a change in *Heating_type*, *Insu_type* and *Solar_type*. . In this example, it can be seen that the value for the variable *In_e* decreases over time due to a change in *Heating_type*, *Insu_type* and *Solar_type*.



Heating_type	Insu_type	Solar_type	Year	H_status	I_status	S_tech	S_insu	In_g	In_e
A	C	F	1	0.0	0.0	0.0	0.0	1084.0	2987.0
		F	2	0.0	0.0	0.0	0.0	1084.0	2987.0
		F	3	0.0	0.0	0.0	0.0	1084.0	2987.0
B	D	G	4	1.0	1.0	1.0	1.0	1.0	2899.0
		G	5	1.0	1.0	0.0	0.0	1.0	2899.0
		G	6	1.0	1.0	0.0	0.0	1.0	2899.0

Figure 53: Example of the values of the variables Heating status, Insulation status, switch heating technique, Switch insulation, Installation natural gas and installation electricity. The values of the variables Installation natural gas and installation electricity are outlined in red.

Heating status (*H_status*)

The variable H_status is a binary variable that indicates which heating technique is used. Per technique, 2 types of heating can be used which are A (heating with natural gas) or B (natural gas free heating system). Each of these heating types has two states, which are “is used” or “is not used”, which is described by this variable, as can be seen in Equation 11. Based on the state of these systems, the required energy consumption will be determined.

Equation 11: States of variable "Heating status"

$$\mathrm{H\_status} = \begin{cases} 0\ is\ not\ used \\ 1\ is\ used \end{cases}$$

Insulation status (*I_status)*

The variable *I_status* is a binary variable that indicates which insulation level is used. There are two levels, which are C (current insulation level) and D (insulation level B). As can be seen in Equation 12, the variable has two states per insulation level, which are "is used" or "is not used". Based on the state of the insulation level, the required energy consumption will be determined.

Equation 12: States of variable "Insulation status"

$$I\_status = \begin{cases} 0\ is\ not\ used \\ 1\ is\ used \end{cases}$$

Switch technique (*S_tech*)

The variable *S_tech* is a binary variable that indicates whether the technique of a dwelling has been changed compared to the previous year, see Equation 13. If *S_tech* is 1, the technique shifts to the different heating technique, which means that the homeowner needs to pay investment costs for the installation of the technique.

Equation 13: Sates of variable "Switch heating technique"

$$S\_tech = \begin{cases} 0\ remain\ on\ the\ same\ situation\ as\ the\ previous\ year \\ 1\ shift\ to\ new\ situation\ compared\ to\ previous\ year \end{cases}$$

Switch insulation level (*S_insu*)

The variable *S_insu* is a binary variable that indicates whether the insulation of a dwelling has been changed compared to the previous year, see Equation 14. If *S_insu* is 1, the insulation level is improved, to level D or B. When this improvement of insulation is installed, the homeowner needs to pay the investment cost.

Equation 14: Sates of variable "Switch insulation level"

$$S\_insu = \begin{cases} 0\ remain\ on\ the\ same\ situation\ as\ the\ previous\ year \\ 1\ shift\ to\ new\ situation\ compared\ to\ previous\ year \end{cases}$$

6.1.1.3. Constants

The constants are the input values of the model that will stay constant independent of the user input and the optimization. The constant values are based on the collected data of the limited cost-benefit analysis, see Chapter 4. The constants that are used in the optimization models are shown in Table 62.

Table 62: Constants of the optimization model

Constant	Name constant	Value	Constant	Name constant	Value
WP per solar panel	Solar_WP_p	345	Yield solar panels	Y_solar	0,85
Share of natural gas used for heating	E_for_heat	0,8	Change energy consumption heating due to heat recovery	Ch_E_WTW	0,90
Conversion of natural gas to electricity	OMF_G_W	0,03168	COP air-to-water heat pump	COP_A_HP	4,5
COP hybrid heat pump	COP_H_HP	3,5	COP ground heat pump	COP_G_HP	5,5
COP booster heat pump	COP_B_HP	2,7	Share of natural gas used for heating tap water	E_for_water	0,15

Investment CW4	CW4	2160	Investment CW5	CW5	2580
Investment mechanical ventilation	Mech_vent	2745	Investment CW6	CW6	3300
kWh for cooking	E_cooking	175	Reinvestment costs mechanical ventilation	Mech_vent_re	350
Conversion of natural gas to electricity	OMF_G_E	9,769	Investment cost of solar panels per Wp	Solar_eu_Wp	1,26
COP ground heat pump	COP_G_HP	5	Investment cost for increasing electricity connection 3x25	Elec_connect_3x25	314,79
Investment costs electric cooking	Inv_elec_cooking	1045	Investment cost replace fuse box	Elec_connect_fuse	900
Max connection costs district heating	Max_connect_DH	4959,14	Max connection cost per meter >25 meter	Max_connect_25	224.49
Investment costs heat recovery	WTW_eu_p	4645	Low-temperature radiator pr radiator	lt_radiator	1100
Investment cost booster heat pump	Inv_Boost_HP	2392	Required W heat pump per W/m2	Req_Watt	55
Investment cost of air-to-water heat pump	Inv_AHP	10381	Investment hybrid heat pump	Inv_hHP	8386
Change cost low in 2023 hybrid heat pump	DevL_hHP_23	0,685	Change cost low in 2036 hybrid heat pump	DevL_hHP_36	0,506
Change cost low in 2023 air-to-water heat pump	DevL_AHP_23	0,734	Change cost low in 2036 air-to-water heat pump	DevL_AHP_36	0,572
Change cost low in 2040 air-to-water heat pump	DevL_AHP_40	0,5	Change cost low in 2023 ground heat pump	DevL_gHP_23	0,734
Change cost low in 2036 ground heat pump	DevL_gHP_36	0,572	Change cost low in 2040 ground heat pump	DevL_gHP_40	0,5
Change cost low in 2023 LT radiator	DevL_LT_23	0,916	Change cost low in 2036 LT radiator	DevL_LT_36	0,812
Change cost low in 2023 natural gas boiler	DevL_g_23	0,867	Change cost low in 2036 natural gas boiler	DevL_g_36	0,746
Subsidy district heating	Sub_DH	3325	Subsidy heat pump	Sub_HP	0,7
Subsidy insulation	Sub_insu	0,7	Maintenance cost boiler (p/y)	Main_boil	153
Maintenance cost of mechanical ventilation	Main_vent_mech	48	Maintenance cost heat recovery ventilation	Main_vent_WTW	66
Maintenance cost of solar panels fixed	Main_sol_fix	90	Maintenance cost of solar panels per panel	Main_sol_pp	2
Maintenance cost hybrid heat pump	Main_HHP	175,68	Maintenance cost of air-to-water heat pump	Main_AHP	119,88
Maintenance cost ground heat pump	Main_GHP	100,32	Replacement cost of electric cooking	Rep_cook	600
Replacement cost ventilation with heat recovery	Rep_WTW	600	Replacement cost solar panels	Rep_solar	1100
Replacement cost of electricity connection	Rep_elec	900	Replacement cost booster heat pump	Rep_boost	2392
Replacement cost mechanical ventilation	Rep_vent	450	Standard discount rate	Disc1	2.25%
Discount rate for fixed, sunk costs	DiscF1	1.6%			

6.1.2. Optimization model description

The UML activity diagram about finding the optimal implementation of a heating technique is documented in Figure 54. All steps are automatically executed by the model unless stated otherwise. The steps that are shown in the diagram and are further explained below. In the diagram, it can be seen in which order the functions need to be executed and if a function

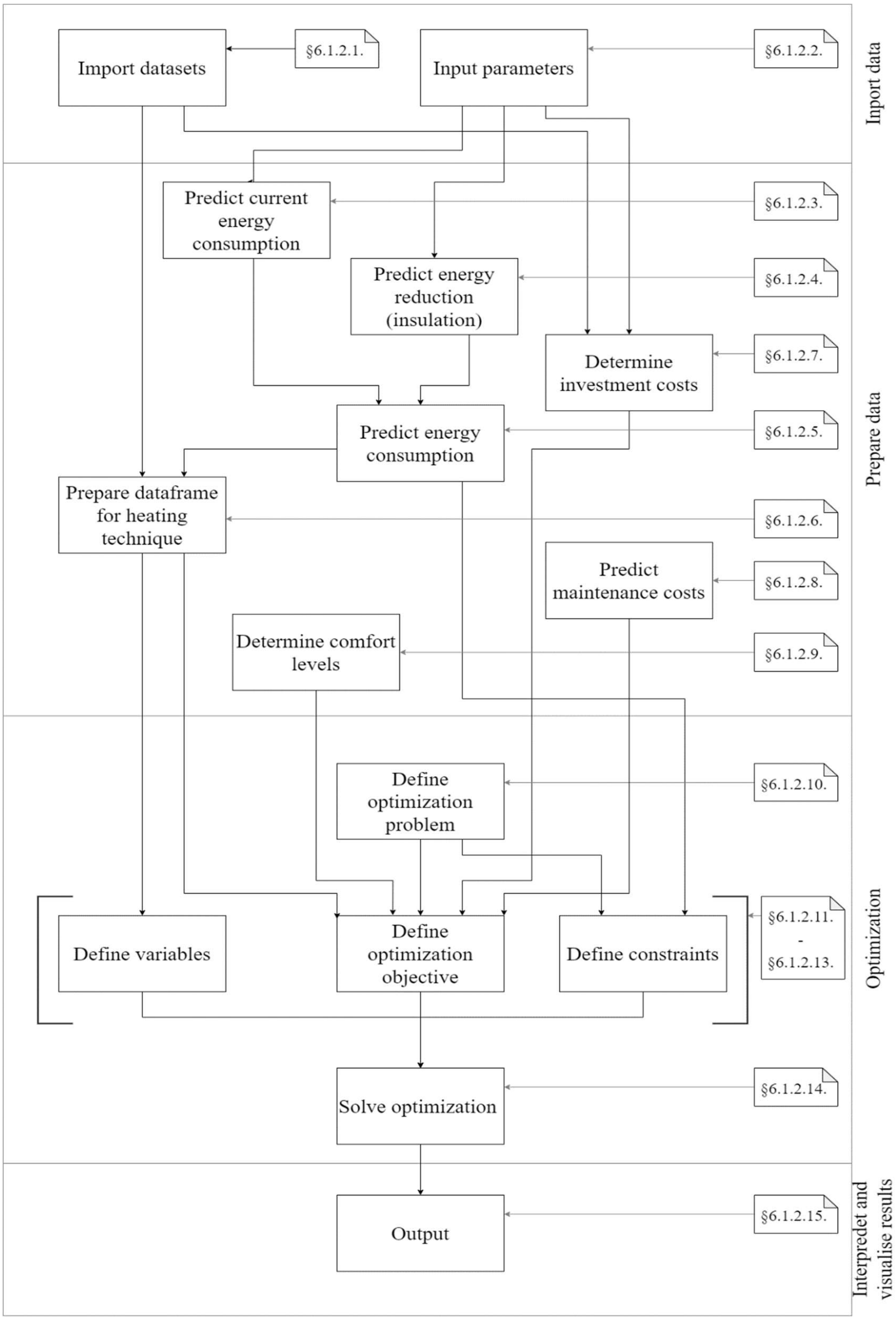


Figure 54: Diagram of finding the optimal implementation of a heating technique

needs inputs from previous functions. For the model, the following Python packages are used: *Pandas, PuLP, Pyomo, seaborn, time, os, Matplotlib.pyplot, Math* and *Numpy*.

6.1.2.1. Import datasets

The model uses different input CSV datasets, which are imported at the start of the script. The model imports four datasets which are shown in Table 63, and they are described below.

Table 63: Datasets that are imported into the model

Name of the datasets	Index	Dataset includes
Heating_technique	Year, heating type and insulation type	- Max capacity of natural gas - Max capacity of electricity - Variable natural gas cost (scenario low, medium and high) - Fixed natural gas cost (scenario low, medium and high) - Variable electricity cost (scenario low, medium and high) - Fixed electricity cost (scenario low, medium and high) - Variable heat cost (scenario low, medium and high) - Fixed heat cost (scenario low, medium and high) - CO_2 emission natural gas - CO_2 emission electricity - CO_2 emission heat
Label_jump_energy_reduction	Current energy label	- Change in energy consumption for heating per insulation label improvement.
Insulation_investment	Insulation label, type of dwelling and construction year	- The investment cost for the insulation label improvement to label D and label B. Investment costs are based on the properties of the dwelling.
Price_reduction	Year	- The expected price reduction of the investment in insulation (scenario low and high).

6.1.2.2. Input parameters

The user of the optimization model can influence the model using the input parameters. There are 18 input parameters which are shown in Table 64. The parameters include the properties of the dwelling and scenario selection. For the scenario selection, the user can decide for which scenario of the development of natural gas price, electricity price and investment costs are assumed for the optimization model.

Table 64: Input parameters optimization model

Input parameter	Name	Label
Housing type	Housing_type	Terraced house Semi-detached house Corner house Detached house
Construction year	Constr_year	Before 1946 1946-1964 1965-1974 1975-1991 1992-2004 2005-2018
Household size	Household_size	1 person 2 persons

		3 persons 4 persons 5 persons or more
Floor size	Floor_size	
Energy label	Energy_label	A B C D E F G
Current natural gas consumption	Current_gas_consumption	
Current electricity consumption	Current_electrcicty_consumption	
Type of roof	T_roof	Flat Slanted
Length of the roof	L_roof	
Width of the roof	W_roof	
Height of the roof	H_roof	
Distance to district heating network	D_net	
Price reduction due to increase in cluster size of district heating cluster	Red_DH_cl	
Development of the natural gas price	G_price	L M H
Development of the electricity price	E_price	L M H
Development of the investment costs	Dev_cost	Low High
Year heat price detaches from natural gas price	D_heat_price	
Number of dwellings in the cluster	Nr_ dwellings	
Incorporate discount rate	Discount	Yes No

6.1.2.3. *Predict current energy consumption*

If the user does not provide the natural gas and/or electricity consumption as an input parameter (which means current natural gas/electricity consumption = 0) the model needs to predict this. To create this predicting function for the energy consumption, a regression analysis has been executed which is described in Section 4.2.1. These predicting equations (Equation 2 and Equation 3) use the dwelling properties to predict the natural gas and electricity consumption. Before the equations can be executed, first, the input data of the parameters housing type, construction year and household size need to be transformed. In Listing 1, an example is given of how the data for the parameter *housing_type* is prepared. This is also done for the parameters *constr_ year* and *household_size*. After the data is prepared, the predicting equations can be executed and the output of the function is the integer predicted natural gas and electricity consumption. This function is executed for every dwelling, to make sure that the current energy consumption is predicted per dwelling using the dwelling-specific properties. This is done using a for loop, in Figure 55 a flowchart of a for loop is shown. The input is the lists containing the dwelling properties and

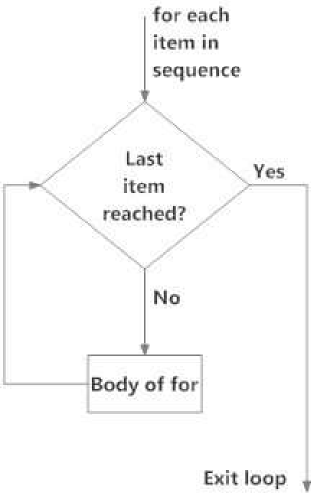


Figure 55: Flowchart of for loop in Python (Programiz, n.d.)

the output of the function are two lists, one containing the current natural gas consumption per dwelling and the other containing the current electricity consumption per dwelling.

Listing 1: Pseudocode of the data preparation for the parameter housing type

```
Data preparation for the parameter housing type
Terraced house = 0
Semi-detached house = 0
Corner house = 0
Detached house = 0
If housing type == “Terraced” then
        Terraced house = 1
    Elif housing type == “Semi_detached_house” then
        Semi-detached house = 1
    Elif housing type == “Corner_house” then
        Corner house = 1
    Else
        Detached house = 1
```

6.1.2.4. *Predict energy reduction due to insulation label jump*

The goal of the function *energy_reduct_label_jump* is to determine the energy reduction for the heating of a dwelling due to the change in insulation label. The input of this function is the input parameter *Energy_label* and the dataset *Label_jump_energy_reduction.* The input parameters have a string value which is the current energy label of the dwelling (for example “G”). With this label, the correct value can be selected from the data frame. The output of this function is the change in energy consumption due to an improvement in the insulation label for a label jump to insulation labels B and D. For this function, a for loop per dwelling in the cluster is used to predict the *energy_reduct_label_jump* per dwelling. In Listing 2, the pseudocode for the prediction of energy reduction due to insulation label jump is shown.

Listing 2: Pseudocode for the prediction of the energy reduction due to the jump in insulation label

```
Predict energy reduction due to insulation label jump
Energy_reduct_LBs = [ ]
Energy_reduct_LDs = [ ]

for Energy_label in Energy_labels then
    if Energy_label =="G" or Energy_label =="F" or Energy_label =="E" or Energy_label =="D" or
    Energy_label=="C" then
        Energy_reduct_B = float((Energy_reduction_df["Label_x_to_B"])[Energy_label])
        Energy_reduct_D = float((Energy_reduction_df["Label_x_to_D"])[Energy_label])
    else
        Energy_reduct_B = 1
        Energy_reduct_D = 1

    Energy_reduct_LBs.append(Energy_reduct_B)
    Energy_reduct_LDs.append(Energy_reduct_B)
```

6.1.2.5. *Predict energy consumption*

In the previous functions, only the current energy consumption has been predicted, but the optimization model will optimize over a period of 30 years which means that the energy consumption needs to be known over that period of time. The current function, *df_energy_cons*, will create a data frame including the natural gas, electricity and heat consumption, based on the current energy consumption of the dwelling. The index of the created data frame is year. In the case that the energy demand does change depending on the interventions, alternative energy consumption needs to be predicted. To understand for which scenarios the energy consumption per heating technique needs to be predicted, an overview of combinations has been created in Figure 56. It can be seen there can be differentiated whether the old or new heating technique is implemented, the old or new insulation label is used and whether or not solar panels are implemented.

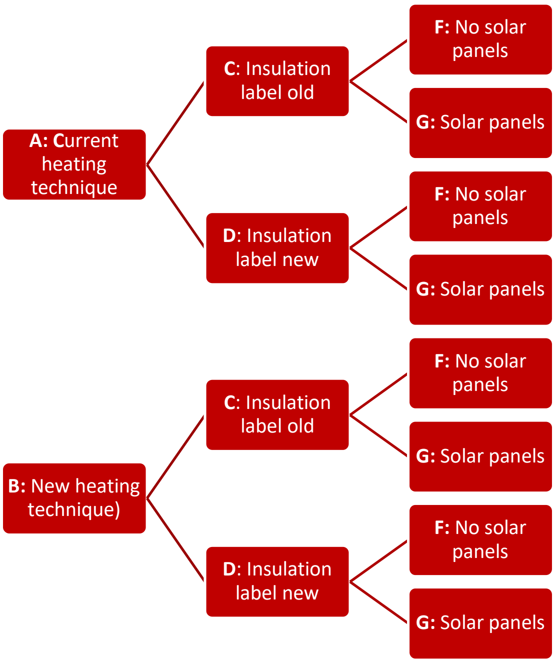


Figure 56: Overview of the index with combinations of implementation per technique

Before the energy consumption per technique can be predicted, first the energy consumption per heating installation needs to be predicted per dwelling. This is done using the assumptions and methods described in Chapter 4. In Listing 3, the pseudocode of the prediction of the energy consumption/production of the different installations is used. The output of this code is used for the prediction of the energy consumption per heating technique per dwelling, of which the pseudocode is described in Listing 4. It can be seen that energy consumption is separately predicted per energy type. Energy consumption for electricity has the most different types because this energy source is implemented for every technique. The values of the constants used for this equation are based on the collected data from Chapter 4. The function is executed for every dwelling in the housing cluster. The pseudocode in Listing 5 shows how the results of every iteration of the loop are separately saved per dwelling.

Listing 3: Energy consumption/production of the different installations

Energy consumption/production of the different installations

Determine electricity production solar panels

```
if T_roof == 1 then
    Nr_panel = int(((L_roof * 100)-200+70)/170)* int(((W_roof*100)-200 + 20)/185)
else:
    Nr_panel = int(((L_roof*100) – 100) /100) * int((((math.sqrt((0.5 * W_roof) **2 + (H_roof)**2)) *100) -100)/165) * 2
E_solar=(Nr_panel * WP_solar * Y_solar)
```

Determine electricity consumption air-to-water heat pump	E_air_HP = (G2 * E_for_heat * Ch_E_WTW * OMF_G_E)/COP_A_HP + (G*0.15*9.769)/COP_B_HP)
Determine electricity consumption booster heat pump	E_boost_HP = (G * E_for_water * OMF_G_E)/COP_B_HP
Determine electricity hybrid heat pump	E_hybr_HP = (G2 * E_for_heat * OMF_G_E * 0.85)/COP_H_HP
Determine electricity consumption ground heat pump	E_ground_HP = (((G2 * E_for_heat * Ch_E_WTW * OMF_G_E)/5.5) + (G*0.15*9.769)/3.75)

Listing 4: Preparation data prediction energy consumption per implementation of a technique

Data preparation natural gas consumption	
Gas consumption when energy label B is implemented	G2 = **int**(G * Energy_reduct_LB)
Gas consumption when energy label D is implemented	G3 = **int**(G * Energy_reduct_LD)
Gas consumption when a hybrid heat pump and energy label B are implemented	G2H = **int**((G2 * E_for_heat *0.15 *0.95) + G * E_for_water)

Data preparation electricity consumption	

Electricity consumption when solar panels are implemented	**if** (E - E_solar)<0.1 **then**
	    ES = **int**(0)
	else:
	    ES = **int**(E - E_solar)

Electricity consumption when the heating technique district heating 1 is implemented (this includes current energy consumption, electricity for electric cooking and ventilation).	ED1_1 = **int**(E + E_cooking + E_vent)

Electricity consumption when the heating technique district heating 1 and solar panels are implemented (this includes current energy consumption, electricity for ventilation, and electricity for electric cooking minus the electricity produced by the solar panels).	**if** (E + E_cooking + E_vent - E_solar)<0.1 **then**
	    ED1_2 =**int**(1)
	    Nr_panel_DH1 = **int**((E + E_cooking)/(WP_solar * Y_solar))
	else
	    ED1_2 = **int**(E + E_cooking + E_vent - E_solar)

Electricity consumption when the heating technique district heating 2 is implemented (this includes current energy consumption, electricity for electric cooking, ventilation with heat recovery, and the booster heat pump).	ED2_1 = **int**(E + E_cooking + E_boost_HP + E_WTW)

Electricity consumption when the heating technique district heating 2 with solar panels is implemented (this includes current energy consumption, electricity for electric cooking, ventilation with heat recovery, and the booster heat pump minus the electricity produced by the solar panels).	**if** (E + E_cooking + E_boost_HP + E_WTW + 680 - E_solar)<0.1 **then**
	    ED2_2 = **int**(1)
	    Nr_panel_DH2 = **int**((E + E_cooking + E_boost_HP + E_WTW + 680)/(WP_solar * Y_solar))
	else:
	    ED2_2 = **int**(E + E_cooking + E_boost_HP + E_WTW + 680 - E_solar)

Electricity consumption when the heating technique baseline alternative with hybrid heat pump is implemented (this includes	EH1_1 = **int**(E + E_hybr_HP + E_vent)

current energy consumption, electricity for ventilation and the hybrid heat pump).

Electricity consumption when the heating technique all-electric 1 is implemented (this includes current energy consumption, electricity for electric cooking, ventilation with heat recovery, and the air-to-water heat pump).

```
EA1_1 = int(E + E_cooking + E_air_HP + E_WTW)
```

Electricity consumption when the heating technique all-electric 1 with solar panels is implemented (this includes current energy consumption, electricity for electric cooking, ventilation with heat recovery, and the air-to-water heat pump minus the electricity produced by the solar panels).

```
if (E + E_cooking + E_air_HP + E_WTW - E_solar)<0.1 then
        EA1_2 =int(1)
        Nr_panel_AL1 = int((E + E_cooking + E_air_HP + E_WTW)/(WP_solar * Y_solar))
else:
        EA1_2 =int(E + E_cooking + E_air_HP + E_WTW - E_solar)
```

Electricity consumption when the heating technique all-electric 2 is implemented (this includes current energy consumption, electricity for electric cooking, ventilation with heat recovery, and the ground heat pump).

```
EA2_1 = int(E + E_cooking + E_ground_HP + E_WTW)
```

Electricity consumption when the heating technique all-electric 2 with solar panels is implemented (this includes current energy consumption, electricity for electric cooking, ventilation with heat recovery, and the ground heat pump minus the electricity produced by the solar panels).

```
if (E + E_cooking + E_ground_HP + E_WTW - E_solar)<0.1 then
        EA2_2 =int(1)
        Nr_panel_AL2 = int((E + E_cooking + E_ground_HP + E_WTW)/(WP_solar * Y_solar))
else
    EA2_2 =(E + E_cooking + E_ground_HP + E_WTW - E_solar)
```

Data preparation heat consumption

Heat consumption when district heating is used.

```
H = int(G * E_for_heat * OMF_G_W) + int(G * E_for_water * OMF_G_W)
```

Heat consumption when district heating is used and the insulation level is improved to level B. HB is the heat consumption with mechanical ventilation and HBWTW is the heat consumption with ventilation with heat recovery.

```
HB = int(G2 * E_for_heat * OMF_G_W) + int(G * E_for_water * OMF_G_W)
HBWTW = int(G2 * E_for_heat * OMF_G_W*Ch_E_WTW*0.75) + int(G*E_for_water*OMF_G_W*0.75)
```

Listing 5: Pseudocode of creating data lists for the output of the function df_energy_cons

```
Create data lists for energy consumption per dwelling
  name = "df_" + str(Dwelling)
  data_list[name] = df2
```

6.1.2.6. Prepare data frame with information for the heating technique

In the first stage, different data frames have been imported, and the data of the data frame with information on the heating techniques (Heat_type) need to be prepared (to Heat_type1) before it can be used in the optimization model. The imported data frame includes the fixed and variable costs of natural gas and electricity for the scenarios low, medium and high. In this function, first, the values of the input parameters of the development of the natural gas price (*G_price)* and the development of the electricity price (*E_price)* are labelled according to the labels in the Heat_type data frame. Based on the scenario selected by the user, for the development of the energy price, the matching fixed and variable costs have been selected and a data frame is created including the *max capacity*, *variable natural gas, electricity* and *heat costs, fixed natural gas, electricity* and *heat costs* and the *CO_2 emission of natural gas, electricity* and *heat* for the index year, heating type, insulation type and solar panels. It can be seen that the scenario of the heat costs is also determined by *G_price* because the heat price is currently still fixed to the natural gas price. The CO_2 emission for heating with natural gas, electricity and heat are added to the data frame for the optimization model for CO_2 emission per technique. In Listing 6, four pseudocode elements for the function *Crea_heat_type1* are shown. In the first element, it is shown how the right scenarios for the energy price are selected based on the user input. After the data is prepared, the data frame Heat_type1 is created, which is shown in the second pseudocode element of Listing 6. In the third element, the detachment of the heat price is incorporated based on the user input (*Detch_heat_price*). The last element in the Listing is the discount rate and the discount rate for fixed, sunk costs is incorporated, which is applied using the same method for the other created fixed and variable costs.

Listing 6: Pseudocode of elements of the function Crea_heat_type1

(1) Data preparation for the parameter variable natural gas price *(V_G_Price)*

```
V_G_price = "Var_gas_cost_"+ G_price
F_G_price = "Fix_gas_cost_"+ G_price
F_GH_price = "Fix_gas_costH_"+G_price
V_E_price = "Var_elec_cost_"+ E_price
F_E_price = "Fix_elec_cost_"+ E_price
V_H_price = "Var_heat_cost_"+ G_price
```

(2) Creation of data frame Heat_type1

```
dataframe = pd.DataFrame(Heat_type, columns = ["Max_Capacity_gas", V_G_price, F_G_price, F_GH_price,
        V_E_price, F_E_price,V_H_price,"Fix_heat_cost","CO2_Gas","CO2_Elec","CO2_Heat"])
Heat_type1 = dataframe.rename(columns"Max_Capacity_gas": "Max_capacity", V_G_price: 'Var_gas_cost',
        F_G_price: "Fix_gas_cost", F_GH_price: "Fix_gasH_cost", V_E_price: "Var_elec_cost", F_E_price:
        "Fix_elec_cost", V_H_price: "Var_heat_cost"}, index={'ONE': 'Row_1'})
```

(3) Detachment of the heat price

```
DHP = (Detch_heat_price - 2021)*8
Heat_type1["Var_heat_cost"].mask(Heat_type1["Var_heat_cost"] > Heat_type1["Var_heat_cost"].iloc[DHP],
Heat_type1["Var_heat_cost"].iloc[DHP], inplace=True)
```

(4) Discount rate variable and fixed energy costs

```
Heat_type1 = Heat_type1.reset_index(drop=False)
Heat_type1["Var_gas_cost"] = Heat_type1["Var_gas_cost"]/((1+Disc)**Heat_type1["Year"])
Heat_type1["Fix_gas_cost"] = Heat_type1["Fix_gas_cost"]/((1+DiscF)**Heat_type1["Year"])
```

6.1.2.7. Predict investment costs

The prediction of the investment costs consists of two functions, which are, to predict investment costs of the improvement of insulation *Inv_insu* and predict investment costs of the installation, for example for an all-electric heating technique *Invest_AL1*. These two functions are the last in the data preparation phases before the optimization. In these functions, the required investment costs are predicted per dwelling for which a for loop is used.

The first function, *Inv_insu* predicts the investment costs of the improvement of insulation. The function uses the data set insulation level and selects the correct values out of this data set using the input parameters *Energy_label*, *Housing_type* and *Constr_year*. Furthermore, the selected investment costs per m^2 are multiplied by the *Floor_size*. In addition, the total investment costs for improving the insulation level are also adapted to the scenario selected by the user. In the first element of Listing 7, the pseudocode is shown for the calculation of *Inv_insu* using the prepared input parameters and the dataset. After this, the data frame is adjusted to the subsidies for insulation, to the selected scenario of the development of the investment cost and discount rate using the input of the dataset *Price_reduction_insu*. The investment costs for ventilation are calculated for the label jump to insulation label D, to insulation label B and from label D to label B.

The second function (for example *Invest_AL1*) predicts the investment costs for the implementation of the all-electric technique. For the investment costs of the all-electric heating technique, the costs of a heat pump, low-temperature radiators, the increase in the electrical connection and heat recovery ventilation are taken into account based on the assumptions of Chapter 4. In the second element of Listing 7, the calculation of the investment costs of solar panels is shown. The number of panels is calculated based on the type of roof and the input parameters *Length_roof, Width_roof* and *Height_roof* in Listing 4. The investment costs are calculated based on the number of solar panels per technique, since the electricity consumption differentiates per technique. The formulas and constants are explained in Chapter 4. In this function also the change in investment costs of a technique based on the size of the heating cluster is incorporated. The optimization model will be allowed to switch the heating type at two moments in time (2023 and 2036). This is done to reduce the freedom of the optimization model and make the scenarios more realistic. The switching moments (2023 and 2036) have been chosen because these are assumed moments the natural gas boiler needs to be replaced which makes them “natural” switching moments in time and the model more realistic. Based on the selected development scenario that the user has selected for the price development, this investment cost can be different based on the moment of investment. Therefore, the investment costs are predicted per heating technique and year of investment. In the third part of Listing 7, the pseudocode for the investment costs of the ventilation with heat recovery per year is shown. In the fourth element, it is shown how the required drilling depth for the ground heat pump is determined based on the required kW and the number of dwellings in the housing cluster. In the fifth element, it can be seen which elements are included to determine the investment costs per heating technique. In the sixth element, the pseudocode is shown for the prediction of the replacement costs. In the seventh element, it is shown how the data frame is created for the investment cost of the heating technique all-electric 1 including the replacement costs.

As has been described in Chapter 4, the different techniques require the replacement of elements after a while. To incorporate the replacement cost, this is predicted per investment year and heating technique. The replacement is separately predicted for the shifting year of the heating technique. An example is when a new technique is implemented in 2036 (instead of 2023) this means that the natural gas boiler needs to be replaced, and some elements do not need to be replaced before 2050 (compared with the investment moment 2023). Furthermore, the replacement costs can be lower based on the selected scenario for the development of the price of the heating technique. From the output of this function, two types of data frames have been created: one containing the investment and replacement costs per heating technique and moment of investment (for example *Inv_AL1*_0) and the other without the replacement costs (*WRInv_AL1_0)*. By using a for loop for this function, the investment costs can be predicted per dwelling in the cluster.

Listing 7: Pseudocode of elements of the functions Investment_insu and Invest_AL1

(1) Determine investment costs for improvement of insulation

```
Inv_conect_insu_select = Insu_invest["Connection_C"]
Inv_insu_m2_select = Insu_invest["per_m2"]
Inv_conect_insu = float(Inv_conect_insu_select[L_Energy_label, L_Housing_type, L_Constr_year])
Inv_insu_m2 = float(Inv_insu_m2_select[L_Energy_label, L_Housing_type, L_Constr_year]) * Floor_size
Inv_insu = int(Inv_conect_insu + Inv_insu_m2)
```

(2) Determine investment costs for solar panels

```
Inv_solar_AL1 = Nr_panel_AL1 * Solar_WP_p * Solar_eu_Wp
```

(3) Determine the investment costs of the heat recovery unit

```
if Housing_type == "Detached_house" then
      Inv_lt_radiator = 7 * lt_radiator
      Inv_vent_WTW = WTW_eu_p * 7
else:
      Inv_lt_radiator = 5 * lt_radiator
      Inv_vent_WTW = WTW_eu_p * 5

Inv_lt_radiator_23 = Inv_lt_radiator * Dev_LT_23
Inv_lt_radiator_36 = Inv_lt_radiator * Dev_LT_36
```

(4) Determine the required drilling depth for the ground heat pump based on the required kW of the ground heat pump and the number of dwellings

```
if sum(kW_gHP[0:6])<14.5 then
   Tot_kW1 = ((sum(kW_gHP[0:Nr_dwellings]))*22.5)/Nr_dwellings
   NR = 1
elif  sum(kW_gHP[0:int(Nr_dwellings/2)])<14.5   and  sum(kW_gHP[int(Nr_dwellings/2):Nr_dwellings])<14.5
then
   Tot_kW1 = (sum(kW_gHP[0:int(Nr_dwellings/2)])*22.5)/Nr_dwellings
   Tot_kW2 = (sum(kW_gHP[int(Nr_dwellings/2):Nr_dwellings]) *22.5)/Nr_dwellings
   NR = 2
else:
   Tot_kW1 = (sum(kW_gHP[0:int(Nr_dwellings/3)])*22.5)/Nr_dwellings
   Tot_kW2 = (sum(kW_gHP[int(Nr_dwellings/3):int(2*(Nr_dwellings/3))]) *22.5)/Nr_dwellings
   Tot_kW3 = (sum(kW_gHP[int(2*(Nr_dwellings/Nr_dwellings)):Nr_dwellings])*22.5)/Nr_dwellings
   NR =3

if NR == 1  then
   Dr_Depth = [Tot_kW1] * Nr_dwellings
elif NR==2:
   Dr_Depth1 = [Tot_kW1] * (int(Nr_dwellings/2))
   Dr_Depth2 = [Tot_kW2] * (int(Nr_dwellings/2))
   Dr_Depth = Dr_Depth1 + Dr_Depth2
else:
   Dr_Depth1 = [Tot_kW1] * (int(Nr_dwellings/3))
   Dr_Depth2 = [Tot_kW2] * (int(Nr_dwellings/3))
   Dr_Depth3 = [Tot_kW3] * (int(Nr_dwellings/3))
   Dr_Depth = Dr_Depth1 + Dr_Depth2 +Dr_Depth3
```

(5) Predict total investment costs per heating technique and moment of investment

```
Invest_DH1_23 = Inv_elec_cooking + Inv_elec_connect + Inv_connect_DH - Sub_DH
Invest_DH1_36 = Inv_elec_cooking + Inv_elec_connect + Inv_connect_DH - Sub_DH
Invest_DH2_23 = Inv_elec_cooking + Inv_elec_connect + Inv_connect_DH - Sub_DH + Inv_Boost_HP * Sub_HP+
                Inv_lt_radiator_23
Invest_DH2_36 = Inv_elec_cooking + Inv_elec_connect + Inv_connect_DH - Sub_DH + Inv_Boost_HP *Sub_HP+
                Inv_lt_radiator_36
Invest_G_36H = Inv_elec_connect + Inv_hHP_23
Invest_AL1_23 = Inv_elec_cooking + Inv_AHP_23 + Inv_lt_radiator_23 + Inv_elec_connect
Invest_AL1_36 = Inv_elec_cooking + Inv_AHP_36 + Inv_lt_radiator_36 + Inv_elec_connect
Invest_AL2_23 = Inv_elec_cooking + Inv_gHPN_23 + Inv_lt_radiator_23 + Inv_elec_connect
Invest_AL2_36 = Inv_elec_cooking + Inv_gHPN_36 + Inv_lt_radiator_36 + Inv_elec_connect
```

(6) Predict the replacement cost per heating technique and moment of investment

```
Rep_G_36 = Inv_g_boiler23/((1+Disc)**(3))

Rep_DH1_23 = Rep_solar/((1+Disc)**(3+15))  + Rep_elec/((1+Disc)**(3+25)) + Rep_cook/((1+Disc)**(3+15)) +
Rep_vent/((1+Disc)**(3+18))
Rep_DH1_36 = Inv_g_boiler23/((1+Disc)**(3))

Rep_DH2_23 = Rep_solar/((1+Disc)**(3+15)) + Rep_elec/((1+Disc)**(3+25)) + (Rep_cook+
Rep_boost)/((1+Disc)**(3+15)) + (Rep_WTW)/((1+Disc)**(3+18))
Rep_DH2_36 = Inv_g_boiler23/((1+Disc)**(3))

Rep_AL2_23 = Rep_solar/((1+Disc)**(3+15))  + Rep_elec/((1+Disc)**(3+25)) + Rep_cook/((1+Disc)**(3+15)) +
(Rep_WTW + Rep_GHP_36 )/((1+Disc)**(3+18))
Rep_AL2_36 = Inv_g_boiler23/((1+Disc)**(3))

Rep_AL1_23 = Rep_solar/((1+Disc)**(3+15))  + Rep_elec/((1+Disc)**(3+25)) + Rep_cook/((1+Disc)**(3+15)) +
(Rep_WTW + Rep_AHP36)/((1+Disc)**(3+18))
Rep_AL1_36 = Inv_g_boiler23/((1+Disc)**(3))
```

(7) Create a data frame for the investment costs of AL1 including the replacement costs

```
df_X_1 = {"Inv": [1000000] * 3 * 8}
df_AL1_2 = {"Inv": [Invest_AL1_23+Inv_solar+Rep_AL1_23] * 8}
df_X_3 = {"Inv": [1000000] * 12 * 8}
df_AL1_4 = {"Inv":[Invest_AL1_36+Inv_solar+Rep_AL1_36] * 8}
df_X_5 = {"Inv":[1000000] * 14 * 8}

df_X_1 = pd.DataFrame(df_X_1, columns = ["Inv"])
df_AL1_2 = pd.DataFrame(df_AL1_2, columns = ["Inv"])
df_X_3 = pd.DataFrame(df_X_3, columns = ["Inv"])
df_AL1_4 = pd.DataFrame(df_AL1_4, columns = ["Inv"])
df_X_5 = pd.DataFrame(df_X_5, columns = ["Inv"])

df_AL1 = [df_X_1, df_AL1_2, df_X_3, df_AL1_4, df_X_5]
df_AL1_C = pd.concat(df_AL1)

df_AL1_C = df_AL1_C.reset_index(drop=True)
Inv_AL1 = pd.concat([INDEX, df_AL1_C], axis=1, join="inner")

Inv_AL1 = pd.DataFrame(Inv_AL1, columns = ["Year", "Heating_tech", "Insu_type", "Solar_type","Inv" ])
```

```
Inv_AL1.set_index(["Year", "Heating_tech", "Insu_type", "Solar_type"], inplace=True)

name= "Inv_AL1_"+str(i)
Invest_AL1[name]=Inv_AL1
```

6.1.2.8. *Predict maintenance costs*

As described in Chapter 4, every heating technique contains maintenance costs. These costs are different based on which technique is implemented and how (for example the number of solar panels). The function *Predict_maintenance_cost* predicts these costs per dwelling of the cluster per heating technique. The pseudocode for the prediction of the maintenance cost of all-electric is shown in Listing 10. The function is looped per dwelling of the housing cluster. The outputs are lists which contain the maintenance costs per heating technique and a data frame containing the maintenance cost per heating technique over a period of 30 years.

Listing 8: Pseudocode of the function predict maintenance costs

Pseudocode predict maintenance costs of the technique all-electric 1

```
Main_AL1_VSHP = [ ]
Main_AL1_VHP = [ ]

for Nr_panel in Nr_panels:

        Main_AL1_VSHP1 = Main_vent_WTW + Main_sol_fix + Main_sol_pp * Nr_panel + Main_AHP
        Main_AL1_VHP1 = Main_vent_WTW + Main_AHP
        Main_AL1 = {"AL1": ([Main_G_B1] + [Main_G_BS1] + [Main_G_BWTW1] + [Main_G_BWTWS1] +
        [Main_AL1_VHP1] + [Main_AL1_VSHP1] + [Main_AL1_VHP1] + [Main_AL1_VSHP1]) * 31}
        Main_AL1 = pd.DataFrame(Main_AL1, columns = ["AL1"])

        Main_AL1 = Main_AL1.reset_index(drop=True)
        Main = pd.concat([Index, Main_AL1, Main_AL2, Main_DH1, Main_DH2], axis=1, join="inner")
        Main = pd.DataFrame(Main, columns = ["Year", "Heating_tech", "Insu_type", "Solar_type","AL1",
"AL2",  "DH1", "DH2" ])
        Main.set_index(["Year", "Heating_tech", "Insu_type", "Solar_type"], inplace=True)

        Main_AL1_VSHP.append(Main_AL1_VSHP1)
        Main_AL1_VHP.append(Main_AL1_VHP1)
```

6.1.2.9. *Determine comfort levels*

For the optimization model in the level of comfort, the input parameters are determined based on the properties of the dwellings of the housing cluster. The comfort level will be determined as described in Chapter 4. In Listing 9, the pseudocode of the function *determine comfort levels* is shown and in Table 65 the explanation of the parameter names is shown. It can be seen that for some parameters the current energy label impacts the current level of insulation for which a for loop is used. Because it is known what the different statuses can be per heating technique, in this function the possible values per comfort parameter are determined. Furthermore, the values are multiplied by the weight to enable the optimization model to predict the optimal implementation of a technique (concerning comfort) taking the importance of the different sub-topics (parameters) into account.

Listing 9: Pseudocode of determining the values of the parameters of the level of comfort

Pseudocode of determining the values of the parameters of the level of comfort

```
Gen_them_c = 1 * 0.1912
Draught_insu_C = 0 * 0.1048
Draught_insu_D = 0.5 * 0.1048
Draught_insu_D_WTW = 1 * 0.1048
Rad_asy_C = [ ]
Temp_grad_C = [ ]
Floor_temp_C = [ ]
Inst_sound_A = [ ]
Amp_int_noise_A = [ ]
Mold_C = [ ]
Pol_vent_air_C = [ ]
Radon_C = [ ]
for Energy_label in Energy_labels:
  if Energy_label == "G" or Energy_label == "F" or Energy_label == "E" then
    Rad_asy_Cx = 0 * 0.0284
    Temp_grad_Cx = 0.5 * 0.0284
    Floor_temp_Cx = 0 * 0.0476
    Inst_sound_Ax = 1 * 0.216
    Amp_int_noise_Ax = 1 * 0.0652
    Mold_Cx = 0 * 0.0466
    Pol_vent_air_Cx = 0 * 0.0292
    Radon_Cx = 0 * 0.0106
  elif Energy_label == "D" or Energy_label == "C" then
    Rad_asy_Cx = 0.5 * 0.0284
    Temp_grad_Cx = 1 * 0.0284
    Floor_temp_Cx = 0.5 * 0.0476
    Inst_sound_Ax = 1 * 0.216
    Amp_int_noise_Ax = 1 * 0.0652
    Mold_Cx = 0.5 * 0.0466
    Pol_vent_air_Cx = 0 * 0.0292
    Radon_Cx = 0 * 0.0106
  else:
    Rad_asy_Cx = 1 * 0.0284
    Temp_grad_Cx = 1 * 0.0284
    Floor_temp_Cx = 1 * 0.0476
    Inst_sound_Ax = 0 * 0.216
    Amp_int_noise_Ax = 0.5 * 0.0652
    Mold_Cx = 1 * 0.0466
    Pol_vent_air_Cx = 1 * 0.0292
    Radon_Cx = 0.5 * 0.0106
  Rad_asy_C.append(Rad_asy_Cx)
  Temp_grad_C.append(Temp_grad_Cx)
  Floor_temp_C.append(Floor_temp_Cx)
  Inst_sound_A.append(Inst_sound_Ax)
  Amp_int_noise_A.append(Amp_int_noise_Ax)
  Mold_C.append(Mold_Cx)
  Pol_vent_air_C.append(Pol_vent_air_Cx)
  Radon_C.append(Radon_Cx)

Rad_asy_D = 1 * 0.0284
Temp_grad_D = 1 * 0.0284
Floor_temp_D = 1 * 0.0476
Amb_noise_A = 0 * 0.1188
Amb_noise_BWTW = 0.5 * 0.1188
Amb_noise_B = 0 * 0.1188
```

```
Inst_sound_B = 0 * 0.216
Amp_int_noise_B = 0.5 * 0.0652
Mold_D = 1 * 0.0466
Pol_vent_air_D = 1 * 0.0292
Comb_gas = 1 * 0.1136
Radon_D = 0.5 * 0.0106
```

Table 65: Meaning of the parameters for comfort

Name of parameter	Explanation
Gen_them	General thermal comfort
Draught_insu	Draught
Rad_asy	Thermal radiation asymmetry
Temp_grad	Temperature gradient
Floor_temp	Floor temperature
Inst_sound	Installation noise
Amp_int_noise	Amplification of internal noise pollution
Amb_noise	Ambient noise
Mold	Mold
Pol_vent_air	Pollution ventilation air
Radon	Combustion gasses
Comb_gas	Radon

6.1.2.10. Define optimization problem

The function, define the optimization problem, defines the optimization problem that needs to be solved. The function is shown in Listing 10. Based on the optimization goal, one of the below-described problems needs to be selected. The goal of the first optimization is to minimize the costs for the implementation of the heating type over a period of 30 years for the technique all-electric 1. The goal of the second is to minimize the CO_2 emission for the implementation of the heating type and the goal of the last optimization is to maximize the level of comfort. PuLP is used for the optimization, which is a linear programming modeller written in Python as described above. The goal of the optimization is to minimize costs. The optimization is executed for the collective heating techniques, for all dwellings in the housing cluster combined. The optimization is executed per dwelling of the cluster (using a for loop) for the optimization of the individual technique (all-electric 1).

Listing 10: Pseudocode of the function define zthe problem

(1) Define problem function AL1 costs

```
def problem_AL1():
        model_AL1 = pulp.LpProblem(“Cost minimising heating type problem AL1”, pulp.LpMinimize)
        return model_AL1
```

(2) Define problem function AL1 CO_2 emission

```
def problem__CO2_AL1():
        model_CO2_AL1 = pulp.LpProblem("Cost_minimising_heating_type_probl", pulp.LpMinimize)
        return model_CO2_AL1
```

(3) Define problem function AL1 comfort level

```
def problem_Com_AL1():
        model_Com_AL1 = pulp.LpProblem("Cost_minimising_heating_type_probl", pulp.LpMaximize)
        return model_Com_AL1
```

6.1.2.11. *Define variables*

The decision variables for the optimization model are created in the function define variables. The decision variables are shown in Listing 11, the variables have been explained in Section 6.1.1.2. It can be seen that numerous variables are binary, they need to indicate whether something appears or not. The variable *Installation_heat* is only implemented in the optimisation models district heating 1 and district heating 2 since the other techniques do not use this energy source.

Listing 11: Pseudocode of define variables function

Create variables function

```
In_g = pulp.LpVariable.dicts("Installation_gas", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type1.index),
lowBound=0,                                   cat='Integer')

In_e = pulp.LpVariable.dicts("Installation_elec", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type.index),
lowBound=0,                                   cat='Integer')

In_h = pulp.LpVariable.dicts("Installation_heat", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type1.index),
lowBound=0,                                   cat='Integer')

H_status = pulp.LpVariable.dicts("Heating_status", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type1.index),
cat='Binary')

I_status = pulp.LpVariable.dicts("Insu_status", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type1.index),
cat='Binary')

S_tech = pulp.LpVariable.dicts("Switch_tech", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type1.index),
cat='Binary')

S_insu = pulp.LpVariable.dicts("Switch_insu", ((Year, Heating_tech, Insu_type, Solar_type) for Year,
                                        Heating_tech, Insu_type, Solar_type in Heat_type1.index),
cat='Binary')
```

6.1.2.12. *Define optimization objective*

The objective function of the optimization model is defined, in the function *define optimization objective*. The objective function for minimizing the investment cost is shown in Listing 12, the objective function for minimizing CO_2 emission is shown in Listing 13 and the objective function for maximizing comfort is shown in Listing 14. In Table 66, the full names of the abbreviated variable names are shown. It can be seen that for the optimization the sum of all costs/CO_2 emission/comfort over a period of 30 years needs to be minimized (or maximized). The different objective functions will separately be described below.

Listing 12 displays the variables for one dwelling. If an individual heating technique is implemented, the optimization is carried out in a for loop per dwelling, as the optimization of this technique has no impact on the optimization of the other dwellings in the cluster. When implementing a collective heating system, the optimal implementation in one dwelling is dependent on the implementation in the other dwellings. This results in a different objective function if the number of dwellings in a cluster increase. To optimize the implementation of the cluster, the same variables are added per dwelling. This means that for two dwellings the objective function contains twice the current function (including unique variables). By expanding the objective function, the size of the housing cluster can increase endlessly. This is not desirable due to limits in computing power and the ability of the model to create realistic results. Therefore the current research creates an optimization model for a cluster that can vary in size between one and five dwellings. A maximum of five dwellings has been selected since this is the maximum number of dwellings which can collectively use the technique district heating 2 (ground heat pump). Furthermore, it is important for the current and following research that the code remains interpretable which will decrease by adding more dwellings to the maximum cluster size.

The first three elements of the cost optimizing function (shown in Listing 12) describe the cost due to the natural gas, electricity and heat consumption, which means that the natural gas, electricity and heat consumption are multiplied by the variable costs per m^3, GJ and kWh for that year (*In_h* is only included in the optimization models for district heating). Elements 4, 5 and 6 describe the fixed costs for natural gas, electricity and heat, when electricity and natural gas are used the binary variable is 1 and the fixed costs are taken into account ("FHC" is only included in the case of district heating). Elements 7 and 8 describe the investment costs when a change in heating type appears. The investment costs for heating type district heating 1, are the investment costs calculated by the function predict investment costs (Section 6.1.2.7). Element 9 describes the maintenance costs per heating technique implementation (combination of the index which has been shown in Figure 56). The predicted maintenance costs of the function *Predict_maintenance_cost* are used in this element. In element 10 the investment costs are described. The investment costs for the improvement in insulation level are predicted in the function *predict_investment_costs*, this includes the development of the cost over time. The investment costs are added per index combination (*Year, Heating_tech, Insu_type and Solar_type).* In the optimization models for the collective techniques, the objective function is expanded with the variables per dwelling, to be able to predict the impact of the change in heating technique per dwelling.

Listing 12: Pseudocode of the objective function minimize costs DH1

Objective function minimize costs DH1

```
Model += minimize∑(
        [In_g[y, h, i, s] * Heat_type1.loc[(y, h, i, s), "VGC"] for y, h, i, s in Heat_type1.index]          (1)
        + [In_e[y, h, i, s] * Heat_type1.loc[(y, h, i, s), "VEC"] for y, h, i, s in Heat_type1.index]        (2)
        + [In_h[y, h, i, s] * Heat_type1.loc[(y, h, i, s), "VHC"] for y, h, i, s in Heat_type1.index]        (3)
        + [H_status[y, h, i, s] * Heat_type1.loc[(y, h, i, s), 'FEC'] for y, h, i, s in Heat_type1.index]    (4)
        + [H_status[y, h, i, s] * Heat_type1.loc[(y, h, i, s), 'FGC'] for y, h, i, s in Heat_type1.index]    (5)
        + [H_status[y, h, i, s] * Heat_type1.loc[(y, h, i, s), 'FHC'] for y, h, i, s in Heat_type1.index]    (6)
        + [S_tech[y, h, i, s] * Invest_DH1["Inv_DH1_"+str(i)].loc[(Y, H, I, S), "Inv"] for y, h, i, s in     (7)
        Heat_tech_A_index]
        + [S_tech[y, h, i, s] * Invest_DH1["Inv_DH1_"+str(i)].loc[(Y, H, I, S), "Inv"] for y, h, i, s in     (8)
        Heat_tech_B_index]
        + [H_status[y, h, i, s] * Main_DH1_V[i] for y, h, i, s in Insu_CF_index2]                           (9)
        + [H_status[y, h, i, s] * Main_DH1_VS[i] for y, h, i, s in Insu_CG_index2]
        + [H_status[y, h, i, s] * Main_DH1_V[i] for y, h, i, s  in Insu_DF_index1]
        + [H_status[y, h, i, s] * Main_DH1_VS[i] for y, h, i, s in Insu_DG_index1]
        + [H_status[y, h, i, s] * Main_G_B[i] for y, h, i, s in Insu_CF_index1]
```

```
        + [H_status[y, h, i, s] * Main_G_BS[i] for y, h, i, s in Insu_CG_index1]
        + [H_status[y, h, i, s] * Main_G_BV[i] for y, h, i, s in Insu_DF_index2]
        + [H_status[y, h, i, s] * Main_G_BVS[i] for y, h, i, s in Insu_DG_index2]
        + [S_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"] +    (10)
        INV_vent[i]+1) for y, h, i, s in Insu_CF_index1]
        + [Switch_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]+1) for y, h, i, s in Insu_CG_index1]
        + [Switch_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]) for y, h, i, s in Insu_DF_index1]
        + [Switch_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]) for y, h, i, s in Insu_DG_index1]
        + [Switch_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]+1) for y, h, i, s in Insu_CF_index2]
        + [Switch_insu1 y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]+1) for y, h, I, s in Insu_CG_index2]
        + [Switch_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]) for y, h, i, s in Insu_DF_index2]
        + [Switch_insu1[y, h, i, s] * (Invest_insu["dataf_"+str(i)].loc[(y, h, i, s), "Invest_insu_Dev"]
+       INV_vent[i]) for y, h, i, s in Insu_DG_index2]
  )
```

Listing 13 displays the variables for one dwelling, The CO_2 optimization model will work similarly for individual and collective heating techniques as the cost optimization objective. The first two elements of the CO_2 emission optimizing function (see Listing 13) describe the CO_2 emission due to the consumption of natural gas, electricity and (in the case of district heating) heat consumption. This means that the natural gas, electricity and heat consumption are multiplied by the CO_2 emission per m^3, GJ and kWh for that year (*In_h* is only included in the optimization models for district heating). Element 3 describes the CO_2 emission for the implementation of a different heating technique and element 4 describes the CO_2 emission of the implementation of the change in insulation level. The goal of the model is to find the optimal implementation of a heating technique by minimizing the CO_2 emission due to energy consumption. For the implementation of the insulation and heating technique, constants have been selected (5000, which is enables the model to shift but disables the model to shift every year). The model will optimize into a reasonable implementation, which means that the heating technique does not change every year. The constants have been chosen because the CO_2 emissions of the separate elements of the different techniques are not known and the goal of the model is to minimize the CO_2 emission due to energy consumption. Although the implementation of the techniques and the insulation constants have been selected, the CO_2 emission due to the implementation of solar panels is taken into account in the model. For this optimization model, the implementation of solar panels is optional as opposed to a change in insulation and heating technique. This emission is taken into account by multiplying *S_insu* by *Emis_insu_CO2_AL1S* instead of *Emis_insu_CO2_AL1* in the case solar panels are implemented.

Listing 13: Pseudocode of the objective function minimize CO_2 emission AL1

```
Objective function minimize CO2 emission AL1
model_CO2_AL1 += minimize∑(
        [In_g [Y, H, I, S] * Heat_type1.loc[(Y, H, I, S), "CO2_Gas"]  for Y, H, I, S in Heat_type1.index]   (1)
        + [In_e [Y, H, I, S] * Heat_type1.loc[(Y, H, I, S), "CO2_Elec"] for Y, H, I, S in Heat_type1.index]   (2)
        + [S_tech [Y, H, I, S] * Emis_tech_CO2_AL1 for Y, H, I, S in Heat_tech_A_index]                      (3)
        + [S_tech [Y, H, I, S] * Emis_tech_CO2_AL1 for Y, H, I, S in Heat_tech_B_index]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1 for Y, H, I, S in Insu_CF_index1]                         (4)
```

```
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1S for Y, H, I, S in Insu_CG_index1]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1 for Y, H, I, S in Insu_DF_index1]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1S for Y, H, I, S in Insu_DG_index1]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1 for Y, H, I, S in Insu_CF_index2]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1S for Y, H, I, S in Insu_CG_index2]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1 for Y, H, I, S in Insu_DF_index2]
        + [S_insu [Y, H, I, S] * Emis_insu_CO2_AL1S for Y, H, I, S in Insu_DG_index2]
        )
```

Listing 14 also displays the variables for one dwelling. The comfort optimization model will work similarly for individual and collective heating techniques as the cost optimization objective. The first and eleventh elements have the same value for the different states of the heating technique because these values are the same for the different techniques. The other subtopics of the comfort level as described in Chapter 4, do differentiate based on the state of the heating technique and the insulation level. The values for the different states have been determined in Section 6.1.2.9. Based on the *I_status* per year, the corresponding level of comfort is added to the sum. For example, in element 2 in which the impact of draught on the comfort level is taken into account. In the first line it states that if *I_status* (*Heating_tech = A* and *Insulation_level = C)* is one, *I_status* is multiplied by the comfort value *Draught_insu_C.* This will be done for all case combinations of *I_status* (*Heating_tech* and *Insulation_level*) per year. The same method is used for the other subtopics of comfort and the sum of these subtopics will result in the level of comfort per year over a period of 30 years.

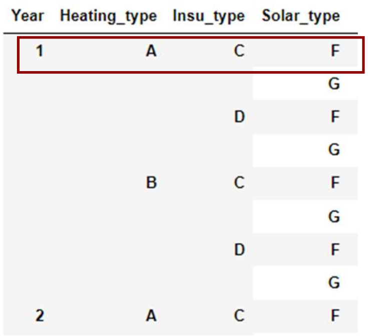
Listing 14: Pseudocode of the objective function maximize comfort AL1

```
Objective function maximize comfort AL1
model_Com_AL1 += maximize∑(
        [H_status[Y, H, I, S] * Gen_them_c for Y, H, I, S in Heat_type1.index]                  (1)
        + [I_status [Y, H, I, S] * Draught_insu_C for Y, H, I, S in Insu_C_index1]               (2)
        + [I_status [Y, H, I, S] * Draught_insu_D_WTW for Y, H, I, S in Insu_C_index2]
        + [I_status [Y, H, I, S] * Draught_insu_C for Y, H, I, S in Insu_D_index1]
        + [I_status[Y, H, I, S] * Draught_insu_D_WTW for Y, H, I, S in Insu_D_index2]
        + [I_status[Y, H, I, S] * Rad_asy_C[i] for Y, H, I, S in Insu_C_index1]                  (3)
        + [I_status[Y, H, I, S] * Rad_asy_C[i] for Y, H, I, S in Insu_C_index2]
        + [I_status [Y, H, I, S] * Rad_asy_D for Y, H, I, S in Insu_D_index1]
        + [I_status [Y, H, I, S] * Rad_asy_D for Y, H, I, S in Insu_D_index2]
        + [I_status[Y, H, I, S] * Temp_grad_C[i] for Y, H, I, S in Insu_C_index1]                (4)
        + [I_status[Y, H, I, S] * Temp_grad_C[i] for Y, H, I, S in Insu_C_index2]
        + [I_status[Y, H, I, S] * Temp_grad_D for Y, H, I, S in Insu_D_index1]
        + [I_status[Y, H, I, S] * Temp_grad_D for Y, H, I, S in Insu_D_index2]
        + [I_status [Y, H, I, S] * Floor_temp_C[i] for Y, H, I, S in Insu_C_index1]              (5)
        + [I_status [Y, H, I, S] * Floor_temp_C[i] for Y, H, I, S in Insu_C_index2]
        + [I_status [Y, H, I, S] * Floor_temp_D for Y, H, I, S in Insu_D_index1]
        + [I_status [Y, H, I, S] * Floor_temp_D for Y, H, I, S in Insu_D_index2]
        + [I_status [Y, H, I, S] * Amb_noise_A for Y, H, I, S in Insu_C_index1]                  (6)
        + [I_status [Y, H, I, S] * Amb_noise_A for Y, H, I, S in Insu_C_index2]
        + [I_status [Y, H, I, S] * Amb_noise_B for Y, H, I, S in Insu_D_index1]
        + [I_status [Y, H, I, S] * Amb_noise_BWTW for Y, H, I, S in Insu_D_index2]
        + [I_status [Y, H, I, S] * Inst_sound_A[i] for Y, H, I, S in Insu_C_index1]              (7)
        + [I_status [Y, H, I, S] * Inst_sound_B for Y, H, I, S in Insu_C_index2]
        + [I_status [Y, H, I, S] * Inst_sound_B for Y, H, I, S in Insu_D_index1]
        + [I_status [Y, H, I, S] * Inst_sound_B for Y, H, I, S in Insu_D_index2]
        + [I_status [Y, H, I, S] * Amp_int_noise_A[i] for Y, H, I, S in Insu_C_index1]           (8)
        + [I_status [Y, H, I, S] * Amp_int_noise_B for Y, H, I, S in Insu_C_index2]
        + [I_status [Y, H, I, S] * Amp_int_noise_B for Y, H, I, S in Insu_D_index1]
```

```
+ [I_status [Y, H, I, S] * Amp_int_noise_B for Y, H, I, S in Insu_D_index2]
 + [I_status [Y, H, I, S] * Mold_C[i] for Y, H, I, S in Insu_C_index1]              (9)
 + [I_status [Y, H, I, S] * Mold_D for Y, H, I, S in Insu_C_index2]
 + [I_status [Y, H, I, S] * Mold_C[i] for Y, H, I, S in Insu_D_index1]
 + [I_status [Y, H, I, S] * Mold_D for Y, H, I, S in Insu_D_index2]
 + [I_status [Y, H, I, S] * Pol_vent_air_C[i] for Y, H, I, S in Insu_C_index1]      (10)
 + [I_status [Y, H, I, S] * Pol_vent_air_D for Y, H, I, S in Insu_C_index2]
 + [I_status [Y, H, I, S] * Pol_vent_air_C[i] for Y, H, I, S in Insu_D_index1]
 + [I_status [Y, H, I, S] * Pol_vent_air_D for Y, H, I, S in Insu_D_index2]
 + [H_status [Y, H, I, S] * Comb_gas for Y, H, I, S in Heat_type1.index]            (11)
 + [I_status [Y, H, I, S] * Radon_C[i] for Y, H, I, S in Insu_C_index1]             (12)
 + [I_status [Y, H, I, S] * Radon_D for Y, H, I, S in Insu_C_index2]
 + [I_status [Y, H, I, S] * Radon_D for Y, H, I, S in Insu_D_index1]
 + [I_status [Y, H, I, S] * Radon_D for Y, H, I, S in Insu_D_index2]
 )
```

Table 66: Variable names

Variable	Variable name
Installation natural gas	In_g
Installation electricity	In_e
Installation heat	In_h
Heating status	H_status
Insulation status	I_status
Switch technique	S_tech
Switch insulation level	S_insu
Reinvestment in technique	ReInv



Year	Heating_type	Insu_type	Solar_type
1	A	C	F
			G
		D	F
			G
	B	C	F
			G
		D	F
			G
2	A	C	F

Figure 57: Example of the combinations Year, Heating_type, Insu_type and Solar_type. The combination Year 1, Heating_type A, Insu_type C and Solar_type Fis outlined in red

6.1.2.13. Define constraints

The *constraints* function describes the constraints the optimization model needs to meet. The constraints are shown in Listing 15. This Listing combines an explanation of the constraints and the pseudocode.

Listing 15: Explanation and pseudocode for the constraints of the optimization model

Constraint	Explanation and pseudocode of the constraint
Energy consumption	
1.	Per year eight combinations can be made between *Heating_type*, *Insu_type* and *Solar_type* an example of this is shown in Figure 57. Per year only one combination of *Heating_type*, *Insu_type* and *Solar_type* can be used, furthermore, the natural gas consumption is different depending on the combination of *Year, Heating_type*, *Insu_type* and *Solar_type.* Below the pseudocode is shown for the constraint for *In_g1* of dwelling 1 is shown. It can be seen that when the *Heating_type* is heating with natural gas (*Heating_type* = A), *Insu_type* is the current insulation level (*Insu_type* = C) the natural gas consumption is equal to the current natural gas consumption. When the *Heating_type* is heating with natural gas (*Heating_type* = A) and *Insu_type* is insulation level B (*Insu_type* = D) the natural gas consumption is equal to the current natural gas consumption times the change in energy consumption due to the increase in insulation label. When the *Heating_type* is heating with the alternative heating technique (*Heating_type* = B) and *Insu_type* is insulation level B (*Insu_type* = D) the natural gas consumption is equal to the current natural gas consumption

times the change in energy consumption due to the increase in insulation label and the change in natural gas consumption due to the change in the heating technique. When an alternative heating technique is implemented there is no natural gas consumption due to this the *In_g1 [(Year, 'B', "D")]* is multiplied by the current natural gas consumption. Because *Heating_type* = B and *Insu_type* = C is not possible because the insulation level needs to be improved before the heating technique is implemented the same method is used as *Heating_type* = B and *Insu_type* = D.

In the pseudocode below the natural gas consumption per year is constrained by setting *In_g1* for each combination of *Heating_type* and *Insu_type* equal to the current natural gas consumption including the above-described alterations. By setting the sum of *In_g1* equal to the current natural gas consumption only one of the *In_g1 [(Year, Heating_type, Insu_type)]* can be used per year.

This constraint is implemented per dwelling in the housing cluster, the example below shows the pseudocode for one dwelling.

```
for G, E, G2, ES, H, HB, ED1_1, ED1_2 in zip(Gas, Elec, Gas2, Elec_S, Heat, HeatB, ElecD1_1, ElecD1_2):
  xG = G/G2
  xES = E/ES
  xH = H/HB
  xED1_1 = E/ED1_1
  xED1_2 = E/ED1_2
  XG.append(xG)
  XES.append(xES)
  XH.append(xH)
  XED1_1.append(xED1_1)
  XED1_2.append(xED1_2)

if Nr_ dwellings ==1 then
  Years1 = data_list["df_1"].index
  for Year in Years1 then
    model_DH1 += In_g1[(Year, 'A', "C", "F")] +In_g1[(Year, 'A', "C", "G")] + In_g1[(Year, 'B', "C", "F")] * Gas[i] + In_g1[(Year, 'B', "C", "G")] * Gas[i] + In_g1[(Year, 'A', "D", "F")] * XG[i]+ In_g1[(Year, 'A', "D", "G")] * XG[i] +In_g1[(Year, 'B', "D", "F")] * Gas[i] + In_g1[(Year, 'B', "D", "G")] * Gas[i] == data_list["df_"+str(i)].loc[Year, "Gas_cons"]
```

2. Constraint 2, is similar to the first constraint but is about the electricity consumption and not the natural gas consumption. In this case, also the alternations in the electricity consumption due to the implemented insulation level and heating type are incorporated into the constraint.

```
if Nr_ dwellings ==1 then
    Years1 = data_list["df_1"].index
    model_DH1 += In_e1[(Year, "A", "C", "F")] + In_e1[(Year, "A", "C", "G")] * XES[0] + In_e1[Year, "A", "D", "F"] + In_e1[Year, "A", "D", "G"] * XES[0] + In_e1[Year, "B", "C", "F"] *XED1_1[0] + In_e1[Year, "B", "C", "G"] * XED1_2[0] + In_e1[Year, "B", "D", "F"] * XED1_1[0] + In_e1[Year, "B", "D", "G"] * XED1_2[0] == data_list["df_0"].loc[Year, "Elec_cons"]
```

4. Constraint 3, is similar to the first constraint but is about the heat consumption. In this case, the alternations in the heat consumption due to the implemented insulation level and heating type are incorporated. Furthermore, when the *heating_type* is “A” there is no heat consumption

```
if Nr_ dwellings ==1 then
    Years1 = data_list["df_1"].index
    model_DH1 += In_h1[(Year, "A", "C", "F")]*Heat[0] + In_h1[(Year, "A", "C", "G")] *Heat[0] + In_h1[Year, "A", "D", "F"] *Heat[0] + In_h1[Year, "A", "D", "G"] * Heat[0] + In_h1[Year, "B", "C", "F"] + In_h1[Year, "B", "C", "G"] + In_h1[Year, "B", "D", "F"] * XH[0] + In_h1 [Year, "B", "D", "G"] * XH[0] == data_list["df_0"].loc[Year, "Heat_cons"]
```

5. Constraint 5 ensures that the natural gas, electricity or heat consumption per year is equal to or smaller than the max consumption. Which is shown in the first part of the pseudocode below. Furthermore, if a heating technique is not used the consumption should be equal to 0. This is done by multiplying the *max_consumption* by the *H_status* per *Year, Heating_tech, Insu_type* and *Solar_type* combination (which can be 1 or 0)

```
for Year, Heating_tech, Insu_type, Solar_type in Heat_type1.index then
    max_consumption = Heat_type1.loc[(Year, Heating_tech, Insu_type, Solar_type), 'Max_capacity']
    model_DH1 += In_g1[(Year, Heating_tech, Insu_type, Solar_type)] <= (max_consumption * H_status1[Year, Heating_tech, Insu_type, Solar_type])
    model_DH1 += In_e1[Year, Heating_tech, Insu_type, Solar_type] <= (max_consumption * H_status1[Year, Heating_tech, Insu_type, Solar_type])
    model_DH1 += In_h1[(Year, Heating_tech, Insu_type, Solar_type)] <= (max_consumption * Heating_status1[Year, Heating_tech, Insu_type, Solar_type])
```

Collective heating technique

6. When a collective heating technique is implemented the housing cluster needs to transfer to the alternative heating technique at the same moment in time, this is done by constraint 6. The variables *H_status* and *I_status* are 1 for the implemented *Heating_type* and *Insu_type* combination per year. *H_status* and *I_status* are set equal for the different dwellings. By doing this the dwellings need to shift to the alternative heating technique at the same moment in time. Below the pseudocode of this constraint is shown for two dwellings.

```
for Year, Heating_tech, Insu_type, Solar_type in Heat_type1.index then
    model_DH1 += H_status1[Year, Heating_tech, Insu_type, Solar_type] == I_status1[Year, Heating_tech, Insu_type, Solar_type] == H_status2[Year, Heating_tech, Insu_type, Solar_type] == I_status2[Year, Heating_tech, Insu_type, Solar_type]
```

7. The first part of constraint 7 ensures that for the variable *H_status* only one can be used per *Year, Heating_tech, Insu_type,* and *Solar_type* combination. In the second part of the constraint, the variable *I_status* is constrained in the same way as *H_status.* If a collective heating technique is implemented this constraint is applied per dwelling of the cluster.

```
for Year in range(1,32) then
    model_DH1 += (I_status1[Year, 'A', "C", "F"] + I_status1[Year, 'A', "C", "G"] + I_status1[Year, 'B', "C", "F"] + I_status1[Year, 'B', "C", "G"] + I_status1[Year, 'A', "D", "F"] + Insu_status1[Year, 'A', "D", "G"] + I_status1[Year, 'B', "D", "F"] + I_status1[Year, 'B', "D", "G"] == 1)
    model_DH1 += (H_status1[Year, 'A', "C", "F"] + H_status1[Year, 'A', "C", "G"] + H_status1[Year, 'B', "C", "F"] + H_status1[Year, 'B', "C", "G"] + H_status1[Year, 'A', "D", "F"] + H_status1[Year, 'A', "D", "G"] + H_status1[Year, 'B', "D", "F"] + H_status1[Year, 'B', "D", "G"] == 1)
```

Individual heating technique

8. If an individual heating technique is implemented, the housing cluster does not need to shift to the alternative heating technique at the same moment in time, but this can be optimized per dwelling. For this heating technique constraint 8. This constraint sets the heating status and insulation status to be equal to each other. As both variables are binary and are dependent on the heating type and insulation type, they should be equal per year, heating type, and insulation type combination.

```
for Year, Heating_tech, Insu_type in Heat_type1.index then
    model_DH1 += H_status[Year, Heating_tech, Insu_type, Solar_type] == I_status[Year, Heating_tech, Insu_type, Solar_type]
```

Switch insulation/technique

9. Constraint 9, ensures that in *Year* 1, *Heating_tech* = A (which is heating using natural gas) and the current insulation level are used. This is done by setting the *Heating_status* of the *Year, Heating_tech,* and *Insu_type* combination equal to 1. The second part of the constraint (shown in the pseudocode) describes that for all other years the switch technique variable should be 1 if the heating technique changed compared to the previous year. If a collective heating technique is implemented this constraint is applied per dwelling of the cluster.

```
if Year == 1 then
    model_DH1 += Heating_status1[Year, "A", "C", Solar_type] == 1
else
    model += S_tech1[Year, Heating_tech, Insu_type , Solar_type] >= (H_status1[Year, Heating_tech, Insu_type , Solar_type] - H_status1[Year-1, Heating_tech, Insu_type , Solar_type])
    model += S_tech1[Year, Heating_tech, Insu_type , Solar_type] <= (1 - H_status1[Year-1, Heating_tech, Insu_type])
    model += S_tech1[Year, Heating_tech, Insu_type , Solar_type] <= (H_status1[Year, Heating_tech, Insu_type , Solar_type])
```

10. Constrain 10 has the same functionality as constrain 9 but is used for insulation level and the variable switch insulation level.

```
if Year == 1 then
    model += Insu_status1[Year, "A", "C" , Solar_type] == 1
else
    model_DH1 += S_insu1[Year, Heating_tech, Insu_type , Solar_type] >= (I_status1[Year, Heating_tech, Insu_type , Solar_type] - I_status1[Year-1, Heating_tech, Insu_type , Solar_type])
    model_DH1 += S_insu1[Year, Heating_tech, Insu_type , Solar_type] <= (1 - I_status1[Year-1, Heating_tech, Insu_type , Solar_type])
    model_DH1 += S_insu1[Year, Heating_tech, Insu_type , Solar_type] <= (I_status1[Year, Heating_tech, Insu_type , Solar_type])
```

11. The dwellings can only shift to an alternative heating technique in 2023 (*Year* = 4) and 2036 (*Year* = 17). This is done by constraint 11, by setting the sum of *S_insu* for *Year* 4 and 17 equal to 1. If a collective heating technique is implemented this constraint is applied per dwelling of the cluster.

```
model += S_insu1[4, "B", "D"] + S_insu1[17, "B", "D"] + S_insu1[4, "B", "F"] + S_insu1[17, "B", "F"] == 1
```

12 If the dwellings shift to the alternative heating technique, it is not realistic if the model can shift back to the original technique a year later. This is automatically constrained due to investment costs in the cost optimization and the extra CO_2 emission in the CO_2 emission model. This “investment” is not incorporated in the comfort model, due to this constraint 12 is added. This constraint describes that the technique cannot shift between the years 5 and 15 (first part) and should remain at heating technique *B* and insulation label *D* between the years 18 and 32.

```
for Year, Heating_tech, Insu_type, Solar_type in Heat_type1.index:
    model  += (S_tech [5, Heating_tech, Insu_type, Solar_type] + S_tech [6, Heating_tech,   Insu_type, Solar_type]+S_tech [7, Heating_tech, Insu_type, Solar_type] + … == 0)
for Year in range(1,32):
    if S_tech[17, 'B', "D", Solar_type] == 1  then
        for Year in range(18, 32) then
            model += H_status [Year, 'B', "D", Solar_type] == 1
```

6.1.2.14. Multi-objective optimization

As described above, besides the single-objective optimizations for costs, CO_2 emission and comfort, a multi-objective optimization needs to be made to combine these functions in one combined model. This combined function needs to be made because homeowners do not only base their decision for the implementation of a sustainable heating technique on one of these objectives but on a combination of factors. To determine the most suitable implementation per heating technique based on a combination of costs, CO_2 emission and comfort a multi-objective optimization has been created. As described above, to find an optimal solution between multiple objectives trade-offs need to be made, since many multi-objective optimization problems can result in a large objective space. To select one of the solutions of the Pareto front, a different level of importance can be assigned to the objective functions. For the preference-based multi-objective optimization the weighted-sum method is used. When the weights are assigned to the composite objective function it is possible to find one trade-off function.

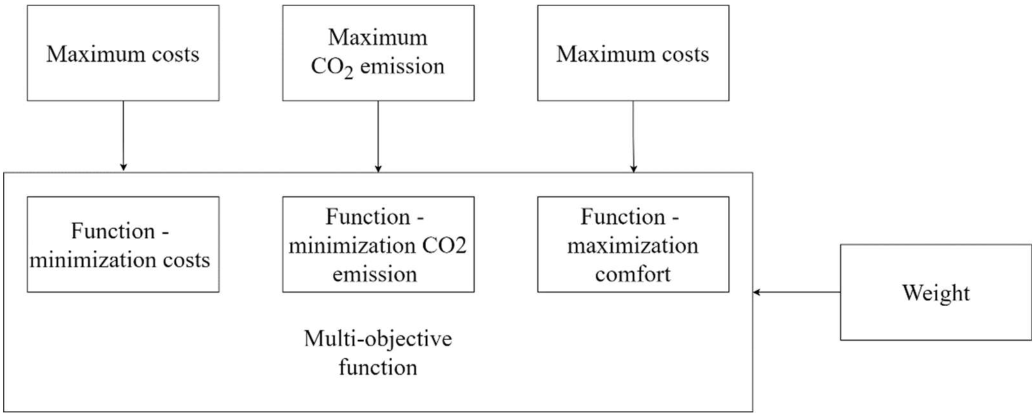


Figure 58: Visualisation of the combination of the single objective models into the multi-objective optimization

The multi-objective optimization will not be created with PuLP but with Pyomo as has been explained in Section 3.3. The multi-objective model will combine the three single-objective functions into one objective function combined with the weight of the single-objective functions, see Figure 58. The weights that are used to weight the objective functions have been based on literature, see Section 2.3. The main risk of using the weighted sum approach is the high influence of the weights on the results. Consequently, if poorly chosen weights are applied, this has a big impact on the outcome. Since the average preferences found in the literature are not fitting for all Dutch homeowners the weights can be modified using the Analytical Hierarchy Process, see Section 4.7.1. By using the AHP the user of the dashboard can generate personalized results, which reduces the risk of utilizing the weighted sum method.

The objective function for the multi-objective optimization is shown in Listing 16. In the listing, *Cost* is the objective function of the single objective optimization for costs, *CO_2* for the CO_2 emission and *comfort* for the comfort optimization. It can be seen that the single objective functions are multiplied by their weights, w_1, w_2 and w_3 which sum to 1. If the objective would only include the sum of the weighed single objectives, the weights would only have little effect on the impact of the single objectives because the single objectives have different measures. Therefore, the functions have been normalized with their maximum values. To find the maximum values, maximization models have been created for the single-objective optimization models. In these maximization models, the argumented maximum has been found, which means that there has been maximized on what can be real homeowner behaviour. For example, there can only once be switched from heating technique. Without this constraint, the model would switch heating technique every year, but this has been judged as unrealistic behaviour.

Listing 16: Simplified objective function of the multi-objective optimization models

Objective function multi-objective optimization
*mod.obj = Objective(expr = w_1 * (sum(Cost)/max_Cost) + w_2 * (sum(CO2)/max_CO2)+ w_3 * (max_Comfort+ (-1*sum(Comfort))/(max_Comfort)))*

6.1.2.15. Solve optimization

The solve function is used to solve the optimization problem. For the different single-objective optimisation problems, PuLPs default solver is used which is CBC as described in Section 3.2. Multiple solvers can be used which are explained in Section 3.2. For the multi-objective optimization the Gurobi solver has been used, this solver has been selected because it cannot only solve multi-objective optimization problems but can also include binary values. The solve function contains the solve command, but also the model status and the model objective. The model status shows the status that is returned from the solver. There are five status codes:

1. Optimal (optimal solution exists and is found);
2. Not solved (default setting before a problem has been solved);
3. Infeasible (the problem has no feasible solution);
4. Unbounded (cost function is unbounded);
5. Undefined (the feasible solution hasn’t been found but may exist).

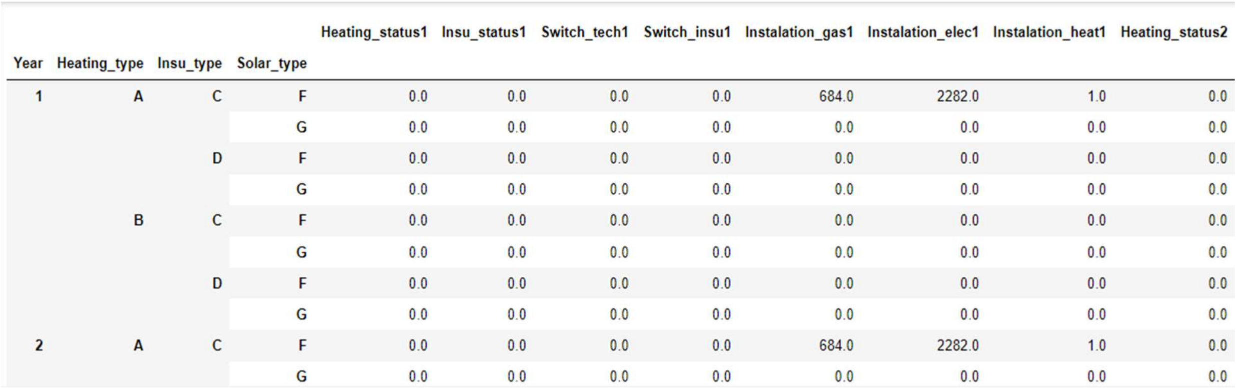
The model status should be optimal. The model objective shows the objective of the optimization which is the optimal costs.

6.2. Output and validation

In this Section, the outputs of the optimization models will be discussed and validated. As has been described in the previous Section, the models will create the most suitable implementation for the single objective functions, costs, CO_2 emission and comfort, and the multi-objective. Before the results can be analysed, first it needs to be determined what the expected results are, to be able to test and check the models.

6.2.1. Expected output

The output of the optimization contains the data which describes the interventions which are needed per technique and housing cluster and the effects of these interventions. This output needs to be communicated and visualized for the user at a later stage of the research. In this Section, the results will be checked and visualized. An example of the output of the optimization is shown in Figure 59. The values of the variables that are used in the optimization are shown in the output, the variables are *H_status*, *I_status*, *S_tech*, *S_insu*, *In_g*, *In_e and In_h*. Before the output will be described, first the expected output will be described for costs, comfort and CO_2 emission. This will help to assess the output of the optimization models.



Year	Heating_type	Insu_type	Solar_type	Heating_status1	Insu_status1	Switch_tech1	Switch_insu1	Instalation_gas1	Instalation_elec1	Instalation_heat1	Heating_status2
1	A	C	F	0.0	0.0	0.0	0.0	684.0	2282.0	1.0	0.0
			G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		D	F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	B	C	F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		D	F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	A	C	F	0.0	0.0	0.0	0.0	684.0	2282.0	1.0	0.0
			G	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 59: Example of output of the optimized implementation of district heating 1 (multiple dwellings are incorporated)

Cost optimization output

The expected development of the output of the cost optimization is shown in Figure 60. As shown in this chart, the costs in Euro are cumulative, therefore small costs can be seen as well. Rather than only a large spike due to high investment costs. In the Figure, the three expected elements can be seen (which are numbered in the figure), which are:

1. A high increase in costs in the year 2023 or 2036 is due to the shift (corresponding investment costs) in the heating technique and insulation level.
2. Multiple smaller spikes in costs indicate reinvestments.
3. A small slope due to the yearly costs, which include, energy costs (fixed and variable) and maintenance costs.

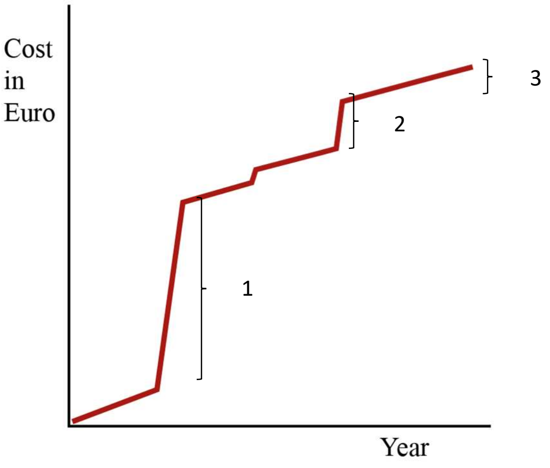


Figure 60: Expected output costs optimization

Comfort optimization output

The expected output of the comfort level optimization is shown in Figure 61. Contrary to costs, this output will be the comfort level per year and not cumulative. This has been applied because if the comfort level was expressed cumulatively, almost a linear line would appear and would be hard to interpret. In the figure, it can be seen that the comfort level remains at a constant level (of a value between 0 and 1) and can shift to a different level when the dwelling shifts in heating technique or insulation level (in the years 2023 or 2036).

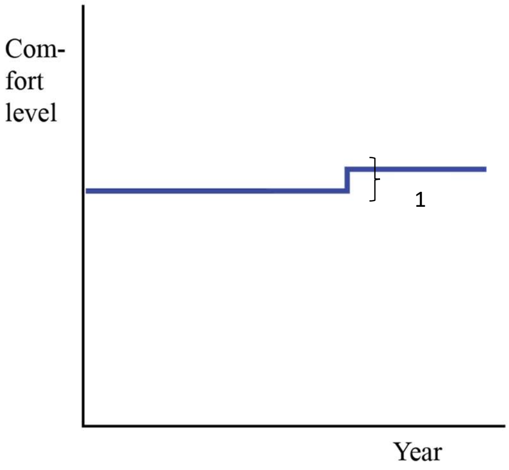


Figure 61: Expected output comfort optimization

CO_2 optimization output

The expected output of the CO_2 emission optimization is shown in Figure 62. In this figure, the CO_2 emission of natural gas, heat and electricity are shown over time. These lines are also not cumulative because this could cause confusion. After all, if the natural gas consumption was 0 the line for the CO_2 emission of natural gas would not indicate 0 but be constant at the level of the current emission. The line of natural gas shows a high natural gas CO_2 emission. However, it will drop to 0 if the heating technique is changed, which can be in 2023 or 2036. With solar panels in place, CO_2 emissions for electricity will decrease, but with a heat pump, CO_2 emissions will increase. CO_2 emissions due to electricity consumption will naturally decline between 2020 and 2030 due to the expected increase in sustainable electricity production in that period in time. A household will begin with 0 CO_2 emissions for heat and quickly increase when the heating is switched to district heating. The CO_2 emission due to heat consumption will naturally decrease between 2020 and 2030 due to the expected increase in sustainable electricity production in that period in time.

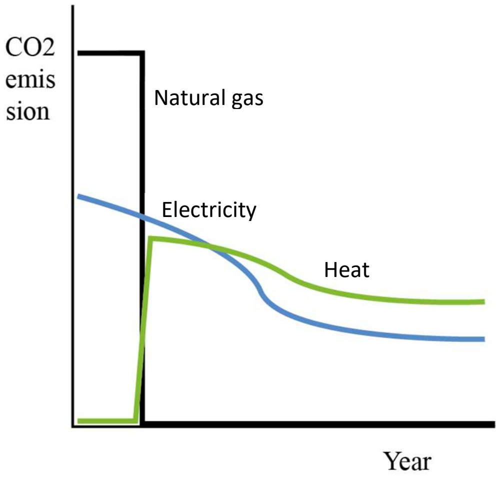


Figure 62: Expected output CO_2 emission optimization

6.2.2. Scenarios and validation

In this Section, the output of the models will be tested and validated using different scenarios. To increase the readability of the Section, only two techniques will be thoroughly described in the report. The techniques that have been selected are all-electric 1 and district heating 1, which are the same techniques as had been described in the previous Chapter. Since the costs and benefits of different heating techniques are highly dependent on the properties of the dwellings and cluster of dwellings, it will be impossible to create one reference housing cluster that is representable for the Dutch owner-occupied housing stock. Therefore, the validation of the optimization will be executed for three housing clusters. The three housing clusters are shown in Table 67, it can be seen that the clusters are contrary to each other. The clusters are based on the energy supply profiles for natural gas homes, created by the CBS (CBS, 2021d). These are the 10 most common housing profiles of homes heated with natural gas which can be seen in *Appendix K: 10 most common housing profiles of homes heated with natural gas*. For the selection, the most common and opposite properties have been selected and tested using the WoON 2018 dataset. The second cluster is a combination of the most common rowhouse as can be seen in *Appendix Y: Number of cases for type of heating in the WoON 2018 dataset* and the average dwelling in the neighbourhood 't Ven (Haren, 2021).

Table 67: Housing clusters

	Housing type	Construction year	Floor size	Household size	Energy label
Cluster 1	Detached house	Before 1946	240	2	F
	Detached house	1946-1964	190	3	E
	Detached house	Before 1946	260	2	F
Cluster 2	Terraced house	Before 1946	120	2	E
	Terraced house	Before 1946	130	5	F
	Terraced house	1946-1964	150	1	D
	Terraced house	1946-1964	110	2	E
	Terraced house	Before 1946	115	2	F
Cluster 3	Terraced house	1975-1991	90	2	C
	Terraced house	1975-1991	80	2	D

Besides the difference in the properties of the dwellings also the different scenarios need to be tested during the validation of the model. The scenarios that will be tested are shown in Table 68, it can be seen that contrasting scenarios have been selected to test the reactivity of the models.

Table 68: Scenario's to test the optimization models

	G_price	E_price	Dev_cost	Detch_heat_price	Red_DH_c_clust
Scenario 1	Low	High	Low	2024	0.05
Scenario 2	High	Low	High	2024	0.05
Scenario 3	Low	Low	Low	2024	0.05
Scenario 4	High	High	High	2035	0.10

The different scenarios have been tested on the three selected housing clusters, using the created optimization models. All outputs for the first are shown in *Appendix Z: Output optimization models* and described below. In the appendix the output for the costs can be seen twice, the first table includes the net present value and the second table excludes the net present value. Furthermore, some of them will be tested which is shown and discussed below.

Output optimization costs:

In *Appendix Z: Output optimization models* the output of the optimized costs is shown for housing cluster 1. Almost all the results obtained for the cluster using the all-electric heating technique 1, are as expected. There is a similarity in many charts, but it is clear that the total costs differ between the dwellings. The results from district heating 1 for the cluster are also in line with expectations. Compared to all-electric 1, this technique has lower investment costs (mainly energy costs). When comparing the results of the different models, if the energy costs are low the total costs are lower than when the energy costs are high. Furthermore, the detachment of the natural gas price has a clear effect on the total costs (comparing scenarios 2 and 4).

Output optimization CO_2:
In *Appendix Z: Output optimization models* the output of the optimized CO_2 emissions is shown for housing cluster 1. The results obtained for the cluster using the heating technique all-electric 1 are as expected. In the charts, it can be seen that the three dwellings in the cluster have different energy consumptions due to differences in properties. The all-electric heating technique 1 with insulation label B will be used in all houses as of 2023, which can be expected because it emits less CO_2 than the original heating technique. Due to a decrease in CO_2 emissions in electricity production, it can be observed that until 2030, CO_2 emissions decrease per year with constant electricity consumption. Accordingly, the results obtained by using district heating 1 for the cluster are also as expected. In the charts, the three dwellings in the cluster have different energy consumption due to differences in properties. All dwellings shift to the heating technique district heating 1 including insulation label B in 2023. This is expected because this state has lower CO_2 emissions than the original heating technique. Since CO_2 emissions from the production of electricity and heat are decreasing, until 2030, CO_2 emissions will decrease per year with constant electricity and heat consumption.

Outputs optimization comfort:
For the cluster, the results obtained using the heating technique all-electric 1, see In *Appendix Z: Output optimization models*, the results obtained for the cluster, using the heating technique all-electric 1, were as expected. In the charts, the three dwellings in the cluster have similar comfort levels. This is because the dwellings have a poor insulation level and a similar heating technique. Furthermore, the comfort level is higher when the heating technique (including increased insulation) is implemented. Therefore, it can be expected that the all-electric heating technique will be implemented at the earliest switching moment (in 2023), which is the case for cluster 1. Accordingly, the results obtained by using district heating 1 for the cluster are also as expected. In the charts, it can be seen that the three dwellings in the cluster have a similar comfort level. This is because the dwellings have a poor insulation level and a similar heating technique. The charts show reduced levels of comfort when the heating technique is implemented (including increased insulation). Therefore, it can be expected that the heating technique will be implemented at the latest switching moment (in 2036), which is the case for cluster 1. It can also be seen that the total comfort level is lower for the district heating technique 1 compared to the all-electric 1 technique.

Testing the variables
Multiple variables are included in the optimization models that influence the results. The impact of these variables has been tested by checking the results for the described clusters and scenarios. In this Section, some of the remarkable scenarios are presented, which demonstrate the model's functionality. For the creation of the charts below, the net present value is used in the optimization functions.

In Figure 63, two dwellings of housing cluster 1 are shown. The model uses individual variables per dwelling. The results can differentiate between the dwellings in the cluster based on what is deemed optimal (for an individual heating technique).

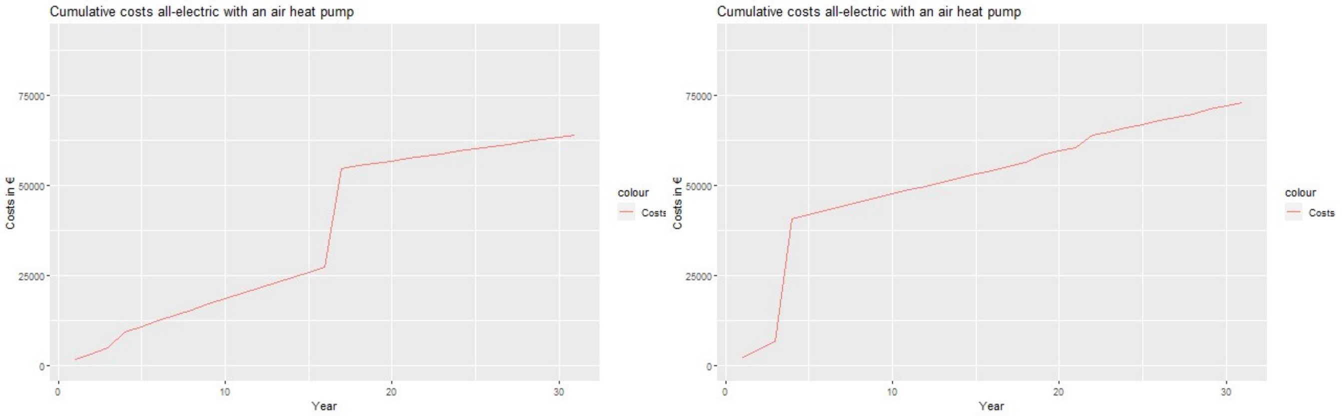


Figure 63: Differences in implementation between dwelling of same cluster, left dwelling 1 and right dwelling 2 (cluster 1, scenario 1)

In Figure 64, the results are shown for the optimization of the costs in the case a different input cluster is used for district heating 1. Left is cluster 1 and right is cluster 2. The differences in the results can be explained since the houses in cluster 2 consist of smaller terraced dwellings which results in lower investment costs. Additionally, these smaller dwellings require lower energy costs (smaller dwellings) and have lowered district heating costs due to their cluster size.

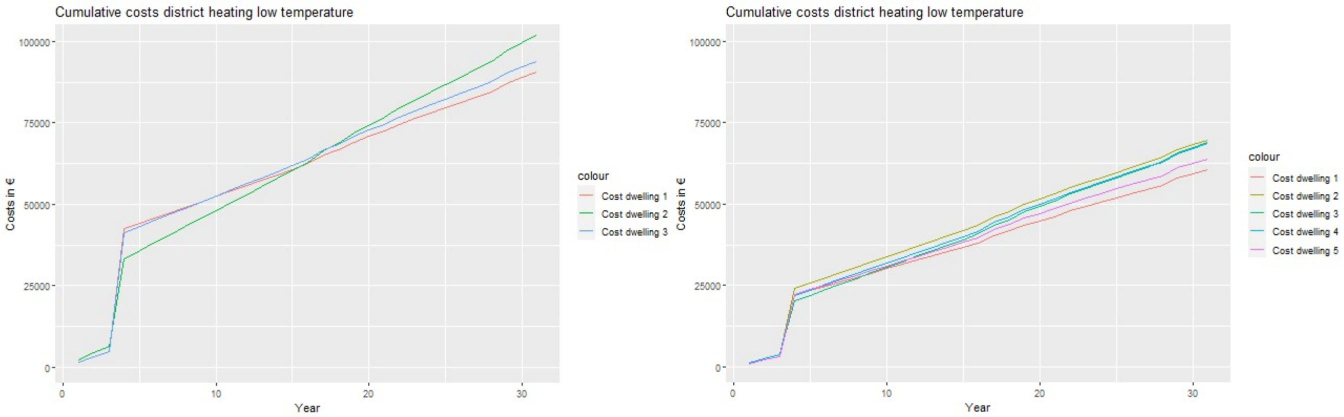


Figure 64: Differences in output due to differences in input cluster, left is cluster 1 and right is cluster 2 (scenario 2, undiscounted)

In Figure 65, the impact of the variables energy costs and development costs can be seen. Right chart: energy and development costs are high, indicating that the homeowner should (based on the results) invest in 2023. In the chart on the left, the costs are very low. Therefore, it will be profitable to invest in the year 2036, since energy costs will be low till then. In addition, investment costs will be lower than in 2023 due to low development costs and the discount rate.

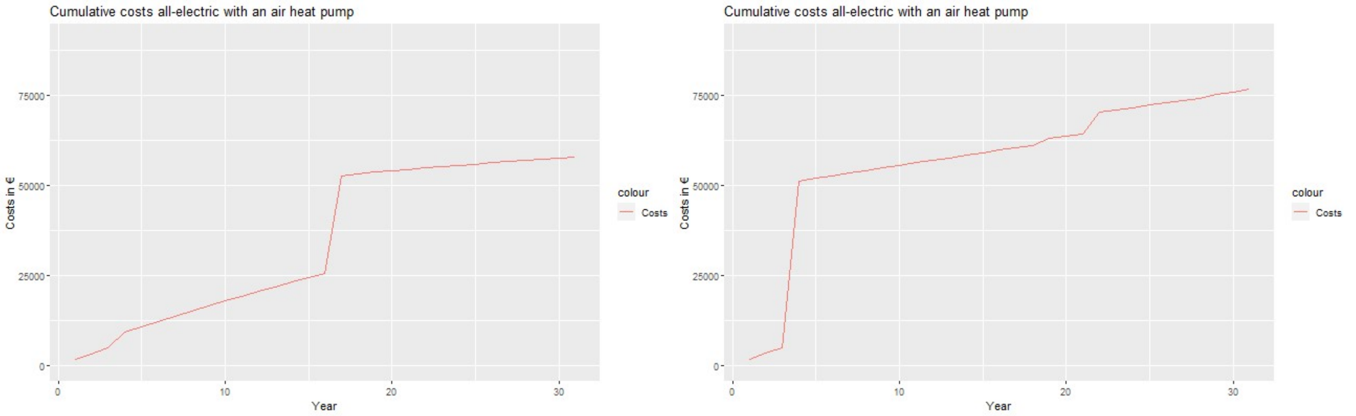


Figure 65: Differences in output due to input scenario 3 or 4 (cluster 1, dwelling 1)

As described in the previous Chapter the discount rate is included in the model. The results of excluding (left chart) or including (right chart) the discount rate are shown in Figure 66. For both outputs, the cumulative costs develop in a similar fashion. But for the discounted chart the costs are relatively lower in the future, which reduces the steepness of the plotted chart.

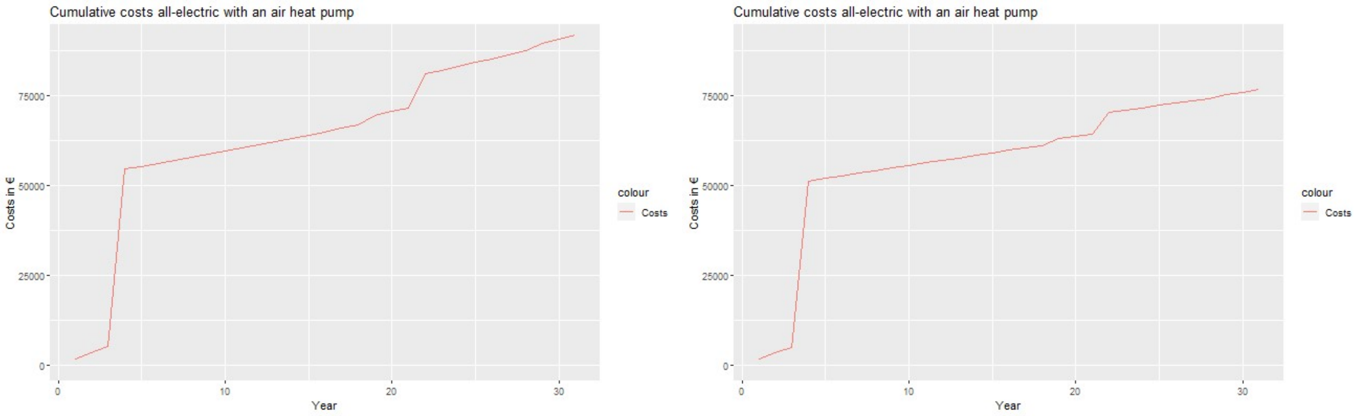


Figure 66: Differences in output due to incorporating net discount rate

The last variable that is tested is the weights used for the multi-objective optimization model. In Figure 67, the outputs of two different weight combinations have been created. In the chart on the left, the weights are divided as costs 77%, comfort 11% and CO_2 emissions 11%. In the right chart, the weights have been divided as costs 11%, comfort 11% and CO_2 emissions 77%.

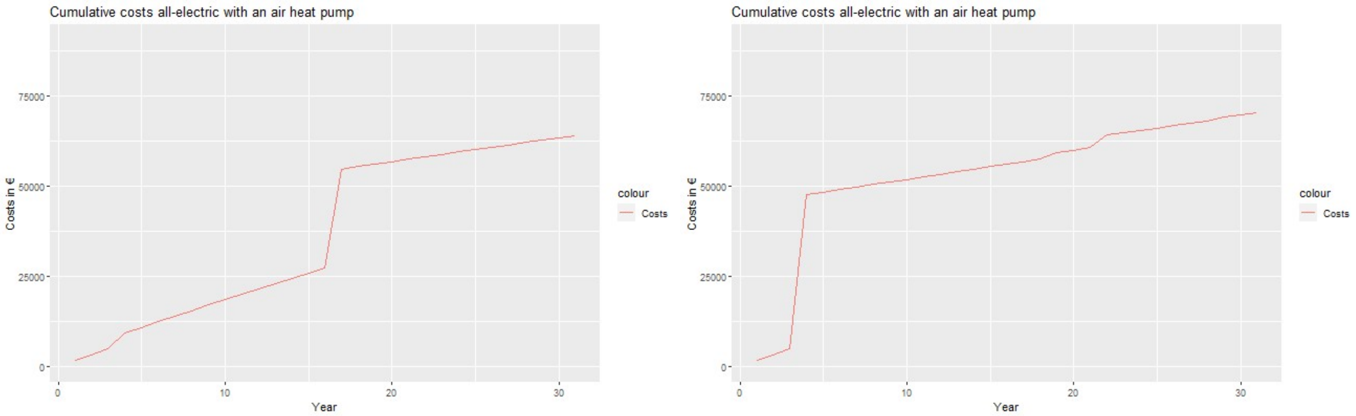


Figure 67: Differences in output due to selected weights of the multi-objective function (scenario 3)

The results are visible in the Figure. In the case of high weight for cost, it would result in lower costs if the sustainable heating technique was implemented. On the contrary, the comfort level increases when the new heating technique is applied. Therefore, it can be seen that if the objective of cost has a dominating weight factor the results will also be tipped toward the most advantageous cost result. Contrary to the first chart, the second chart indicates that if CO_2 emissions are the most important factor, the new heating technology will be implemented at the moment that is most advantageous for comfort.

6.2.3. Real case comparison

To test the predictability of the optimization models the results will be compared to a reference housing cluster. The selected cluster consists of dwellings in the neighbourhood ‘t Ven in Eindhoven. In 2021, the municipality of Eindhoven studied the cost of converting these owner-occupied homes to gas-free heating techniques, which were district heating and all-electric with air-to-water heat pumps. Table 69 lists the dwellings that were included in the research.

Table 69: Reference housing types of neighbourhood 't Ven

Dwelling	Housing type	Floor space	Construction year	Energy label
Bredalaan	Corner house	109 m^2	1935	D
Bergen op Zoomstraat	Terraced house	155 m^2	1934	D
Steenbergenstraat	Teracced houe	127 m^2	1938	E
Moerdijkstraat	Corner house	71 m^2	1935	F

In the research of the municipality, only the investment costs for the different heating techniques have been analysed. The techniques that were included in the research were all-electric 1 and district heating 1. Therefore, the investment costs for the techniques all-electric 1 and district heating 1 will be compared to the results of the reference cluster. In Table 70 the comparison between the results of the reference cluster and the investment costs for heating technique all-electric 1 are shown. Before the comparison can be made some remarks are required. Firstly, in the previous study of the municipality, the heat recovery unit was only used in the living room. This study, however, applies it to every room of the house. In addition, no solar panels are used in the research of the municipality. In some cases, adjustments are not required or only partially required due to the current state of the dwelling. Due to the necessity for extensive research of the dwelling, this is only included in the research of the municipality and is not possible with optimization models. In the table, some of the costs are a close approximation of the real costs but there are also some differences. The main differences are the costs of solar panels and ventilation, which were expected. Furthermore, some differences in investment costs for insulation can be explained by interventions that homeowners have already taken to improve their insulation level. The overall difference between the predicted results of the optimization model and the reference dwellings is 24%. This is quite high but is partly caused by extra costs (like solar panels) which are not included in the municipal research. If these costs are not included, a difference of 6,7% can be found. This is still a deviation from the real costs but the dashboard aims at providing an approximation of the costs which can be achieved with these margins.

Table 70: Comparison of reference dwellings with results AL1

	Bredalaan				**Bergen op zoomstraat**			
	Optimisation results	**Reference dwelling**	**Difference**	**Difference %**	**Optimisation results**	**Reference dwelling**	**Difference**	**Difference %**

Insulation	€ 10.633	€ 7.075	*€ 3.558*	50%	€ 8.190	€ 6.863	*€ 1.327*	19%
Heat pump	€ 7.267	€ 10.198	€ - *2.931*	-29%	€ 7.267	€ 10.198	€ - *2.931*	-29%
LT heat release	€ 5.500	€ 5.162	€ *338*	7%	€ 5.500	€ 6.667	€ - *1.167*	-18%
Ventilation	€ 4.645	€ 1.185	*€ 3.460*	292%	€ 4.645	€ 1.185	*€ 3.460*	292%
Electric cooking	€ 1.045	€ -	*€ 1.045*		€ 1.045	€ 1.450	*€ -405*	-28%
Electricity connection	€ 1.215	€ 1.433	€ *-218*	-15%	€ 1.215	€ 1.433	*€ -218*	-15%
Solar	€ 6.086	€ -	*€ 6.086*		€ 3.912	€ -	*€ 3.912*	
Total	€ 36.390	€ 25.053	*€ 11.337*	45%	€ 31.774	€ 27.796	*€ 3.978*	14%

	Steenbergenstraat				**Moerdijkstraat**			
	Optimisation results	**Reference dwelling**	**Difference**	**Difference %**	**Optimisation results**	**Reference dwelling**	**Difference**	**Difference %**
Insulation	€ 7.671	€ 4.238	*€ 3.433*	81%	€ 9.351	€ 6.314	€ - *3.037*	48%
Heat pump	€ 7.267	€ 10.072	€ - *2.805*	-28%	€ 7.267	€ 9.051	*€ 1.784*	-20%
LT heat release	€ 5.500	€ 7.503	€ - *2.003*	-27%	€ 5.500	€ 8.341	*€ 2.841*	-34%
Ventilation	€ 4.645	€ 1.185	*€ 3.460*	292%	€ 4.645	€ 1.185	€ - *3.460*	292%
Electric cooking	€ 1.045	€ 1.450	€ - *405*	-28%	€ 1.045	€ 1.450	*€ 405*	-28%
Electricity connection	€ 1.215	€ 1.433	€ *-218*	-15%	€ 1.215	€ 1.433	*€ 218*	-15%
Solar	€ 3.912	€ -	€ *3.912*		€ 3.912	0	€ - *3.912*	
Total	€ 31.254	€ 25.881	*€ 5.373*	21%	€ 32.935	€ 27.774	€ - *5.161*	19%

In Table 71, the comparison between the results of the reference cluster and the investment costs for heating technique district heating 1 are shown. Before the comparison can be made some remarks are required. Firstly, no solar panels will be used in the research of the municipality. Additionally, since the municipal research team could have conducted extensive research on the selected dwelling, the cost of installing the district heating pipelines in the dwelling can be added to the cost of connecting the dwelling to the district heating system. Last of all, in some cases adjustments are not required or only partially required due to the current state of the dwelling. This is only included in the research provided by the municipality since this requires an extensive investigation of the dwelling, which is not possible with the optimization models. In the table, some of the costs are a close approximation of the real costs but there are also some differences. The main differences are the costs of solar panels and ventilation, which were expected. Furthermore, there are differences in investment costs for insulation due to interventions that homeowners have already taken to improve their insulation level. The comprehensive approach of the municipal research also allowed the connection costs to district heating to be more accurately calculated. This is also reflected in the differences in results. The overall difference between the predicted results of the optimization model and the reference dwellings is -10,5%. This shows that the optimization model for district heating makes a better approximation of the real costs for the housing cluster than the All-electric 1 optimization. Without adding extra costs (like solar panels), a difference of 1,2% can be found, which is a fairly accurate approximation of the actual costs.

Table 71: Comparison of reference dwellings with DH1

	Bredalaan				**Bergen op zoomstraat**			
	Optimisation results	**Reference dwelling**	**Difference**	**Difference %**	**Optimisation results**	**Reference dwelling**	**Difference**	**Difference %**
Insulation	€ 10.633	€ 7.075	*€ 3.558*	50%	€ 8.190	€ 6.863	*€ 1.327*	19%
Connection district heating	€ 2.476	€ 6.616	*€ -4.140*	-63%	€ 2.476	€ 6.801	*€ -4.325*	-64%

LT heat release	€ -	€ 5.162	*€ -5.162*	-100%	€ -	€ 6.667	*€ -6.667*	-100%
Ventilation	€ 2.745	€ 1.185	*€ 1.560*	132%	€ 2.745	€ 1.185	*€ 1.560*	132%
Electric cooking	€ 1.045	€ -	*€ 1.045*		€ 1.045	€ 1.450	*€ -405*	-28%
Electricity connection	€ 1.215	€ 1.433	*€ -218*	-15%	€ 1.215	€ 1.433	*€ -218*	-15%
Solar	€ 4.347	€ -	*€ 4.347*		€ 3.912	€ -	*€ 3.912*	
Total	€ 22.461	€ 21.471	*€ 990*	5%	€ 19.583	€ 24.399	*€ -4.816*	-20%

	Steenbergenstraat				**Moerdijkstraat**			
	Optimisation results	**Reference dwelling**	**Difference**	**Difference %**	**Optimisation results**	**Reference dwelling**	**Difference**	**Difference %**
Insulation	€ 7.671	€ 4.238	*€ 3.433*	81%	€ 9.351	€ 6.314	*€ -3.037*	48%
Connection district heating	€ 2.476	€ 6.801	*€ -4.325*	-64%	€ 2.476	€ 7.293	*€ 4.817*	-66%
LT heat release	€ -	€ 7.503	*€ -7.503*	-100%	€ -	€ 5.613	*€ 5.613*	-100%
Ventilation	€ 2.745	€ 1.185	*€ 1.560*	132%	€ 2.745	€ 1.185	*€ -1.560*	132%
Electric cooking	€ 1.045	€ 1.450	*€ -405*	-28%	€ 1.045	€ 1.450	*€ 405*	-28%
Electricity connection	€ 1.215	€ 1.433	*€ -218*	-15%	€ 1.215	€ 1.433	*€ 218*	-15%
Solar	€ 3.912	€ -	*€ 3.912*		€ 3.912	€ -	*€ -3.912*	
Total	€ 19.064	€ 22.610	*€ -3.546*	-16%	€ 20.744	€ 23.288	*€ 2.544*	-11%

6.3. Conclusion

In this Chapter the optimization models have been developed and validated. In the multi-objective optimization models the objectives ‘costs’, ‘CO_2 emissions’ and ‘comfort’ are taken into account by using a weight factor. The default weight factor was based on literature research, but can be tailored to the preferences of a homeowner using AHP. The optimization was validated by testing the output and by real case comparison with neighbourhood ‘t Ven.

7. Dashboard

In this Chapter, the interaction of the optimization models with the dashboard will be described. As described before, the optimization model is created using Python and the dashboard will be made using R shiny. When these two languages are combined, the benefits of both languages can be utilized in the creation of a dashboard. The RStudio package Reticulate will be used for weaving Python directly into RStudio. Reticulate is a RStudio package that works by embedding a Python session within an R session. This helps to provide a seamless interface between Python and RStudio. The library of the Reticulated package supports the translation between RStudio and Python objects. Furthermore, it allows for the calling of Python scripts/modules from R in numerous settings. One of the benefits is that Python can be used within RStudio in the same way R would be used, leveraging the console for a combined Python + R REPL (Hickey, 2019). In this Chapter, the dashboard will be discussed. First, the user requirements that the dashboard needs to meet will be discussed (Section 7.1). Secondly, the dashboard design will be described (Section 7.2). Thirdly the output of the model will be described and it will be judged whether the dashboard meets the user's requirements. Furthermore, the dashboard will be tested by the municipality of Eindhoven to judge its usability (Section 7.3). Figure 68, shows how the creation of the dashboard contributes to the research.

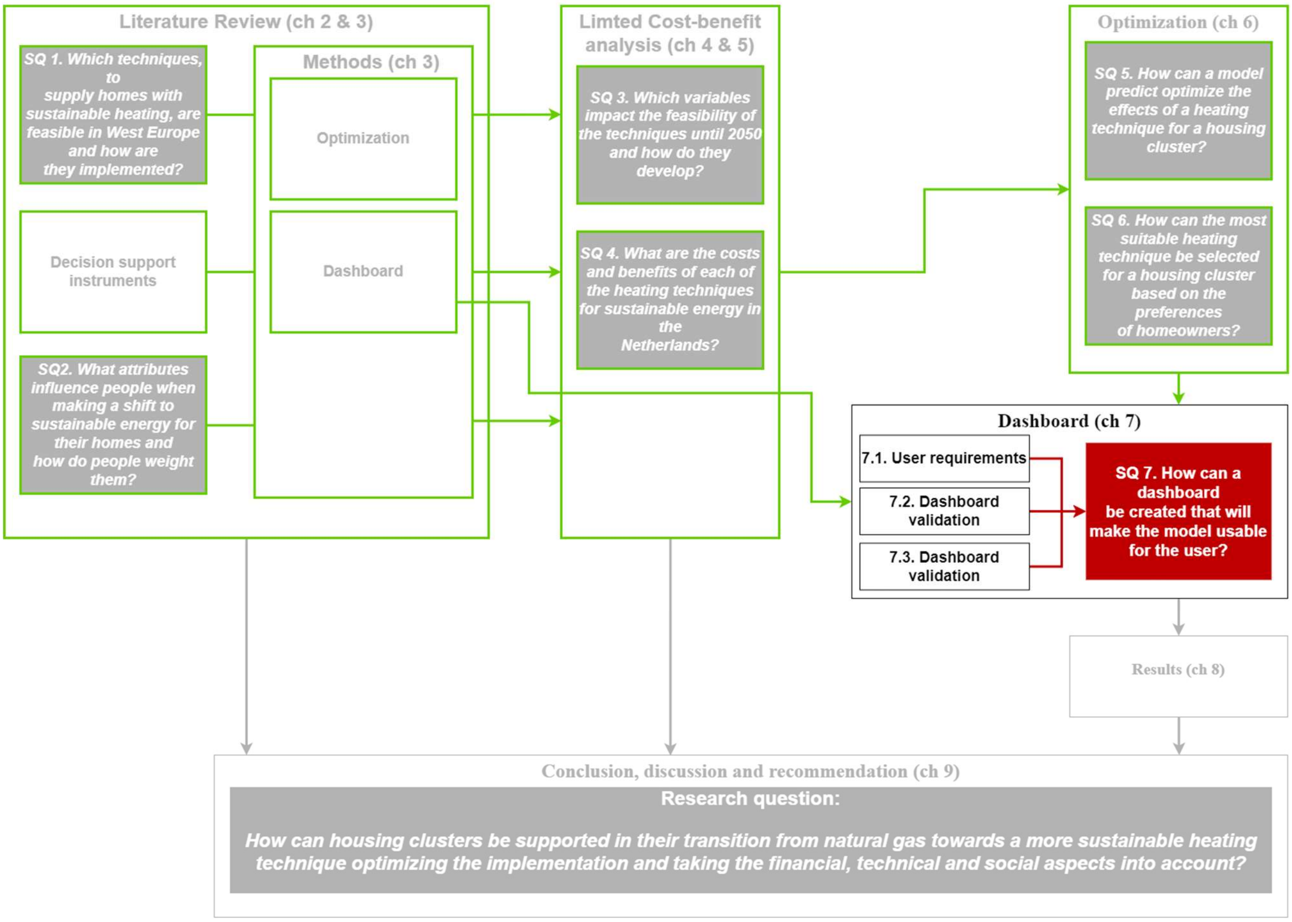


Figure 68: Creation of the dashboard within the overall research design

The optimization models can provide a quick insight into the optimal implementation (based on input variables) of the different alternatives. This insight is required to determine the costs and benefits of the reference housing cluster. The models have been created in such a way that they can optimize all types of housing clusters. Therefore, the created models will not only add to the research into the energy transition of housing stock but also contribute to the speed of the energy transition. By providing homeowners with information about the potential impacts of different heating techniques, the models can contribute to the speed of this transition. This information will only have an added value if the models are usable for homeowners. This will be done by creating an interface (dashboard) for the optimization models.

7.1. User requirements

The dashboard will be built to inform users about the consequences of the various heating techniques for the heating of homes. The dashboard will be an interactive dashboard that can, by using different optimization models, provide an overview and advice about the different techniques for a housing cluster. This will be based on user input. A housing cluster is a group of dwellings that can have different characteristics but are situated close to each other. An example of this could be a group of dwellings in the same street. Due to the cluster's proximity, collective heating techniques can be used in addition to individual heating techniques. The most appropriate heating method varies per cluster based on the cluster properties and the homeowner preferences. The dashboard needs to have the option to be a web-based dashboard ensuring high accessibility for the users of the dashboard. The dashboard will provide an insight into the implementation of the different heating techniques (technical and financial), this will be visualized in tables and charts. By providing a clear insight into the consequences of the heating techniques over a time period of 2020 until 2050 the dashboard will allow the user to compare the different techniques to each other and the current situation. In addition, the dashboard will optimize "for the most appropriate implementation of the heating technique" based on the preferences of homeowners. The dashboard will use data which is provided by the developer. This data consists of the results of a Cost-Benefit Analysis, literature review and expert opinion, which include the key numbers and requirements used in calculations of the dashboard. The data will be provided in 2D charts, which show information like investment costs per technique and yearly costs.

7.1.1. General description

Production perspective

The dashboard aims to help speed up the process of the transition from heating dwellings with natural gas to a more sustainable source. This will be done by providing the user with a better insight into the implementation and consequences of each heating technique in a specific situation. The natural gas-free heating techniques that will be part of the dashboard are the above-described heating techniques (middle-temperature district heating, low-temperature district heating, individual air-to-water heat pump and a collective ground heat pump). Besides these natural gas-free heating techniques, heating with natural gas (which will shift to a hybrid heat pump) will be included. This enables the user to compare the results of the natural gas-free heating techniques with the current situation (heating using natural gas). The dashboard will calculate the results per technique based on the characteristics of a housing cluster, that the user will provide as input. To make the results more comprehensible, they will be interactive and visualized. The dashboard will furthermore have the option to be a web-based application to ensure its accessibility for the user. The main focus of the dashboard lies in providing the user with more information about the implementation of the different techniques. To assist the user in making decisions about the implementation of techniques for switching from natural gas and accelerate this process for Dutch housing stock.

General capabilities

The dashboard has two types of users, which are government users and public users. These different users have a similar level of accessibility to the functionalities and information of the dashboard since the goal of the dashboard for both users is to inform. During future developments of the dashboard, different functionalities for these two types of users could be developed.

The dashboard allows users to modify the properties of the housing cluster. This is the input of the dashboard. The user can modify the input cluster by adding and deleting dwellings of the cluster and by editing the properties per dwelling. Properties that will be taken into account are the energy label, the type of dwelling, construction year, dimensions of the dwelling, household size and energy consumption. The user can also modify the variables of the project according to the scenarios. Until 2050, the feasibility of the different heating techniques depends on the price of natural gas, the price of electricity, the price of heat (from district heating), the price of purchase and the development of the costs of the various heating techniques. For these different variables, scenarios of their development until 2050 have been created (Section 4.2) and the user of the dashboard can decide which scenario he wants to take into account. The dashboard will calculate the optimal implementation per technique dependent on the optimization focus. The optimization focus can be decided by the user. The implementation is optimized based on the objectives: costs (minimize), climate (minimize CO_2 emissions) and comfort (maximize), which have been described in the previous Chapters. The weights of these objectives can be adapted based on the preferences of the user. After the user provides the above-described input information, the dashboard will show the impact of the implementation per heating technique until 2050 for the selected housing cluster. The results are displayed over different taps to keep the dashboard clear. First of all, there will be a page with the main overview of the results of the technique. This page should enable the user to compare the different techniques to natural gas and each other. The page should provide information such as the difference in the cost per technique, and the CO_2 emission until 2050 compared to heating with natural gas. Besides the overview page, the dashboard will also contain separate tabs per heating technique. These tabs will provide more detailed information on the implementation of a certain technique, which means that the user can select a dwelling of the input cluster and get an overview of which interventions are required, when and what the impact is for the household. The results will be visualized by tables and charts. The dashboard must be usable for the user without any required prior knowledge.

User characteristics

For the dashboard, there are, as described above, two types of users. The governmental user and the public user. Both users will have the same level of access and functionalities for the dashboard. Public users can access the input page and add, delete and change the dwellings included in the housing cluster. Additionally, the user can customize the scenarios for the variables. This user can personalize the optimization preferences. After completing the input, access the results on the overview page and heating technique-specific pages. The accessibility of the public user matches the level of access of the governmental user. The governmental user includes employees of municipalities. The benefit to the governmental user is that it can function as a tool to inform homeowners (public users). Therefore, the capabilities can be similar for both users.

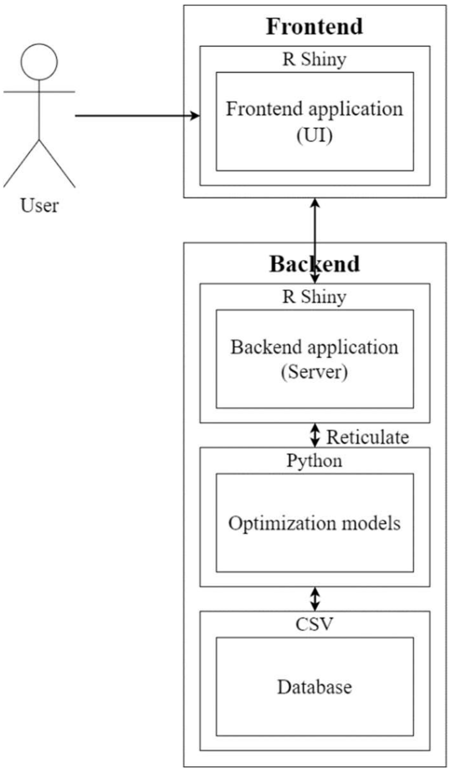


Figure 69: Diagram of the environment model

Environment description

In Figure 69, a diagram of the environment model is shown. It can be seen that there is a frontend and a backend to the environment. The user of the dashboard only interacts with the frontend of the environment, which is the dashboard. The dashboard will be created with RStudio Shiny (which is written in the R programming language). The frontend of the application interacts with the backend of the application, which includes the optimization models. The optimization models are created using phyton which will interact with the R Shiny dashboard using the (RStudio) package “Reticulate”. The optimization models in the backend of the application use a database for the calculation of the optimal implementation per technique until 2050. The database includes the information needed for these models, which includes information like investment costs and CO_2 emissions per energy source.

Dependencies

For the application to function as specified above the dashboard is dependent on the following programs and packages:

- Shiny
- Rstudio
- Phyton
- Reticulate package
- Dplyr
- Ggplot2
- Gapminder
- Shinymanager
- Rintrojs
- Gurobi
- Tidyverse
- Pandas
- PuLP
- Numpy
- Math
- Matplotlib
- Pyomo
- Seaborn

7.1.2. Specific requirements

In this Section, the capability and constraint requirements will be specified. The capability requirements concern what the application should be able to do and the constraint requirements concern how the application should perform. These requirements will be classified and prioritized using the MoSCoW method. This method assigns priority to all requirements. These priorities are shown in Table 72. The scope will be on the core capabilities of the dashboard. Which is to enable the user to use the optimization models and visualize the results in a way that is understandable for the user.

Table 72: Priority levels MoSCoW method

Level of priority	Explanation
Must have	The requirements of this level of priority must be met at the end of the project otherwise the application will have little use.
Should have	The requirements of this level of priority should be met at the end of the project. It will be important to meet these requirements but it will not be vital for the application.
Could have	The requirements of this level of priority are desirable to have at the end of the project but are less important.
Won't have	The requirements of this level of priority will not be implemented at the end of the project. This category will help establish the scope and expectations.

Capability requirements

Authentication & Authorization

ID	Requirement	Priority
AUT001	The system should have a "Login" function.	COULD HAVE
AUT002	The "Login" function should have a user name field.	COULD HAVE
AUT003	The "Login" function should have a password field.	COULD HAVE
AUT004	The "Login" function should check whether the username and password combination is valid.	COULD HAVE
AUT005	When during the "Login" functionality the username and password combination is determined valid, the system should log in the user.	COULD HAVE
AUT006	When during the "Login" functionality the username and password combination is determined invalid, the system should not log in the user and state an invalid login.	COULD HAVE
AUT007	The login page should contain contact information to request a password.	WON'T HAVE
AUT008	When the user is logged in the system should allow the user to log out.	COULD HAVE
AUT009	An account should have a username.	COULD HAVE
AUT010	An account should have a password.	COULD HAVE
AUT011	An account should have one role.	COULD HAVE
AUT012	An account shall have all the authorizations of their roles.	COULD HAVE
AUT013	The user should be logged in to access the system's functionalities.	COULD HAVE

Cluster selection

ID	Requirement	Priority
CS001	The system must have a "select number of dwellings" function.	MUST
CS002	The "select number of dwellings" function should have a choice option to select the number of dwellings.	SHOULD HAVE
CS003	If the number of dwellings is selected input area could appear where the properties of the dwelling can be added.	COULD HAVE
CS004	The input area must consist of the input fields; "type of dwelling", "construction year", "household size", "floor size", "energy label", "type of roof", "length of roof", "width of roof", "height of roof", "natural gas consumption" and "electricity consumption".	MUST
CS005	Before the user selects the input values for the dwelling, default values should be selected.	SHOULD HAVE

Selecting scenarios

ID	Requirement	Priority
SV001	The system must have a "select scenarios" function.	MUST

SV002	The "select scenarios" function must include the variables "development of price of natural gas", "development of price of electricity", "year heat price detaches form natural gas", "incorporate discount rate" and "distance of the housing cluster to the district heating network".	MUST
SV003	The "select scenarios" function could include the variables "development of investment cost" and "percentage price reduction decrease connection costs based on cluster size",	COULD HAVE
SV004	For the "select scenarios" function the scenarios low, medium and high should be the options for the variables "development of price of natural gas" and "development of price of electricity".	SHOULD HAVE
SV005	For the "select scenarios" function the scenarios low and high should be the options for the variable "investment costs technique".	SHOULD HAVE
SV006	The "select scenarios" function variable "incorporate discount rate" should have the options Yes and No.	SHOULD HAVE
SV007	For the "select scenarios" function the variables "year heat price detaches from natural gas", "incorporate discount rate", "distance of the housing cluster to the district heating network" and "percentage price reduction decrease connection costs based on cluster size". The user should be able to adjust the height of the numeric value.	SHOULD HAVE
SV008	When a user did not select a scenario a default value should be selected.	SHOULD HAVE
SV010	The system must have a "select optimization focus" functionality.	MUST
SV011	The "select optimization focus" functionality must include the options, "Default values" and "personal preferences".	MUST
SV012	If the option "personal preferences" is selected for the "select optimization focus" functionality, the user must select the preferences using an Analytical hierarchy process (AHP).	COULD HAVE

Overview page

ID	Requirement	Priority
OP001	An overview of the results must be shown on the overview page.	MUST
OP002	The overview page must have a "select dwelling" function.	MUST
OP003	The "select dwelling" function should have a choice option to select the dwelling.	SHOULD HAVE
OP004	If a dwelling is selected the overview page must show the results for the selected dwelling.	MUST
OP005	The overview page must have a "select heating technique" function.	MUST
OP006	The "select heating technique" function should have a choice option to select a heating technique.	SHOULD HAVE
OP007	If a heating technique is selected the overview page must show the results for the selected heating technique.	MUST
OP008	The overview page should contain charts that show the cumulative costs and CO_2 emissions until 2050. For the selected heating technique and the technique heating with natural gas.	SHOULD HAVE
OP009	The user should be able to select which heating techniques they want to have visualized in the graphs for cumulative costs and CO_2 emission.	SHOULD HAVE
OP010	The page must show the difference in investment costs, reinvestment costs, average yearly maintenance costs, average yearly energy costs, total costs and CO_2 emission of the selected heating technique compared to the baseline alternative.	MUST

Heating technique overview (these requirements apply to every separate heating technique page)

ID	Requirement	Priority
HTP001	There should be separate pages for the heating techniques: DH1, DH2, AL1, AL2 and baseline alternative.	SHOULD HAVE
HTP002	The overview page must have a "select dwelling" function.	MUST

HTP003	The "select dwelling" function should have a choice option to select the dwelling.	SHOULD HAVE
HTP004	If a dwelling is selected the overview page must show the results for the selected dwelling.	MUST
HTP005	The heating technique page should contain charts that show the cumulative costs and CO_2 emissions until 2050.	SHOULD HAVE
HTP006	The page must show the investment costs, reinvestment costs, average yearly maintenance costs, average yearly energy costs, total costs and CO_2 emission of the heating technique.	MUST

Constraint requirements

General

ID	**Requirement**	**Priority**
GE001	The user must be able to operate the system without needing the support of the system designer.	MUST
GE002	The system should be able to operate the system without prior knowledge of the heating techniques	SHOULD HAVE
GE003	The dashboard could be online available.	COULD HAVE
GE004	The dashboard could be available through a mobile browser.	COULD HAVE

Safety & Security

ID	**Requirement**	**Priority**
SS001	The data in the system is the property of the Eindhoven University of Technology.	MUST

7.2. Dashboard description

As described above a Shiny application consists of two main Sections, which are UI and Server, see Figure 70. The UI contains the code for the front end of the dashboard. The server includes the code for the backend of the dashboard. This can include data retrieval and manipulation. The UI, Server and Python script are briefly discussed below. In the UI of the dashboard, the front end is described. The front end of the dashboard is made up of an input page and six output pages which show the results of the functions. In the UI the input that the user of the dashboard needs to provide is specified. It is also described in the UI how the dashboard asks for this information from the user. The dwelling properties can be entered by the user on the input page. Table 73 shows which inputs the user can give on the input page, which control widgets are used and the input values. All parameters will be shown per dwelling, which means that in the case of 5 dwellings, for the parameter "Housing type" there will be five input parameters for "Housing type".

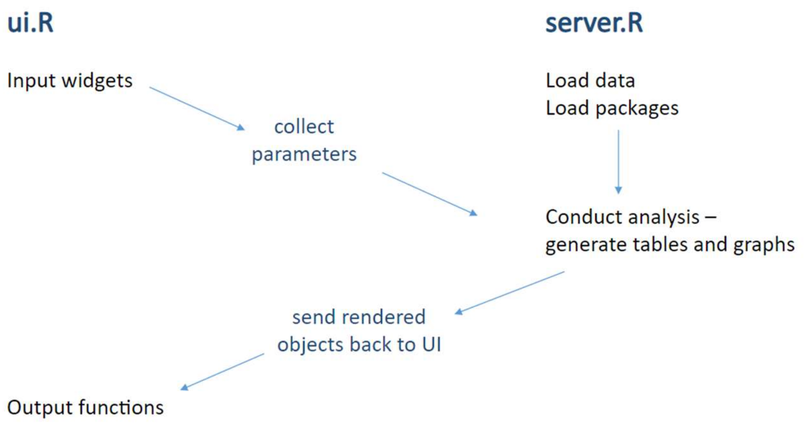
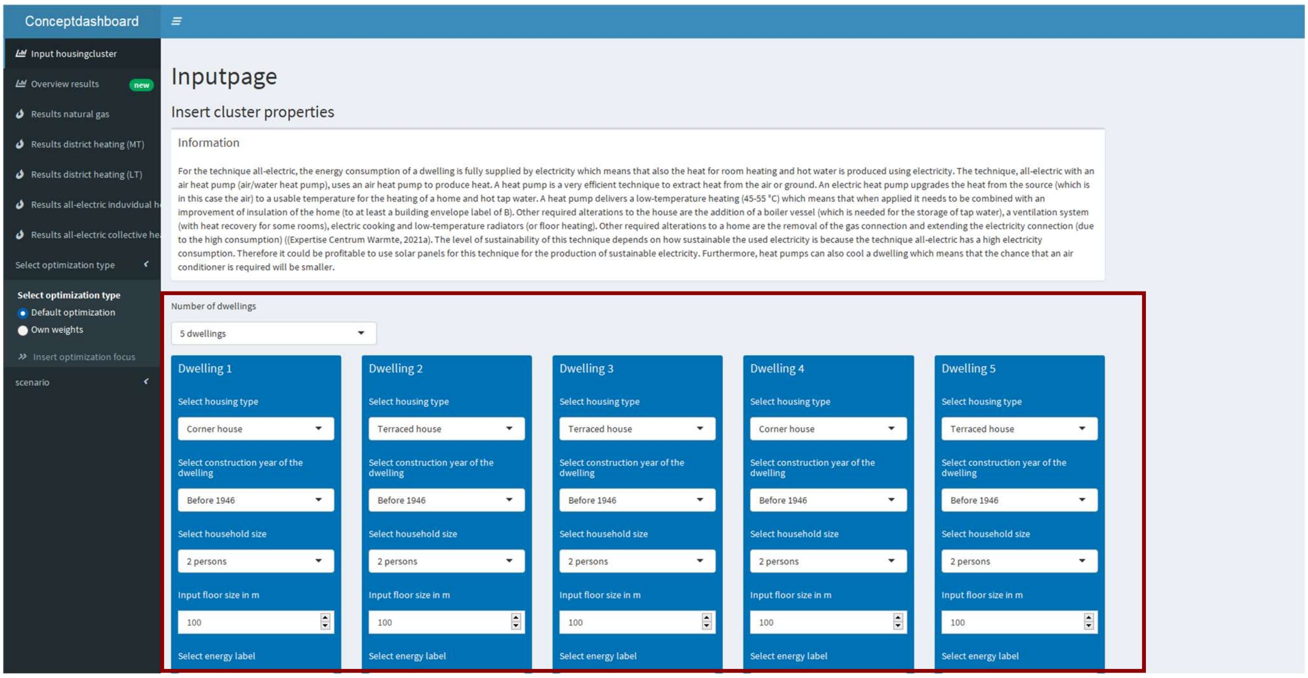


Figure 70: Anatomy of a Shiny app: data flow (Lecy, n.d.)

Table 73: Input dwelling properties of the input page

Input parameter	Control widgets	Default value	Options
Number of dwellings in the cluster	Select input	1 dwelling	1 dwelling 2 dwellings 3 dwellings 4 dwellings 5 dwellings
Housing type	Select input	Terraced house	Terraced house Semi-detached house Corner house Detached house
Construction year	Select input	Before 1946	Before 1946 1946-1964 1965-1974 1975-1991 1992-2004 2005-2018
Household size	Select input	2 persons	1 person 2 persons 3 persons 4 persons 5 persons or more
Floor size	Numeric input	100	
Energy label	Select input	G	A B C D E F G
Current natural gas consumption	Numeric input	0	
Current electricity consumption	Numeric input	0	
Type of roof	Select input	Flat roof	Flat roof Slanted roof
Length of the roof	Numeric input	3	
Width of the roof	Numeric input	3	
Height of the roof	Numeric input	1	

Figure 71 shows the visualisation of the input of the dwelling properties described in the table above. It can be seen that the input page consists of a title, an information box with an explanation about the dashboard and the page, the select input box for the number of dwellings in the cluster and per dwelling in the cluster a box with the input fields of the dwelling properties.



Inputpage

Insert cluster properties

Information

For the technique all-electric, the energy consumption of a dwelling is fully supplied by electricity which means that also the heat for room heating and hot water is produced using electricity. The technique, all-electric with an air heat pump (air/water heat pump), uses an air heat pump to produce heat. A heat pump is a very efficient technique to extract heat from the air or ground. An electric heat pump upgrades the heat from the source (which is in this case the air) to a usable temperature for the heating of a home and hot tap water. A heat pump delivers a low-temperature heating (45-55 °C) which means that when applied it needs to be combined with an improvement of insulation of the home (to at least a building envelope label of B). Other required alterations to the house are the addition of a boiler vessel (which is needed for the storage of tap water), a ventilation system (with heat recovery for some rooms), electric cooking and low-temperature radiators (or floor heating). Other required alterations to a home are the removal of the gas connection and extending the electricity connection (due to the high consumption) ((Expertise Centrum Warmte, 2021a). The level of sustainability of this technique depends on how sustainable the used electricity is because the technique all-electric has a high electricity consumption. Therefore it could be profitable to use solar panels for this technique for the production of sustainable electricity. Furthermore, heat pumps can also cool a dwelling which means that the chance that an air conditioner is required will be smaller.

Number of dwellings: 5 dwellings

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Select housing type	Corner house	Terraced house	Terraced house	Corner house	Terraced house
Select construction year of the dwelling	Before 1946	Before 1946	Before 1946	Before 1946	Before 1946
Select household size	2 persons	2 persons	2 persons	2 persons	2 persons
Input floor size in m	100	100	100	100	100
Select energy label					

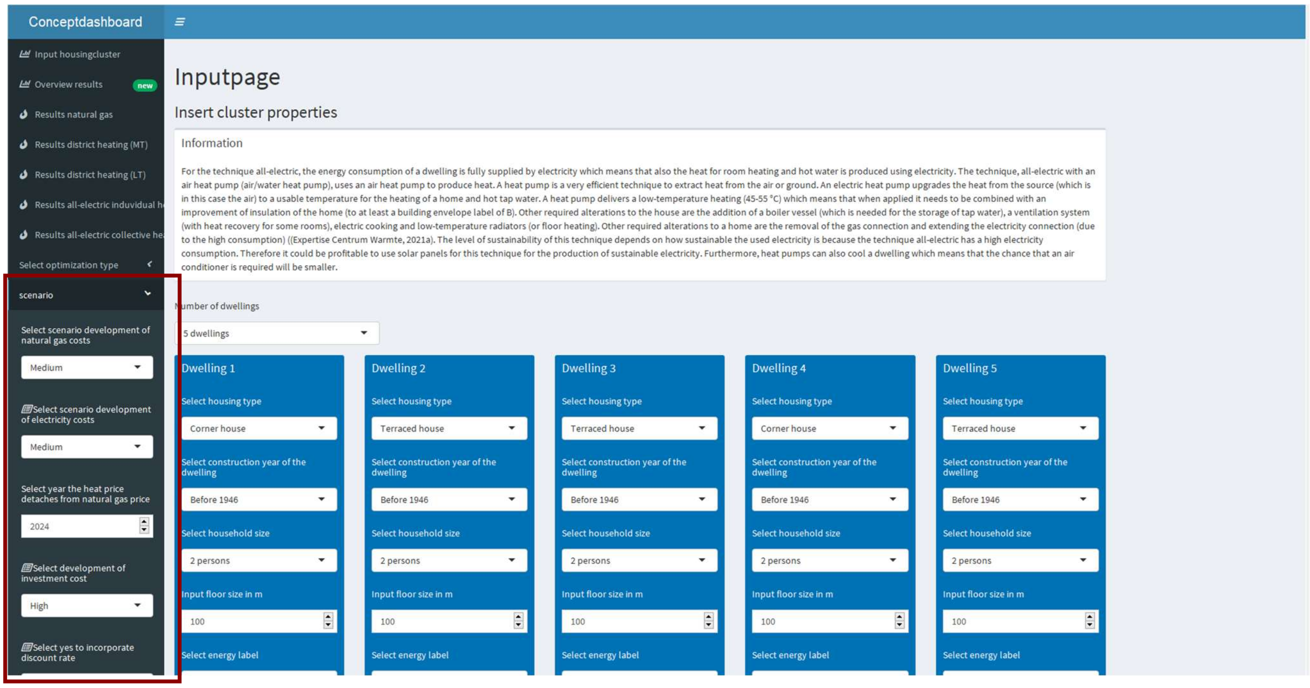
Figure 71: Impression of input page of the dashboard, the dwelling property input fields are outlined in red

Besides the building properties, the user of the dashboard can also modify the scenario the optimization models take into account. These variables are not displayed on the input page because the user needs to be able to change these variables on any page. Therefore, the scenario variables are shown in the sidebar menu. Table 74 displays which variables the user can change within the sidebar menu to modify the scenario, which control widgets are being used and the input values.

Table 74: Input variables the user can change to adapt the scenario, which are displayed in the sidebar menu

Input parameter	Control widgets	Default value	Options
Distance to district heating network	Numeric input	30	
Price reduction due to increase in cluster size of district heating cluster	Numeric input	0.05	
Development of the natural gas price	Select input	Medium	Low Medium High
Development of the electricity price	Select input	Medium	Low Medium High
Development of the investment costs	Select input	High	Low High
Year heat price detaches from natural gas price	Numeric input	2024	2020-2050
Incorporate discount rate	Numeric input	No	Yes No

Figure 73 shows the visualisation of the input variables the user can change to adapt to the scenario as described in the table above. The input variables are displayed in a dropdown menu in the sidebar. The sidebar can be opened on every page of the dashboard. Therefore, the user can adapt the scenario on every subpage.



Select scenario development of natural gas costs: Medium

Select scenario development of electricity costs: Medium

Select year the heat price detaches from natural gas price: 2024

Select development of investment cost: High

Select yes to incorporate discount rate

Inputpage

Insert cluster properties

Information

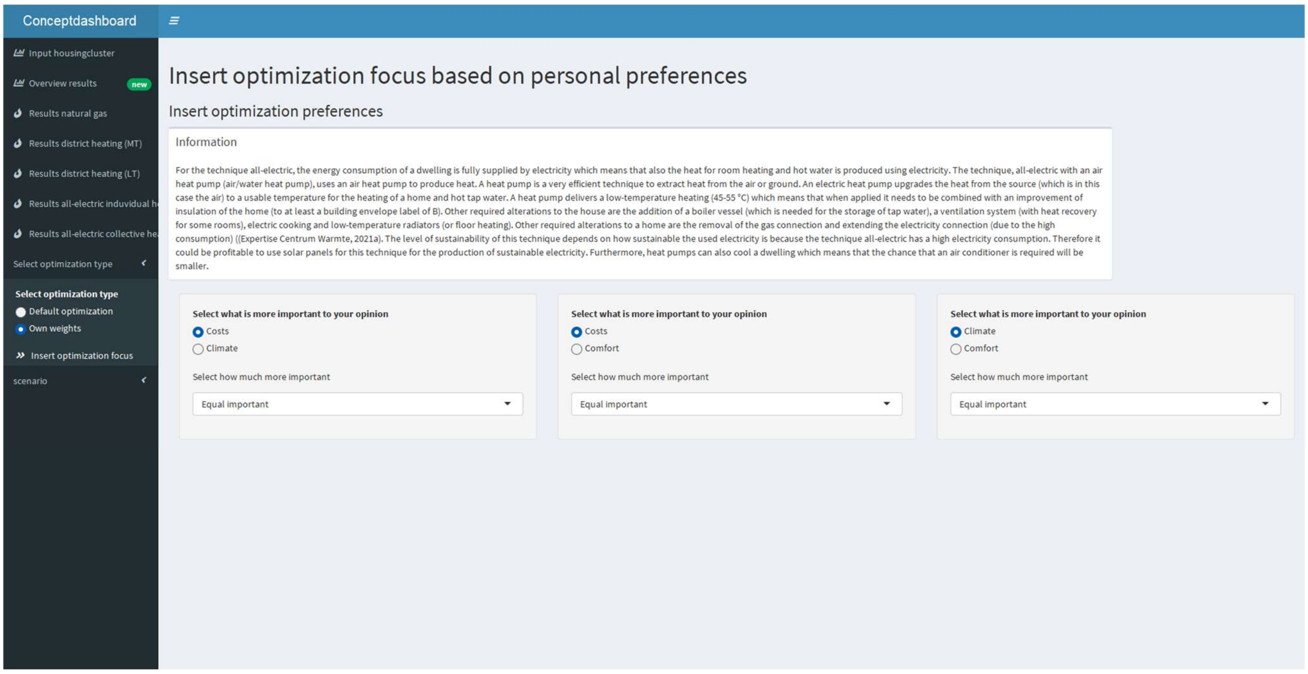
For the technique all-electric, the energy consumption of a dwelling is fully supplied by electricity which means that also the heat for room heating and hot water is produced using electricity. The technique, all-electric with an air heat pump (air/water heat pump), uses an air heat pump to produce heat. A heat pump is a very efficient technique to extract heat from the air or ground. An electric heat pump upgrades the heat from the source (which is in this case the air) to a usable temperature for the heating of a home and hot tap water. A heat pump delivers a low-temperature heating (45-55 °C) which means that when applied it needs to be combined with an improvement of insulation of the home (to at least a building envelope label of B). Other required alterations to the house are the addition of a boiler vessel (which is needed for the storage of tap water), a ventilation system (with heat recovery for some rooms), electric cooking and low-temperature radiators (or floor heating). Other required alterations to a home are the removal of the gas connection and extending the electricity connection (due to the high consumption) ((Expertise Centrum Warmte, 2021a). The level of sustainability of this technique depends on how sustainable the used electricity is because the technique all-electric has a high electricity consumption. Therefore it could be profitable to use solar panels for this technique for the production of sustainable electricity. Furthermore, heat pumps can also cool a dwelling which means that the chance that an air conditioner is required will be smaller.

Number of dwellings: 5 dwellings

	Dwelling 1	Dwelling 2	Dwelling 3	Dwelling 4	Dwelling 5
Select housing type	Corner house	Terraced house	Terraced house	Corner house	Terraced house
Select construction year of the dwelling	Before 1946	Before 1946	Before 1946	Before 1946	Before 1946
Select household size	2 persons	2 persons	2 persons	2 persons	2 persons
Input floor size in m	100	100	100	100	100
Select energy label					

Figure 73: Impression the input page with the scenario variables in the sidebar menu outlined in red

The dashboard uses the optimization models created in the previous Section to optimize the implementation per heating technique. The weighted sum method is applied. The weight of the objectives is very important. As described in Section 6.1, the default weights that are used are selected from the literature review, and the user can adapt the default weights through an AHP. Figure 72 shows how the user can set their own preferences as weights for the optimization. In the figure, it can be seen that by default the “default weight” is applied. If the user wants to use their own preferences for the optimization the user can select “own weights” and redirect to the page “Insert optimization focus based on personal preferences”. This page consists of a title, an information box with an explanation about the page, and the input fields of the AHP. If the user selects “own weights” and fills in the AHP, the user's preferences are applied as weights in the optimization. Before the weights are



Select optimization type
○ Default optimization
● Own weights

Insert optimization focus based on personal preferences

Insert optimization preferences

Information

For the technique all-electric, the energy consumption of a dwelling is fully supplied by electricity which means that also the heat for room heating and hot water is produced using electricity. The technique, all-electric with an air heat pump (air/water heat pump), uses an air heat pump to produce heat. A heat pump is a very efficient technique to extract heat from the air or ground. An electric heat pump upgrades the heat from the source (which is in this case the air) to a usable temperature for the heating of a home and hot tap water. A heat pump delivers a low-temperature heating (45-55 °C) which means that when applied it needs to be combined with an improvement of insulation of the home (to at least a building envelope label of B). Other required alterations to the house are the addition of a boiler vessel (which is needed for the storage of tap water), a ventilation system (with heat recovery for some rooms), electric cooking and low-temperature radiators (or floor heating). Other required alterations to a home are the removal of the gas connection and extending the electricity connection (due to the high consumption) ((Expertise Centrum Warmte, 2021a). The level of sustainability of this technique depends on how sustainable the used electricity is because the technique all-electric has a high electricity consumption. Therefore it could be profitable to use solar panels for this technique for the production of sustainable electricity. Furthermore, heat pumps can also cool a dwelling which means that the chance that an air conditioner is required will be smaller.

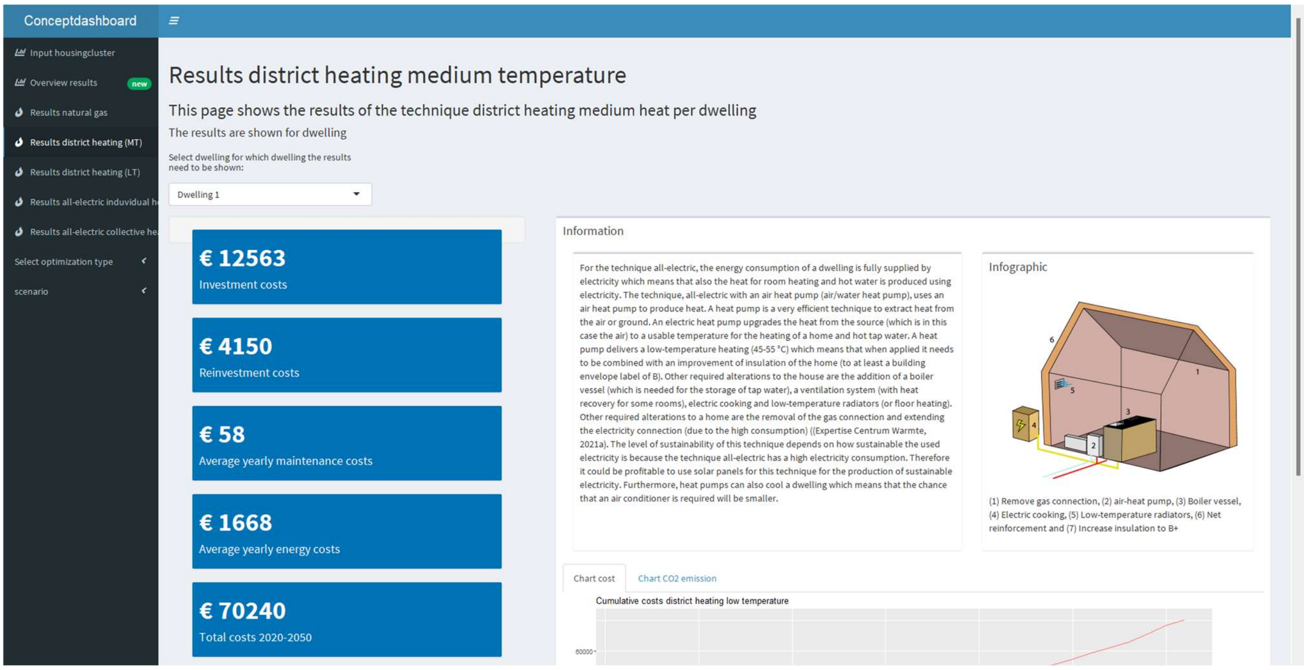
Select what is more important to your opinion
● Costs
○ Climate
Select how much more important: Equal important

Select what is more important to your opinion
● Costs
○ Comfort
Select how much more important: Equal important

Select what is more important to your opinion
● Climate
○ Comfort
Select how much more important: Equal important

Figure 72: Impression the insert optimization focus based on the personal preferences of the user

applied, the consistency ratio (CR) of the input AHP is checked to be lower than 0,10. If this is the case the input weights of the user are used. If the CR is higher the dashboard will display an error and the default weights will be used.



Results district heating medium temperature

This page shows the results of the technique district heating medium heat per dwelling

The results are shown for dwelling

Select dwelling for which dwelling the results need to be shown: Dwelling 1

€ 12563
Investment costs

€ 4150
Reinvestment costs

€ 58
Average yearly maintenance costs

€ 1668
Average yearly energy costs

€ 70240
Total costs 2020-2050

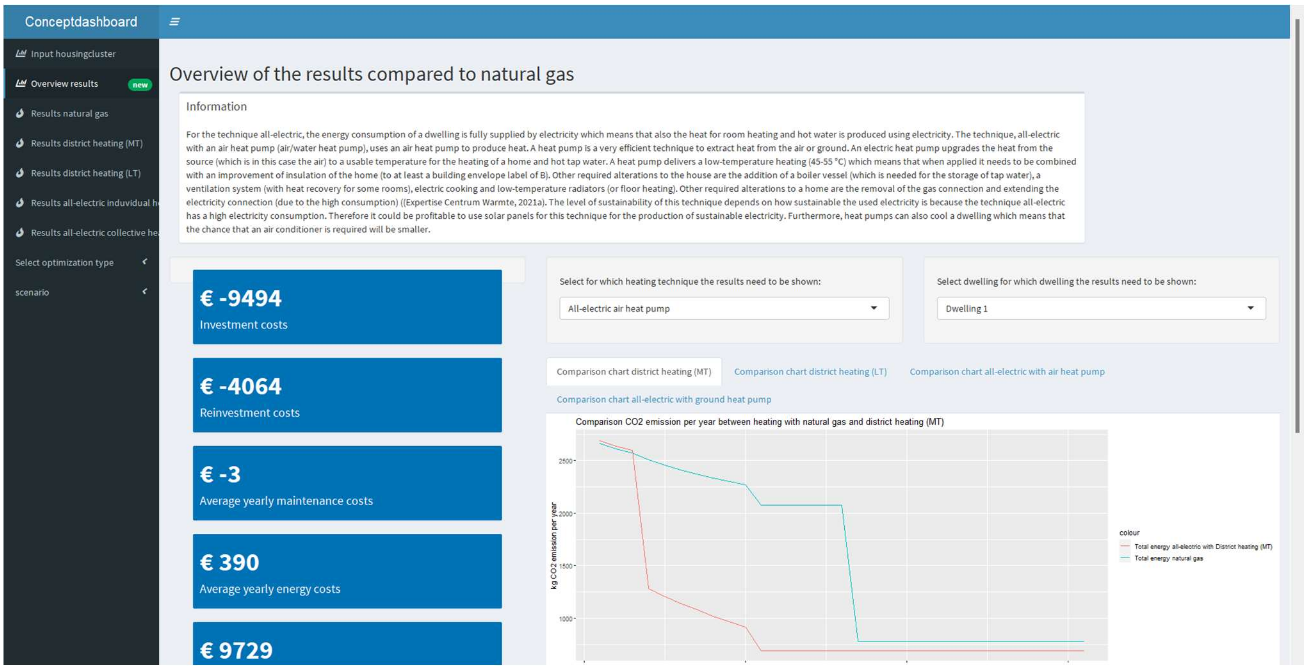
Information

For the technique all-electric, the energy consumption of a dwelling is fully supplied by electricity which means that also the heat for room heating and hot water is produced using electricity. The technique, all-electric with an air heat pump (air/water heat pump), uses an air heat pump to produce heat. A heat pump is a very efficient technique to extract heat from the air or ground. An electric heat pump upgrades the heat from the source (which is in this case the air) to a usable temperature for the heating of a home and hot tap water. A heat pump delivers a low-temperature heating (45-55 °C) which means that when applied it needs to be combined with an improvement of insulation of the home (to at least a building envelope label of B). Other required alterations to the house are the addition of a boiler vessel (which is needed for the storage of tap water), a ventilation system (with heat recovery for some rooms), electric cooking and low-temperature radiators (or floor heating). Other required alterations to a home are the removal of the gas connection and extending the electricity connection (due to the high consumption) ((Expertise Centrum Warmte, 2021a). The level of sustainability of this technique depends on how sustainable the used electricity is because the technique all-electric has a high electricity consumption. Therefore it could be profitable to use solar panels for this technique for the production of sustainable electricity. Furthermore, heat pumps can also cool a dwelling which means that the chance that an air conditioner is required will be smaller.

(1) Remove gas connection, (2) air-heat pump, (3) Boiler vessel, (4) Electric cooking, (5) Low-temperature radiators, (6) Net reinforcement and (7) Increase insulation to B+

Figure 74: Impression one of the result pages per heating technique

The dashboard gives the results for the optimal implementation per heating technique based on the user input. The dashboard contains an output page per heating technique. On this page, the results of the optimal implementation of the heating technique are displayed. In Figure 74 the output page for the alternative district heating 1 is shown. The output page consists of a title, an information box with an explanation of the heating technique, an input box for selecting which dwelling of the cluster to display the results, the main output results,



Overview of the results compared to natural gas

Information

For the technique all-electric, the energy consumption of a dwelling is fully supplied by electricity which means that also the heat for room heating and hot water is produced using electricity. The technique, all-electric with an air heat pump (air/water heat pump), uses an air heat pump to produce heat. A heat pump is a very efficient technique to extract heat from the air or ground. An electric heat pump upgrades the heat from the source (which is in this case the air) to a usable temperature for the heating of a home and hot tap water. A heat pump delivers a low-temperature heating (45-55 °C) which means that when applied it needs to be combined with an improvement of insulation of the home (to at least a building envelope label of B). Other required alterations to the house are the addition of a boiler vessel (which is needed for the storage of tap water), a ventilation system (with heat recovery for some rooms), electric cooking and low-temperature radiators (or floor heating). Other required alterations to a home are the removal of the gas connection and extending the electricity connection (due to the high consumption) ((Expertise Centrum Warmte, 2021a). The level of sustainability of this technique depends on how sustainable the used electricity is because the technique all-electric has a high electricity consumption. Therefore it could be profitable to use solar panels for this technique for the production of sustainable electricity. Furthermore, heat pumps can also cool a dwelling which means that the chance that an air conditioner is required will be smaller.

Select for which heating technique the results need to be shown: All-electric air heat pump

Select dwelling for which dwelling the results need to be shown: Dwelling 1

€ -9494
Investment costs

€ -4064
Reinvestment costs

€ -3
Average yearly maintenance costs

€ 390
Average yearly energy costs

€ 9729

Figure 75: Impression of the page overview of the results

an infographic of the required home adaptations, the optimal switching year, and output charts for costs and CO_2 emissions over 30 years. The main output results are shown in boxes and the results that are visualized are the investment costs, the reinvestment costs, the average yearly maintenance costs, the average yearly energy costs, the total costs and the total CO_2 emissions in kg. If an output page is opened the optimization for that technique is automatically executed. There is not a separate function for all results of the page because if this were the case, optimization would need to be performed many times. This makes the display of the results very slow. Therefore, the function is only executed for the investment costs and creates a data frame which is used to visualize the output and the charts. If an adaptation is made to the dashboard's input, the results are automatically updated.

Besides the result pages per heating technique, the dashboard also contains an overview page on which the results are compared to natural gas (baseline alternative). This output page is shown in Figure 75. The overview page consists of a title, an information box with the explanation of the page, an input box for selecting which dwelling of the cluster to display the results, an input box for which heating technique the results should be shown, the main output results and output charts for costs and CO_2 emissions per technique for 30 years. For this page, a function is executed that includes all optimization models.

7.3. Dashboard validation

The dashboard will be validated twice. First, by evaluating whether it meets the set user requirements and second by testing it on a potential user which is the municipality of Eindhoven.

7.3.1. Validation user requirements

The dashboard will be validated by evaluating whether it meets the set user requirements. In Table 75 it can be seen how well the dashboard meets the set user requirements. It can be seen that the dashboard satisfies all high-priority requirements. One selection of requirements is not satisfied by the dashboard, which is the login page. This does not affect the results or the main functionality of the dashboard, therefore the priority of these requirements was “COULD HAVE”. This means that it is not problematic for the dashboard to miss these requirements and it could still be added at a later moment in time. By testing the dashboard with the set user requirements it can be concluded that the dashboard meets the (critical) user requirements.

Table 75: Performance of the dashboard on the user requirements

ID	Priority	Meets requirement	ID	Priority	Meets requirement
AUT001	COULD HAVE	No	SV010	MUST	Yes
AUT002	COULD HAVE	No	SV011	MUST	Yes
AUT003	COULD HAVE	No	SV012	COULD HAVE	Yes
AUT004	COULD HAVE	No	OP001	MUST	Yes
AUT005	COULD HAVE	No	OP002	MUST	Yes
AUT006	COULD HAVE	No	OP003	SHOULD HAVE	Yes
AUT007	WON’T HAVE	No	OP004	MUST	Yes
AUT008	COULD HAVE	No	OP005	MUST	Yes
AUT009	COULD HAVE	No	OP006	SHOULD HAVE	Yes

AUT010	COULD HAVE	No
AUT011	COULD HAVE	No
AUT012	COULD HAVE	No
AUT013	COULD HAVE	No
CS001	MUST	Yes
CS002	SHOULD HAVE	Yes
CS003	COULD HAVE	No
CS004	MUST	Yes
CS005	SHOULD HAVE	Yes
SV001	MUST	Yes
SV002	MUST	Yes
SV003	COULD HAVE	Yes
SV004	SHOULD HAVE	Yes
SV005	SHOULD HAVE	Yes
SV006	SHOULD HAVE	Yes
SV007	SHOULD HAVE	Yes
SV008	SHOULD HAVE	Yes
OP007	MUST	Yes
OP008	SHOULD HAVE	Yes
OP009	SHOULD HAVE	Yes
OP010	MUST	Yes
HTP001	SHOULD HAVE	Yes
HTP002	MUST	Yes
HTP003	SHOULD HAVE	Yes
HTP004	MUST	Yes
HTP005	SHOULD HAVE	Yes
HTP006	MUST	Yes
GE001	MUST	Yes
GE002	SHOULD HAVE	Yes
GE003	COULD HAVE	Yes
GE004	COULD HAVE	Yes
SS001	MUST	Yes

7.3.2. User validation

To determine whether the dashboard is used and interpreted by the target group as intended. It should be tested and validated by the target group. This is done by an energy transition project leader of the municipality of Eindhoven. To test the dashboard the project leader was asked to do a set of assignments. These assignments were selected to test the main functionalities of the dashboard in a limited set of tasks. The tasks are shown in *Appendix AA: Tasks user validation*. The project leader was able to execute all tasks but had some recommendations:

1. The project leader intuitively felt that there should be a "run" button (which is not necessary since the model runs the inputs automatically);
2. Many attributes of the used scenario can be modified, it can be confusing which scenario is used for the shown results;
3. It would feel more logical if only the input blocks were visible for the selected number of homes in the cluster.

Apart from the comments, the project leader indicated the dashboard was a good proof of concept and the possibilities were extensive. She was also positive about the capabilities of the dashboard and that she was able to execute the tasks without an explanation. She also indicated that the dashboard could be used by homeowners, for which the dashboard would preferably be in Dutch. This tool added the most value to the municipality as a participation tool, in terms of educating neighbourhoods and homeowners about heating techniques. By using it as a participation tool, a supervisor will be available, while homeowners use the tool, to provide additional information. This would be beneficial since the heating techniques are quite complicated for a part of the Dutch homeowners. Due to the findings from the user validation, it can be assumed that the dashboard is usable for the target group. Furthermore, usable information and recommendations were gained during this validation. Although these recommendations included comments which can be used to improve the dashboard, it was also found that all tasks could be executed. This proved the usability of the dashboard. Although the user validation resulted in positive results it is advisable to conduct more extensive research with a target group of homeowners. This will increase the usability of the dashboard for this group and improve it.

7.4. Conclusion

In this Chapter a dashboard was developed using the Shiny package in RStudio. First, insights have been created into the user requirements for the dashboard, which subsequently were translated into the dashboard. The dashboard was tested and validated by testing the user requirements. From this validation in could be concluded that the model meets all important requirements. The second validation was done by an energy transition project leader of the municipality of Eindhoven who confirmed its added value in informing Dutch homeowners.

8. Results

In Chapters 4 and 5, the limited costs benefit analysis has been executed and the direct costs and benefits for the homeowners have been identified. In the Chapters, the magnitude of the costs and benefits have been determined based on augmented assumptions for the reference cluster. In Chapter 6, optimization models have been created that can optimize the implementation of the different alternatives based on the properties of the cluster, the scenarios and the optimization objective (costs, climate or/and comfort). The models have been used to optimize the implementation of the different policy alternatives. The results of the limited cost-benefit analysis will be compared to the optimal results for the reference cluster in the current Chapter. In Figure 76 it can be seen how this Section contributes to the research.

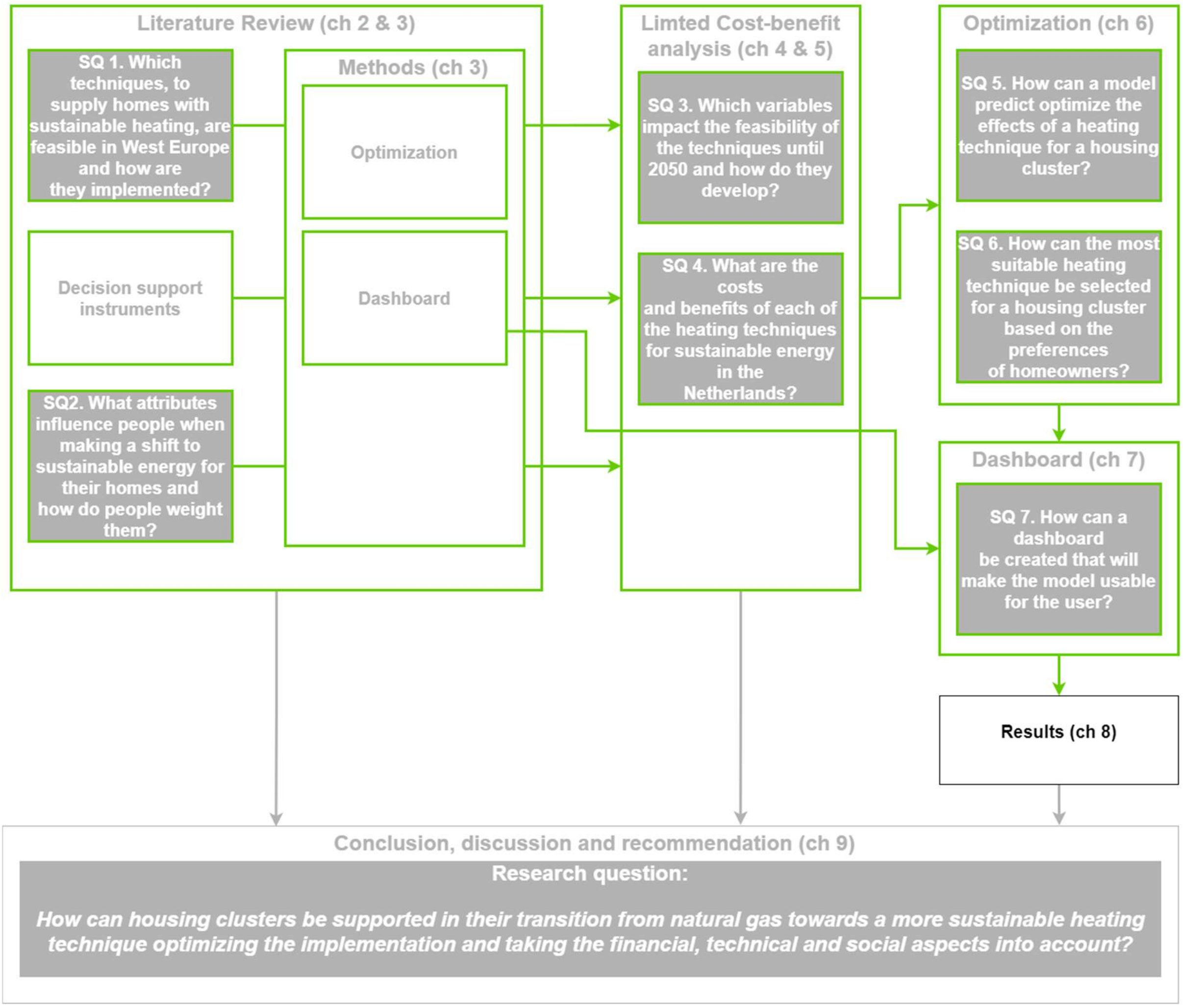


Figure 76: Results within the overall research design

By utilizing the optimization models created in the previous Chapters, the optimal switching year of the alternative heating technique can be calculated. The optimal switching year has been determined for the two policy alternatives and the two scenarios. By using the single objectives of cost, climate and comfort, the switching year is optimized. The optimal switching year has also been determined using multi-objective optimization in addition to the single objective optimization. In this optimization, the weight of the sub-objectives has been calculated based on the literature review (costs: 54%, climate: 4% and comfort: 40%). The results of the optimized switching year are shown in Table 76.

Table 76: Optimized switching year for the reference cluster using based on the different optimization objectives with and without discount rate

	Costs	Climate	Comfort	Multi-objective
	District heating 1			
Scenario low	2036	2023	2036	2023
Scenario high	2036	2023	2036	2023
	All-electric 1			
Scenario low	2023	2023	2023	2023
Scenario high	2023	2023	2023	2023

In Table 76, it can be seen that the optimal switching moment is 2023 for both alternatives for most of the optimization objectives. The exceptions are the objectives costs and comfort of district heating. The calculated optimal switching moment is as can be expected because:

- Costs: The total costs are lower for all-electric if the cluster switches in the year 2023 instead of 2036 for both alternatives. For the alternative district heating 1, the optimal switching moment is 2036. The difference between all-electric and district heating are the low energy costs of all-electric 1.
- Climate: the yearly CO_2 emission is lower after switching the heating technique, than heating using natural gas which means that the total CO_2 emission is lowest if the cluster switches to the alternative heating technique at an early moment in time.
- Comfort: The comfort level is lower after the cluster shifts to district heating, which means the total comfort level is highest when the cluster shifts at a late moment in time (2036). The comfort level for all-electric 1 is higher after the dwelling shifts to heating using an air-to-waterheat pump. This means that the total comfort level is maximized if the dwellings shift to the all-electric 1 technique at an early moment in time.
- Multi-objective: When these models are combined with the above-described weight factors in the multi-objective optimization, the optimal multi-objective switching moment is 2023 for both alternatives. It is in line with what was expected for the all-electric 1 alternative, since the optimal switching moment of costs and comfort is 2023 and climate has a very low weight. The optimal switching moment of district heating 1 is caused by the high weight of the objective comfort and the limited difference in costs between 2023 and 2036.

In Table 77, the results of the LCBA and the optimization relative to the baseline alternative can be compared to each other. These results are based on cost-objective optimization which uses the above-described switching moment. As described above, for the alternative district heating 1 the optimal switching moment is the year 2036. This results in lower total costs, a lower comfort level and a higher CO_2 emission. This is the case for both scenarios. For the alternative all-electric 1, the optimal switching moment for the comfort optimization is similar to the moment assumed in the LCBA. This results in similar results for the LCBA to the output of the optimization model.

Table 77: Overview of the results from the LCBA and the optimization compared to the baseline alternative with the discount rate

	Baseline alternative	District heating 1 LCBA	**District heating 1 optimal**	All-electric 1 LCBA	**All-electric 1 optimal**

Effect	***Scenario low***				
Investment costs	*€ 16,54*	€ 2,34	€ -2,40	€ 14,07	€ 14,07
Maintenance costs	*€ 6,11*	€ 1,04	€ -0,71	€ 0,77	€ 0,77
Replacement cost	*€ 3,81*	€ -1,90	€ -1,71	€ 1,21	€ 1,21
Energy costs	*€ 21,54*	€ 1,96	€ 4,02	€ -17,20	€ -17,20
Total costs	*€ 48,00*	*€ 3,44*	*€ -0,81*	*€ -1,15*	*€ -1,15*
Comfort	*0,65*	-0,06	-0,04	0,04	0,04
Required space	*0,58*	-0,53	-0,53	1,91	1,91
Impact renovation process	*14*	-6,5	-6,5	3	3
Energy price sensitivity	*0*	+	+	+	+
Freedom of choice of energy supplier	*0*	--	--	+	+
Safety	*0*	++	++	+	+
Climate	*0,42 tonnes*	-0,22 tonnes	0 tonnes	-0,30 tonnes	-0,30 tonnes

	Scenario high				
Investment costs	*€ 16,54*	€ 2,34	€ -2,40	€ 14,07	€ 14,07
Maintenance costs	*€ 6,11*	€ 1,04	€ -0,71	€ 0,77	€ 0,77
Replacement cost	*€ 3,81*	€ -1,90	€ -1,71	€ 1,21	€ 1,21
Energy costs	*€ 31,43*	€ -5,62	€ -3,97	€ -23,01	€ - 23,01
Total costs	*€ 57,89*	*€ -4,14*	*€ -8,80*	*€ -6,96*	*€ -6,96*
Comfort	*0,65*	-0,06	-0,04	0,04	0,04
Required space	*0,58*	-0,53	-0,53	1,91	1,91
Impact renovation process	*14*	-6,5	-6,5	3	3
Energy price sensitivity	*0*	+	+	+	+
Freedom of choice of energy supplier	*0*	--	--	+	+
Safety	*0*	++	++	+	+
Climate	*0,42 tonnes*	-0,22 tonnes	0 tonnes	-0,30 tonnes	-0,30 tonnes

In Table 78 the multi-objective optimized results relative to the baseline alternative are shown. In this table, not only the optimal results for the policy alternatives district heating 1 (MT) and All-electric 1 are shown but also the results for the alternatives district heating 2 (LT) and all-electric 2. These alternatives have been optimized using the assumption described in Chapter 4 and the optimization method described in Chapter 6. If the effects of all alternatives are compared to the baseline alternative, the sub-costs are highly differentiated between the alternatives but the total costs are somewhat comparable to the baseline alternative. It is noteworthy that the technique all-electric 1 is the only technique which is less expensive than the baseline alternative, in the low scenario. In the high scenario, only district heating 2 is more expensive than the baseline alternative. It should be noted that the CO_2 emissions from technique district heating 1 are similar to those from the alternative district heating 2. This is caused by the electricity consumption of a booster pump. In reality, this difference is more likely to be bigger. In low-temperature district heating, CO_2 emissions are on average lower due to the production method and fewer transport losses. This is not taken into account in the current research. The CO_2 emission for district heating is highly dependent on the production process, which is why averages are used in the study. If the district heating production method is known, it can be easily incorporated into the model. The averages are imported into the optimization model using a CSV file, which enables the user to finetune these input values to a certain situation. The main difference that can be seen between the alternatives all-electric 1 and all-electric 2 is the higher investment costs for all-electric 2 due to the installation of the ground heat pump and the drilling costs. These higher investment costs are partly compensated by the lower energy costs since a ground heat pump is more effective than an air-to-water heat pump.

Table 78: Overview of the results from the multi-objective optimization compared to the baseline alternative with the discount rate

	Baseline alternative	**District heating 1 (MT)**	**District heating 2 (LT)**	**All-electric 1**	**All-electric 2**
Effect	*Scenario low*				
Investment costs	*€ 16,54*	€ 2,34	€ 11,24	€ 14,07	€ 18,99
Maintenance costs	*€ 6,11*	€ 1,04	€ 1,48	€ 0,77	€ 0,34
Replacement cost	*€ 3,81*	€ -1,90	€ 0,53	€ 1,21	€ 0,40
Energy costs	*€ 21,54*	€ 1,96	€ 0,24	€ -17,20	€ -16,94
Total costs	*€ 48,00*	€ *3,44*	€ 13,48	€ *-1,15*	€ 2,80
Comfort	0,65	-0,06	0,04	0,04	0,04
Required space	0,58	-0,53	1,97	1,91	1,66
Impact renovation process	14	-6,5	1	3	3
Energy price sensitivity	0	+	+	+	+
Freedom of choice of energy supplier	0	--	--	+	+
Safety	0	++	++	+	+
Climate	0,42 tonnes	-0,22 tonnes	-0,22 tonnes	-0,30 tonnes	-0,30 tonnes
	Scenario high				
Investment costs	*€ 16,54*	€ 2,34	€ 11,24	€ 14,07	€ 18,99
Maintenance costs	*€ 6,11*	€ 1,04	€ 1,48	€ 0,77	€ 0,34
Replacement cost	*€ 3,81*	€ -1,90	€ 0,53	€ 1,21	€ 0,40
Energy costs	*€ 31,43*	€ -5,62	€ -5,25	€ -23,01	€ -22,85
Total costs	*€ 57,89*	€ *-4,14*	€ 7,99	€ *-6,96*	€ -3,11
Comfort	*0,65*	-0,06	0,04	0,04	0,04
Required space	0,58	-0,53	1,97	1,91	1,66
Impact renovation process	14	-6,5	1	3	3
Energy price sensitivity	0	+	+	+	+
Freedom of choice of energy supplier	0	--	--	+	+
Safety	0	++	++	+	+
Climate	0,42 *tonnes*	-0,22 tonnes	-0,22 tonnes	-0,30 tonnes	-0,30 tonnes

In Table 79, an overview is given of the costs and benefits of the four alternatives using a qualitative scale (from -- lowest to ++ highest). The benefit of this interpretation of the results is that it is possible to compare the costs and benefits of the different alternatives. If the effects are simply added up, all policy alternatives have higher benefits than the baseline alternative. Although this addition of effects results in an overall welfare effect, the overall welfare effects are likely different in reality. When effects are simply added up, all effects have a similar weight, although homeowners are likely to evaluate them differently. Therefore, the weights for gain effects, hedonic effects and normative effects have been used, see Section 2.3.2. Using this weight, the overall welfare can be determined (e.g. using the gain weight for the gain effects). The weighted scores have been normalized (using the maximum possible results). Therefore the weighted scores can have a value between -1 (minimum) and 1 (maximum), with 0 being equal to the baseline alternative. For the low scenario (lower-end energy price development), the all-electric alternative is most beneficial for the homeowner (weighted score +0,10). When comparing the alternatives, all policy alternatives except district heating 2 (-0,21) are overall more beneficial than the baseline alternative. District heating 2 is mainly less beneficial due to the costs. The alternative All-electric 1 is most beneficial compared to the other alternatives (added up 5 and weighted +0,33).

Table 79: Overview of the optimized costs and benefits scenario high

Type of effect	*Effect*	*Baseline alternative*	District heating 1 (MT)	District heating 2 (LT)	All-electric 1	All-electric 2
Gain effects	Costs	*0*	+	--	++	+
Hedonic effects	Comfort	*0*	-	+	+	+
	Required space	*0*	+	-	-	-

	Impact renovation process	*0*	-	-	-	-
	Energy price sensitivity	*0*	+	+	0	0
	Freedom of choice of energy supplier	*0*	--	--	+	+
	Safety	*0*	++	++	+	+
Normative effects	Climate	*0*	++	++	++	++
Total	*Added up*	*0*	*3*	*1*	5	*4*
	With weight	*0*	*0,13*	*-0,21*	*0,33*	*0,21*

In this Chapter, the results of the LCBA and the optimization models have been discussed and compared. From these results, it can be concluded that using the assumptions of the LCBA, the results are well approximated compared to the optimal implementation. In some cases, though, it is possible to see that the optimization implementation is different from the LCBA assumptions. This shows the added value of using optimization techniques. Since the LCBA was not able to find the most suitable implementation of the heating techniques in all cases, it will be very unlikely that a homeowner is able to do so. This highlights the added value of the dashboard. It enables the homeowner to use the optimization models and obtain this information for the decision making process.

9. Conclusion, discussion and recommendations

This thesis contributes to the energy transition in the Netherlands, by creating insights into the transition of natural gas towards a more sustainable heating technique, taking the gain, hedonic, and normative aspects into account. The effects of different heating techniques and their optimized implementation on the homeowner, the stakeholder, have come forward in the results. This Chapter summarizes the research process and most important results, followed by several recommendations and lessons learned.

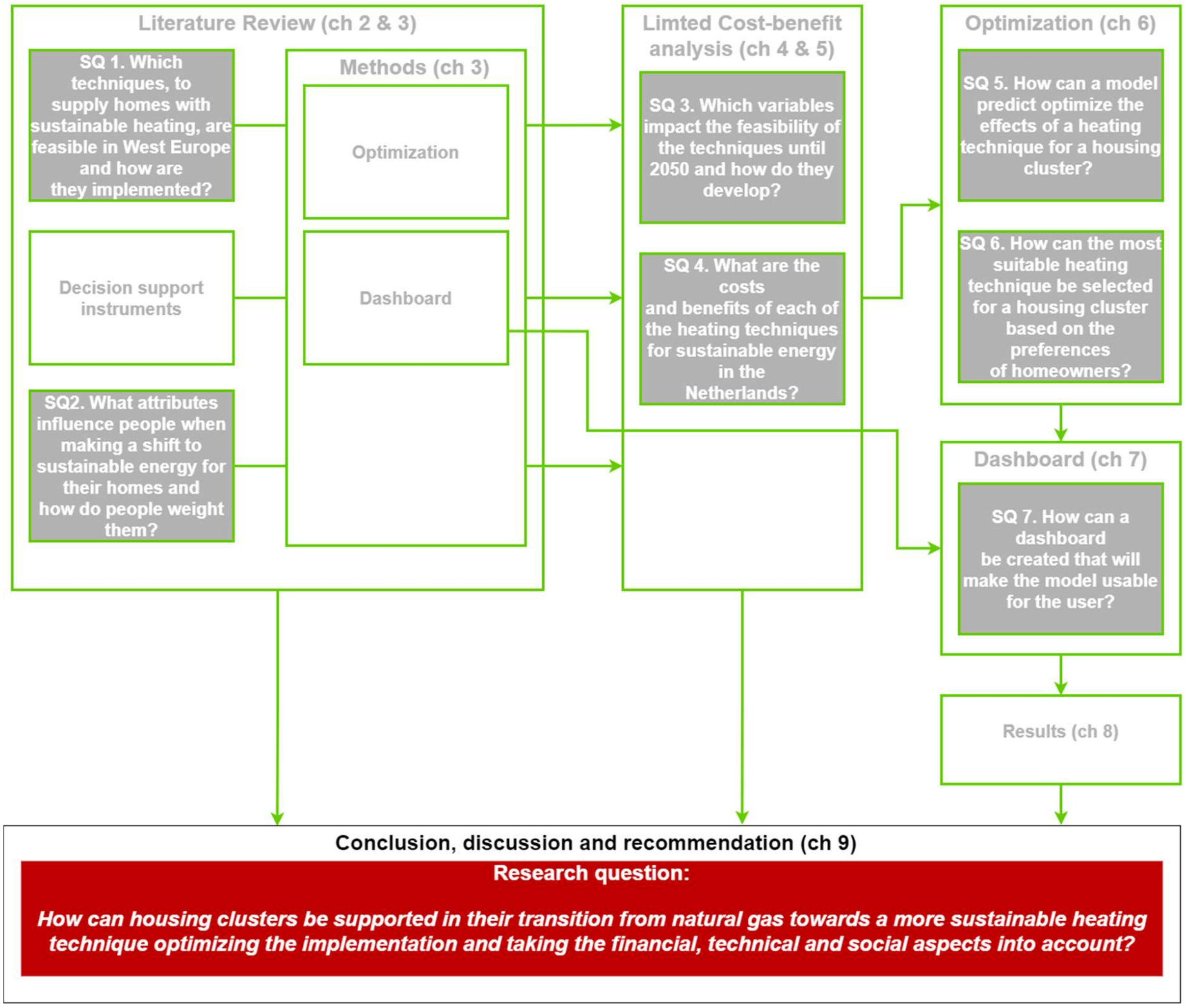


Figure 77: Conclusion, discussion and recommendations within the overall research design

Figure 77 shows how this Chapter relates to the overall research, and how the insights and results generated in previous Chapters will be used. In this Chapter, first a conclusion will be drawn, resulting in an answer to the research question. The discussion will follow the conclusion. In the discussion, remarks will be made regarding the research process, made decisions, and generated results of this research. The Chapter will be concluded with recommendations for future research.

9.1. Conclusion

Within this Section, the main research question: How can housing clusters be supported in their transition from natural gas towards a more sustainable heating technique optimizing the implementation and taking gain (financial), hedonic (comfort-related) and normative (environmental) aspects into account*,* will be answered. To answer the main research question, the research parts and seven sub-questions will be reviewed first.

Sub-question 1: *Which techniques, to supply homes with sustainable heating, are feasible in West Europe and how are they implemented?* In the discussed literature, multiple alternative heating techniques to replace heating with natural gas have been mentioned. In the analysis of these techniques, it has been concluded that there is not one superior alternative to replace heating with natural gas. The different techniques have contrasting advantages and disadvantages, based on implementation and the properties of a housing cluster. This results in a selection of the most beneficial techniques, already proven through implementation. The selected techniques are: district heating at middle temperature, district heating at low temperature, all-electric with an air-to-water heat pump and all-electric with a collective ground heat pump.

Sub-question 2: *What attributes influence people when making a shift to sustainable energy for their homes and how do people weigh them?* By conducting literature research, the second sub-question was answered. The goal-framing theory is used to find the factors that influence pro-environmental behaviour. Through reviewing the literature, the following drivers and barriers for households implementing natural gas-free renovations could be identified: cost, nuisance, comfort, environmental concerns, and heating technology. In terms of these drivers and barriers, the cost of implementing natural gas-free renovations has the biggest influence on pro-environmental behaviour. Besides these attributes, the influence of the sociodemographic and dwelling characteristics on the willingness to perform energy renovations is also investigated. This has been incorporated into the conceptual model. These preferences have been compared with the preferences of other European countries, which implied that, when generalizing the preferences of techniques, this can be best accomplished in an area with matching climate and cultures.

After the literature review, a limited cost-benefit analysis (LCBA) has been conducted. Before the execution of the LCBA, existing CBAs have been analysed to determine which effects should be incorporated and to identify possible research gaps. The discovered gap showed limited identified effects for the stakeholder, the homeowner. Accordingly, the focus of the LCBA in this research has been on identifying the effects on homeowners specifically. It has been decided to execute a LCBA, with a focus on the direct effects on the homeowners, due to pre-existing research and the scope of the current research. During the execution of the LCBA, it has been discovered that the development of the effects with an impact on the feasibility of heating techniques is uncertain over a selected period of 30 years.

Sub-question 3: *Which variables impact the feasibility of the techniques until 2050 and how do they develop?* Research on the variables that impact the feasibility of the heating techniques was used to answer the third sub-question. The primary identified variables were 'the development of the energy costs', 'the disconnection year of the heat price from the natural gas price', 'the price reduction of the connection cost for increased size housing clusters' and 'the development of the investment costs of the heating techniques'. For the energy costs and the development of the investment costs of the heating techniques, several developmental scenarios have been established, based on literature research. As part of the LCBA, a baseline alternative and policy alternatives have been developed, incorporating the selected heating techniques.

Sub-question 4: *What are the costs and benefits of each of the heating techniques for sustainable energy in the Netherlands*? The costs and benefits of these alternatives have been determined to answer the fourth sub-question. The identified costs and benefits were: costs, comfort, required space, the impact of the renovation process, energy price sensitivity, freedom of choice of energy supplier, safety and climate. The results of the LCBA showed first of all, that over 30 years the two policy alternatives generate similar financial benefits as compared to natural gas heating. Secondly, in the scenario with high growth of energy prices, it is financially attractive to switch to district heating or all-electric, in the scenario with low growth it is financially attractive to switch to all-electric. Third, sensitivity analysis showed that the properties of the dwellings in a cluster impact the financial benefits per alternative. Fourth, in contrast to the alternative all-electric, district heating requires less investment costs, but has higher yearly costs, which makes district heating more feasible for homeowners.

The second main part of this research is the creation of optimization models. The first step of this part was the creation of optimization models to enhance and optimize the implementation of the alternatives.
Sub-question 5: *How can a model predict and optimize the effects of a technique for a housing cluster*? By constructing these models the fifth sub-question can be answered. In each alternative, three types of optimization models have been created with different single objectives. These objectives are: minimizing costs, minimizing CO_2 emissions and maximizing comfort.
Sub-question 6: *How can the most suitable technique be selected for a housing cluster based on the preferences of homeowners?* Multi-objective optimization models have been created to answer the sixth sub-question. In these multi-objective optimization models the objectives 'costs', 'CO_2 emissions' and 'comfort' are taken into account by using a weight factor. The default weight factor was based on literature research, but can be tailored to the preferences of a homeowner using AHP.
Sub-question 7: *How can a dashboard be created that will make the model usable for the user?* To answer this question a dashboard was developed using the Shiny package in RStudio. First, insights have been created into the user requirements for the dashboard, which subsequently were translated into the dashboard. The dashboard was tested and validated by an energy transition project leader of the municipality of Eindhoven who confirmed its added value in informing Dutch homeowners. The LCBA and optimization models have been executed for a reference housing cluster, 't Ven. The results of the two parts were similar and showed an overall positive value compared to the baseline alternative.

Overall, an answer to the main research question can be formulated: There are multiple factors influencing the decision of homeowners to implement natural gas-free renovations. When an alternative heating technique is implemented, it has multiple direct effects on the homeowner. A better understanding of the effects of each heating technique per housing cluster can be gained by optimizing the implementation of these techniques and making these models accessible to homeowners.

This research contributes to multiple fields of research. First of all, insight is generated into the factors influencing the decisions of homeowners for implementing natural gas-free renovations. In the field of CBA for sustainable heating techniques, a contribution is made to the effects on the stakeholder, the homeowner. By creating optimization models the gained insights can be optimized, and the different objectives can be combined in finding the most suitable implementation. Furthermore, due to these models, an understanding of the effects of the different alternatives can be gained very quickly per cluster. As a result of the addition of the dashboard, the model can also be made accessible to the stakeholder. Although the usability of the dashboard is shown, the models do require further improvement to become more accurate. Additionally, the dashboard needs to be made online accessible to enable the homeowner to use the models.

9.2. Discussion

During the research, the methods that have been applied and the results have been discussed. In the literature review, the heating techniques have been selected from literature research and the techniques that are most suitable and already implemented (proven to work) have been selected. This decision could be expanded with other techniques which are not proven to study their feasibility for the homeowner. This was not achievable for the current research due to a lack of data for these types of heating techniques. This is not a problem for the current research because for these new techniques the homeowner cannot decide to implement them, since they are not available yet. The preferences of homeowners and the attributes they focus on when deciding to implement a natural gas-free heating technique have been selected based on literature research. Furthermore, the weight has been determined based on the literature. The used study focused on social tenants which make it likely the results have some deviation with the target group homeowners. This method can be used to create the conceptual model but if separate research would have been conducted on the weight of the attributes more accurate values could be selected. The risk of a deviation in weights by basing them on literature is caused by the different objectives in the literature and the additional attributes that have been taken into account. The risk of executing the multi-objective optimization using not the exact weights has been reduced by incorporating the AHP. Enabling a user to determine their weights in the optimization, this means that the weights are always applicable to the homeowner.

To address the research gap in previous studies, a LCBA was conducted to determine the direct effects of the alternatives on the stakeholder homeowners. If a full CBA had been conducted, this would have provided a more thorough insight into the effects of the alternatives on the homeowner. This was not part of the scope of the current research since the indirect effects were part of the reference CBAs in the literature review. Nevertheless if these effects had been incorporated into the results, this would add to the CBA research and have helped to check the results of the reference CBAs. Many assumptions have been made based on literature and expert opinion, in the LCBA to assess the effects and their magnitude. Some of the assumptions that could impact the results are: (i) Subsidies have been included in the calculation of investment costs as is in 2022. Changes in subsidies will affect the results. It results in higher costs for installation of insulation, heat pumps, solar panels, and the connection of district heating. (ii) Per extra dwelling included in the cluster, the connection price is reduced by 5% (up to 50%). (iii) The heat price is disconnected from the natural gas price in 2024. By basing the effects on these two types of sources the goal was to reduce the error rate. The probabilities of these assumptions seem to be reasonably reliable when compared to the estimates provided by the cost expert for the housing cluster 't Ven. The assumptions have been made in such a way that they can be applied to all types of housing clusters, resulting in advantages and disadvantages. A disadvantage is that the results are less precise (more general) than if the LCBA would have been executed merely on the housing cluster in ‘t Ven. As a result of this approach, it is possible to determine the magnitude of the effects for other types of housing clusters without having to repeat the entire study. The comfort level is one of the effects of LCBA. The assessment of the comfort level has been done based on the research of Brandenburg & Vroom (2013). The challenge in determining the comfort level is that it needs to be determined based on a limited set of known properties of the dwelling. With the selected indicators the comfort level could be determined but the weight of these effects was not known. To solve this, the weights have been calculated using an AHP. More reliable results could be reached if additional research was conducted on the indicators and how homeowners weigh them. While the limited cost-benefit analysis approaches the homeowner's overall welfare effects, the limitations of the electricity network (and the related costs for the homeowner) have not been taken into account. Furthermore, assumptions have been made about the district heating network to make a reasoned estimation of the costs. But if the network needs to be newly constructed, this could also have a big impact on the costs for the homeowner.

For the optimization models, many decisions and assumptions needed to be made, based on the LCBA. Therefore, the data used in the optimization models was based on the LCBA. This data is relevant during the current research but will be outdated over time. To reduce the risk of the model becoming outdated the data is loaded into the model from .csv files which can easily be updated without required programming knowledge. This enables a user of the model to use the model with up-to-date data and reduces the risk of being outdated. The only risk of this approach is that if the user uploads faulty data this would also result in faulty results. In the optimization model, it has been decided that there are two possible switching moments, which are selected based on no augmented natural switching moments in time. Therefore, the degree of freedom of the optimization model is limited. However, this does make the model more transparent and small differences in switching years do not have a big impact on the total effect on the homeowner. Although the decision to incorporate only two switching moments is a benefit for the model, more degrees of freedom could provide the user of the model with more reliable and other insights. The dashboard, which is the interface that enables a user to use and interpret the optimization models without knowledge of Python, has been developed and is usable. The set user requirements have been achieved except for making the dashboard online accessible. The research has shown that the created dashboard can be uploaded and used online, which means the dashboard can be accessed online. But further development of the dashboard is required to make it online available and widely accessible for Dutch homeowners.

The LCBA and the optimization models have been executed and tested for the housing cluster in the neighbourhood ‘t Ven. This helps to test and validate the methods and assumptions used in the research. Validation of the results indicated that the results are within an acceptable margin of reality. Although these validations have been done, the validation would have been more conclusive if it had been executed on a selection of different clusters. This was not within the scope of the research. Furthermore, the results have been validated based on expert opinion and the reference cluster. This risk has been reduced by creating and testing scenarios but cannot be eliminated with absolute certainty.

9.3. Recommendations

As has been described in the conclusion, the research answers the research question but, further research and improvements can be done. The current Section provides recommendations on how to improve the research and what would make for worthwhile follow-up research. The current research meets its research goals but the research can be improved by further follow-up research. The main follow-up researches that can improve the research are:

1. Further research into the preferences of homeowners for natural gas-free heating techniques.
2. Expanding research into the effects of implementing heating techniques on large scale housing clusters.
3. Further research on comfort levels of homeowners and their comfort preferences.
4. Further CBA research incorporating the indirect social effects of the heating techniques, expressing all effects in euros.
5. Expanding the optimization models and the created dashboard to increase usability.

A selection of heating techniques has been incorporated into the research. An expansion of the heating techniques could increase the usability of the results and could provide insights into rarely applied heating techniques. To increase the number of heating techniques included, more research is required into these techniques. The key figures about the costs and technical aspects of these techniques must be identified. Besides an expansion of techniques, a more significant improvement in the research can be made by researching the preferences of homeowners and the attributes they focus on when deciding to implement a natural gas-free heating technique. This research could be done by conducting a stated choice experiment among Dutch homeowners on houses heated with natural gas. With the results of this research, the weights of the attributes can be identified and insights into the preferences of homeowners can be obtained. Additionally, weights can be assigned to the attributes of the cost-benefit analysis. These results could also be used to create improved default values for the multi-objective optimization models. A stated choice experiment to determine the weights of the attributes for comfort would improve the results of the current study. As a result, the reliability comfort level and comfort optimalisation model could be improved. In addition to investigating the preferences of homeowners regarding comfort, it is important to study how natural gas-free heating techniques affect homeowners' comfort levels.

As described in the report, a LCBA has been executed. Worthwhile follow-up research would be to expand the LCBA to a full CBA. This would result in more reliable results and could create interesting insights into the indirect effects of the selected heating techniques. In the current research some of the effects have been expressed on a qualitative scale (-- lowest to ++ highest). An improvement for the results of the research would be if these effects would be expressed in Euro (which is the standard in CBA research). Further research is required to find out how these effects can be expressed in Euros.

The created optimization models are able to optimize the implementation of the selected heating techniques and show the results of the implementation within the set constraints. Using the created optimization models, a quick understanding of the effects of the implementation of the heating techniques can be generated. This is for a wide variety of housing clusters. These insights can be beneficial for further research but also for practical applications, such as informing municipalities and homeowners. The reliability of these models is very important for this application. In further research, this reliability could be further improved by increasing the degrees of freedom of the model and increasing the input properties of the housing clusters. An example could be to enable the user to state the age of the current boiler and adapt the potential switching moments to this information. This would make the model more realistic for the selected housing cluster. Another addition to the optimization models is to make them location bound which could be done by importing GIS (Geographic information system) layers into the model. By incorporating location-specific characteristics, the optimization models could improve the results. The results would be more reliable for the selected housing cluster. GIS layers could be incorporated with location-specific properties to provide additional information about the maximum drilling depth of a ground heat pump, the location of existing district heating networks, or the potential expansion of electricity networks. The optimization models have been made interactive for different users by creating a dashboard. A user without programming knowledge or knowledge of the heating techniques can use this dashboard to interact with the optimization models and interpret the results. Even though the dashboard met its recommendations, improvements can be made to improve its usability. Using the current optimization models, more information could be provided by expanding the dashboard. The current dashboard is only validated using the user requirements and expert opinion. For further research, the dashboard should also be tested on a reference group of homeowners. The insights from this research could help improve the dashboard. Lastly, the further developed dashboard can be deployed online to enable the target audience to interact with it.

Although the research provides opportunities for follow-up research, the research does provide insights into the multiple factors influencing the decision of homeowners to implement natural gas-free renovations. The LCBA finds the multiple direct effects on the homeowner of alternative heating technique. A better understanding of the effects of each heating technique per housing cluster have been gained by optimizing the implementation of these techniques and making these models accessible to homeowners.

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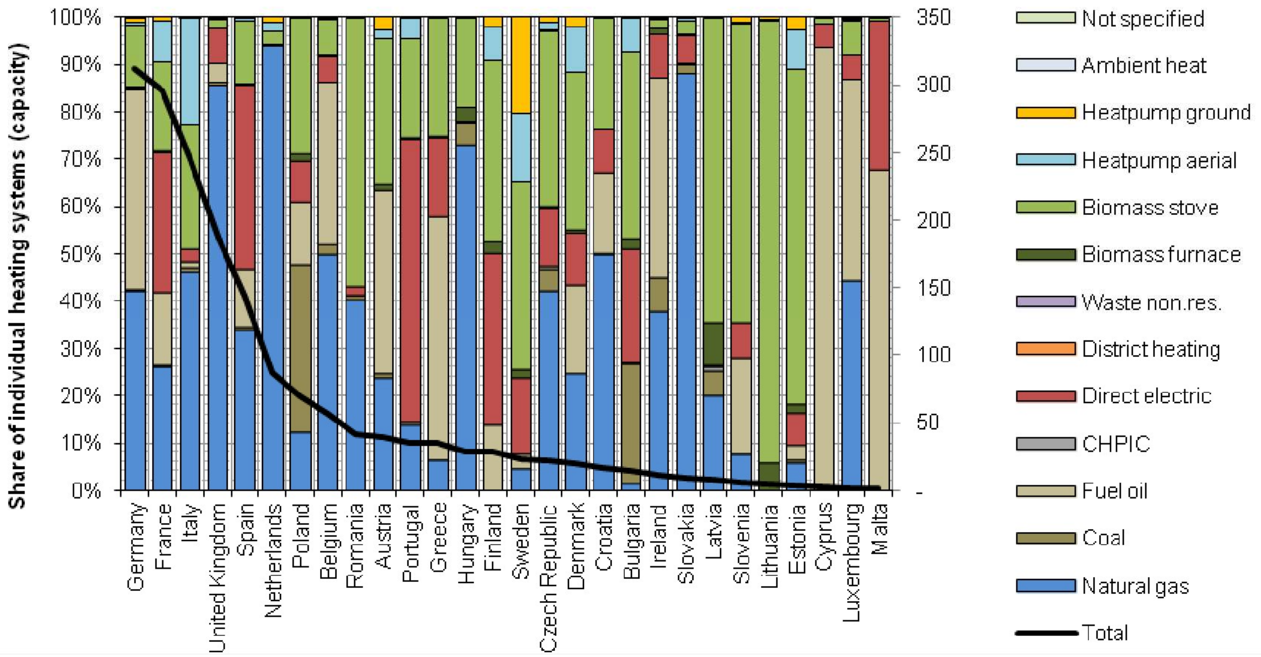
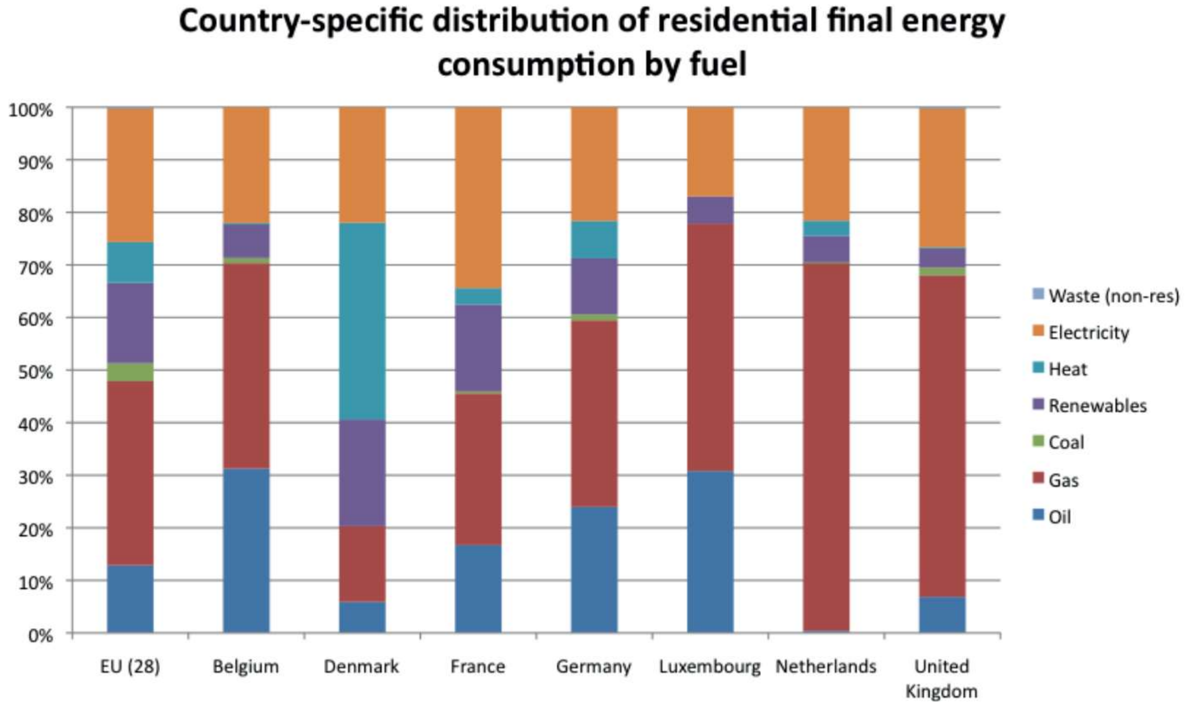
Appendix

Appendix A: Share of heating technologies and total installed capacity by country



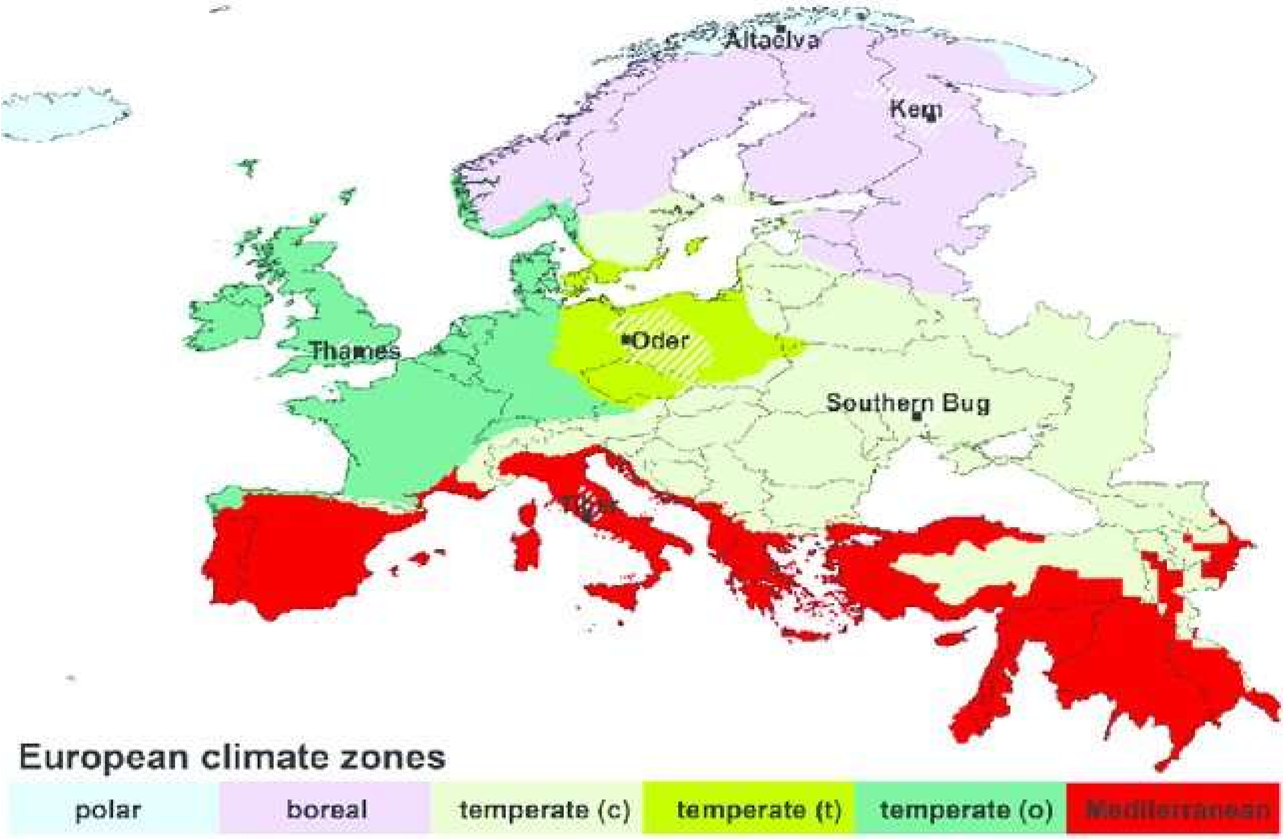
(Fleiter et al., 2016)



(Klip, 2017)

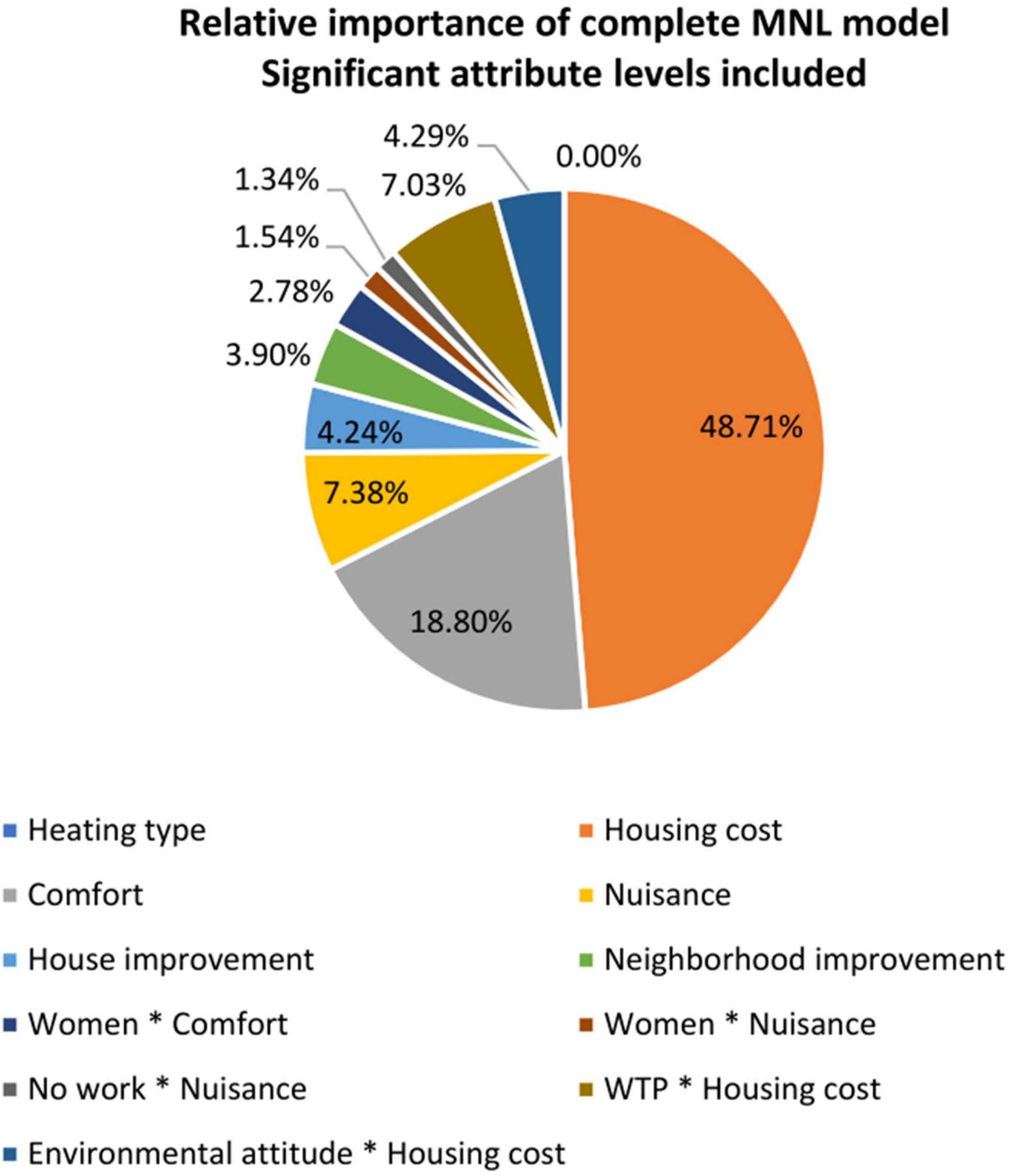
Appendix B: European climate zones

European climate zones based on information provided by EUCA15000 (Schneider et al., 2013).



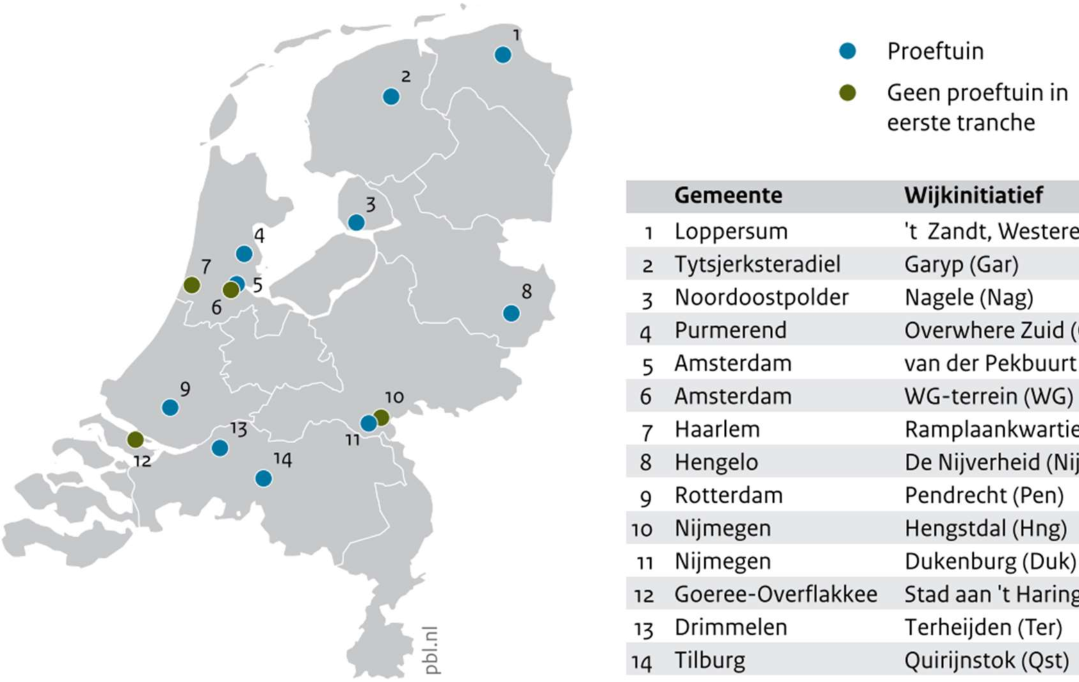
Appendix C: Relative importance of the MNL model

Relative importance of the complete MNL model, significant attribute levels included (Wielders, 2021)



Appendix D: Research natural gas-free neighbourhood initiatives

(Dignum et al., 2021)



	Gemeente	Wijkinitiatief
1	Loppersum	't Zandt, Westeremden (Lop)
2	Tytsjerksteradiel	Garyp (Gar)
3	Noordoostpolder	Nagele (Nag)
4	Purmerend	Overwhere Zuid (OvZ)
5	Amsterdam	van der Pekbuurt (vdP)
6	Amsterdam	WG-terrein (WG)
7	Haarlem	Ramplaankwartier (Ram)
8	Hengelo	De Nijverheid (Nijv)
9	Rotterdam	Pendrecht (Pen)
10	Nijmegen	Hengstdal (Hng)
11	Nijmegen	Dukenburg (Duk)
12	Goeree-Overflakkee	Stad aan 't Haringvliet (StH)
13	Drimmelen	Terheijden (Ter)
14	Tilburg	Quirijnstok (Qst)

Bron: PBL

Appendix E: Overview of five European countries and their energy mixes

(Sovacool, Demski, et al., 2021)

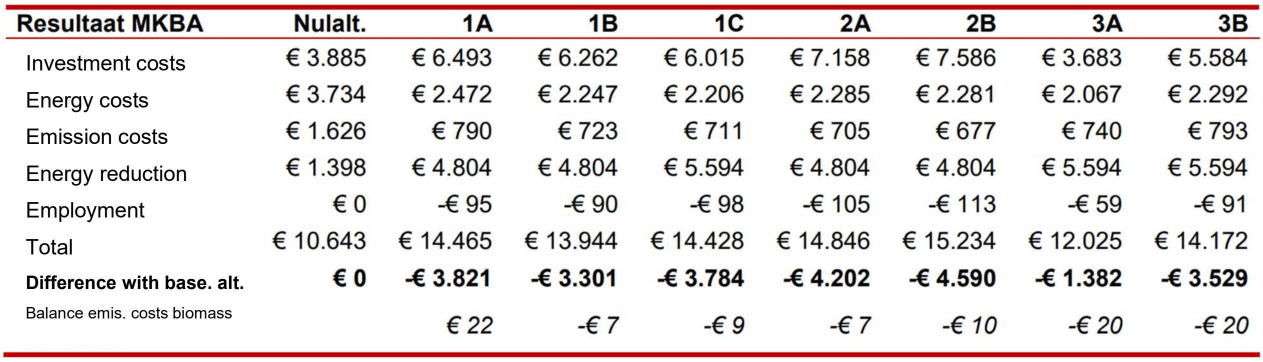
Appendix F: Cost of infrastructure

Article	Content
(Blommaert et al., 2020)	Introduces an alternative adjoint-based numerical optimization strategy to enable large-scale nonlinear thermal network optimization for large-scale district heating networks. The study solves an optimization problem that aims at minimizing the cost associated with the installed network piping and installed pump capacity and its operation while meeting the thermal demand of all consumers within areas.
(Santarelli et al., 2021)	A thermo-economic optimization model is presented of an electrified district heating network consisting of a wind power plant, gas-fired combined heat and power plant and heat pumps.
(Mazairac et al., 2015)	An approach is developed to determine the optimal topology of a hybrid energy distribution network. This approach determines the location of energy distribution lines, conversion and storage units, given the location of energy producers and consumers to find the optimal balance between capital, operational and maintenance costs on the one hand and revenue on the other hand. In the research two optimization techniques have been applied, single-carrier networks and multi-carrier networks.
(Spiliotis et al., 2016)	Describes the congestion issues of the electric grid due to increasing volumes of intermittent renewable energy sources and electric vehicles. The research developed the FlexMart model, which provides the ability for the Distribution System Operator to purchase demand flexibility offered by residential consumers. The model is a long-term planning tool and can provide an optimal combination of physical expansions and flexibility dispatch for a stable and secure operation of the grid.

Appendix G: Results of reference CBA

Policy alternatives of the CBA of Tieben et al. (2020):
1A Regional heat network: focus mainly on biomass;
1B focus mainly on geothermal energy;
1C The same heat mix as variant B with extra energy saving;
2A Using local sources with a limited expansion of the regional heat network;
2B Focus on local sources whereby the existing regional heat network disappears;
3A Use of solar thermal and green gas + extra energy savings;
3B Focus on all-electric solutions (ground and air-to-water heat pump) + extra energy savings (Tieben et al., 2020).

Table 80: Results CBA (Tieben et al., 2020)



Resultaat MKBA	Nulalt.	1A	1B	1C	2A	2B	3A	3B
Investment costs	€ 3.885	€ 6.493	€ 6.262	€ 6.015	€ 7.158	€ 7.586	€ 3.683	€ 5.584
Energy costs	€ 3.734	€ 2.472	€ 2.247	€ 2.206	€ 2.285	€ 2.281	€ 2.067	€ 2.292
Emission costs	€ 1.626	€ 790	€ 723	€ 711	€ 705	€ 677	€ 740	€ 793
Energy reduction	€ 1.398	€ 4.804	€ 4.804	€ 5.594	€ 4.804	€ 4.804	€ 5.594	€ 5.594
Employment	€ 0	-€ 95	-€ 90	-€ 98	-€ 105	-€ 113	-€ 59	-€ 91
Total	€ 10.643	€ 14.465	€ 13.944	€ 14.428	€ 14.846	€ 15.234	€ 12.025	€ 14.172
Difference with base. alt.	**€ 0**	**-€ 3.821**	**-€ 3.301**	**-€ 3.784**	**-€ 4.202**	**-€ 4.590**	**-€ 1.382**	**-€ 3.529**
Balance emis. costs biomass		*€ 22*	*-€ 7*	*-€ 9*	*-€ 7*	*-€ 10*	*-€ 20*	*-€ 20*

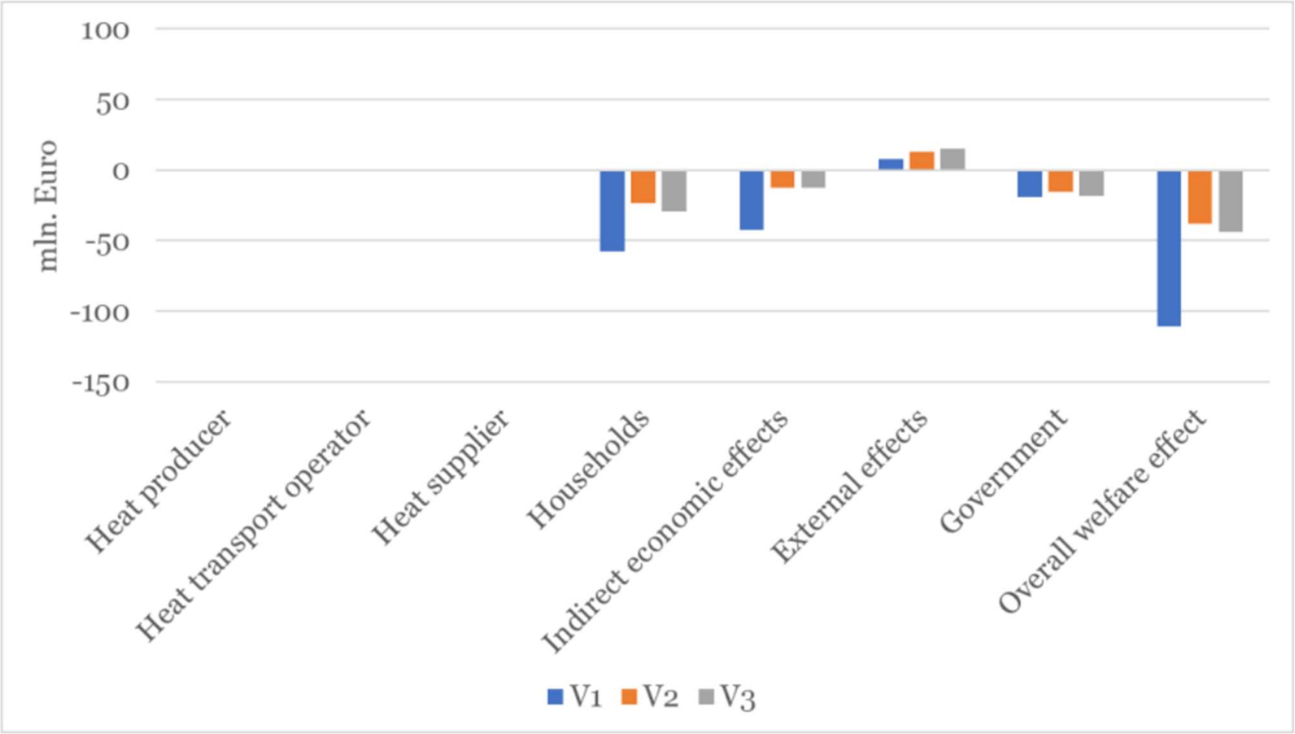


Figure 78: Results CBA (M. Mulder & Hulshof, 2021)

Appendix H: Overview of research towards motivators to shift towards sustainable heating

(Broers et al., 2019; Ebrahimigharehbaghi et al., 2019; Haas, 2020; Jansma et al., 2020; Wielders, 2021)

Source	Goal	Motivators	Concerns
(Haas, 2020) NL	Find why inhabitants of Veldhoven make a shift towards sustainable energy or not.	1) Environmental considerations 2) cost saving 3) living comfort	1) Financial means

(Wielders, 2021) NL	Find motivators and barriers that determine the decision making process towards gas-free heating for tenants.	1) heating type, 2) house and 3) neighbourhood improvements.	1) housing costs 2) comfort 3) nuisance
(Jansma et al., 2020) NL	The main benefits and concerns of renters and homeowners (compared) to shift from natural gas towards a more sustainable energy source for their homes.	1) decrease in CO_2 emission 2) decrease of seismic activities in Groningen 3) less dependent on other countries	1) costs 2)feasibility 3)comfort of living
(Ebrahimigharehbaghi et al., 2019)	Finding drivers and hinders in the decision-making behaviour towards energy efficiency renovations of Dutch homeowners.	1) financial benefits 2) enhancing the quality of life.	1) lack of reliable information 2) complexities of the renovations 3) costs.
(Broers et al., 2019)	Conducting empirical analysis to identify the decision-making process of Dutch homeowners for energy renovation measures.	1) saving energy 2) saving costs 3) environmental concern 4) improve comfort	1) financial 2) other priorities

Appendix I: Optimization methods

There are many different categories of optimization, in this appendix an overview is given of the different categories, see Figure 79 which are further explained in Table 81.

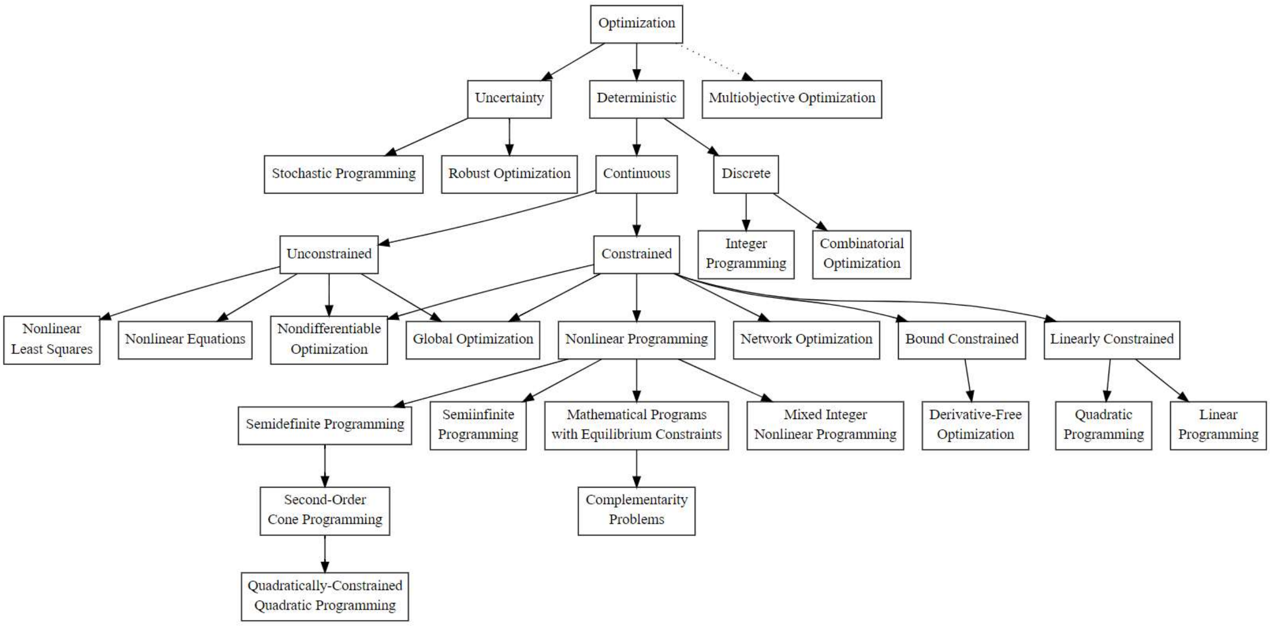


Figure 79: Taxonomy of optimization fields (NEOS, 2013n)

Table 81: Overview of optimization subfields multiobjective optimization, nonlinear programming and linear programming explained. The explanations are collected from multiple sources, the source that created the explanation of the subfield is shown in the column "source"

Explanation	Source

Uncertainty	For optimization under uncertainty, there is optimized for problems where the problem data cannot be known accurately, due to: 1. Measurement error 2. Some of the data represents information about the future (cannot be known with certainty) The most popular frameworks are stochastic programming and robust optimization.	(NEOS, 2020)
Deterministic	Deterministic optimization embodies algorithms that heavily rely on linear algebra. Cavazzuti (2013) describes that they are mostly based on the computation of the gradient and in some cases also of the Hessian, of the response variables. An advantage is that the convergence to a solution is much faster than when the stochastic optimization algorithms are used. A disadvantage is that they look for stationary points in the response variable, which means that the optimal solution found could be a local optimum and not the global optimum. Another disadvantage is that deterministic algorithms are intrinsically single objective.	(Cavazzuti, 2013)
Multiobjective optimization	For Multiobjective optimization, an optimization problem is solved that consist out more than one objective (that needs to be optimized simultaneously). For these multiobjective optimization problems, an optimal decision needs to be found with trade-offs between two or more conflicting objectives. Often there is not one solution that optimizes each objective. I this case a set of Pareto optimal solutions exists. Mathematically the multiobjective problem can be formulated a s $\mathrm{Min}(f_1(x), f_2(x), \ldots, f_k(x))$ s. t. $x \in X$, where the integer $k \geq 2$ is the number of objectives and the set X is the feasible set of decision vectors. The feasible set is defined by some constraint functions. In addition, the vector-valued objective function is often defined as $f : X \rightarrow R^k$, $f(x) = (f_1(x), \ldots, f_k(x))^T$. An element $x^* \in X$ is a feasible solution; a feasible solution $x^1 \in X$ is said to (Pareto) dominate another solution $x^2 \in X$, if $f_i(x^1) \leq f_i(x^2)$ for all indices $I \in \{1,2,\ldots,k\}$ and $f_j(x^1) < f_j(x^2)$ for at least one index $j \in \{1,2,\ldots,k\}$. A solution $x^1 \in X$ is called Pareto optimal if there does not exist another solution that dominates it (NEOS, 2013k). One of the classic multiobjective optimization methods is the weighted sum method. This method scalarizes a set of objectives into one single objective by adding each objective pre-multiplies by a supplied weight. If there are m alternatives and n criteria: $A^*_{wsm} = Max \sum_i^j a_{ij} w_j$ For $i = 1,2,\ldots,m$ where A^*_{wsm} is the weighted sum method score of the best alternative, *n* is the number of decision criteria, a_{ij} is the actual value of the ith alternative in terms of the jth criterion and w_j is the weight of importance of the jth criterion (Mateo, 2012).	(Mateo, 2012; NEOS, 2013k)
Stochastic programming	Stochastic programs are mathematical programs where some of the data incorporated into the objective or constraints is uncertain. Uncertainty is usually characterized by a probability distribution on the parameters. Although the uncertainty is rigorously defined, in practice it can range in detail from a few scenarios to specific and precise joint probability distributions. The outcomes are generally described in terms of elements w of a set W. W can be, for example, the set of possible demands over the next few months. When some of the data is random, then solutions and the optimal objective value to the optimization problem are themselves random.	(Holmes, n.d.)
Robust optimization	Robust Optimization is an approach to modelling uncertainty in optimization problems. Where stochastic programming assumes there is a probabilistic description of the uncertainty, robust optimization uses a deterministic, set-based description of the uncertainty. The robust optimization approach constructs a solution that is feasible for any realization of the uncertainty in a given set. For a given optimization problem, there can be multiple robust versions depending on the structure of the uncertainty set. When formulating a robust counterpart of an optimization problem, maintaining traceability is an important issue.	(NEOS, 2013q)
Continuous optimization	In a continuous optimization model, the variables can take any value in a range of values. This is in contrast to discrete optimization, for which some or all values are binary, integer or more abstract objects drawn from sets with finitely many elements.	(NEOS, 2013d)

Discrete optimization	For a discrete optimization, the (or some of the) variables need to belong to a discrete set. The two main subbranches of discrete optimization are integer programming and combinatorial optimization.	(NEOS, 2013f)
Unconstrained optimization	An unconstrained optimization problem considers the problem of minimizing an objective function that depends on real variables with no restrictions on their values. Mathematically, let $x \in R^n$ be a real vector with $n \geq 1$ components and let $f : R^n \rightarrow R$ be a smooth function. Then, the unconstrained optimization problem is: $\min_x \quad f(x)$	(NEOS, 2013u)
Constrained optimization	Constrained optimization problems consider the problem of optimizing an objective function subject to constraints on the variables. There are many different subfields in constrained optimization problems. In general constrained optimization problems consist of Minimize $f(x)$ Subject to $c_i(x) = 0 \ \forall_i \in \varepsilon$ $c_i(x) =< 0 \ \forall_i \in I$ where f and the functions $c_i(x)$ are all smooth, real-valued functions on a subset of R^n and ε and I are index sets for equality and inequality constraints, respectively. The feasible set is the set of points x that satisfy the constraints.	(NEOS, 2013c)
Integer optimization	For integer linear programming problems, often a linear cost function is minimized over all n-dimensional vectors x subject to a set of linear equality and inequality constraints as well as integrality restrictions on some or all of the variables in x. Min $c^T x$ s.t. $Ax = b$ $x >= 0$ $x \in Z^n$ - If only some of the variables $x_i \in x$ are restricted to take on integer values, then the problem is a mixed-integer linear programming (MILP) problem. If the objective function and/or constraints are nonlinear functions, then the problem is a mixed-integer nonlinear programming problem (MINLP). - If all of the variables $x_i \in x$ are restricted to take on integer values, then the problem is called a pure integer programming problem. - If all of the variables $x_i \in x$ are restricted to take on binary values (0 or 1), then the problem is called a binary optimization problem, which is a special case of a pure integer programming problem.	(NEOS, 2013h)
Combinatorial optimization	Combinatorial optimization is a class of methods to find an optimal object from a finite set of objects when an exhaustive search is not feasible. This entire approach of optimizing outcomes is often referred to as "heuristic programming" in machine learning (DeepAI, n.d.). Most common applications include: - Travelling salesman problem - Cutting Stock Problem - Packing Problems - Minimum Spanning Tree	(DeepAI, n.d.; NEOS, 2013a)
Nonlinear least squares	Nonlinear least-squares is used to fit a set of b observations with a model that is non-linear in c unknown parameters ($b \geq c$). The nonlinear least-squares problem has the general form: Min $\{r(x) : x \in R^n\}$ where r is the function defined by $r(x)=1/2\|f(x)\|^2_2$ for some vector-valued function f that maps R^n to R^m. Least-squares problems often arise in data-fitting applications.	(NEOS, 2013v)
Nonlinear equations	There are many applications in which the goal is to find values for the variables that satisfy a set of given constraints without the need to optimize a particular objective function. When there are n variables and n equality constraints, the problem is one of solving a system of nonlinear equations. Mathematically, the problem is: $f(x) = 0$, where $f : R^n \rightarrow R^n$ is a vector function, $f(x) = [\begin{matrix} f1(x) \\ \dots \\ fn(x) \end{matrix}]$	(NEOS, 2013l)

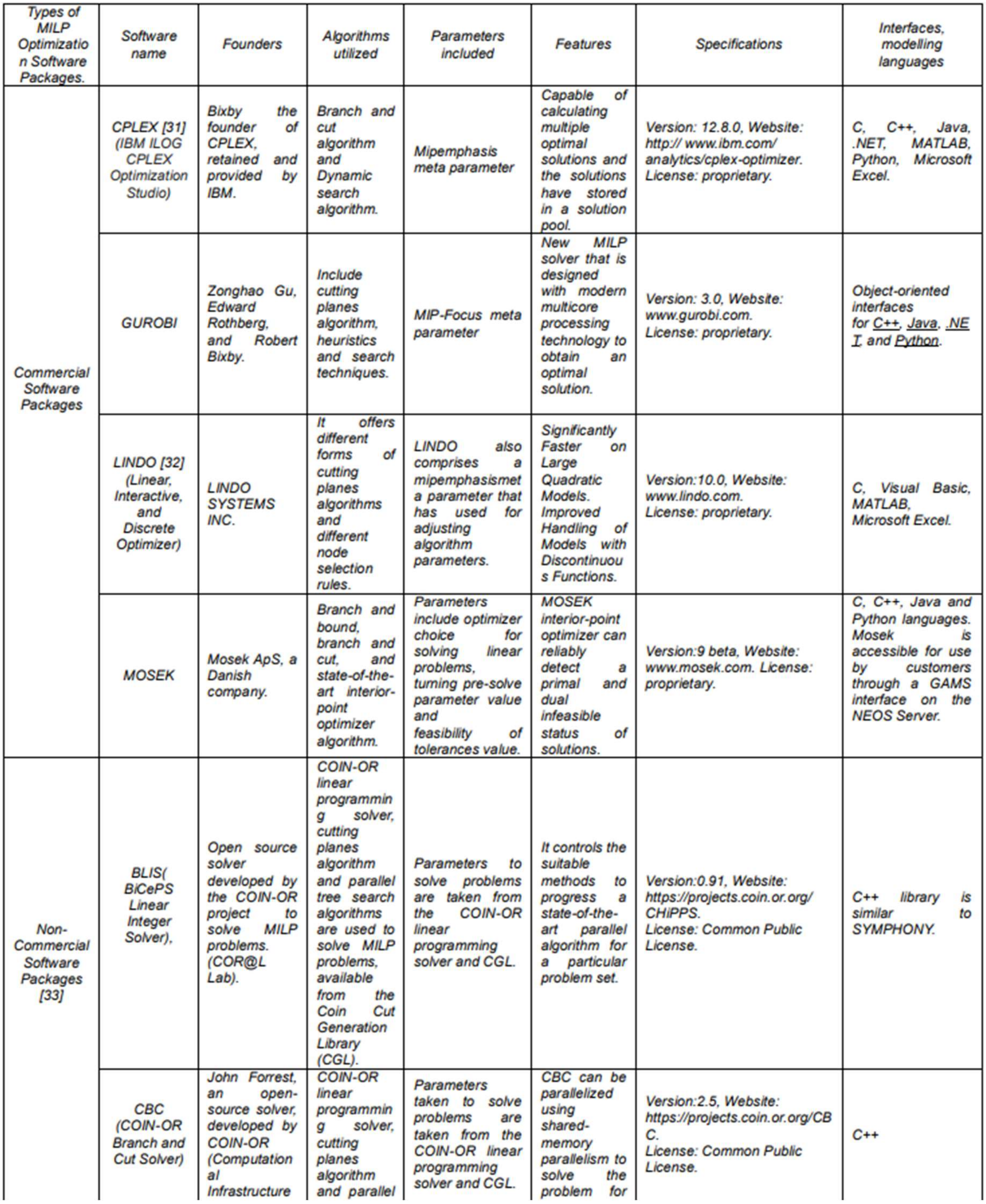
	where each $f_i(x):R^n \rightarrow R$, i=1,2,⋯,ni=1,2,⋯,n is smooth. A vector x^* satisfying f(x) = 0 is called a solution or a root of the nonlinear equations. In general, a system of nonlinear equations will have no solution, a unique solution or many solutions. Many algorithms for nonlinear equations are related to algorithms for unconstrained optimization and nonlinear least-squares. There are close connections to the nonlinear least-squares problem since several algorithms for nonlinear equations proceed by minimizing the sum of squares of the equations. But despite the similarities, there are important differences between algorithms for the two problems. In nonlinear equations, the number of equations is equal to the number of variables and all of the equations must be satisfied at a solution point.	
Nondifferentiable optimization	Nondifferentiable optimization optimizes problems where the smoothness assumption on the functions is relaxed, this means that gradients do not necessarily exist. In nondifferentiable optimization, the functions may have kinks or corner points, so they cannot be approximated locally by a tangent hyperplane or by a quadratic approximation. Nondifferentiable optimization problems arise in a variety of contexts such as applications in rectilinear data fitting, problems involving $\ell 1$ (Euclidean) or $\ell\infty$ (Chebychev) norms, and algorithms such as exact penalty methods that change constrained problems into unconstrained problems. Because the non-smoothness manifests itself in many different ways, there are no "black box" solution techniques to be applied; instead, solution techniques are developed to handle the particular structure of the problem.	(NEOS, 2013w)
Global optimization	Global optimization methods are algorithms with the purpose to find the global optimum of a real-valued continuous function over a feasible set, in situations where there exist several so-called local (not global) optima (Hendrix, 1998). It considers the problem of finding a global solution that minimizes an objective function. A local minimum is a point at which the objective function value is less than or equal to the value at nearby points (but it may be larger than the value at a distant point). A global minimum is a point at which the objective function value is less than or equal to the value at all other feasible points (NEOS, 2013g).	(Hendrix, 1998; NEOS, 2013g)
Nonlinear Programming	The general form of a nonlinear programming problem is to minimize a scalar-valued function f of several variables x subject to other functions (constraints) that limit or define the values of the variables. In mathematical terms, Minimize f(x) Subject to $c_i(x) = 0 \ \forall_i \in \varepsilon$ $c_i(x) =< 0 \ \forall_i \in I$ where $c_i(x)$ is a mapping from R^n to R and ε and I are index sets for equality and inequality constraints, respectively. Nonlinear programming is a broad field with several well-studied subfields, some of which are listed below. For many general nonlinear programming problems, the objective function has many locally optimal solutions; finding the best of all such minima, the global solution is often difficult. An important special case of nonlinear programming is convex programming in which all local solutions are global solutions. - If there are no constraints at all on the objective function f, then the problem is an unconstrained optimization problem. - When the objective function f is linear and all of the constraint functions c_i are linear, the problem is a linear programming (LP) problem. - When the objective function f is quadratic and the constraint functions c_i are linear, the problem is a quadratic programming (QP) problem. - When the objective function f is quadratic and the constraint functions c_i are quadratic, the problem is a quadratically constrained quadratic programming (QCQP) problem. - In a second-order cone programming (SOCP) problem, a linear function f is minimized over the interSection of an affine set and the product of second-order (quadratic) cones. - In a semidefinite programming (SDP) problem, a linear function f is minimized subject to a linear matrix inequality.	(NEOS, 2013m)
Bound Constrained	Bound constrained optimization problems consider the problem of optimizing an objective function subject to bound constraints on the values of the variables. In mathematical terms: Minimize f(x) Subject to $l \leq x \leq u$	(NEOS, 2013x)

	Bound constrained optimization problems, play an important role in the development of algorithms and software for the general constrained problem because many algorithms reduce the solution of the general problem to the solution of a sequence of bound-constrained problems.	
Semidefinite programming	The (linear) semidefinite programming (SDP) problem is essentially an ordinary linear program where the nonnegativity constraint is replaced by a semidefinite constraint on matrix variables. The standard form for the primal problem is: $\text{Minimize} \quad C\,X$ $\text{Subject to} \quad A_k \cdot X = b_k \; k = 1,\ldots,m$ $X \geq 0$ where C, A_k and X are all symmetric n × n matrices, b_k is a scalar, and the constraint $X \geq 0$ means that X, the unknown matrix, must lie in the closed, convex cone of positive semidefinite. Here, · refers to the standard inner product on the space of symmetric matrices, i.e., for symmetric matrices A and B, $A \cdot B = \text{trace}(AB)$. SDP reduces to LP when all the matrices are diagonal. SDP (also LP) is a special instance of a more general problem class called conic linear programs, where one seeks to minimize a linear objective function subject to linear constraints and a cone constraint. Both the semidefinite cone (for SDP) and the non-negative orthant (for LP) are homogeneous, self-dual cones - there are only 5 such nonisomorphic categories of cones. One of the main aspects in which SDP differs from LP is that the non-negative orthant is a polyhedral cone, whereas the semidefinite cone is not.	(NEOS, 2013t)
Semi-infinite programming	Semi-infinite programming (SIP) problems are optimization problems in which there is an infinite number of variables or an infinite number of constraints (but not both). A general SIP problem can be formulated as: $(P) \; \min_x \quad f(x)$ $\text{Subject to} \quad g(x,t) \geq 0 \; \forall t \in T(x),$ where $x=(x1,\cdots,xn) \in R^n$, T is an infinite set, and all the functions are real-valued.	(NEOS, 2013s)
Mathematical programs with equilibrium constraints	A Mathematical Program with Equilibrium Constraints (MPEC) is a constrained optimization problem in which the constraints include equilibrium constraints, such as variational inequalities or complementarity conditions. MPECs can be difficult to solve because the feasible region is not necessarily convex or connected. A special case of an MPEC is a Mathematical Program with Complementarity Constraints (MPCC) in which the equilibrium constraints are complementarity constraints. $\text{Minimize}_x \quad f(x)$ $\text{Subject to} \quad g(x) \geq 0$ $h(x) = 0$ $0 \leq x_1 \perp x_2 \geq 0$	(NEOS, 2013i)
Mixed integer nonlinear programming	Mixed integer nonlinear programming (MINLP) refers to optimization problems with continuous and discrete variables and nonlinear functions in the objective function and/or the constraints. MINLPs arise in applications in a wide range of fields. The general form of a MINLP is: $\text{Min} \quad f(x,y)$ $\text{s. t.} \quad c_i\,(x,y) = 0 \; \forall_i \in E$ $c_i\,(x,y) \leq 0 \; \forall_i \in I$ $x \in X$ $y \in Y \text{ integer}$ where each $c_i(x,y)$ is a mapping from R^n to R, and E and I are index sets for equality and inequality constraints, respectively. Software developed for Mixed integer nonlinear programming has generally followed two approaches: - Outer Approximation/Generalized Bender's Decomposition: These algorithms alternate between solving a mixed-integer LP master problem and nonlinear programming subproblems. - Branch-and-Bound: Branch-and-bound methods for mixed-integer LP can be extended to MINLP with several tricks added to improve their performance.	(NEOS, 2013j)
Derivative-free optimization	Derivative-free optimization refers to the solution of bound-constrained optimization problems using algorithms that do not require derivative information, only objective function values.	(NEOS, 2013e)
Quadratic programming	The quadratic programming (QP) problem involves minimizing a quadratic function subject to linear constraints. A general formulation is $\text{Minimize} \quad \tfrac{1}{2}\, x^T Q x + c^T x$	(NEOS, 2013p)

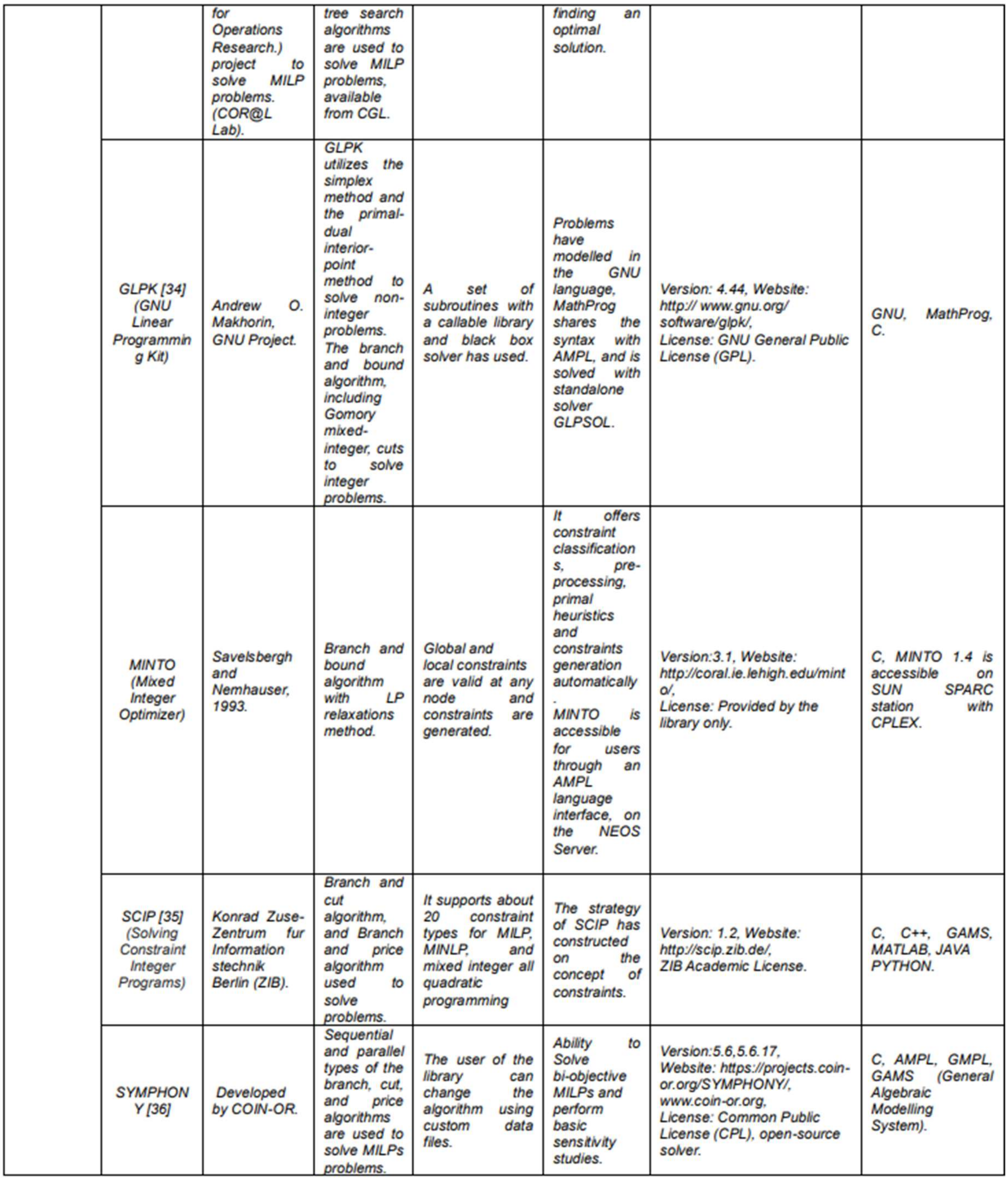
	Subject to $a^T_i x = b_i \quad \forall_i \in \varepsilon$ $a^T_i x \geq b_i \quad \forall_i \in I$ where $Q \in R^{n\times n}$ is symmetric, and the index sets ε and I specify the equality and inequality constraints, respectively. Quadratic programs are an important class of problems on their own and as subproblems in methods for general constrained optimization problems, such as sequential quadratic programming (SQP) and augmented Lagrangian methods.	
Linear programming	The general form of a linear programming (LP) problem is to minimize a linear objective function of continuous real variables subject to linear constraints. To describe and analyze algorithms, the problem is often stated in standard form as Min $c^T x$ s. t. $Ax = b$ $x \geq 0$ where x is the vector of unknown variables, c is the cost vector, and A is the constraint matrix. The matrix A is generally not square; therefore, solving the LP is not as simple as just inverting the A matrix. Usually, A has more columns than rows, which means that A is likely to be under-determined; as a result, there is great latitude in the choice of x that will minimize $c^T x$ over the feasible region. The feasible region is a polyhedron determined by the set $\{x \in R^n \mid Ax = b, x \geq 0\}$ Any specification of values for the decision variables is a solution; a feasible solution is a solution for which all the constraints are satisfied. An optimal solution is a feasible solution that has the smallest value of the objective function for a minimization problem. An LP may have one, more than one or no optimal solutions. An LP has no optimal solutions if it has no feasible solutions or if the constraints are such that the objective function is unbounded. In a linear program, a variable can take on any continuous (fractional) value within its lower and upper bounds. For many applications, fractional values do not make sense. Integer programming (IP) problems are optimization problems in which the objective function and all of the constraint functions are linear but some or all of the variables are constrained to take integer values. Integer programming problems often have the advantage of being more realistic than linear programming problems but they have the disadvantage of being much more difficult to solve.	(NEOS, 2014)
Second-order cone programming	In a second-order cone program (SOCP) a linear function is minimized over the interSection of an affine set and the product of second-order (quadratic) cones. SOCPs are nonlinear convex problems that include linear and (convex) quadratic programs as special cases and arise in many engineering problems (Lobo et al., 1998). The general form of the problem is: Minimize to $f^T x$ Subject to $\lVert A_i x + b_i \rVert_2 \leq c^T_i x + d_i, i=1,\dots,m$ $Fx = g$ where $f \in R^n$, $A_i \in R^{n_i \times n}$, $b_i \in R^{n_i}$, $c_i \in R^n$, $d_i \in R$, $F \in R^{p\times n}$, and $g \in R^p$. The inequalities, $\lVert A_i x + bi \rVert_2 \leq c^T_i x + d_i$ are the second-order cone constraints. Special cases: - When $A_i = 0$ for $i = 1,\dots,m$ the SOCP reduces to a linear programming problem. - When $c_i = 0$ for $i = 1,\dots,m$ the SOCP is equivalent to a convex quadratically constrained quadratic programming problem. (NEOS, 2013r)	(Lobo et al., 1998; NEOS, 2013r)
Complementarity problems	Complementarity problems aim to optimize a function of two vector variables. Fundamental to all complementarity problems are the complementarity conditions, each of which requires the product of two (or more) non-negative quantities to be zero. Mathematically, x is complementary to y if $x \geq 0, y \geq 0, \text{and } x^T y = 0$	(NEOS, 2013b)
Quadratically-constrained quadratic programming	Quadratically-constrained quadratic programming (QCQP) problems are optimization problems with a quadratic objective function and quadratic constraints. The general QCQP problem has the following form (NEOS, 2013o): Minimize $f_0(x)$ Subject to $f_i(x) <= 0$ for all $I = 1,\dots,m$ Where the functions $f_i(x) = : R^n \rightarrow R$ have the form $f_i(x) = x^T P_i x + q_i^T x + r_i$ (Parrilo & Lall, 2003)	(NEOS, 2013o; Parrilo & Lall, 2003)

Appendix J: MILP optimization software packages

(Kumar & Mageshvaran, 2020)



Types of MILP Optimization Software Packages.	Software name	Founders	Algorithms utilized	Parameters included	Features	Specifications	Interfaces, modelling languages
Commercial Software Packages	CPLEX [31] (IBM ILOG CPLEX Optimization Studio)	Bixby the founder of CPLEX, retained and provided by IBM.	Branch and cut algorithm and Dynamic search algorithm.	Mipemphasis meta parameter	Capable of calculating multiple optimal solutions and the solutions have stored in a solution pool.	Version: 12.8.0, Website: http:// www.ibm.com/ analytics/cplex-optimizer. License: proprietary.	C, C++, Java, .NET, MATLAB, Python, Microsoft Excel.
	GUROBI	Zonghao Gu, Edward Rothberg, and Robert Bixby.	Include cutting planes algorithm, heuristics and search techniques.	MIP-Focus meta parameter	New MILP solver that is designed with modern multicore processing technology to obtain an optimal solution.	Version: 3.0, Website: www.gurobi.com. License: proprietary.	Object-oriented interfaces for C++, Java, .NET and Python.
	LINDO [32] (Linear, Interactive, and Discrete Optimizer)	LINDO SYSTEMS INC.	It offers different forms of cutting planes algorithms and different node selection rules.	LINDO also comprises a mipemphasismeta parameter that has used for adjusting algorithm parameters.	Significantly Faster on Large Quadratic Models. Improved Handling of Models with Discontinuous Functions.	Version:10.0, Website: www.lindo.com. License: proprietary.	C, Visual Basic, MATLAB, Microsoft Excel.
	MOSEK	Mosek ApS, a Danish company.	Branch and bound, branch and cut, and state-of-the-art interior-point optimizer algorithm.	Parameters include optimizer choice for solving linear problems, turning pre-solve parameter value and feasibility of tolerances value.	MOSEK interior-point optimizer can reliably detect a primal and dual infeasible status of solutions.	Version:9 beta, Website: www.mosek.com. License: proprietary.	C, C++, Java and Python languages. Mosek is accessible for use by customers through a GAMS interface on the NEOS Server.
Non-Commercial Software Packages [33]	BLIS(BiCePS Linear Integer Solver),	Open source solver developed by the COIN-OR project to solve MILP problems. (COR@L Lab).	COIN-OR linear programming solver, cutting planes algorithm and parallel tree search algorithms are used to solve MILP problems, available from the Coin Cut Generation Library (CGL).	Parameters to solve problems are taken from the COIN-OR linear programming solver and CGL.	It controls the suitable methods to progress a state-of-the-art parallel algorithm for a particular problem set.	Version:0.91, Website: https://projects.coin.or.org/ CHiPPS. License: Common Public License.	C++ library is similar to SYMPHONY.
	CBC (COIN-OR Branch and Cut Solver)	John Forrest, an open-source solver, developed by COIN-OR (Computational Infrastructure	COIN-OR linear programming solver, cutting planes algorithm and parallel	Parameters taken to solve problems are taken from the COIN-OR linear programming solver and CGL.	CBC can be parallelized using shared-memory parallelism to solve the problem for	Version:2.5, Website: https://projects.coin.or.org/CBC. License: Common Public License.	C++



		for Operations Research.) project to solve MILP problems. (COR@L Lab).	tree search algorithms are used to solve MILP problems, available from CGL.		finding an optimal solution.		
	GLPK [34] (GNU Linear Programming Kit)	Andrew O. Makhorin, GNU Project.	GLPK utilizes the simplex method and the primal-dual interior-point method to solve non-integer problems. The branch and bound algorithm, including Gomory mixed-integer, cuts to solve integer problems.	A set of subroutines with a callable library and black box solver has used.	Problems have modelled in the GNU language, MathProg shares the syntax with AMPL, and is solved with standalone solver GLPSOL.	Version: 4.44, Website: http:// www.gnu.org/ software/glpk/, License: GNU General Public License (GPL).	GNU, MathProg, C.
	MINTO (Mixed Integer Optimizer)	Savelsbergh and Nemhauser, 1993.	Branch and bound algorithm with LP relaxations method.	Global and local constraints are valid at any node and constraints are generated.	It offers constraint classifications, pre-processing, primal heuristics and constraints generation automatically. MINTO is accessible for users through an AMPL language interface, on the NEOS Server.	Version:3.1, Website: http://coral.ie.lehigh.edu/minto/, License: Provided by the library only.	C, MINTO 1.4 is accessible on SUN SPARC station with CPLEX.
	SCIP [35] (Solving Constraint Integer Programs)	Konrad Zuse-Zentrum fur Information stechnik Berlin (ZIB).	Branch and cut algorithm, and Branch and price algorithm used to solve problems.	It supports about 20 constraint types for MILP, MINLP, and mixed integer all quadratic programming	The strategy of SCIP has constructed on the concept of constraints.	Version: 1.2, Website: http://scip.zib.de/, ZIB Academic License.	C, C++, GAMS, MATLAB, JAVA PYTHON.
	SYMPHONY [36]	Developed by COIN-OR.	Sequential and parallel types of the branch, cut, and price algorithms are used to solve MILPs problems.	The user of the library can change the algorithm using custom data files.	Ability to Solve bi-objective MILPs and perform basic sensitivity studies.	Version:5.6,5.6.17, Website: https://projects.coin-or.org/SYMPHONY/, www.coin-or.org, License: Common Public License (CPL), open-source solver.	C, AMPL, GMPL, GAMS (General Algebraic Modelling System).

Appendix K: 10 most common housing profiles of homes heated with natural gas (CBS, 2021d)

Profiel #	Beschrijving	Woningtype	Aantal bewoners	Bouwjaarklasse	Oppervlakteklasse	Aantal
aardgaswoning 1	Een bewoner in nieuw, klein appartement	Appartement	1	nieuw (1991 tot en met 2019)	klein (2 m^2 tot 100 m^2)	4
aardgaswoning 2	Een bewoner in oud, klein appartement	Appartement	1	oud (1200 tot en met 1991)	klein (2 m^2 tot 100 m^2)	11,8
aardgaswoning 3	Twee of meer bewoners in oud, klein appartement	Appartement	2 of meer	oud (1200 tot en met 1991)	klein (2 m^2 tot 100 m^2)	7,8
aardgaswoning 4	Een bewoner in oude, kleine rijwoning	Rijwoning	1	oud (1200 tot en met 1991)	klein (2 m^2 tot 100 m^2)	4,7
aardgaswoning 5	Een bewoner in oude, middelgrote rijwoning	Rijwoning	1	oud (1200 tot en met 1991)	middel (100 m^2 tot 150 m^2)	5,1
aardgaswoning 6	Twee of meer bewoners in oude, kleine rijwoning	Rijwoning	2 of meer	oud (1200 tot en met 1991)	klein (2 m^2 tot 100 m^2)	7,5
aardgaswoning 7	Twee of meer bewoners in nieuwe, middelgrote rijwoning	Rijwoning	2 of meer	nieuw (1991 tot en met 2019)	middel (100 m^2 tot 150 m^2)	5,4
aardgaswoning 8	Twee of meer bewoners in oude, middelgrote rijwoning	Rijwoning	2 of meer	oud (1200 tot en met 1991)	middel (100 m^2 tot 150 m^2)	18,7
aardgaswoning 9	Twee of meer bewoners in oude, grote rijwoning	Rijwoning	2 of meer	oud (1200 tot en met 1991)	groot (150 m^2 tot 10.000m^2)	4,6
aardgaswoning 10	Twee of meer bewoners in oude, grote vrijstaande woning	Vrijstaande woning	2 of meer	oud (1200 tot en met 1991)	groot (150 m^2 tot 10.000m^2)	5

Appendix L: Prediction of energy consumption of dwellings

To be able to predict the costs and benefits of the different technologies, information on the current energy consumption (natural gas and electricity) needs to be available. If this information is not available about the dwellings of the cluster, the energy consumption needs to be predicted based on a limited set of available properties. Research by Wyatt (2013) showed that energy consumption is associated with the type of dwelling. Therefore, a model needs to be created that can predict the energy consumption based on the type of house (Wyatt, 2013). The analysis method that will be used is a regression analysis using RStudio. First, the variables will be selected and transformed. Later the regression will be executed including housing characteristics and occupier characteristics. Using the results of the regression a prediction model can be created which incorporates the influence of the different variables on energy consumption.

Dataset

For the determination of the housing types, the data from the "Woononderzoek Nederland 2018" also called "WoON 2018" will be used. The WoON 2018 was executed by the CBS and commissioned by the Ministry of Homeland Affairs and Kingdom Relations. The most recent version of this survey was conducted in 2018 using the WoON questionnaire, which focuses on the housing market and is conducted every three years in the Netherlands. The results of the WoON research contain statistical information about the housing situation of the Dutch population and their wishes, needs and terms for housing (CBS, n.d.). The advantage of the WoON 2018 dataset is the large sample size (around 67.500 cases). In addition, it contains housing characteristics as well as occupier characteristics. By using the information from this dataset, types of housing can be created.

Data analysis

The goal is to create types of housing that are representable for the Dutch housing stock using the WoON 2018 dataset. The research will focus on owner-occupied houses, and consequently, dwellings that are not owner-occupied will be filtered out of the dataset, see Table 82. Furthermore, the focus will be on houses that are currently heated using natural gas. Thus, dwellings that are not using natural gas for heating will also be deleted, because they are already using a more sustainable technique for heating. In Table 82, the number of cases of the filtered data are shown. In the bottom row, the number of cases is shown after the data is cleaned, which will be further explained below. The number of cases that are left after the data preparation is sufficient for reliable results of a regression analysis.

Table 82: Number of cases WoON 2018 dataset

Case	N
Complete WoON 2018 dataset	67523
Filtered for only homeowners	37898
Filtered for homes without sustainable heating	31878
Cleaned data	29709

Representability of the dataset

This sample needs to be tested in order to determine if it I representative of the Dutch population. This will be done by comparing the data with the data of the CBS for the Dutch population. When looking at the distribution by gender (men-women) in 2018 it can be seen that it is quite equally distributed, men 49.5% - women 50.5% (CBS, 2019). To test the representativeness of the data a Chi-square test is executed on the men-women distribution. The formula for the Chi-square test is shown in Equation 15.

Equation 15: Chi-square test

$$X^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i}$$

For the Chi-square test, the null hypothesis (H0) is the situation that the distribution of the WoON respondents is the same as the men-women distribution of the Dutch population in 2018. For the alternative hypothesis (H1) it is assumed that the distribution is not the same.

Gender

The first Chi-square test is performed for gender, to test whether the men-women ratio is the same as the Dutch population, following the above-stated hypothesis. In Table 83 the men-women distribution from the WoON 2018 database and the CBS data are shown. Using this information the input for the Chi-square test can be generated as shown in Table 84.

Table 83: Men-women distribution comparing the WoON and CBS data (CBS, 2019; Ministerie van Binnenlandse Zaken en Koninkrijksrelaties & Centraal Bureau voor de Statistiek, 2019)

	Frequency (WoON data)	Percentage (WoON data)	Percentage (CBS data)
men	18493	48.8	49.5%
Women	19405	51.2	50.5%

Table 84: Chi-square goodness of fit test men-women

	o_i	e_i	$(o_i-e_i)^2/e_i$
men	18493	18760	3.8
Women	19405	19138	3.7
Total	37898	37898	7.5

The variable has two categories (men/women) which means that k = 2 and it has one degree of freedom (df = k – 1). In the Chi-square distribution table, the value for the combination of df = 1 and $x^2_{0.05}$ is the value of 3.841 is received (in the case of df=1 and $X^2_{0.05}$). Because 7.5 > χ^2 .050 the null hypothesis is rejected so the sample is not representative of the Dutch population.

Household size

Also, the household size is compared with the CBS data from 2018 to check whether the database is representative. The two databases are compared in Table 85, from this data the observed (o_i) and expected (e_i) numbers can be found, see Table 86. For household size, a hypothesis is made following the principle mentioned above.

Table 85: Household size comparing the WoON and CBS data (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties & Centraal Bureau voor de Statistiek, 2019; Statline, 2020)

	Frequency (WoON data)	Percentage (WoON data)	Percentage (CBS data)
1 person	7986	21.1%	38.1%
2 persons	15814	41.7%	32.6%
3 persons	5250	13.9%	11.8%

4 persons	6346	16.7%	12.2%
5 persons	2505	6.6%	5.15%

Table 86: Chi-square goodness of fit test household size

	o_i	e_i	$(o_i-e_i)^2/e_i$
1 person	7986	14439	2884
2 persons	15814	12355	968
3 persons	5250	4472	135
4 persons	6346	4624	641
5 persons	2502	1942	161
Total	37898	3792	4790

The variable has five categories which means that k = 5 and it has one degree of freedom (df = k – 1). In the Chi-square distribution table, the value for the combination of df = 4 and $x^2_{0.05}$ the value of 9.488 is received (in the case of df = 4 and $X^2_{0.05}$). Because 4790 > χ^2 .050 the null hypothesis is rejected so the sample is not representative of the Dutch population. The tests show that the sample is not statistically representative for the Dutch population but it is the dataset that contains the needed information that will best approach the Dutch population.

Variables

Based on the literature, six variables have been selected from the WoON dataset, that will likely determine the energy consumption of the household. The research of Wyatt (2013) showed a clear association of the degree of detachment and floor area with energy consumption.

Guerra Sating et al. (2009) investigated the effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. The study showed that occupant characteristics and behaviour significantly affect energy use (4.2%), but building characteristics still determine a large part of the energy use in a dwelling (42%). The most important aspects of occupant characteristics in the research were the number of heated bedrooms but also the size, age and income of the household and whether the dwelling is owned or rented. For the building characteristics, the most important aspects were the living area, the age of the dwelling, the level of insulation and the number and type of rooms (Guerra Santin et al., 2009). The variables that were selected for the current research are based on the outcomes of these researches, and the goal is to accomplish a good prediction of energy consumption by using as few variables as possible. The model will be parsimonious. Furthermore, the variables (from the WoON dataset) that will be included must be known to the user, which means that it must be possible to extract them from open data.

The occupant characteristic that will be included is the size of the household. This is a variable that, according to the research of Guerra Sating et al. (2009), has a positive impact on energy consumption and can be collected from open-source data. Other occupant characteristics also can have a predictive factor on the energy consumption but can make the model unusable, due to lack of data. Moreover, the building characteristics have a higher predictive influence on energy consumption (Guerra Santin et al., 2009). For the home characteristics the variables floor space, construction year and type of dwelling (degree of detachment) are incorporated, which, based on previous research, all have major influences on the energy consumption of a dwelling. An effort has been made to incorporate the level of insulation by using the variable energy label. However, based on input from the municipality of Eindhoven, it has been decided not to use the variable energy label as these labels are often not up to date. Hence, the construction year of a dwelling will be a better predictor of the level of insulation. Furthermore, in the WoON 2018 dataset, the information on the energy label is missing, in

80% of the cases for owner-occupied homes, which will result in unreliable predictions of when the energy label will be used.
As a result, the selected variables are household size, floor space, construction year, type of dwelling, gas consumption (dependent) and electricity consumption (dependent).

Transformed variables
Before the variables could be used for the regression analysis, the variables needed to be transformed into variables that could be used for the analysis. The variables construction year, household size and housing type have been transformed into categories to be able to see the effect of a category on the energy consumption and increase the usability of the dashboard. In Table 87, the categories created and their respective sizes are shown. It can be seen that the distribution of cases is generally similar to some outliers. For the variables, some transformations are required to make the variable reliable for the regression analysis, due to categories are not needed for the research or with too few cases. The categories apartment and others are removed because these housing types are not part of the research. The housing type semi-terraced house is merged with the category semi-detached house because it had too few cases to be of predictive value for the research and the category semi-detached house had the most similarities, as can be seen in Table 88. This is also the case for the category of detached house. In Table 89 the descriptive statistics of all variables have been shown. It can be seen that before the transformations to the variables, housing type had quite a high number of missing values (30%). Due to this high amount, the missing values could not be assigned to the mean, but an extra category has been created that is called “Missing”. Before the transformations, also quite extreme (outliers) minimum and maximum values were found for the variables gas consumption, electricity consumption and floor space. Because of this, the top and bottom 1% cases have been removed from the data. When comparing the descriptive statistics before and after this transformation it can be seen that the means are comparable but the minimum and maximum results are more realistic for the Dutch housing stock.

Table 87: Categories of the variables household size, construction year and housing type

Descriptive statistics						
Variable	Category	N	Percent	Category	N	Percent
Household size	1 person	6859	21,5	1 person	6641	21,7
	2 persons	13469	42,3	2 persons	12886	42,0
	3 persons	4340	13,6	3 persons	4198	13,7
	4 persons	5274	16,5	4 persons	5087	16,6
	5 persons or more	1936	6,1	5 persons or more	1861	6,1
Construction year	Before 1946	6102	19,2	Before 1946	5840	19,0
	1946-1964	4109	12,9	1646-1964	4112	13,4
	1965-1974	5050	15,9	1965-1974	4882	15,9
	1975-1991	8338	26,2	1975-1991	7975	26,0
	1992-2004	5351	16,8	1992-2004	5096	16,6
	2005-2018	2847	9,0	2005-2018	2768	9,0
Housing type	Terraced house	9761	30,6	Terraced house	9761	32,3
	Corner house	4798	15,1	Corner house	4798	15,9
	Semi-detached house	5242	16,4	Semi-detached house	5242	17,4
	Semi-terraced house	668	2,1	Missing	10389	34,4

Detached house	483	1,5
Apartment	20	0,1
Other	517	1,6
Missing	10389	32,6

Table 88: Comparison of the housing types most similar to semi-terraced house and detached house

	Gas consumption	Electricity consumption	Floor space	Construction year	Household size
Semi-detached house	1682	3614	144	1975-1991	2
Terraced house	1313	3181	120	1975-1991	2
Semi-terraced house	1792	3675	158	1975-1991	2
Detached house	1634	3231	282	Before 1946	2
Semi-detached + Semi-terraced + Detached house	1682	3614	144	1975-1991	2

Table 89: Descriptive statistics of the variables

Descriptive statistics								
	Before data mutations				After data transformations			
	N	Min	Max	Mean	N	Min	Max	Mean
Gas consumption	30673	1	9196	1584	29057	270	4331	1556
Electricity consumption	30673	1	11248	3380	29057	444	8646	3363
Floor space	30673	15	1000	138	29057	54	416	135
Construction year	30673	1	6	4	29057	1	6	4
Household size	30673	1	5	2	29057	1	5	2
Housing type	30673	1	5	5	29057	1	5	1

Regression analysis

To determine the effects of the variables on energy consumption, a regression analysis has been executed. For the regression analysis, the dependent variables are gas consumption and electricity consumption. For each of these variables, the regression will be executed separately. The variables gas consumption, electricity consumption and floor space have been log-transformed, in order to transform non-normal data distributions. Due to potential interaction effects between floor space and housing type, the interactions between these two variables have been added to the regression model. The categorical variables construction year, household size and housing type are used as dummy variables.
The equation of the regression model describes the consumption of energy based on the building and occupier characteristics.

Table 90: Results regression analysis

	Dependent variable:	
	log(Gas_consumption) (1)	log(Electricity_consumption) (2)
Construction_year1946-1964	−0.010 (0.009)	0.007 (0.010)
Construction_year1965-1974	−0.043*** (0.008)	0.004 (0.009)
Construction_year1975-1991	−0.174*** (0.007)	0.060*** (0.008)
Construction_year1992-2004	−0.352*** (0.008)	0.066*** (0.009)
Construction_year2005-2018	−0.483*** (0.010)	−0.011 (0.011)
log(Floor_space)	0.481*** (0.025)	0.284*** (0.028)
Household_size2 persons	0.080*** (0.007)	0.305*** (0.007)
Household_size3 persons	0.136*** (0.009)	0.433*** (0.010)
Household_size4 persons	0.158*** (0.008)	0.503*** (0.009)
Household_size5 persons or more	0.173*** (0.012)	0.541*** (0.013)
Housing_typeMissing	−1.348*** (0.130)	−0.716*** (0.148)
Housing_typeSemi-detached house	1.278*** (0.153)	0.516*** (0.175)
Housing_typeTerraced house	−0.421*** (0.147)	−0.177 (0.168)
log(Floor_space):Housing_typeMissing	0.280*** (0.027)	0.147*** (0.031)
log(Floor_space):Housing_typeSemi-detached house	−0.253*** (0.031)	−0.102*** (0.036)
log(Floor_space):Housing_typeTerraced house	0.058* (0.031)	0.031 (0.035)
Constant	5.022*** (0.120)	6.310*** (0.137)
Observations	23,767	23,767
R^2	0.352	0.239
Adjusted R^2	0.351	0.239
Residual Std. Error (df = 23750)	0.374	0.425
F Statistic (df = 16; 23750)	805.152***	466.825***
Note:		*p<0.1; **p<0.05; ***p<0.01

To increase the predictive value of the results, the regression analysis has been created using a training dataset which consists of 80% of the dataset which is tested using a testing dataset which consists of the other 20% of the dataset. This process has been repeated twenty times using different random samples. To select the best predicting models (for natural gas and electricity), the Mean Absolute Error (RAE) and the (tested and predicted) averages of the models have been tested for the different samples. For the RAE, which is the average of all absolute errors, the lowest value has been selected. The results of the RAE and the averages are shown in Table 92. For the natural gas consumption sample 7 provided the best results and for the electricity consumption sample 15 provided the best results.

Results

In Table 90, the results and the R squared value of the model can be found. In this case, the R squared value for gas consumption is 0,351 indicating that the variables explain 35,1% of the dependent variable gas consumption. This is not a very high value which means the model can predict the gas consumption but the prediction is not very strong. The R squared value for electricity consumption is 0,239.

A 95% confidence interval for the F statistic (prediction model natural gas consumption F=805,152, p<0,01 and the prediction model for electricity consumption F = 466, p<0,01) showed that both models are statistically significant. This means that there is a significant relationship between the dependent variable (natural gas consumption or electricity consumption) and a minimum of one of the independent variables. Considering that the regression is done for a parsimonious model, which means that limited input variables have been used, it can be stated that the model is fairly accurate.

The B coefficients in Table 90 show that most predictors are statistically significant at the 0,01 level and for the predictive model for the natural gas consumption, the predictors “construction year 1946-1964” and the interaction between “Floor space” and “Terraced house” are not statistically significant. For the predictive model for the electricity consumption also the predictors “construction year 1965-1974”, “construction year 2005-2008” and “terraced house”.

The B coefficients have an expected effect on energy consumption. Both for natural gas and electricity consumption a relation was found between the age of the house and energy consumption, i.e., the younger the house, the smaller the energy consumption. This often can be explained by improved insulation and heating techniques. Furthermore, the bigger the house the higher the energy consumption because more energy is needed to heat a bigger area. Also, a bigger household will require more energy, which can be explained that in this case more often people are at home which means that energy will be used more often, above that more appliances will be used. The models would predict relatively high values for Semi-detached houses, due to the high value for the housing type and the given that this type of house often has a high floorspace, this is compensated by the interaction effect between housing type and floor space.

Further use of the regression results

With the regression results, the energy consumption of dwellings can be predicted using the input variables construction year, housing type, floor space and household size. Using these results, Equation 2 and Equation 3 can be created. Using these independent variables as an input for these equations the energy consumption per housing type can be predicted. The equations will be used during the research to predict the natural gas and electricity consumption when it is not known. Note here that the variables construction year, household size and housing type are using dummy coding.

Equation 16: Prediction of natural gas consumption

$$\mathrm{EXP}(\textit{Natural gas consumption}) = 5{,}022 - 0{,}043 * \textit{Construction year 1965-1974} - 0{,}174 * \textit{Construction year 1975-1991} - 0{,}352 * \textit{Construction year 1992-2004} - 0{,}483 * \textit{Construction year 2005-2018} + 0{,}481 * \mathrm{LN}(\textit{Floor space}) + 0{,}080 * \textit{2 persons} + 0{,}136 * \textit{3 persons} + 0{,}158 * 4\ \textit{persons} + 0{,}173 * \textit{5 persons or more} - 0{,}421 * \textit{Terraced house} + 1{,}278 * \textit{Detached house} + 1{,}278 * \textit{Semi-detached house} - 0{,}253 * \mathrm{LN}(\textit{Floor space}) * \textit{Semi-detached house} - 0.253 * \mathrm{LN}(\textit{Floor space}) * \textit{Detached house}\ \backslash$$

Equation 17: Prediction of electricity consumption

EXP(*Electricity consumption*) = 6,310 + 0,060 * *Construction year 1975-1991* + 0,066 * *Construction year 1992-2004* + 0,284 * LN(*Floor space)* + 0,305 * *2 persons* + 0,433 * *3 persons* + 0,503 * 4 *persons* + 0,541 * *5 persons or more* + 0,516 * *Detached house* + 0,516 * *Semi-detached house* -0,102 * LN(*Floor space*) * *Detached house* -0,102 * LN(*Floor space*) * *Semi-detached house*

Comparison of results

Because the created equations only predict the energy consumption per type of house, it is very useful to test the performance. This is done by comparing the real electricity and natural gas consumption from the WoON 2018 dataset with the energy consumption as predicted by the equation for a similar type of house. The results of this comparison are shown in Table 91. In this table the type of house is shown, the predicted and real energy consumption, the number of cases of this type of house in the WoON 2018 dataset and the deviation in floor space which is used to select the cases in the WoON 2018 dataset. Most results are generally comparable, indicating that the equation is quite reliable for predicting the energy consumption (see Table 91). But it can be noticed that the equation of natural gas consumption makes a better prediction than the equation for electricity consumption, which could be explained by the higher amount of significant variables in the natural gas regression. Besides that, in the dataset frequently a type of housing did not exist or had very few cases which makes the comparison in some cases less reliable. But this also confirms the added value of the predictive equations because using these equations, prediction can also be done about types of houses for which no references are present in the dataset, which means that the dashboard can be used for all different types of housing.

Table 91: Comparison of predicted and real energy consumption per type of house

Dwelling properties					Predicted		WoON 2018			
Case	Housing type	Construction period	Floor space(m^2)	Household size	Gas consumption (m^3)	Electricity consumption (kWh)	N	Deviation floor space	Gas consumption (m^3)	Electricity consumption (kWh)
1	Detached house	1975-1991	100	2 persons	1477	3173	0			
2	Semi-detached house	1975-1991	170	2 persons	1599	3380	47	5	1802	3633
3	Terraced house	1946-1964	120	3 persons	1441	3303	8	5	1738	3604
4	Corner house	1946-1964	195	3 persons	2196	3792	2	5	1348	5652
5	Terraced house	1946-1964	120	2 persons	1079	2906	46	5	1454	2945
6	Corner house	1946-1964	85	3 persons	1473	2995	17	5	1468	2855

Table 92: Mean Absolute Error

Sample	1	2	3	4	5	6	7	8	9	10
sed.seed	1	1486	2972	4457	5943	7428	8914	10399	11885	13370
Gas										
MAE	421,2723	423,9221	421,5505	423,833	421,1484	427,4314	**415,4332**	423,5035	423,7037	423,5617

Predicted mean	1565	1558	1566	1555	1550	1565	1553	1567	1542	1554
Tested mean	1572	1556	1560	1563	1569	1558	1557	1554	1544	1558
Elec										
MAE	996,1256	1017	1016,086	997,3428	1001,406	1013,587	996,6975	987,4275	1011	1002,323
Predicted mean	3386	3367	3394	3370	3363	3376	3357	3378	3331	3358
Tested mean	3344	3360	3357	3358	3349	3398	3364	3366	3338	3355

1485,45	11	12	13	14	15	16	17	18	19	20
sed.seed	14856	16341	17826	19312	20797	22283	23768	25254	26739	28225
Gas										
MAE	427,9028	428,9348	422,2706	426,5856	427,2173	429,3795	419,4485	421,452	427	429,8934
Predicted mean	1562	1560	1560	1556	1571	1571	1549	1553,9	1569	1557
Tested mean	1573	1565	1554	1558	1559	1567	1548	1569	1568	1556
Elec										
MAE	1003,806	1015,331	1015,518	1011,784	**985,3251**	1008,906	1005,328	1015,279	1011,085	1014,738
Predicted mean	3372	3377	3372	3363	3385	3378	3361	3362	3378	3366
Tested mean	3372	3370	3366	3385	3368	3385	3350	3365	3379	3364

Appendix M: Calculation investment costs and energy consumption air-to-water and ground heat pump

Equation 18: Required capacity heat pump (Warmtepompinfo, 2019)

$$\begin{aligned}&Capacity\ heat\ pump\ (in\ kW)\\&\quad = needed\ capacity\ per\ m2 * heated\ area\ (m2) *\ \beta\ /\ 1000\end{aligned}$$

Air-to-water heat pump
The reinvestment costs of an air-to-water heat pump can be calculated using Equation 18 and Equation 19.

Equation 19: Reinvestment costs of an air-to-water heat pump

$$Reinvestment\ costs = 1897{,}82 + 450{,}29 * Capacity\ heat\ pump\ (in\ kW)$$

Ground heat pump
For the ground heat pump, the cost for a ground heat pump which have a closed vertical ground loop. For the calculations it will be assumed a new ground heat pump will be installed including an integrated boiler.

Verder uitleggen wat er wordt gebruikt

A

The needed power of the ground heat pump will be calculated using the natural gas consumption of a dwelling. According to the WKO tool of the Rijksdienst voor Ondernemend Nederland the dwelling need to have a minimum energy label C for a ground heat pump. For the

Equation 20: Calculation of the needed power for the heat pump

$$\begin{aligned}(Natural\ gas\ use\ for\ heating\ (m3) * ((35{,}17/3{,}6)/1600) * 1\\= needed\ power\ for\ heat\ pump(kW)\end{aligned}$$

Full load hours heat pump for heating/cooling: 1600/600
Natural gas: 35,17 MJ/m^3
Conversion factor MJ to kW: 3,6
Heat supply by heat pump (beta factor): 100%

Full load hours is a unit for the effective annual yield of an energy source with varying power. The full load hours can be seen as the time during which the energy source has effectively produced energy at full power.

B
To calculate the investment price of the heat pump the following equation is used

$$\frac{€}{kW} * needed\ power\ for\ heat\ pump(kW) = investment\ price\ heat\ pump\ (€)$$

For this equation the costs of €1100/kW (including VAT) are assumed.

C

The efficiency of a heat pump during a year can be expressed using the Seasonal Coefficient of Performance (SCOP). The SCOP is specified at two different release temperatures, 35 ˚C and 55 ˚C. Below the SCOP for the different release temperatures are shown.
SCOP: release temperature 35 ˚C: 5
SCOP: release temperature 45 ˚C: 4,2
SCOP: release temperature 55 ˚C: 3,75

D

The equation that can be used to calculate the capacity of the soil energy (kW) is

$$capacity\ of\ the\ soil\ energy\ (kW) = needed\ power\ for\ heat\ pump(kW) * (1 - \frac{1}{SCOP})$$

E

The yield of the soil energy (W/m) is in the Netherlands on average similar. The hight of the yield is dependent on the type of soil but also weather the heat is regenerated. In this research it is assumed (in accordance with the RVO) that the heat in the soil will be balanced. Which means that the amount of heat which is withdrawn from the soil is similar to the input of energy. This is assumed because the soil temperature does not fully recover (by cooling) from a heating season which results in the further cooling of the soil and a lower efficiency of the heat pump. To create a balance in the soil energy, extra heat needs to be supplied to the soil, this can be done using solar collectors or PVT panels. A PVT panel is a solar panel with a heat exchanger at the back of the panel.

$$Full\ load\ hours\ = full\ load\ hours\ (heating) + full\ load\ hours\ (tap\ water\ heating)$$

Soil yield (W/m)	Without regeneration	50% regeneration	100% regeneration
Full load hours 1000-1500	Y = -0,014 * X + 40	Y = -0,018 * X + 51	Y = -0,024 * X + 64
Full load hours 1500-2500	Y = -0,003 * X + 23,5	Y = -0,005 * X + 31,5	Y = -0,004 * X + 34

F

The calculate how deep there needs to be drilled for the closed vertical ground loop the following equation can be used. For this equation it is assumed that the heat will be 100% regenerated in the soil.

$$\frac{capacity\ of\ the\ soil\ energy\ (kW) * 1000}{Soil\ yield\ (\frac{W}{m})} = Required\ drilling\ depth\ (m)$$

To calculate the number of needed PVT panels the following equation can be used. For this equation it is assumed that the PVT-panels supply maximal 40% of the source heat and the ground loop supplies at least 60% of the heat. The results will be round down to determine the required number of PVT panels.

$$Required\ drilling\ depth\ (m) * \frac{0{,}4}{20} = Needed\ number\ of\ PVT\ panels$$

The maximum drilling depth is 500 m but it can differentiate per location which can be checked on the site of the WKO tool (Rijksdienst voor ondernemend Nederland, n.d.). If the needed drilling depth is higher than the maximum allowed drilling depth multiple wells can be drilled.

G

To calculate the investment costs of the heat source the following equation can be used.

$$investment\ heat\ source\ (€) = U\ loop\ investment\ (€) + investment\ PVT\ panels\ (€)$$

U-loop investment costs can be calculated using the following equation

$$Investment\ costs\ U\ loop\ (€) = required\ drilling\ depth\ (m) * drilling\ costs\ per\ meter\ (\frac{€}{m})$$

Drilling costs per meter €40/m including VAT.

For the investment costs PVT panels can be calculated using in following equation

$$Investment\ costs\ PVT\ panels = 1000 + Required\ number\ of\ PVT\ panels * 500$$

H

To calculate the electricity consumption of the heat pump can be done using the following equation.

$$Electricity\ consumption\ (kWh) = (\ power\ of\ heat\ pump(kW) - capacity\ of\ the\ soil\ energy\ (kW)) * \text{Full load hours heat pump}$$

I

For heat pumps with an integrated boiler not only the electricity consumption for the heat pump need to be calculated but also the electricity consumption for the boiler. Because a heat pump need to produce higher temperatures for tap water an electric heat element is used which means that the SCOP (2,55) will be lower of the heating of tap water.

$$Electricity\ consumption\ heating\ of\ tap\ water = \frac{heat\ requirements\ tap\ water)}{SCOP\ (tap\ water)}$$

$$Net\ Electricity\ consumption\ heating\ of\ tap\ water\ (kWh) = \left(\frac{heat\ requirements\ tap\ water}{SCOP}\right) + 119$$

J

To calculate the full load hours for the heating of tap water using the net electricity consumption.

$$Full\ load\ hours\ tap\ water = \frac{net\ electricity\ consumption\ heating\ of\ tap\ water\ (kWh)}{Power\ heat\ pump\ (kW)}$$

L

There is a well pump in in a heat pump. A heat pump uses electricity when there needs to be heated or cooled or when tap water needs to be heated. The needed electricity consumption can be calculated using the following equation.

$$Power\ well\ pump\ (kW) = power\ heat\ pump\ (kW) * 0{,}015$$

$$\begin{aligned} Electricity\ consumption\ well\ pump\ (kWh) \\ &= power\ well\ pump\ (kW) \\ &* full\ load\ hours\ (of\ heating, cooling\ and\ tap\ water\ heating) \end{aligned}$$

M

The total electricity consumption can be calculated using the following equation.

$$\begin{aligned} Total\ electricity\ consumption\ (kWh) \\ &= Electricity\ consumption\ heat\ pump\ (kWh) \\ &+\ Electricity\ consumption\ tap\ water\ heating\ (kWh) \\ &+ Electricity\ consumption\ well\ pump\ (kWh) \end{aligned}$$

The imbalance can be calculated using the following equation

$$\begin{aligned} Inbalance\ (GJ) \\ &=\ heating\ hours - cooling\ hours) \\ &* capacity\ of\ the\ soil\ energy\ (kW) 3{,}6 * 1000 \end{aligned}$$

Needed PVT panels inbalance

$$\frac{Inbalance\ (GJ)}{yield\ PVT\ panels\ (GJ)} = Needed$$

Investment warmtebroninvestering

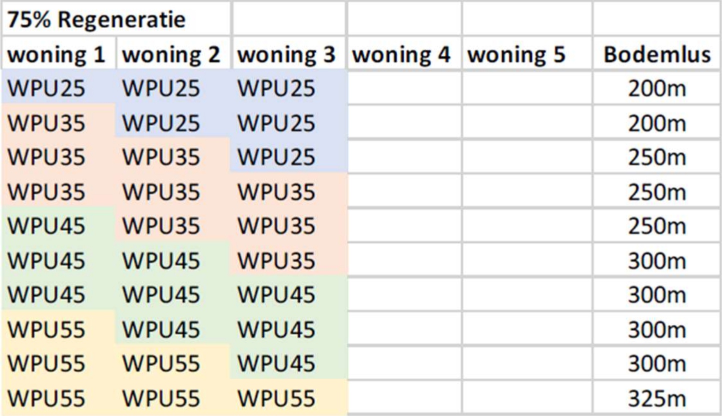
$$Heat\ source\ investment = U - loop\ investment + Investment\ PVT\ panels$$

$$Drilling\ depth\ (m) * Drilling\ costs\ per\ meter\ \left(\frac{€}{m}\right) = U - loop\ investement\ (€)$$

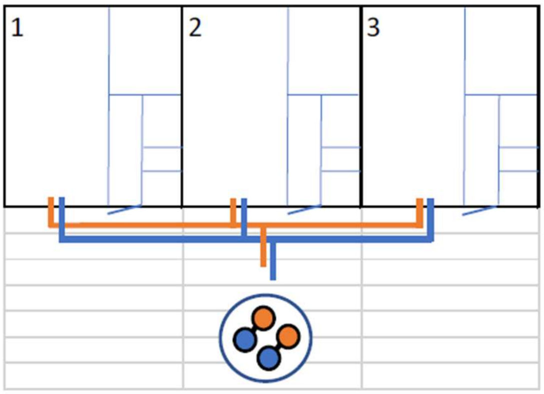
Drilling costs per meter= €40/m including VAT

$$1000 + Needed\ number\ of\ PVT\ panels * 500 = investment\ costs\ PVT_{pannels}(€)$$

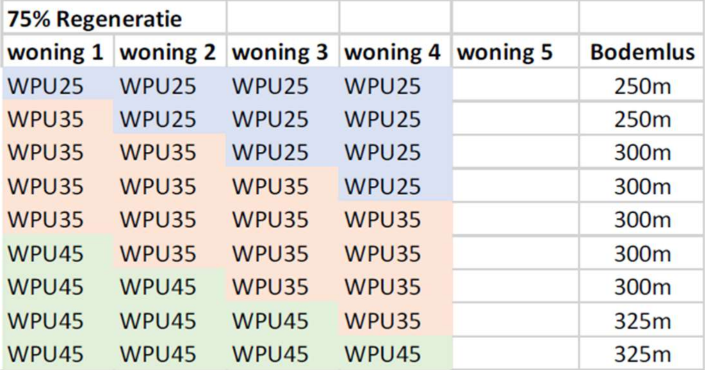
3 homes on 1 source: WPU types, bottom loop length – 75% regeneration



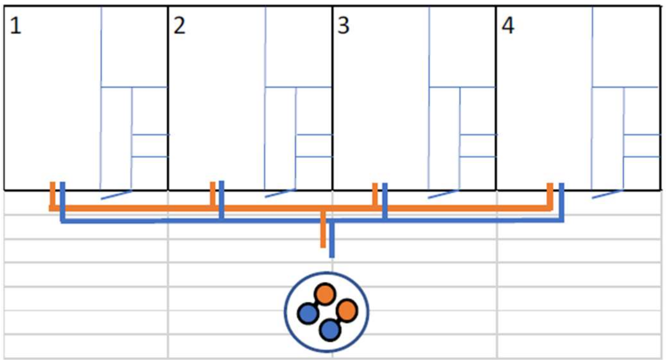
75% Regeneratie					
woning 1	**woning 2**	**woning 3**	**woning 4**	**woning 5**	**Bodemlus**
WPU25	WPU25	WPU25			200m
WPU35	WPU25	WPU25			200m
WPU35	WPU35	WPU25			250m
WPU35	WPU35	WPU35			250m
WPU45	WPU35	WPU35			250m
WPU45	WPU45	WPU35			300m
WPU45	WPU45	WPU45			300m
WPU55	WPU45	WPU45			300m
WPU55	WPU55	WPU45			300m
WPU55	WPU55	WPU55			325m



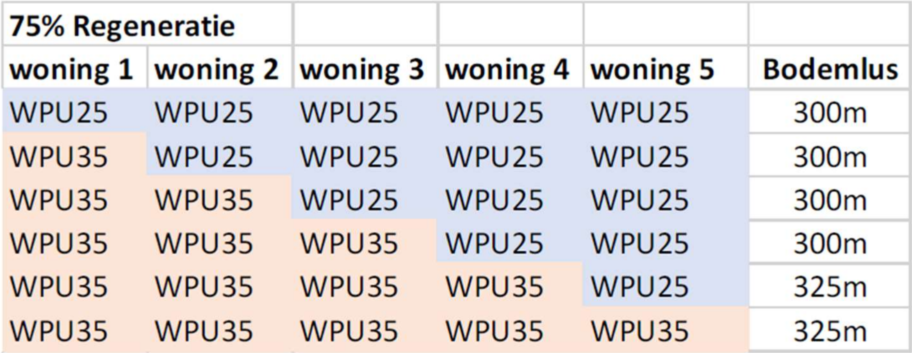
4 homes on 1 source: WPU types, bottom loop length – 75% regeneration



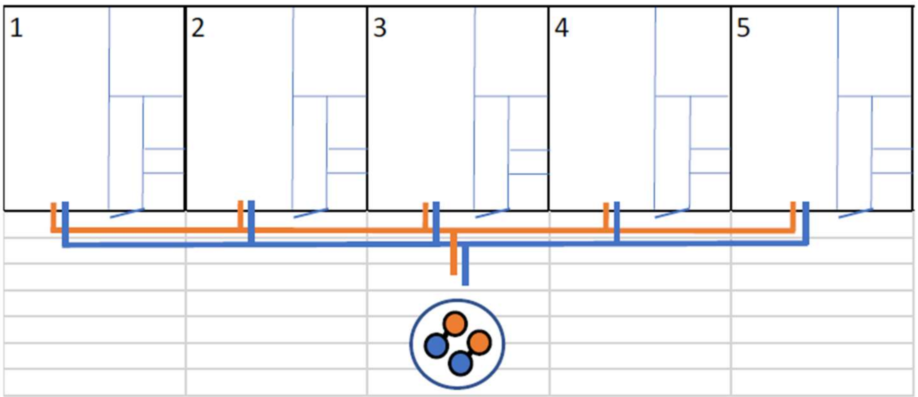
75% Regeneratie					
woning 1	**woning 2**	**woning 3**	**woning 4**	**woning 5**	**Bodemlus**
WPU25	WPU25	WPU25	WPU25		250m
WPU35	WPU25	WPU25	WPU25		250m
WPU35	WPU35	WPU25	WPU25		300m
WPU35	WPU35	WPU35	WPU25		300m
WPU35	WPU35	WPU35	WPU35		300m
WPU45	WPU35	WPU35	WPU35		300m
WPU45	WPU45	WPU35	WPU35		300m
WPU45	WPU45	WPU45	WPU35		325m
WPU45	WPU45	WPU45	WPU45		325m



5 homes on 1 source: WPU types, bottom loop length – 75% regeneration



75% Regeneratie					
woning 1	**woning 2**	**woning 3**	**woning 4**	**woning 5**	**Bodemlus**
WPU25	WPU25	WPU25	WPU25	WPU25	300m
WPU35	WPU25	WPU25	WPU25	WPU25	300m
WPU35	WPU35	WPU25	WPU25	WPU25	300m
WPU35	WPU35	WPU35	WPU25	WPU25	300m
WPU35	WPU35	WPU35	WPU35	WPU25	325m
WPU35	WPU35	WPU35	WPU35	WPU35	325m



Appendix N: Investment costs insulation

Type of housing	Construction year	Isolation shell jump Label G to Label D				Isolation shell jump Label F to Label D			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 16.845,30	€ 16,17	€ 18.566,19	€ 40,28	€ 2.528,16	€ 24,49	€ 2.311,22	€ 47,14
Detached	1930 - 1945	€ 11.617,08	€ 37,53	€ 12.608,00	€ 67,27	€ 2.528,16	€ 24,49	€ 2.311,22	€ 47,14
Detached	1946 - 1964	€ 11.617,08	€ 37,53	€ 12.608,00	€ 67,27	€ 413,29	€ 34,54	€ 716,87	€ 49,66
Detached	1965 - 1974	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	1975 - 1991	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	1992 - 1995	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	1996 - 1999	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	2000 - 2005	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	2006 - 2010	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	2011 - 2014	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Detached	2015 - 2020	€ 12.025,38	€ 36,46	€ 13.449,37	€ 65,07	€ 2.616,86	€ 28,51	€ 2.653,23	€ 49,87
Semi-detached	voor 1930	€ 6.619,39	€ 31,87	€ 16.590,72	€ 12,82	€ 1.192,79	€ 32,12	€ 6.066,75	€ 38,69
Semi-detached	1930 - 1945	€ 6.619,39	€ 31,87	€ 16.590,72	€ 12,82	€ 488,98	€ 32,92	€ 3.369,72	€ 42,70
Semi-detached	1946 - 1964	€ 6.619,39	€ 31,87	€ 16.590,72	€ 12,82	€ 488,98	€ 32,92	€ 3.369,72	€ 42,70
Semi-detached	1965 - 1974	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	1975 - 1991	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	1992 - 1995	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	1996 - 1999	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	2000 - 2005	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	2006 - 2010	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	2011 - 2014	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Semi-detached	2015 - 2020	€ 7.206,86	€ 29,48	€ 15.926,91	€ 15,52	€ 870,98	€ 32,19	€ 3.754,56	€ 41,97
Terraced hoek	voor 1930	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 3.577,43	€ 6,55	€ 4.584,49	€ 16,87
Terraced hoek	1930 - 1945	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 3.577,43	€ 6,55	€ 4.584,49	€ 16,87
Terraced hoek	1946 - 1964	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.466,64	€ 10,76	€ 4.501,07	€ 3,05
Terraced hoek	1965 - 1974	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	1975 - 1991	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	1992 - 1995	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	1996 - 1999	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	2000 - 2005	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	2006 - 2010	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	2011 - 2014	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced hoek	2015 - 2020	€ 10.368,00	€ -	€ 14.255,00	€ -	€ 2.789,00	€ 17,25	€ 3.377,24	€ 33,26
Terraced tussen	voor 1930	€ 4.308,02	€ 10,51	€ 9.456,76	€ 12,72	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	1930 - 1945	€ 4.308,02	€ 10,51	€ 9.456,76	€ 12,72	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	1946 - 1964	€ 4.308,02	€ 10,51	€ 9.456,76	€ 12,72	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	1965 - 1974	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	1975 - 1991	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	1992 - 1995	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	1996 - 1999	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	2000 - 2005	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	2006 - 2010	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	2011 - 2014	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Terraced tussen	2015 - 2020	€ 5.408,11	€ 6,27	€ 10.269,25	€ 9,37	€ 3.707,03	€ 5,97	€ 4.979,15	€ 18,41
Apartment: low and middle	voor 1930	€ 4.468,40	€ 37,72	€ 14.293,00	€ 15,82	€ 1.860,21	€ 23,18	€ 5.266,69	€ 8,52
Apartment: low and middle	1930 - 1945	€ 1.615,52	€ 54,79	€ 8.276,88	€ 58,31	€ 2.236,85	€ 7,84	€ 3.309,92	€ 30,68
Apartment: low and middle	1946 - 1964	€ 3.094,95	€ 20,46	€ -1.345,72	€ 169,18	€ 2.236,85	€ 7,84	€ 3.309,92	€ 30,68
Apartment: low and middle	1965 - 1974	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ -2.098,70	€ 71,13	€ 4.975,45	€ 51,36
Apartment: low and middle	1975 - 1991	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ -1.437,40	€ 63,02	€ 1.812,11	€ 90,14
Apartment: low and middle	1992 - 1995	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ -1.437,40	€ 63,02	€ 1.812,11	€ 90,14
Apartment: low and middle	1996 - 1999	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: low and middle	2000 - 2005	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: low and middle	2006 - 2010	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: low and middle	2011 - 2014	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: low and middle	2015 - 2020	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: high	voor 1930	€ 4.468,40	€ 37,72	€ 14.293,00	€ 15,82	€ 1.860,21	€ 23,18	€ 5.266,69	€ 8,52
Apartment: high	1930 - 1945	€ 1.615,52	€ 54,79	€ 8.276,88	€ 58,31	€ 2.236,85	€ 7,84	€ 3.309,92	€ 30,68
Apartment: high	1946 - 1964	€ 3.094,95	€ 20,46	€ -1.345,72	€ 169,18	€ 2.236,85	€ 7,84	€ 3.309,92	€ 30,68
Apartment: high	1965 - 1974	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ -2.098,70	€ 71,13	€ 4.975,45	€ 51,36
Apartment: high	1975 - 1991	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ -1.437,40	€ 63,02	€ 1.812,11	€ 90,14
Apartment: high	1992 - 1995	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ -1.437,40	€ 63,02	€ 1.812,11	€ 90,14
Apartment: high	1996 - 1999	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: high	2000 - 2005	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: high	2006 - 2010	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31

Apartment: high	2011 - 2014	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31
Apartment: high	2015 - 2020	€ 1.683,60	€ 52,60	€ 8.281,75	€ 55,68	€ 1.305,90	€ 22,55	€ 3.265,54	€ 46,31

Type of housing	Construction year	Isolation shell jump Label E to Label D				Isolation shell jump Label G to Label C			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 11.425,02	€ 65,80	€ 13.910,79	€ 93,59
Detached	1930 - 1945	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	1946 - 1964	€ -427,05	€ 21,59	€ 1.648,45	€ 18,48	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	1965 - 1974	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	1975 - 1991	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	1992 - 1995	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	1996 - 1999	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	2000 - 2005	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	2006 - 2010	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	2011 - 2014	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Detached	2015 - 2020	€ 4.205,00	€ -	€ 7.016,00	€ -	€ 411,13	€ 122,48	€ -3.490,47	€ 191,23
Semi-detached	voor 1930	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	1930 - 1945	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	1946 - 1964	€ 1.903,47	€ 4,37	€ 2.828,83	€ 5,09	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	1965 - 1974	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	1975 - 1991	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	1992 - 1995	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	1996 - 1999	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	2000 - 2005	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	2006 - 2010	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	2011 - 2014	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Semi-detached	2015 - 2020	€ 1.382,56	€ 10,71	€ 1.914,44	€ 19,08	€ 8.852,04	€ 34,09	€ 10.864,62	€ 65,73
Terraced hoek	voor 1930	€ 963,64	€ 15,53	€ 1.428,07	€ 28,92	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	1930 - 1945	€ 963,64	€ 15,53	€ 1.428,07	€ 28,92	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	1946 - 1964	€ -333,40	€ 28,17	€ -1.502,69	€ 61,73	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	1965 - 1974	€ 1.612,22	€ 0,51	€ 1.755,37	€ 25,32	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	1975 - 1991	€ 1.612,22	€ 0,51	€ 1.755,37	€ 25,32	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	1992 - 1995	€ 1.612,22	€ 0,51	€ 1.755,37	€ 25,32	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	1996 - 1999	€ 1.678,59	€ 5,72	€ 1.617,43	€ 26,91	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	2000 - 2005	€ 1.678,59	€ 5,72	€ 1.617,43	€ 26,91	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	2006 - 2010	€ 1.678,59	€ 5,72	€ 1.617,43	€ 26,91	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	2011 - 2014	€ 1.678,59	€ 5,72	€ 1.617,43	€ 26,91	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced hoek	2015 - 2020	€ 1.678,59	€ 5,72	€ 1.617,43	€ 26,91	€ 14.207,00	€ -	€ 20.414,00	€ -
Terraced tussen	voor 1930	€ 2.330,13	€ 1,50	€ 3.577,56	€ 3,05	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	1930 - 1945	€ 1.388,48	€ 3,61	€ 2.473,66	€ 4,02	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	1946 - 1964	€ 540,39	€ 8,35	€ 1.233,85	€ 10,63	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	1965 - 1974	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	1975 - 1991	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	1992 - 1995	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	1996 - 1999	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	2000 - 2005	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	2006 - 2010	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	2011 - 2014	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Terraced tussen	2015 - 2020	€ 1.315,59	€ 3,67	€ 2.452,85	€ 5,14	€ 10.939,00	€ -	€ 17.077,00	€ -
Apartment: low and middle	voor 1930	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.329,36	€ 27,73	€ 11.157,66	€ 35,93
Apartment: low and middle	1930 - 1945	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.329,36	€ 27,73	€ 11.157,66	€ 35,93
Apartment: low and middle	1946 - 1964	€ -50,45	€ 18,22	€ 1.741,16	€ 19,08	€ 3.641,40	€ 11,58	€ 9.524,85	€ 5,97
Apartment: low and middle	1965 - 1974	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 5.105,12	€ 26,53	€ 15.562,26	€ 16,58
Apartment: low and middle	1975 - 1991	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 5.105,12	€ 26,53	€ 15.562,26	€ 16,58
Apartment: low and middle	1992 - 1995	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 5.105,12	€ 26,53	€ 15.562,26	€ 16,58
Apartment: low and middle	1996 - 1999	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: low and middle	2000 - 2005	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: low and middle	2006 - 2010	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: low and middle	2011 - 2014	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: low and middle	2015 - 2020	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: high	voor 1930	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.329,36	€ 27,73	€ 11.157,66	€ 35,93
Apartment: high	1930 - 1945	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.329,36	€ 27,73	€ 11.157,66	€ 35,93
Apartment: high	1946 - 1964	€ -50,45	€ 18,22	€ 1.741,16	€ 19,08	€ 3.641,40	€ 11,58	€ 9.524,85	€ 5,97
Apartment: high	1965 - 1974	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 5.105,12	€ 26,53	€ 15.562,26	€ 16,58
Apartment: high	1975 - 1991	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 5.105,12	€ 26,53	€ 15.562,26	€ 16,58
Apartment: high	1992 - 1995	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 5.105,12	€ 26,53	€ 15.562,26	€ 16,58
Apartment: high	1996 - 1999	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: high	2000 - 2005	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: high	2006 - 2010	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: high	2011 - 2014	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24
Apartment: high	2015 - 2020	€ -2,39	€ 22,42	€ 889,30	€ 46,88	€ 4.651,96	€ 25,64	€ 12.615,52	€ 26,24

Type of housing	Construction year	Isolation shell jump Label G to Label C				Isolation shell jump Label E to Label C			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 8.776,77	€ 28,23	€ 7.795,88	€ 59,26	€ 4.451,38	€ 31,24	€ 7.063,84	€ 41,39
Detached	1930 - 1945	€ 6.897,52	€ 31,30	€ 6.358,18	€ 64,96	€ 4.124,37	€ 28,41	€ 7.125,73	€ 32,80
Detached	1946 - 1964	€ 6.897,52	€ 31,30	€ 6.358,18	€ 64,96	€ 4.124,37	€ 28,41	€ 7.125,73	€ 32,80
Detached	1965 - 1974	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 13.069,77	€ 22,92	€ 17.448,50	€ 30,06
Detached	1975 - 1991	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 12.890,36	€ 19,76	€ 13.593,15	€ 38,20
Detached	1992 - 1995	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 12.890,36	€ 19,76	€ 13.593,15	€ 38,20
Detached	1996 - 1999	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 6.900,75	€ 24,85	€ 9.519,48	€ 31,71
Detached	2000 - 2005	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 6.900,75	€ 24,85	€ 9.519,48	€ 31,71
Detached	2006 - 2010	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 6.900,75	€ 24,85	€ 9.519,48	€ 31,71

Detached	2011 - 2014	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 6.900,75	€ 24,85	€ 9.519,48	€ 31,71
Detached	2015 - 2020	€ 9.145,44	€ 31,46	€ 9.333,91	€ 68,81	€ 6.900,75	€ 24,85	€ 9.519,48	€ 31,71
Semi-detached	voor 1930	€ 7.152,34	€ 30,00	€ 10.639,39	€ 40,38	€ 3.892,22	€ 29,72	€ 4.897,25	€ 38,41
Semi-detached	1930 - 1945	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.898,67	€ 33,43	€ 2.484,30	€ 43,22
Semi-detached	1946 - 1964	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 2.757,02	€ 21,98	€ 3.567,73	€ 27,21
Semi-detached	1965 - 1974	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	1975 - 1991	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	1992 - 1995	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	1996 - 1999	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	2000 - 2005	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	2006 - 2010	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	2011 - 2014	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Semi-detached	2015 - 2020	€ 5.366,49	€ 33,16	€ 9.037,74	€ 43,64	€ 1.315,89	€ 47,50	€ 1.598,17	€ 64,63
Terraced hoek	voor 1930	€ 7.265,90	€ 7,67	€ 8.346,03	€ 22,58	€ 1.335,50	€ 36,69	€ 2.395,23	€ 42,12
Terraced hoek	1930 - 1945	€ 7.265,90	€ 7,67	€ 8.346,03	€ 22,58	€ 1.335,50	€ 36,69	€ 2.395,23	€ 42,12
Terraced hoek	1946 - 1964	€ 7.265,90	€ 7,67	€ 8.346,03	€ 22,58	€ 2.844,07	€ 20,78	€ 5.180,15	€ 8,40
Terraced hoek	1965 - 1974	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	1975 - 1991	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	1992 - 1995	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	1996 - 1999	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	2000 - 2005	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	2006 - 2010	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	2011 - 2014	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced hoek	2015 - 2020	€ 6.491,96	€ 18,43	€ 7.410,21	€ 35,59	€ 3.675,55	€ 26,63	€ 6.187,15	€ 18,59
Terraced tussen	voor 1930	€ 6.096,47	€ 26,00	€ 8.322,90	€ 57,18	€ 3.332,87	€ 11,07	€ -1.939,00	€ 103,62
Terraced tussen	1930 - 1945	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 1.476,30	€ 24,23	€ 1.190,67	€ 43,45
Terraced tussen	1946 - 1964	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 790,74	€ 28,26	€ 84,11	€ 58,46
Terraced tussen	1965 - 1974	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	1975 - 1991	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	1992 - 1995	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	1996 - 1999	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	2000 - 2005	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	2006 - 2010	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	2011 - 2014	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Terraced tussen	2015 - 2020	€ 3.853,38	€ 35,61	€ 5.007,86	€ 71,06	€ 2.026,26	€ 21,26	€ -792,86	€ 73,97
Apartment: low and middle	voor 1930	€ 619,01	€ 72,35	€ 5.755,36	€ 75,91	€ 596,47	€ 45,41	€ 879,62	€ 72,69
Apartment: low and middle	1930 - 1945	€ 1.376,79	€ 43,02	€ 4.247,90	€ 73,49	€ -551,96	€ 62,19	€ 2.396,07	€ 67,32
Apartment: low and middle	1946 - 1964	€ 1.376,79	€ 43,02	€ 4.247,90	€ 73,49	€ 409,69	€ 43,19	€ 3.492,22	€ 44,09
Apartment: low and middle	1965 - 1974	€ 4.664,30	€ 12,27	€ 12.873,40	€ 17,92	€ -914,04	€ 68,07	€ 538,09	€ 131,02
Apartment: low and middle	1975 - 1991	€ 1.481,66	€ 53,62	€ 11.258,02	€ 38,90	€ 1.190,93	€ 45,01	€ 4.184,21	€ 92,31
Apartment: low and middle	1992 - 1995	€ 1.481,66	€ 53,62	€ 11.258,02	€ 38,90	€ 1.190,93	€ 45,01	€ 4.184,21	€ 92,31
Apartment: low and middle	1996 - 1999	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: low and middle	2000 - 2005	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: low and middle	2006 - 2010	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: low and middle	2011 - 2014	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: low and middle	2015 - 2020	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: high	voor 1930	€ 619,01	€ 72,35	€ 5.755,36	€ 75,91	€ 596,47	€ 45,41	€ 879,62	€ 72,69
Apartment: high	1930 - 1945	€ 1.376,79	€ 43,02	€ 4.247,90	€ 73,49	€ -551,96	€ 62,19	€ 2.396,07	€ 67,32
Apartment: high	1946 - 1964	€ 1.376,79	€ 43,02	€ 4.247,90	€ 73,49	€ 409,69	€ 43,19	€ 3.492,22	€ 44,09
Apartment: high	1965 - 1974	€ 4.664,30	€ 12,27	€ 12.873,40	€ 17,92	€ -914,04	€ 68,07	€ 538,09	€ 131,02
Apartment: high	1975 - 1991	€ 1.481,66	€ 53,62	€ 11.258,02	€ 38,90	€ 1.190,93	€ 45,01	€ 4.184,21	€ 92,31
Apartment: high	1992 - 1995	€ 1.481,66	€ 53,62	€ 11.258,02	€ 38,90	€ 1.190,93	€ 45,01	€ 4.184,21	€ 92,31
Apartment: high	1996 - 1999	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: high	2000 - 2005	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: high	2006 - 2010	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: high	2011 - 2014	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91
Apartment: high	2015 - 2020	€ 1.116,57	€ 50,19	€ 4.026,16	€ 91,85	€ 740,69	€ 43,06	€ 4.593,12	€ 49,91

Type of housing	Construction year	Isolation shell jump Label D to Label C				Isolation shell jump Label G to Label B			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 5.138,84	€ 2,93	€ 7.785,72	€ 2,73	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	1930 - 1945	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	1946 - 1964	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	1965 - 1974	€ 3.479,47	€ 13,10	€ 4.961,73	€ 22,84	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	1975 - 1991	€ 4.269,83	€ 10,56	€ 7.226,87	€ 13,65	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	1992 - 1995	€ 4.269,83	€ 10,56	€ 7.226,87	€ 13,65	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	1996 - 1999	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	2000 - 2005	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	2006 - 2010	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	2011 - 2014	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Detached	2015 - 2020	€ 5.371,49	€ 3,92	€ 8.263,90	€ 4,62	€ 32.393,62	€ 0,31	€ 40.584,79	€ 12,61
Semi-detached	voor 1930	€ -464,60	€ 34,06	€ -849,32	€ 49,79	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	1930 - 1945	€ 2.136,90	€ 8,39	€ 2.814,18	€ 20,76	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	1946 - 1964	€ 514,75	€ 23,71	€ 628,53	€ 36,23	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	1965 - 1974	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	1975 - 1991	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	1992 - 1995	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	1996 - 1999	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -

Semi-detached	2000 - 2005	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	2006 - 2010	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	2011 - 2014	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Semi-detached	2015 - 2020	€ 1.358,14	€ 17,72	€ 972,37	€ 35,69	€ 18.139,30	€ -	€ 28.809,50	€ -
Terraced hoek	voor 1930	€ 1.566,31	€ 7,18	€ 2.595,39	€ 11,63	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	1930 - 1945	€ 1.566,31	€ 7,18	€ 2.595,39	€ 11,63	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	1946 - 1964	€ 1.620,20	€ 4,12	€ 2.785,78	€ 5,51	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	1965 - 1974	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	1975 - 1991	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	1992 - 1995	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	1996 - 1999	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	2000 - 2005	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	2006 - 2010	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	2011 - 2014	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced hoek	2015 - 2020	€ 1.572,07	€ 11,77	€ 3.256,72	€ 15,90	€ 13.359,75	€ -	€ 20.769,75	€ -
Terraced tussen	voor 1930	€ 37,70	€ 17,81	€ -720,84	€ 34,79	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	1930 - 1945	€ 1.135,43	€ 3,59	€ 1.592,77	€ 8,64	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	1946 - 1964	€ 634,33	€ 10,00	€ 1.316,48	€ 11,39	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	1965 - 1974	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	1975 - 1991	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	1992 - 1995	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	1996 - 1999	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	2000 - 2005	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	2006 - 2010	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	2011 - 2014	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Terraced tussen	2015 - 2020	€ -31,06	€ 18,36	€ -1.159,85	€ 41,30	€ 9.072,12	€ 25,96	€ 4.821,31	€ 126,06
Apartment: low and middle	voor 1930	€ 1.288,25	€ 3,19	€ 785,81	€ 23,86	€ 7.995,55	€ 47,82	€ 19.436,87	€ 30,53
Apartment: low and middle	1930 - 1945	€ 399,25	€ 12,91	€ 873,09	€ 17,06	€ 8.033,98	€ 47,40	€ 20.899,36	€ 21,05
Apartment: low and middle	1946 - 1964	€ 1.288,25	€ 3,19	€ 785,81	€ 23,86	€ 8.033,98	€ 47,40	€ 20.899,36	€ 21,05
Apartment: low and middle	1965 - 1974	€ 828,56	€ 18,20	€ -640,85	€ 65,62	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	1975 - 1991	€ -148,11	€ 32,63	€ 329,61	€ 68,06	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	1992 - 1995	€ -148,11	€ 32,63	€ 329,61	€ 68,06	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	1996 - 1999	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	2000 - 2005	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	2006 - 2010	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	2011 - 2014	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: low and middle	2015 - 2020	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	voor 1930	€ 1.288,25	€ 3,19	€ 785,81	€ 23,86	€ 7.995,55	€ 47,82	€ 19.436,87	€ 30,53
Apartment: high	1930 - 1945	€ 399,25	€ 12,91	€ 873,09	€ 17,06	€ 8.033,98	€ 47,40	€ 20.899,36	€ 21,05
Apartment: high	1946 - 1964	€ 1.288,25	€ 3,19	€ 785,81	€ 23,86	€ 8.033,98	€ 47,40	€ 20.899,36	€ 21,05
Apartment: high	1965 - 1974	€ 828,56	€ 18,20	€ -640,85	€ 65,62	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	1975 - 1991	€ -148,11	€ 32,63	€ 329,61	€ 68,06	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	1992 - 1995	€ -148,11	€ 32,63	€ 329,61	€ 68,06	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	1996 - 1999	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	2000 - 2005	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	2006 - 2010	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	2011 - 2014	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37
Apartment: high	2015 - 2020	€ 894,55	€ 12,24	€ 585,24	€ 40,77	€ 8.257,94	€ 46,11	€ 20.149,71	€ 25,37

Type of housing	Construction year	Isolation shell jump Label F to Label B				Isolation shell jump Label E to Label B			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 13.735,34	€ 36,26	€ 16.872,46	€ 58,53
Detached	1930 - 1945	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 13.735,34	€ 36,26	€ 16.872,46	€ 58,53
Detached	1946 - 1964	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 13.735,34	€ 36,26	€ 16.872,46	€ 58,53
Detached	1965 - 1974	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	1975 - 1991	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	1992 - 1995	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	1996 - 1999	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	2000 - 2005	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	2006 - 2010	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	2011 - 2014	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Detached	2015 - 2020	€ 6.301,15	€ 112,17	€ 263,68	€ 219,79	€ 11.664,96	€ 72,76	€ 11.311,76	€ 136,62
Semi-detached	voor 1930	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	1930 - 1945	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	1946 - 1964	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -

Semi-detached	1965 - 1974	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	1975 - 1991	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	1992 - 1995	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	1996 - 1999	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	2000 - 2005	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	2006 - 2010	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	2011 - 2014	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Semi-detached	2015 - 2020	€ 18.139,30	€ -	€ 28.809,50	€ -	€ 20.054,50	€ -	€ 27.982,50	€ -
Terraced hoek	voor 1930	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	1930 - 1945	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	1946 - 1964	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	1965 - 1974	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	1975 - 1991	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	1992 - 1995	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	1996 - 1999	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	2000 - 2005	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	2006 - 2010	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	2011 - 2014	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced hoek	2015 - 2020	€ 13.359,75	€ -	€ 20.769,75	€ -	€ 12.519,32	€ 20,85	€ 17.927,84	€ 24,90
Terraced tussen	voor 1930	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 8.710,32	€ 17,70	€ 13.997,61	€ 4,97
Terraced tussen	1930 - 1945	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 7.947,19	€ 26,11	€ 11.812,67	€ 29,26
Terraced tussen	1946 - 1964	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 5.417,60	€ 44,61	€ 5.787,35	€ 80,37
Terraced tussen	1965 - 1974	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	1975 - 1991	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	1992 - 1995	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	1996 - 1999	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	2000 - 2005	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	2006 - 2010	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	2011 - 2014	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Terraced tussen	2015 - 2020	€ 7.734,24	€ 42,47	€ 9.948,81	€ 82,22	€ 9.227,07	€ 21,49	€ 13.777,52	€ 22,95
Apartment: low and middle	voor 1930	€ -2.499,40	€ 179,06	€ 1.142,90	€ 205,47	€ 3.478,28	€ 70,89	€ 1.505,10	€ 155,90
Apartment: low and middle	1930 - 1945	€ -1.175,70	€ 151,59	€ 3.071,77	€ 171,98	€ 2.554,81	€ 93,07	€ 4.530,19	€ 136,40
Apartment: low and middle	1946 - 1964	€ -1.175,70	€ 151,59	€ 3.071,77	€ 171,98	€ 3.717,80	€ 44,89	€ 12.549,80	€ 3,97
Apartment: low and middle	1965 - 1974	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	1975 - 1991	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	1992 - 1995	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	1996 - 1999	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	2000 - 2005	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	2006 - 2010	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	2011 - 2014	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: low and middle	2015 - 2020	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	voor 1930	€ -2.499,40	€ 179,06	€ 1.142,90	€ 205,47	€ 3.478,28	€ 70,89	€ 1.505,10	€ 155,90
Apartment: high	1930 - 1945	€ -1.175,70	€ 151,59	€ 3.071,77	€ 171,98	€ 2.554,81	€ 93,07	€ 4.530,19	€ 136,40
Apartment: high	1946 - 1964	€ -1.175,70	€ 151,59	€ 3.071,77	€ 171,98	€ 3.717,80	€ 44,89	€ 12.549,80	€ 3,97
Apartment: high	1965 - 1974	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	1975 - 1991	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	1992 - 1995	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	1996 - 1999	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19

Apartment: high	2000 - 2005	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	2006 - 2010	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	2011 - 2014	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19
Apartment: high	2015 - 2020	€ 2.768,11	€ 93,78	€ 5.157,98	€ 155,19	€ 2.651,62	€ 74,03	€ 3.577,58	€ 140,19

Type of housing	Construction year	Isolation shell jump Label D to Label B				Isolation shell jump Label C to Label B			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	1930 - 1945	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	1946 - 1964	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	1965 - 1974	€ 21.217,99	€ 28,45	€ 25.852,41	€ 49,32	€ 4.853,33	€ 42,79	€ 3.955,09	€ 76,30
Detached	1975 - 1991	€ 19.308,28	€ 41,44	€ 23.583,57	€ 64,25	€ 7.114,10	€ 23,43	€ 11.145,91	€ 29,94
Detached	1992 - 1995	€ 19.308,28	€ 41,44	€ 23.583,57	€ 64,25	€ 3.936,16	€ 44,04	€ 6.132,41	€ 61,14
Detached	1996 - 1999	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	2000 - 2005	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	2006 - 2010	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	2011 - 2014	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Detached	2015 - 2020	€ 16.415,64	€ 39,54	€ 21.297,79	€ 53,60	€ 8.177,93	€ 22,28	€ 11.199,02	€ 33,06
Semi-detached	voor 1930	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 2.769,64	€ 63,84	€ 4.826,26	€ 75,32
Semi-detached	1930 - 1945	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 2.769,64	€ 63,84	€ 4.826,26	€ 75,32
Semi-detached	1946 - 1964	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 2.769,64	€ 63,84	€ 4.826,26	€ 75,32
Semi-detached	1965 - 1974	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 5.646,11	€ 14,62	€ 7.245,31	€ 29,63
Semi-detached	1975 - 1991	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 4.549,78	€ 16,42	€ 6.139,05	€ 29,44
Semi-detached	1992 - 1995	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 5.646,11	€ 14,62	€ 7.245,31	€ 29,63
Semi-detached	1996 - 1999	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 4.190,44	€ 27,70	€ 4.114,21	€ 55,56
Semi-detached	2000 - 2005	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 4.190,44	€ 27,70	€ 4.114,21	€ 55,56
Semi-detached	2006 - 2010	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 4.190,44	€ 27,70	€ 4.114,21	€ 55,56
Semi-detached	2011 - 2014	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 4.190,44	€ 27,70	€ 4.114,21	€ 55,56
Semi-detached	2015 - 2020	€ 15.261,50	€ -	€ 20.666,50	€ -	€ 4.190,44	€ 27,70	€ 4.114,21	€ 55,56
Terraced hoek	voor 1930	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	1930 - 1945	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	1946 - 1964	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	1965 - 1974	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	1975 - 1991	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	1992 - 1995	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	1996 - 1999	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	2000 - 2005	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	2006 - 2010	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	2011 - 2014	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced hoek	2015 - 2020	€ 5.601,70	€ 87,97	€ 3.373,75	€ 149,79	€ 6.874,11	€ 1,93	€ 9.406,49	€ 4,35
Terraced tussen	voor 1930	€ 6.945,01	€ 30,68	€ 9.443,51	€ 50,92	€ 3.248,04	€ 38,46	€ 4.551,81	€ 51,58
Terraced tussen	1930 - 1945	€ 5.987,95	€ 31,17	€ 8.083,74	€ 52,53	€ 5.530,33	€ 6,45	€ 6.448,86	€ 20,01
Terraced tussen	1946 - 1964	€ 6.756,48	€ 12,41	€ 4.821,64	€ 82,34	€ 5.602,63	€ 18,09	€ 9.239,90	€ 11,90
Terraced tussen	1965 - 1974	€ 3.615,13	€ 77,71	€ 6.793,11	€ 83,22	€ 2.518,02	€ 35,12	€ 2.005,91	€ 63,67
Terraced tussen	1975 - 1991	€ 2.052,80	€ 94,86	€ 2.456,01	€ 131,09	€ 2.518,02	€ 35,12	€ 2.005,91	€ 63,67
Terraced tussen	1992 - 1995	€ 2.052,80	€ 94,86	€ 2.456,01	€ 131,09	€ 2.518,02	€ 35,12	€ 2.005,91	€ 63,67
Terraced tussen	1996 - 1999	€ 5.187,12	€ 53,30	€ 6.875,61	€ 78,26	€ 2.203,70	€ 39,91	€ 1.924,43	€ 67,12
Terraced tussen	2000 - 2005	€ 5.187,12	€ 53,30	€ 6.875,61	€ 78,26	€ 2.203,70	€ 39,91	€ 1.924,43	€ 67,12
Terraced tussen	2006 - 2010	€ 5.187,12	€ 53,30	€ 6.875,61	€ 78,26	€ 2.203,70	€ 39,91	€ 1.924,43	€ 67,12
Terraced tussen	2011 - 2014	€ 5.187,12	€ 53,30	€ 6.875,61	€ 78,26	€ 2.203,70	€ 39,91	€ 1.924,43	€ 67,12

Terraced tussen	2015 - 2020	€ 5.187,12	€ 53,30	€ 6.875,61	€ 78,26	€ 2.203,70	€ 39,91	€ 1.924,43	€ 67,12
Apartment: low and middle	voor 1930	€ 6.194,71	€ 22,68	€ 6.614,94	€ 73,15	€ 3.705,42	€ 33,59	€ 4.382,47	€ 68,66
Apartment: low and middle	1930 - 1945	€ 3.420,39	€ 47,85	€ 5.302,29	€ 60,54	€ 1.783,31	€ 45,82	€ 1.909,49	€ 67,77
Apartment: low and middle	1946 - 1964	€ 4.479,12	€ 41,50	€ 3.621,78	€ 106,82	€ 3.075,60	€ 24,49	€ 4.337,67	€ 41,90
Apartment: low and middle	1965 - 1974	€ 5.464,63	€ 24,85	€ 3.787,46	€ 114,44	€ 3.682,19	€ 21,25	€ 6.244,59	€ 26,95
Apartment: low and middle	1975 - 1991	€ 6.086,29	€ 21,86	€ 7.702,76	€ 84,28	€ 4.046,26	€ 19,05	€ 8.381,37	€ 6,20
Apartment: low and middle	1992 - 1995	€ 6.086,29	€ 21,86	€ 7.702,76	€ 84,28	€ 3.682,19	€ 21,25	€ 6.244,59	€ 26,95
Apartment: low and middle	1996 - 1999	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: low and middle	2000 - 2005	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: low and middle	2006 - 2010	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: low and middle	2011 - 2014	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: low and middle	2015 - 2020	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: high	voor 1930	€ 6.194,71	€ 22,68	€ 6.614,94	€ 73,15	€ 3.705,42	€ 33,59	€ 4.382,47	€ 68,66
Apartment: high	1930 - 1945	€ 3.420,39	€ 47,85	€ 5.302,29	€ 60,54	€ 1.783,31	€ 45,82	€ 1.909,49	€ 67,77
Apartment: high	1946 - 1964	€ 4.479,12	€ 41,50	€ 3.621,78	€ 106,82	€ 3.075,60	€ 24,49	€ 4.337,67	€ 41,90
Apartment: high	1965 - 1974	€ 5.464,63	€ 24,85	€ 3.787,46	€ 114,44	€ 3.682,19	€ 21,25	€ 6.244,59	€ 26,95
Apartment: high	1975 - 1991	€ 6.086,29	€ 21,86	€ 7.702,76	€ 84,28	€ 4.046,26	€ 19,05	€ 8.381,37	€ 6,20
Apartment: high	1992 - 1995	€ 6.086,29	€ 21,86	€ 7.702,76	€ 84,28	€ 3.682,19	€ 21,25	€ 6.244,59	€ 26,95
Apartment: high	1996 - 1999	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: high	2000 - 2005	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: high	2006 - 2010	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: high	2011 - 2014	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23
Apartment: high	2015 - 2020	€ 5.391,55	€ 29,61	€ 6.452,56	€ 74,53	€ 5.175,97	€ 5,89	€ 7.874,91	€ 21,23

Type of housing	Construction year	Isolation shell jump Label G to Label A				Isolation shell jump Label F to Label A			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 21.203,09	€ 101,37	€ 45.139,92	€ 241,62	€ 21.203,09	€ 101,37	€ 45.139,92	€ 241,62
Detached	1930 - 1945	€ 21.203,09	€ 101,37	€ 45.139,92	€ 241,62	€ 21.203,09	€ 101,37	€ 45.139,92	€ 241,62
Detached	1946 - 1964	€ 10.994,31	€ 179,90	€ 20.631,97	€ 430,14	€ 10.994,31	€ 179,90	€ 20.631,97	€ 430,14
Detached	1965 - 1974	€ 21.527,62	€ 92,85	€ 26.511,25	€ 344,75	€ 21.527,62	€ 92,85	€ 26.511,25	€ 344,75
Detached	1975 - 1991	€ 28.247,75	€ 49,21	€ 51.158,62	€ 184,70	€ 28.247,75	€ 49,21	€ 51.158,62	€ 184,70
Detached	1992 - 1995	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	1996 - 1999	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	2000 - 2005	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Detached	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Detached	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	voor 1930	€ 11.481,58	€ 134,87	€ 21.331,25	€ 314,37	€ 11.481,58	€ 134,87	€ 21.331,25	€ 314,37
Semi-detached	1930 - 1945	€ 11.481,58	€ 134,87	€ 21.331,25	€ 314,37	€ 11.481,58	€ 134,87	€ 21.331,25	€ 314,37
Semi-detached	1946 - 1964	€ 14.857,40	€ 104,18	€ 32.344,97	€ 214,24	€ 14.857,40	€ 104,18	€ 32.344,97	€ 214,24
Semi-detached	1965 - 1974	€ 19.888,83	€ 56,95	€ 46.464,39	€ 89,84	€ 19.888,83	€ 56,95	€ 46.464,39	€ 89,84
Semi-detached	1975 - 1991	€ 20.436,04	€ 52,50	€ 36.471,09	€ 171,08	€ 20.436,04	€ 52,50	€ 36.471,09	€ 171,08
Semi-detached	1992 - 1995	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	1996 - 1999	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	2000 - 2005	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	voor 1930	€ 9.690,96	€ 97,39	€ 15.829,74	€ 239,45	€ 9.690,96	€ 97,39	€ 15.829,74	€ 239,45
Terraced hoek	1930 - 1945	€ 9.690,96	€ 97,39	€ 15.829,74	€ 239,45	€ 9.690,96	€ 97,39	€ 15.829,74	€ 239,45
Terraced hoek	1946 - 1964	€ 18.277,98	€ -	€ 37.195,89	€ -	€ 18.277,98	€ -	€ 37.195,89	€ -
Terraced hoek	1965 - 1974	€ 14.239,62	€ 40,43	€ 17.660,23	€ 193,17	€ 14.239,62	€ 40,43	€ 17.660,23	€ 193,17
Terraced hoek	1975 - 1991	€ 9.039,60	€ 89,49	€ 17.179,90	€ 197,70	€ 9.039,60	€ 89,49	€ 17.179,90	€ 197,70
Terraced hoek	1992 - 1995	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27
Terraced hoek	1996 - 1999	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27
Terraced hoek	2000 - 2005	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27
Terraced hoek	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	voor 1930	€ 10.115,33	€ 92,51	€ 17.135,02	€ 224,44	€ 10.115,33	€ 92,51	€ 17.135,02	€ 224,44
Terraced tussen	1930 - 1945	€ 10.115,33	€ 92,51	€ 17.135,02	€ 224,44	€ 10.115,33	€ 92,51	€ 17.135,02	€ 224,44
Terraced tussen	1946 - 1964	€ 17.578,10	€ 6,73	€ 35.492,29	€ 13,44	€ 17.578,10	€ 6,73	€ 35.492,29	€ 13,44
Terraced tussen	1965 - 1974	€ 18.525,56	€ -	€ 38.136,71	€ -	€ 18.525,56	€ -	€ 38.136,71	€ -
Terraced tussen	1975 - 1991	€ 9.862,44	€ 81,73	€ 14.908,34	€ 219,13	€ 9.862,44	€ 81,73	€ 14.908,34	€ 219,13
Terraced tussen	1992 - 1995	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	1996 - 1999	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	2000 - 2005	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	voor 1930	€ 10.425,53	€ 62,67	€ 12.071,46	€ 189,35	€ 10.425,53	€ 62,67	€ 12.071,46	€ 189,35

Apartment: low and middle	1930 - 1945	€ 10.425,53	€ 62,67	€ 12.071,46	€ 189,35	€ 10.425,53	€ 62,67	€ 12.071,46	€ 189,35
Apartment: low and middle	1946 - 1964	€ 3.818,30	€ 162,78	€ -2.248,04	€ 406,31	€ 3.818,30	€ 162,78	€ -2.248,04	€ 406,31
Apartment: low and middle	1965 - 1974	€ 7.232,41	€ 94,83	€ 3.449,10	€ 281,72	€ 7.232,41	€ 94,83	€ 3.449,10	€ 281,72
Apartment: low and middle	1975 - 1991	€ 10.011,31	€ 55,13	€ 19.310,74	€ 122,48	€ 10.011,31	€ 55,13	€ 19.310,74	€ 122,48
Apartment: low and middle	1992 - 1995	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15
Apartment: low and middle	1996 - 1999	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15
Apartment: low and middle	2000 - 2005	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15
Apartment: low and middle	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	voor 1930	€ 9.938,67	€ 56,38	€ 11.195,63	€ 163,80	€ 9.938,67	€ 56,38	€ 11.195,63	€ 163,80
Apartment: high	1930 - 1945	€ 9.938,67	€ 56,38	€ 11.195,63	€ 163,80	€ 9.938,67	€ 56,38	€ 11.195,63	€ 163,80
Apartment: high	1946 - 1964	€ 3.994,84	€ 146,44	€ -1.191,67	€ 351,48	€ 3.994,84	€ 146,44	€ -1.191,67	€ 351,48
Apartment: high	1965 - 1974	€ 7.037,60	€ 83,66	€ 3.785,62	€ 237,13	€ 7.037,60	€ 83,66	€ 3.785,62	€ 237,13
Apartment: high	1975 - 1991	€ 9.489,29	€ 48,64	€ 13.168,30	€ 103,09	€ 9.489,29	€ 48,64	€ 13.168,30	€ 103,09
Apartment: high	1992 - 1995	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52
Apartment: high	1996 - 1999	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52
Apartment: high	2000 - 2005	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52
Apartment: high	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -

Type of housing	Construction year	Isolation shell jump Label E to Label A				Isolation shell jump Label D to Label A			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 18.978,98	€ 59,52	€ 40.286,88	€ 211,09	€ 18.978,98	€ 59,52	€ 40.286,88	€ 211,09
Detached	1930 - 1945	€ 18.978,98	€ 59,52	€ 40.286,88	€ 211,09	€ 18.978,98	€ 59,52	€ 40.286,88	€ 211,09
Detached	1946 - 1964	€ 10.994,31	€ 179,90	€ 20.631,97	€ 430,14	€ 12.884,59	€ 120,23	€ 24.679,93	€ 341,58
Detached	1965 - 1974	€ 21.527,62	€ 92,85	€ 26.511,25	€ 344,75	€ 21.527,62	€ 92,85	€ 26.511,25	€ 344,75
Detached	1975 - 1991	€ 28.247,75	€ 49,21	€ 51.158,62	€ 184,70	€ 28.247,75	€ 49,21	€ 51.158,62	€ 184,70
Detached	1992 - 1995	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	1996 - 1999	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	2000 - 2005	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Detached	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Detached	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	voor 1930	€ 9.572,42	€ 105,08	€ 19.189,52	€ 274,08	€ 9.572,42	€ 105,08	€ 19.189,52	€ 274,08
Semi-detached	1930 - 1945	€ 9.572,42	€ 105,08	€ 19.189,52	€ 274,08	€ 9.572,42	€ 105,08	€ 19.189,52	€ 274,08
Semi-detached	1946 - 1964	€ 17.547,31	€ 49,78	€ 35.634,74	€ 146,13	€ 17.547,31	€ 49,78	€ 35.634,74	€ 146,13
Semi-detached	1965 - 1974	€ 19.888,83	€ 56,95	€ 46.464,39	€ 89,84	€ 17.979,46	€ 34,16	€ 44.555,02	€ 67,05
Semi-detached	1975 - 1991	€ 20.436,04	€ 52,50	€ 36.471,09	€ 171,08	€ 20.436,04	€ 52,50	€ 36.471,09	€ 171,08
Semi-detached	1992 - 1995	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	1996 - 1999	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	2000 - 2005	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	voor 1930	€ 9.522,58	€ 76,63	€ 16.390,39	€ 206,23	€ 11.570,93	€ 27,73	€ 18.273,51	€ 152,08
Terraced hoek	1930 - 1945	€ 9.522,58	€ 76,63	€ 16.390,39	€ 206,23	€ 11.570,93	€ 27,73	€ 18.273,51	€ 152,08
Terraced hoek	1946 - 1964	€ 18.277,98	€ -	€ 37.195,89	€ -	€ 15.383,70	€ -	€ 32.056,18	€ -
Terraced hoek	1965 - 1974	€ 14.239,62	€ 40,43	€ 17.660,23	€ 193,17	€ 14.239,62	€ 40,43	€ 17.660,23	€ 193,17
Terraced hoek	1975 - 1991	€ 9.039,60	€ 89,49	€ 17.179,90	€ 197,70	€ 9.039,60	€ 89,49	€ 17.179,90	€ 197,70
Terraced hoek	1992 - 1995	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27
Terraced hoek	1996 - 1999	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27
Terraced hoek	2000 - 2005	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27
Terraced hoek	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	voor 1930	€ 10.115,33	€ 92,51	€ 17.135,02	€ 224,44	€ 9.522,58	€ 76,63	€ 16.390,39	€ 206,23
Terraced tussen	1930 - 1945	€ 10.115,33	€ 92,51	€ 17.135,02	€ 224,44	€ 9.522,58	€ 76,63	€ 16.390,39	€ 206,23
Terraced tussen	1946 - 1964	€ 17.578,10	€ 6,73	€ 35.492,29	€ 13,44	€ 14.436,55	€ 2,49	€ 30.299,47	€ 7,96
Terraced tussen	1965 - 1974	€ 18.525,56	€ -	€ 38.136,71	€ -	€ 18.525,56	€ -	€ 38.136,71	€ -
Terraced tussen	1975 - 1991	€ 9.862,44	€ 81,73	€ 14.908,34	€ 219,13	€ 9.862,44	€ 81,73	€ 14.908,34	€ 219,13
Terraced tussen	1992 - 1995	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	1996 - 1999	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	2000 - 2005	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	voor 1930	€ 10.425,53	€ 62,67	€ 12.071,46	€ 189,35	€ 8.057,32	€ 62,67	€ 9.889,10	€ 184,32

Apartment: low and middle	1930 - 1945	€ 10.425,53	€ 62,67	€ 12.071,46	€ 189,35	€ 8.057,32	€ 62,67	€ 9.889,10	€ 184,32
Apartment: low and middle	1946 - 1964	€ 3.818,30	€ 162,78	€ -2.248,04	€ 406,31	€ 4.630,48	€ 130,29	€ 1.577,10	€ 323,73
Apartment: low and middle	1965 - 1974	€ 7.232,41	€ 94,83	€ 3.449,10	€ 281,72	€ 7.232,41	€ 94,83	€ 3.449,10	€ 281,72
Apartment: low and middle	1975 - 1991	€ 10.011,31	€ 55,13	€ 19.310,74	€ 122,48	€ 10.011,31	€ 55,13	€ 19.310,74	€ 122,48
Apartment: low and middle	1992 - 1995	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15
Apartment: low and middle	1996 - 1999	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15
Apartment: low and middle	2000 - 2005	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15
Apartment: low and middle	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	voor 1930	€ 9.938,67	€ 56,38	€ 11.195,63	€ 163,80	€ 7.570,47	€ 56,38	€ 9.013,27	€ 158,77
Apartment: high	1930 - 1945	€ 9.938,67	€ 56,38	€ 11.195,63	€ 163,80	€ 7.570,47	€ 56,38	€ 9.013,27	€ 158,77
Apartment: high	1946 - 1964	€ 3.994,84	€ 146,44	€ -1.191,67	€ 351,48	€ 4.807,02	€ 113,95	€ 2.633,47	€ 268,91
Apartment: high	1965 - 1974	€ 7.037,60	€ 83,66	€ 3.785,62	€ 237,13	€ 7.037,60	€ 83,66	€ 3.785,62	€ 237,13
Apartment: high	1975 - 1991	€ 9.489,29	€ 48,64	€ 13.168,30	€ 103,09	€ 9.489,29	€ 48,64	€ 13.168,30	€ 103,09
Apartment: high	1992 - 1995	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52
Apartment: high	1996 - 1999	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52
Apartment: high	2000 - 2005	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52
Apartment: high	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -

Type of housing	Construction year	Isolation shell jump Label C to Label A				Isolation shell jump Label B to Label A			
		Natural moment		Independent		Natural moment		Independent	
		€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2	€ / connection	€ / m2
Detached	voor 1930	€ 6.913,67	€ 27,22	€ 26.758,11	€ 148,16	€ 6.913,67	€ 27,22	€ 26.758,11	€ 148,16
Detached	1930 - 1945	€ 6.913,67	€ 27,22	€ 26.758,11	€ 148,16	€ 6.913,67	€ 27,22	€ 26.758,11	€ 148,16
Detached	1946 - 1964	€ 5.179,75	€ 81,91	€ 12.933,83	€ 296,26	€ 5.179,75	€ 81,91	€ 12.933,83	€ 296,26
Detached	1965 - 1974	€ 11.673,05	€ 53,25	€ 17.888,51	€ 254,72	€ 11.673,05	€ 53,25	€ 17.888,51	€ 254,72
Detached	1975 - 1991	€ 28.247,75	€ 49,21	€ 51.158,62	€ 184,70	€ 20.733,31	€ 39,87	€ 41.702,14	€ 159,52
Detached	1992 - 1995	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	1996 - 1999	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	2000 - 2005	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70	€ 22.035,24	€ 49,21	€ 44.946,12	€ 184,70
Detached	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Detached	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Detached	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	voor 1930	€ 4.279,65	€ 35,52	€ 11.734,88	€ 183,87	€ 4.279,65	€ 35,52	€ 11.734,88	€ 183,87
Semi-detached	1930 - 1945	€ 4.279,65	€ 35,52	€ 11.734,88	€ 183,87	€ 4.279,65	€ 35,52	€ 11.734,88	€ 183,87
Semi-detached	1946 - 1964	€ 7.036,79	€ 49,78	€ 20.729,97	€ 146,13	€ 7.036,79	€ 49,78	€ 20.729,97	€ 146,13
Semi-detached	1965 - 1974	€ 17.979,46	€ 34,16	€ 44.555,02	€ 67,05	€ 10.297,41	€ 30,87	€ 31.789,93	€ 64,52
Semi-detached	1975 - 1991	€ 20.436,04	€ 52,50	€ 36.471,09	€ 171,08	€ 14.538,12	€ 42,99	€ 29.142,86	€ 148,43
Semi-detached	1992 - 1995	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	1996 - 1999	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	2000 - 2005	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08	€ 14.223,54	€ 52,50	€ 30.258,58	€ 171,08
Semi-detached	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Semi-detached	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	voor 1930	€ 2.950,61	€ 1,46	€ 7.163,85	€ 106,20	€ 2.950,61	€ 1,46	€ 7.163,85	€ 106,20
Terraced hoek	1930 - 1945	€ 2.950,61	€ 1,46	€ 7.163,85	€ 106,20	€ 2.950,61	€ 1,46	€ 7.163,85	€ 106,20
Terraced hoek	1946 - 1964	€ 15.383,70	€ -	€ 32.056,18	€ -	€ 7.508,43	€ -	€ 22.094,14	€ -
Terraced hoek	1965 - 1974	€ 6.546,75	€ 19,74	€ 10.489,84	€ 132,68	€ 6.546,75	€ 19,74	€ 10.489,84	€ 132,68
Terraced hoek	1975 - 1991	€ 9.039,60	€ 89,49	€ 17.179,90	€ 197,70	€ 4.871,43	€ 61,90	€ 11.691,34	€ 158,19
Terraced hoek	1992 - 1995	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -6.833,43	€ 165,12	€ -18.356,86	€ 423,40
Terraced hoek	1996 - 1999	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -6.833,43	€ 165,12	€ -18.356,86	€ 423,40
Terraced hoek	2000 - 2005	€ -7.413,33	€ 179,13	€ -20.432,28	€ 471,27	€ -6.833,43	€ 165,12	€ -18.356,86	€ 423,40
Terraced hoek	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced hoek	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -

Terraced tussen	voor 1930	€ 4.258,36	€ 32,06	€ 9.448,83	€ 134,45	€ 4.258,36	€ 32,06	€ 9.448,83	€ 134,45
Terraced tussen	1930 - 1945	€ 4.258,36	€ 32,06	€ 9.448,83	€ 134,45	€ 4.258,36	€ 32,06	€ 9.448,83	€ 134,45
Terraced tussen	1946 - 1964	€ 14.436,55	€ 2,49	€ 30.299,47	€ 7,96	€ 7.133,71	€ 2,49	€ 20.275,69	€ 7,96
Terraced tussen	1965 - 1974	€ 8.302,95	€ -	€ 24.608,31	€ -	€ 8.302,95	€ -	€ 24.608,31	€ -
Terraced tussen	1975 - 1991	€ 9.862,44	€ 81,73	€ 14.908,34	€ 219,13	€ 5.520,56	€ 58,16	€ 9.993,31	€ 178,17
Terraced tussen	1992 - 1995	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	1996 - 1999	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	2000 - 2005	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13	€ 3.690,80	€ 81,73	€ 8.311,80	€ 219,13
Terraced tussen	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Terraced tussen	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	voor 1930	€ 4.247,71	€ 25,52	€ 6.139,47	€ 112,70	€ 4.247,71	€ 25,52	€ 6.139,47	€ 112,70
Apartment: low and middle	1930 - 1945	€ 4.247,71	€ 25,52	€ 6.139,47	€ 112,70	€ 4.247,71	€ 25,52	€ 6.139,47	€ 112,70
Apartment: low and middle	1946 - 1964	€ 4.630,48	€ 130,29	€ 1.577,10	€ 323,73	€ 1.154,10	€ 106,40	€ -3.272,18	€ 289,52
Apartment: low and middle	1965 - 1974	€ 3.396,00	€ 62,43	€ 809,94	€ 198,09	€ 3.396,00	€ 62,43	€ 809,94	€ 198,09
Apartment: low and middle	1975 - 1991	€ 10.011,31	€ 55,13	€ 19.310,74	€ 122,48	€ 5.930,61	€ 45,00	€ 14.162,07	€ 96,91
Apartment: low and middle	1992 - 1995	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -399,67	€ 112,67	€ -1.485,43	€ 236,18
Apartment: low and middle	1996 - 1999	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -399,67	€ 112,67	€ -1.485,43	€ 236,18
Apartment: low and middle	2000 - 2005	€ -442,79	€ 124,82	€ -1.736,87	€ 276,15	€ -399,67	€ 112,67	€ -1.485,43	€ 236,18
Apartment: low and middle	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: low and middle	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	voor 1930	€ 3.760,86	€ 19,22	€ 5.263,63	€ 87,15	€ 3.760,86	€ 19,22	€ 5.263,63	€ 87,15
Apartment: high	1930 - 1945	€ 3.760,86	€ 19,22	€ 5.263,63	€ 87,15	€ 3.760,86	€ 19,22	€ 5.263,63	€ 87,15
Apartment: high	1946 - 1964	€ 4.807,02	€ 113,95	€ 2.633,47	€ 268,91	€ 1.330,65	€ 90,05	€ -2.215,81	€ 234,69
Apartment: high	1965 - 1974	€ 3.201,20	€ 51,27	€ 1.146,46	€ 153,50	€ 3.201,20	€ 51,27	€ 1.146,46	€ 153,50
Apartment: high	1975 - 1991	€ 9.489,29	€ 48,64	€ 13.168,30	€ 103,09	€ 5.408,59	€ 38,50	€ 8.019,63	€ 77,52
Apartment: high	1992 - 1995	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -680,85	€ 103,04	€ -1.862,72	€ 202,75
Apartment: high	1996 - 1999	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -680,85	€ 103,04	€ -1.862,72	€ 202,75
Apartment: high	2000 - 2005	€ -762,84	€ 115,44	€ -2.237,29	€ 243,52	€ -680,85	€ 103,04	€ -1.862,72	€ 202,75
Apartment: high	2006 - 2010	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	2011 - 2014	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Apartment: high	2015 - 2020	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -

Appendix O: Operation mechanical ventilation system

(Ventilatiesysteemabcd, n.d.)

Appendix P: Investment costs ventilation system

Ventilation system	2020	Source
Installation mechanical ventilation (single dwelling)	€2745	(Peppelman et al., 2021)
Installation mechanical ventilation (project-based)	€2694	(Peppelman et al., 2021)
Installation decentral heat recovery ventilation system (single dwelling)	€4645	(Peppelman et al., 2021)
Installation decentral heat recovery ventilation system (project-based)	€4358	(Peppelman et al., 2021)
Installation mechanical ventilation system	€2800	(Ventilatiesysteemabcd, n.d.)
Installation mechanical ventilation system	€2500-€3000	(Alpha ventilatie, 2021)
Installation mechanical ventilation system	€1700 - €2100	(MYGO, 2021a)
Replacement mechanical ventilation box (per 17 years)	€350	(Feenstra, 2021; Kosten-Ventilatie.nl, n.d.)
Average cost construction new mechanical ventilation system	€2350	
New ventilation system	€1500	(Kosten-ventillatie, 2021)
Renovation of old ventilation system	€600	(Kosten-ventillatie, 2021)
Decentral heat recovery unit	€400 - €2500	(Alpha Ventilatie, n.d.)
Decentral heat recovery unit	€1000 - €1500	(Ventilatiesysteemabcd, n.d.)
Average costs decentral heat recovery unit	€1350	(Duurzaam Bouwloket, n.d.)
Maintenance decentral heat recovery unit	€4-€7 per month	(Mechanischeventiatie.net, n.d.)
Maintenance mechanical ventilation system	€ 4 per month	(Feenstra, n.d.)
Energy reduction heating due to heat recovery unit	10%	(wtw-filters, n.d.)

Appendix Q: Investment costs induction cooker

Home adaptation cooking	2020	Source
Induction cooker	€600	(Milieu Centraal, n.d.-b; Natuur & Milieu, n.d.)
Extra power wire + new groups	€600	(Milieu Centraal, n.d.-b; Natuur & Milieu, n.d.)
Home adaptation cooking	€500	(Tigchelaar et al., 2021)
Connecting the induction cooker	€70 - €140	(MYGO, 2021b)
Milling kitchen worktop	€50	(MYGO, 2021b)
Power cord	€10 - €20	(MYGO, 2021b)
Perlex plug	€10 - €20	(MYGO, 2021b)
Install Perilex socket	€85	(MYGO, 2021b)
New pan set	€50-€350	(Milieu Centraal, n.d.-b)
Average cost	€1.045	

Appendix R: Size and investment costs of solar panels

(Groessens, 2022)

Size and cost of solar panels		
Type of solar panel	Size	Area (m²)
Canadian Solar CS5P 250 Wp	1602 × 1061 mm	1.7 m²
Suntech STP250-20/Wd	1640 × 992 mm	1.62 m²
Trina Solar TSM-250 250 Wp	1650 × 992 mm	1.63 m²
JA Solar JAM6 60-250/SI 250 Wp	1650 × 991 mm	1.63 m²
ET Solar ET-M660250WW 250 Wp	1640 × 992 mm	1.62 m²
Yingli YL250C-30b 250 Wp	1650 x 990 mm	1.63 m²
Jinko Solar 250 Wp	1650 × 992 mm	1.62 m²
Sharp ND-R250A5 250 Wp	1652 × 994 mm	1.64 m²
Average	1642 x 1000 mm	1.64 m²

Solar panel brand	Number of panels	Wp	Total Wp	Converter	Price (excl VAT)	€/Wp
LG	8	340	2720	SolarEdge	4052,8	1,49
Jinko Solar	8	355	2840	Huawei	3663,6	1,29
Sunpower	9	325	2925	Goodwe	4153,5	1,42
Solarwatt	10	320	3200	SMA	4512	1,41
Sunpower	10	325	3250	Goodwe	4907,5	1,51
Bisol	10	325	3250	SMA	4355	1,34
Axitec	10	340	3400	SMA	4964	1,46
Qcells	10	340	3400	SolarEdge	4488	1,32
Viessmann	12	295	3540	Huawei	4814,4	1,36
Denim	10	360	3600	SolarEdge	4644	1,29
Longi	10	365	3650	Solis	4745	1,3
Qcells	10	370	3700	Huawei	4625	1,25
Viessmann	12	310	3720	Goodwe	4984,8	1,34
Bauer	12	310	3720	SolarEdge	5170,8	1,39
Qcells	11	340	3740	SolarEdge	6507,6	1,74
Sunpower	12	320	3840	SMA	4992	1,3
Bauer	12	320	3840	SolarEdge	5644,8	1,47
Hyundai	11	350	3850	Huawei	5236	1,36
Astronergy	12	325	3900	SMA	5694	1,46
Hyundai	10	390	3900	SMA	5460	1,4
Sunpower	12	325	3900	SMA	4914	1,26
Bauer	12	330	3960	Huawei	4474,8	1,13
Sunpower	12	330	3960	Huawei	5227,2	1,32
Axitec	12	330	3960	SMA	5940	1,5

Trina Solar	12	335	4020	SMA	4703,4	1,17
Qcells	12	340	4080	Huawei	4406,4	1,08
Qcells	12	340	4080	SolarEdge	5018,4	1,23
Qcells	12	340	4080	SolarEdge	5875,2	1,44
Solarwatt	13	315	4095	SolarEdge	5159,7	1,26
Qcells	12	345	4140	SMA	5340,6	1,29
Longi	12	350	4200	SolarEdge	5208	1,24
Jinko Solar	13	340	4420	Huawei	4685,2	1,06
Jinko Solar	14	320	4480	SMA	5062,4	1,13
Axitec	13	345	4485	SolarEdge	5202,6	1,16
Sunpower	14	325	4550	SMA	6415,5	1,41
JA Solar	14	325	4550	SolarEdge	5187	1,14
Bauer	15	305	4575	SMA	4758	1,04
JA Solar	14	335	4690	Huawei	5252,8	1,12
LG	14	340	4760	SMA	5854,8	1,23
Qcells	14	340	4760	SolarEdge	5616,8	1,18
Bisol	15	320	4800	SMA	5568	1,16
Sunpower	12	400	4800	SolarEdge	6672	1,39
REC	13	380	4940	SolarEdge	6471,4	1,31
Longi	14	355	4970	SMA	5814,9	1,17
Qcells	15	340	5100	SolarEdge	6630	1,3
Panasonic	16	325	5200	SolarEdge	6812	1,31
Axitec	16	330	5280	SolarEdge	6864	1,3
Viessmann	16	335	5360	Huawei	5306,4	0,99
LG	15	360	5400	SMA	7452	1,38
JA Solar	16	340	5440	SMA	5276,8	0,97
JA Solar	16	340	5440	SMA	5766,4	1,06
Sunpower	17	320	5440	SMA	8105,6	1,49
Axitec	17	320	5440	SolarEdge	7344	1,35
Jinko Solar	14	395	5530	SMA	7023,1	1,27
Sunpower	14	395	5530	SMA	7133,7	1,29
Hyundai	16	350	5600	SolarEdge	7448	1,33
LG	16	355	5680	SolarEdge	6645,6	1,17
JA Solar	14	410	5740	Enphase	7863,8	1,37
Amerisol	18	320	5760	SMA	6105,6	1,06
Solarwatt	18	320	5760	SolarEdge	7776	1,35
Solarwatt	18	320	5760	SolarEdge	8064	1,4
Solarwatt	18	320	5760	SolarEdge	8179,2	1,42
Sunpower	18	325	5850	Enphase	7488	1,28
Solarwatt	16	370	5920	SMA	7814,4	1,32
Trina Solar	18	335	6030	SolarEdge	6874,2	1,14
LG	18	340	6120	SMA	8017,2	1,31
LG	18	340	6120	SolarEdge	7466,4	1,22
JA Solar	16	385	6160	SMA	7022,4	1,14
Bauer	20	310	6200	SolarEdge	7626	1,23
REC	17	370	6290	SMA	7673,8	1,22
Solarwatt	20	315	6300	Fronius	8253	1,31
Axitec	18	350	6300	Huawei	5859	0,93
Panasonic	19	335	6365	SMA	8465,5	1,33
LG	18	355	6390	SolarEdge	8946	1,4
Qcells	18	355	6390	SolarEdge	9265,5	1,45
Viessmann	16	400	6400	Huawei	6528	1,02
Longi	18	360	6480	SolarEdge	5832	0,9
LG	19	350	6650	SMA	8312,5	1,25
Bauer	22	320	7040	SolarEdge	8166,4	1,16
Sunpower	17	415	7055	SMA	8677,7	1,23
LG	20	355	7100	SolarEdge	9940	1,4
DMEGC	16	445	7120	SMA	9327,2	1,31
Aleo	22	325	7150	SMA	8794,5	1,23
Longi	20	360	7200	Huawei	6480	0,9
Bauer	24	305	7320	SolarEdge	9076,8	1,24

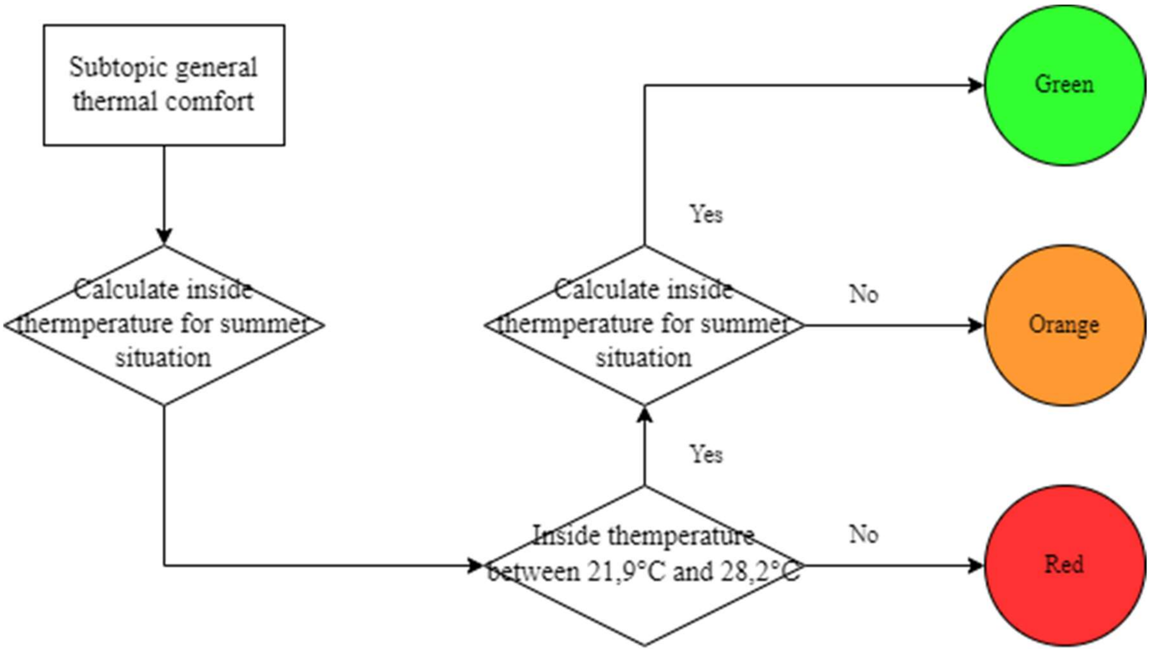
Jinko Solar	24	315	7560	SMA	8467,2	1,12
REC	21	360	7560	SolarEdge	8996,4	1,19
Solarwatt	24	315	7560	SolarEdge	10130	1,34
Qcells	23	340	7820	SolarEdge	11026	1,41
Sunpower	21	375	7875	SolarEdge	10631	1,35
Longi	18	445	8010	SolarEdge	8971,2	1,12
Qcells	23	355	8165	SMA	10370	1,27
Sunpower	21	395	8295	Huawei	10535	1,27
Bauer	26	320	8320	Huawei	8236,8	0,99
Solarwatt	27	315	8505	SMA	11227	1,32
LG	24	355	8520	SMA	10991	1,29
IBC	27	330	8910	SMA	10425	1,17
Qcells	30	340	10200	SolarEdge	15300	1,5
Hyundai	28	390	10920	Huawei	9282	0,85
Denim	36	340	12240	Fronius	14566	1,19
Average	16,12	344,4	5548,7	0	6932,999	1,2643

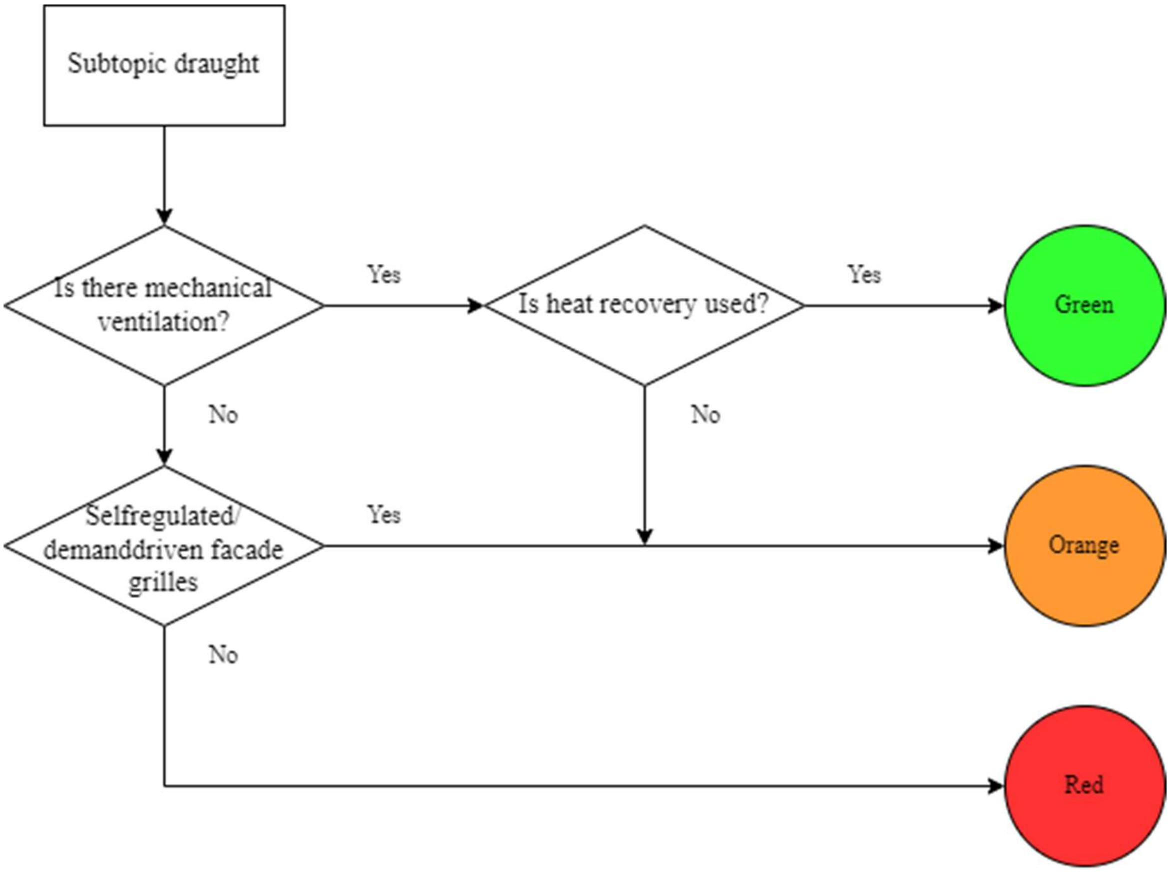
Appendix S: Average number of rooms per type of dwelling

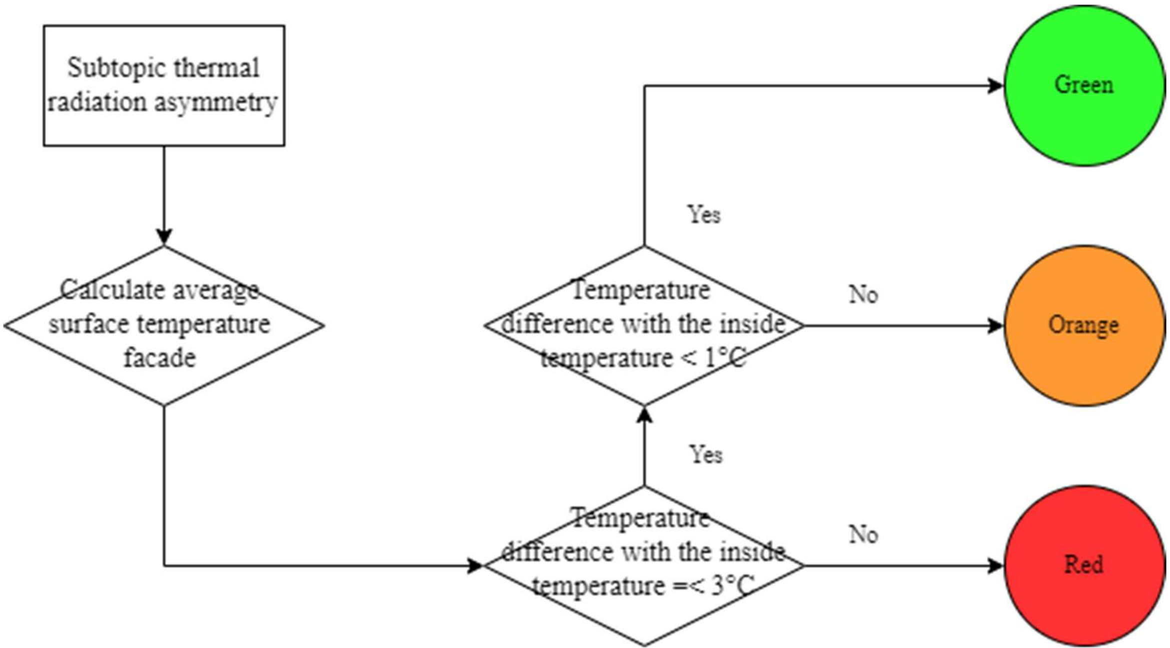
(based on the data of WoON 2018)

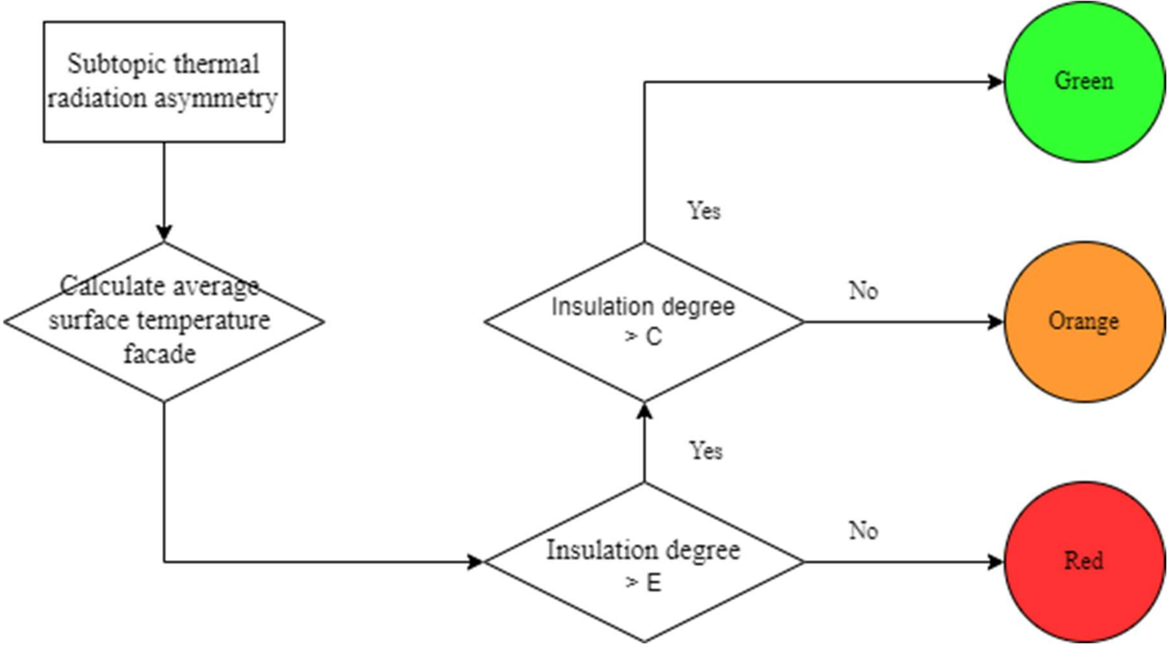
Type of dwelling	The average number of rooms
Terraced house	5
Corner house	5
Semi-detached house	5
Detached house	7

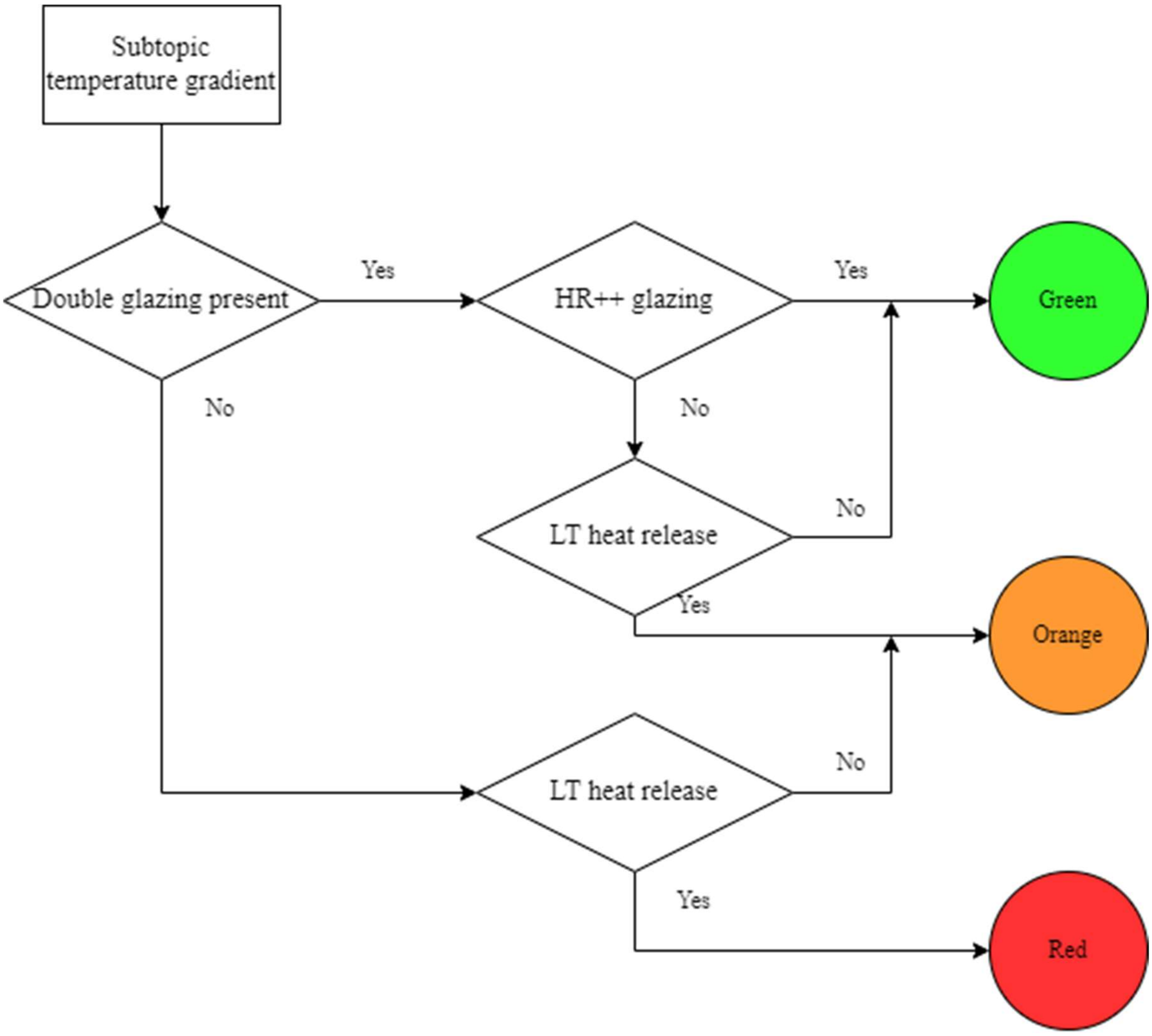
Appendix T: Assessment models subtopics comfort

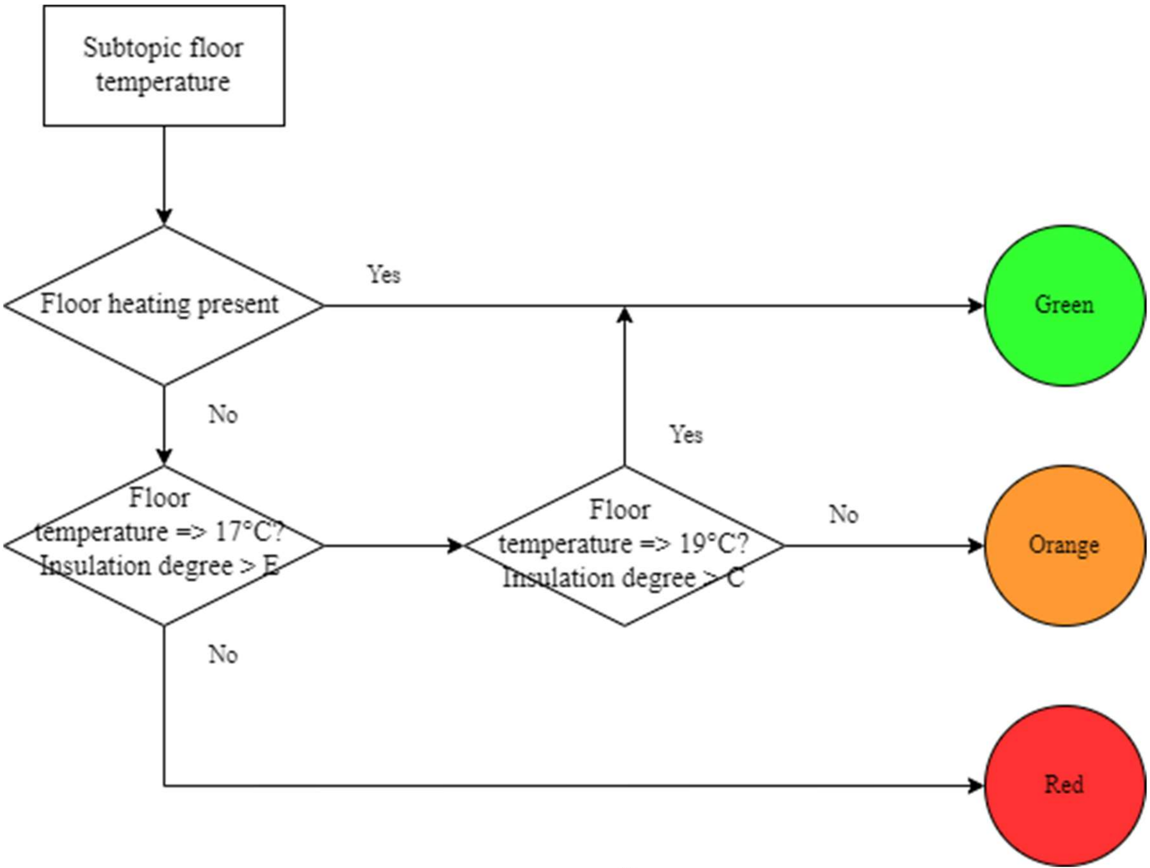


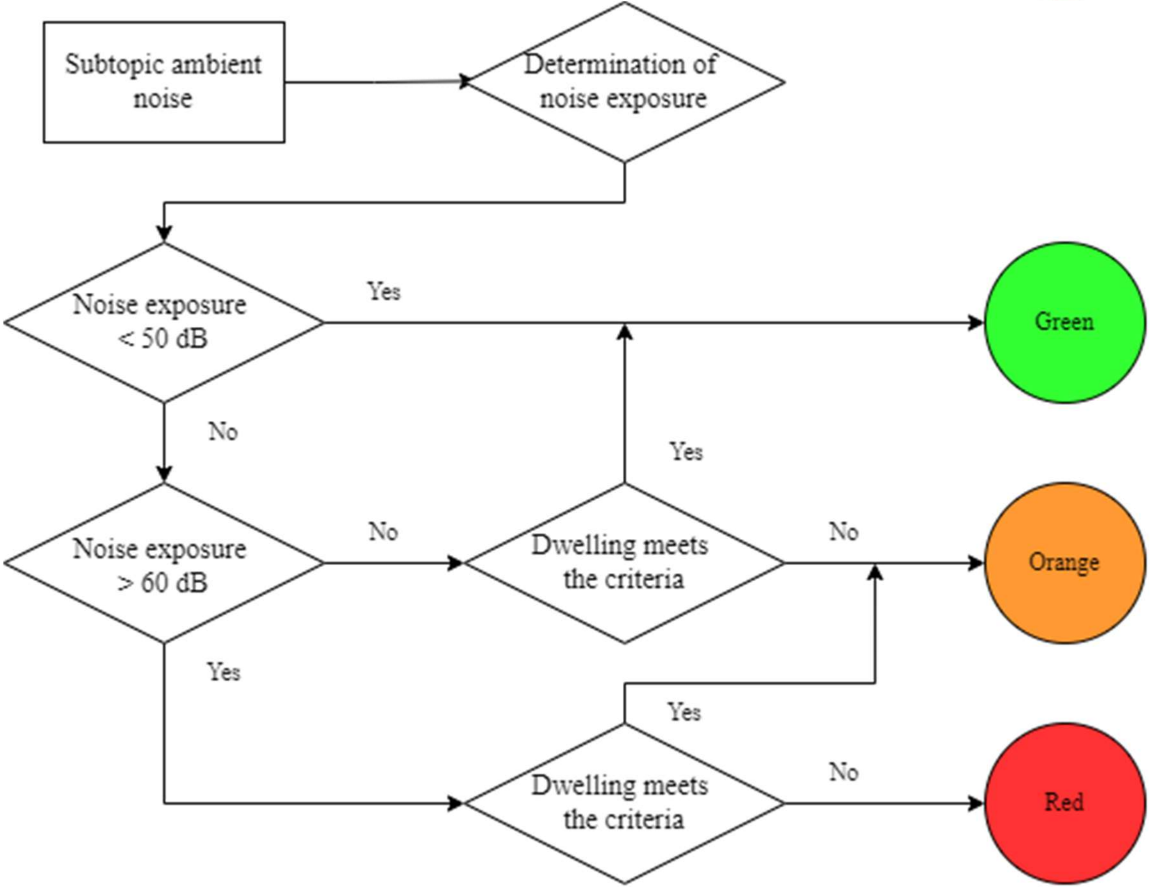

Subtopic draught
Is there mechanical ventilation?
Yes
No
Is heat recovery used?
Yes
No
Selfregulated/ demanddriven facade grilles
Yes
No
Green
Orange
Red

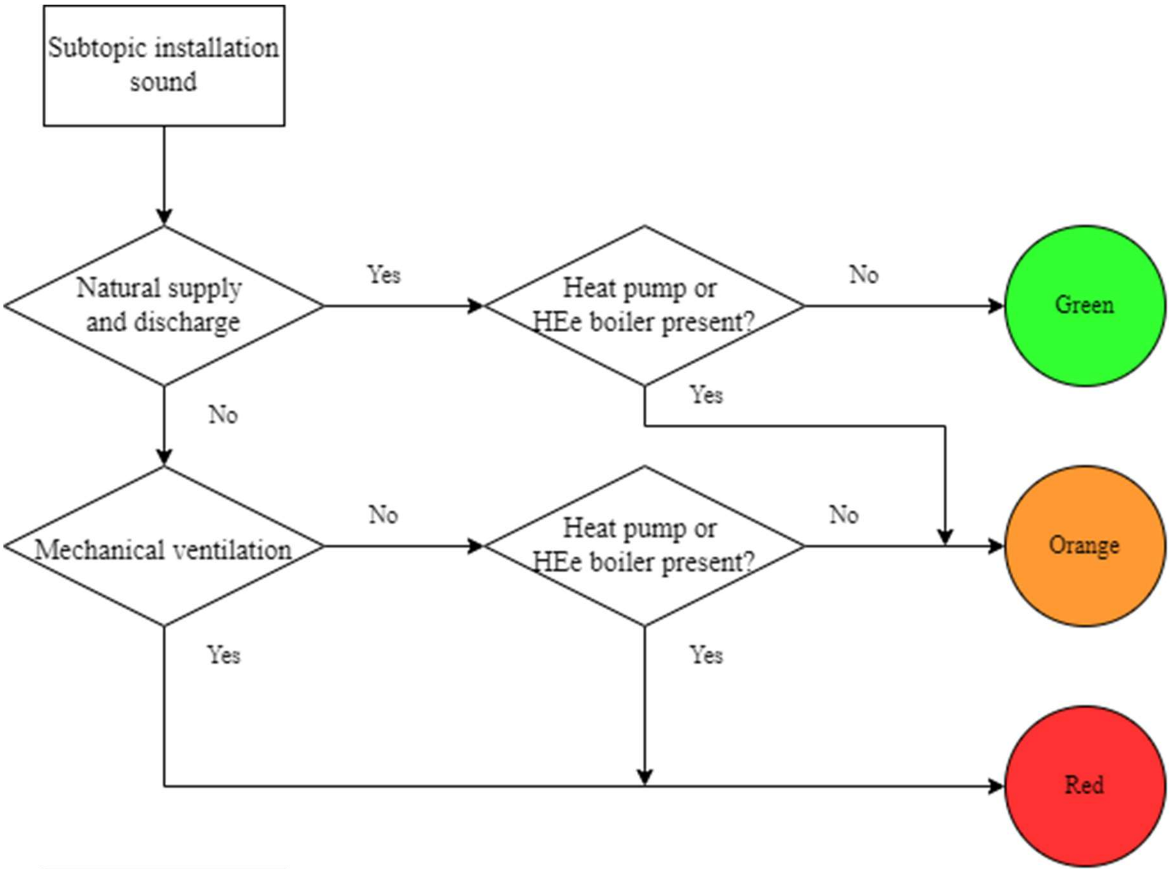

Subtopic thermal radiation asymmetry
Calculate average surface temperature facade
Temperature difference with the inside temperature =< 3°C
Yes
No
Temperature difference with the inside temperature < 1°C
Yes
No
Green
Orange
Red

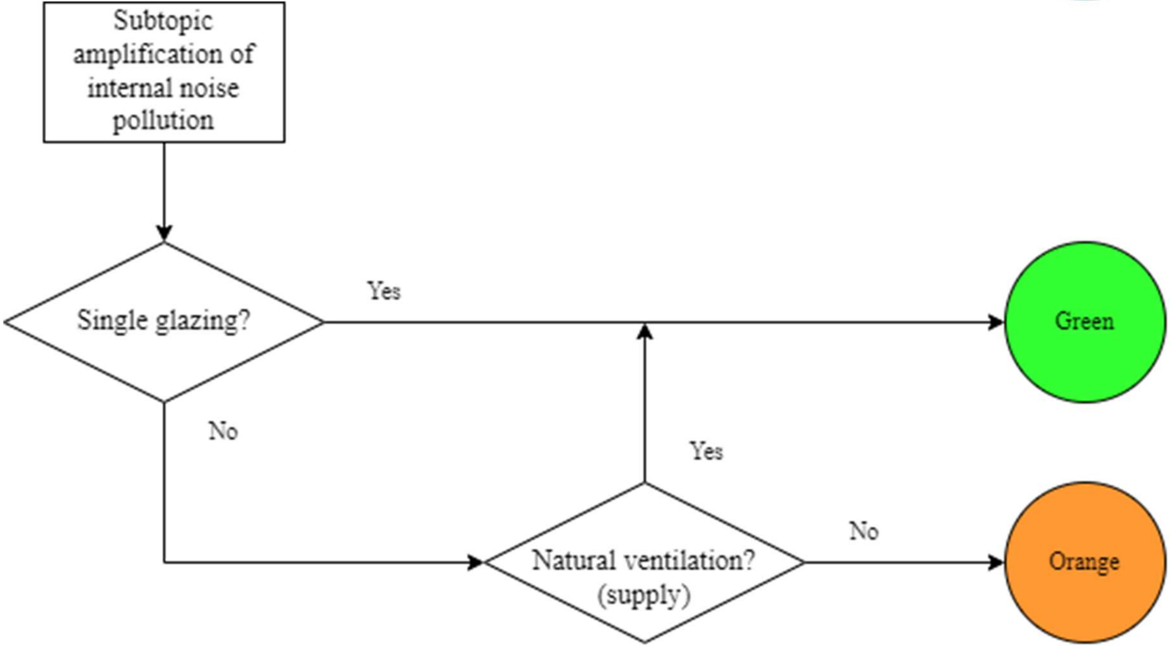

Subtopic thermal radiation asymmetry
Calculate average surface temperature facade
Insulation degree > E
Yes
No
Insulation degree > C
Yes
No
Green
Orange
Red

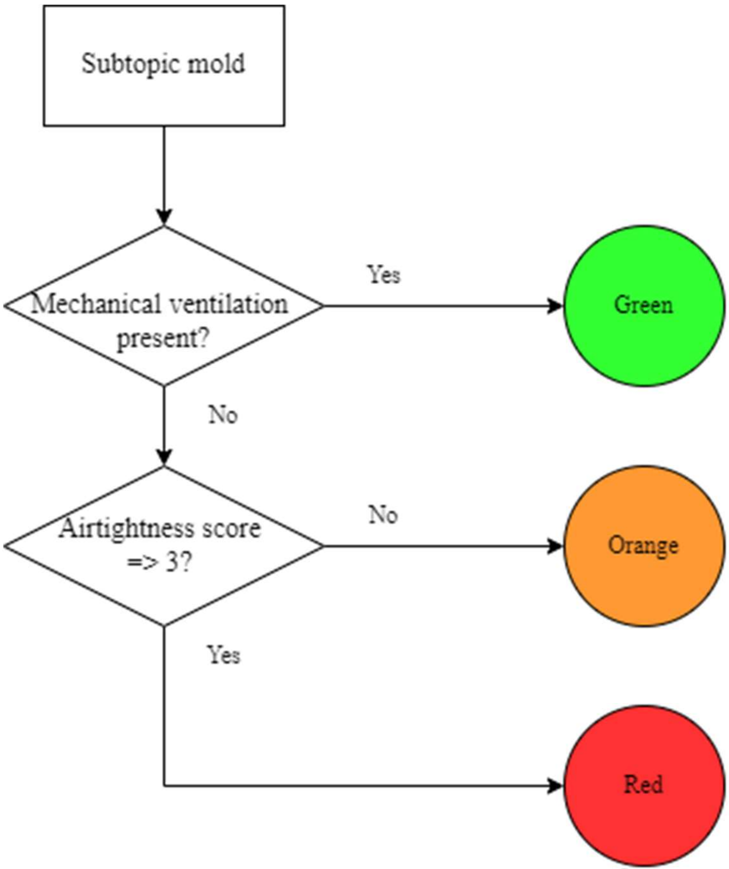

Subtopic temperature gradient
Double glazing present
Yes
No
HR++ glazing
Yes
No
LT heat release
No
Yes
LT heat release
No
Yes
Green
Orange
Red

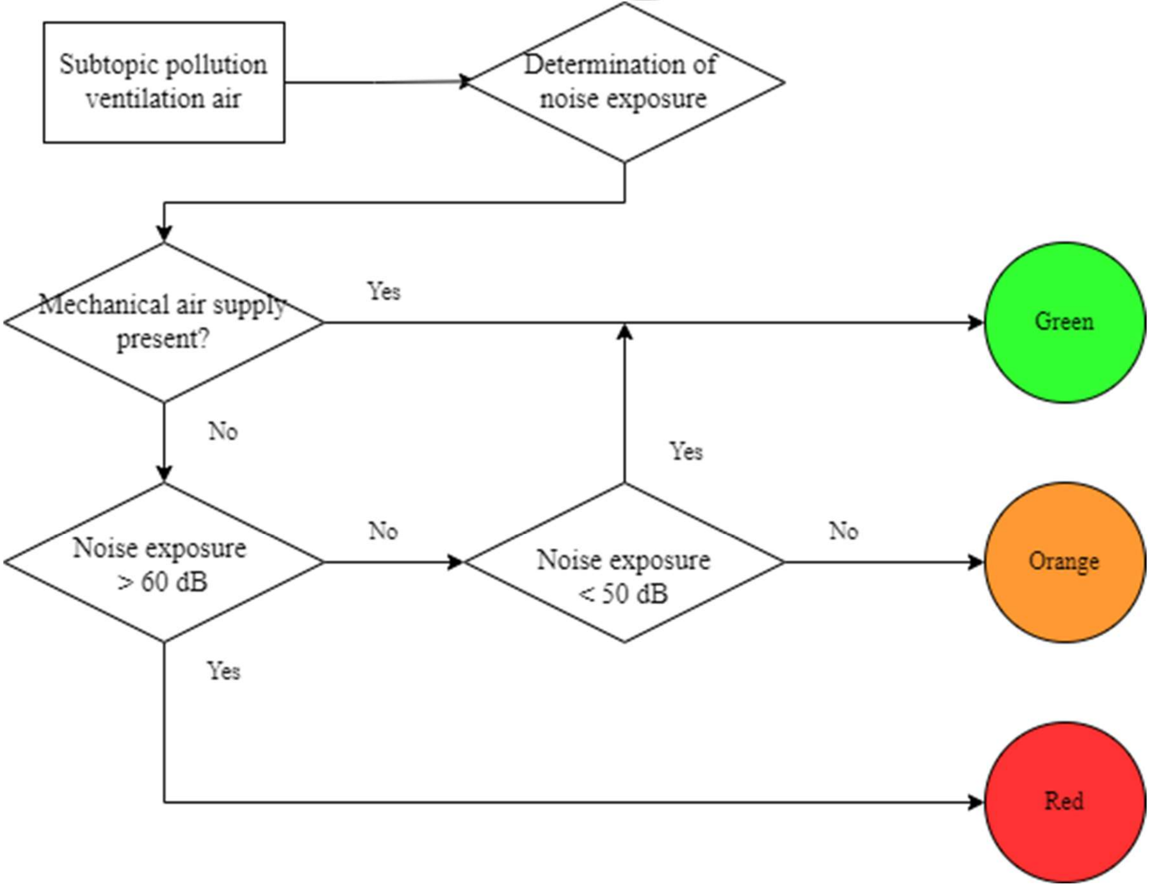

Subtopic floor temperature
Floor heating present
Yes
Green
No
Yes
Floor temperature => 17°C? Insulation degree > E
Floor temperature => 19°C? Insulation degree > C
No
Orange
No
Red

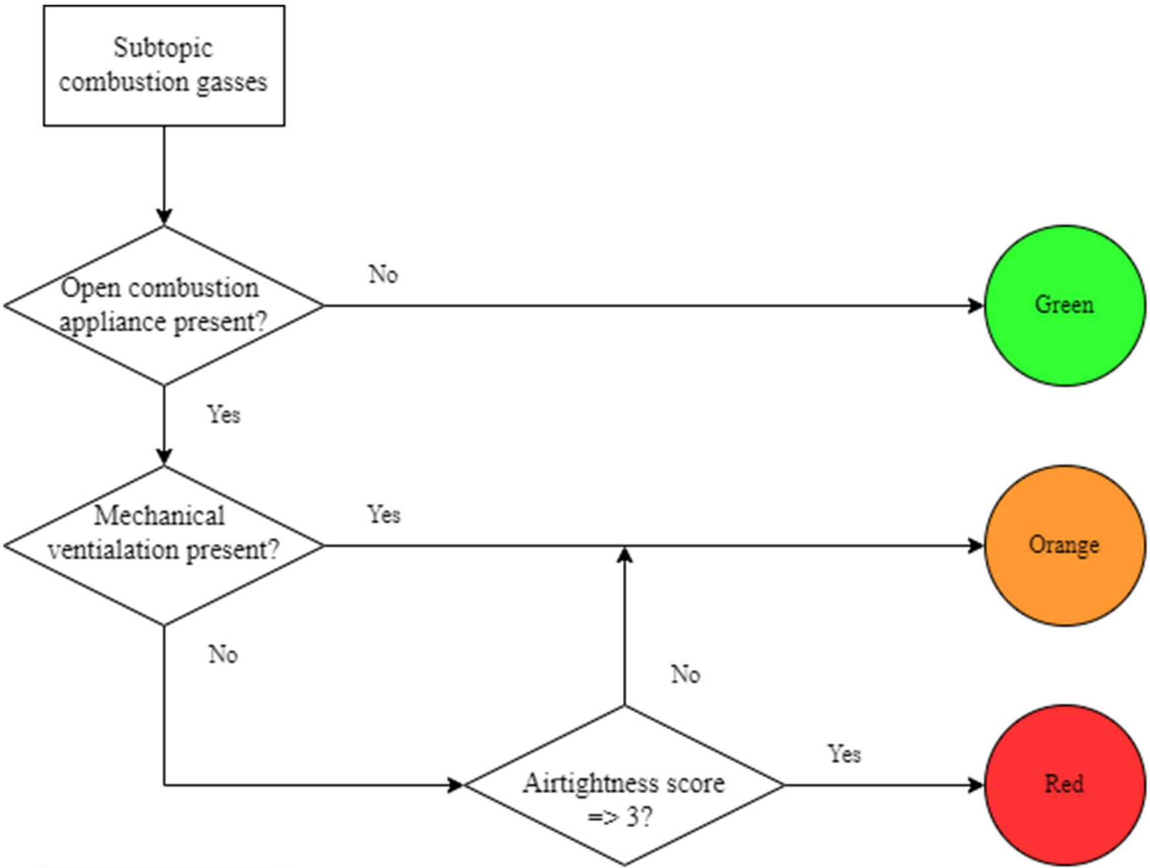

Subtopic ambient noise
Determination of noise exposure
Noise exposure < 50 dB
Yes
Green
No
Yes
Noise exposure > 60 dB
No
Dwelling meets the criteria
No
Orange
Yes
Yes
Dwelling meets the criteria
No
Red

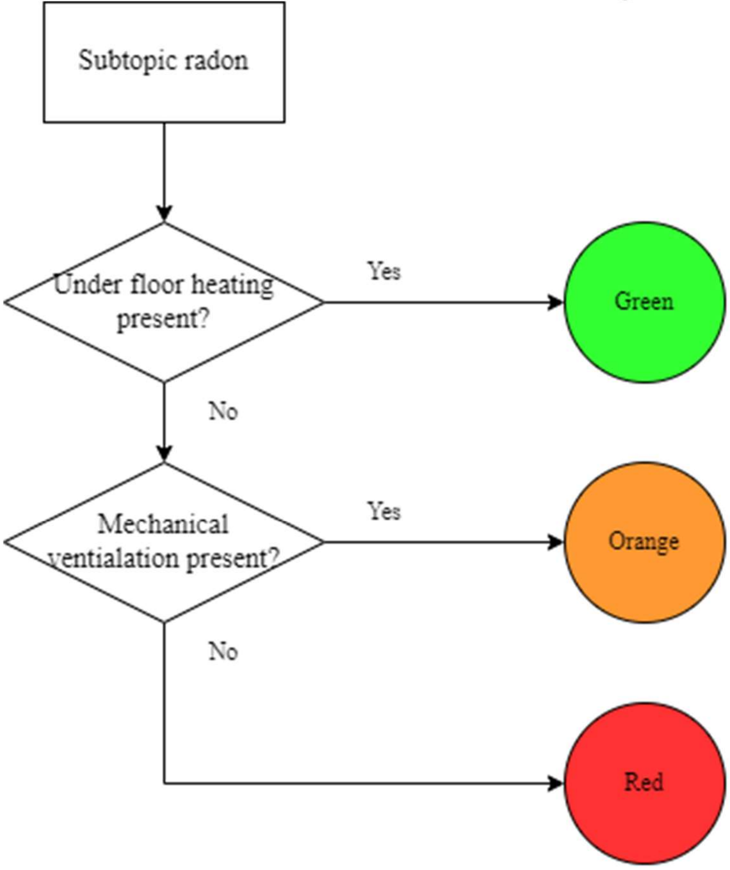

Subtopic installation sound
Natural supply and discharge
Yes
Heat pump or HEe boiler present?
No
Green
No
Yes
Mechanical ventilation
No
Heat pump or HEe boiler present?
No
Orange
Yes
Yes
Red


Subtopic amplification of internal noise pollution
Single glazing?
Yes
Green
No
Yes
Natural ventilation? (supply)
No
Orange


Subtopic mold
Mechanical ventilation present?
Yes
Green
No
Airtightness score => 3?
No
Orange
Yes
Red

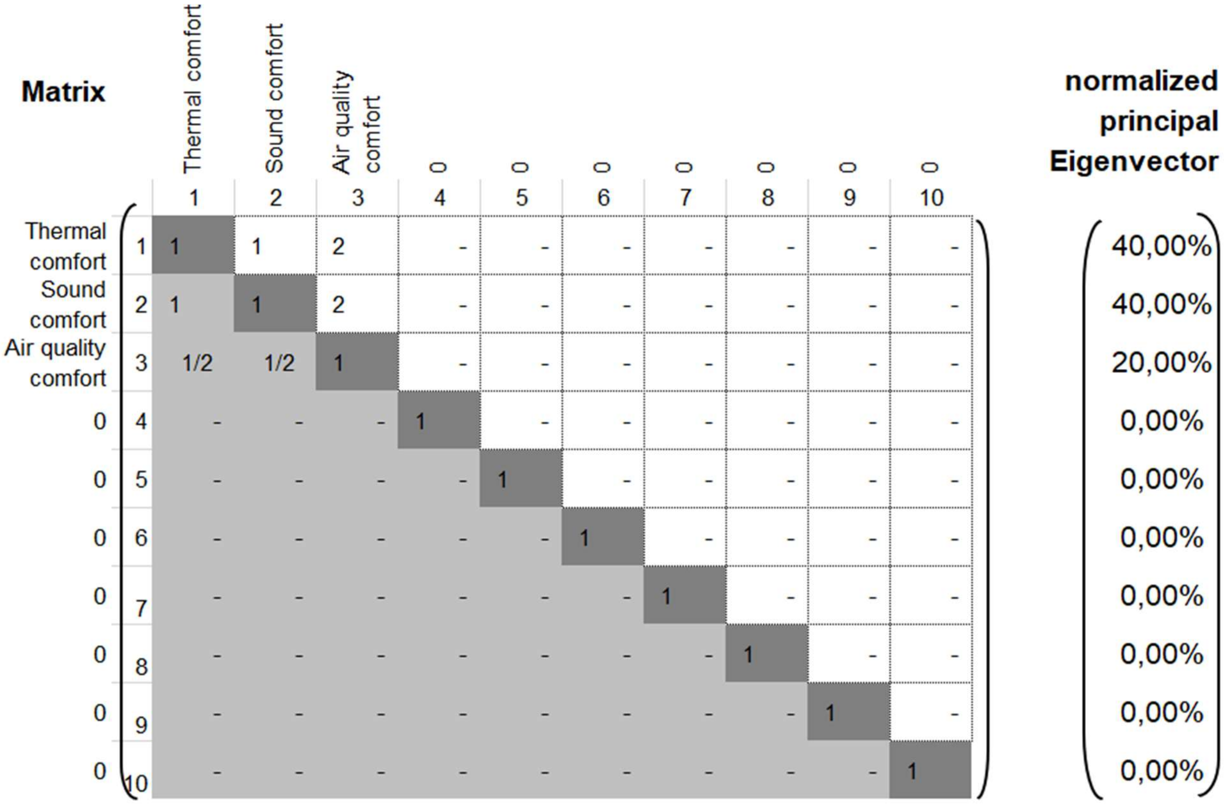

Subtopic pollution ventilation air
Determination of noise exposure
Mechanical air supply present?
Yes
Green
No
Yes
Noise exposure > 60 dB
No
Noise exposure < 50 dB
No
Orange
Yes
Red


Subtopic combustion gasses
Open combustion appliance present?
No
Green
Yes
Mechanical ventialation present?
Yes
Orange
No
No
Airtightness score => 3?
Yes
Red


Subtopic radon
Under floor heating present?
Yes
Green
No
Mechanical ventialation present?
Yes
Orange
No
Red

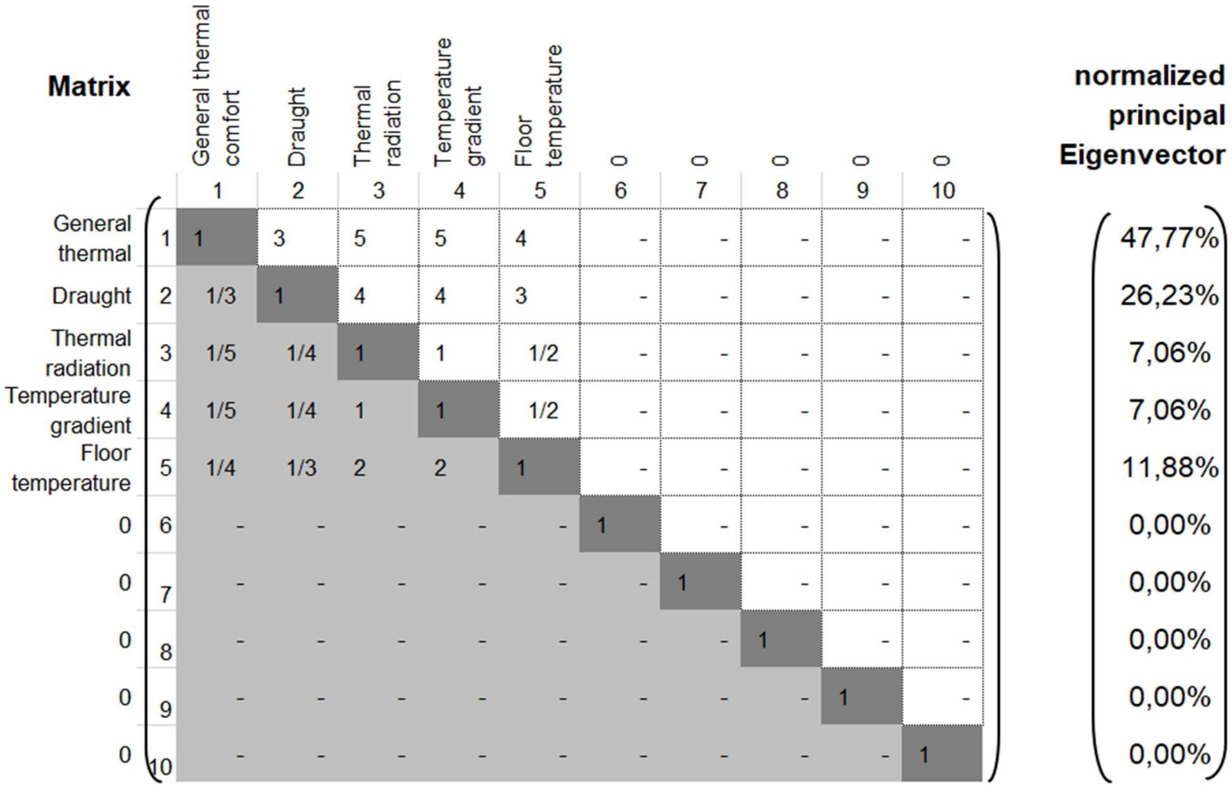
Appendix U: Analytic hierarchy process

1. Overall comfort



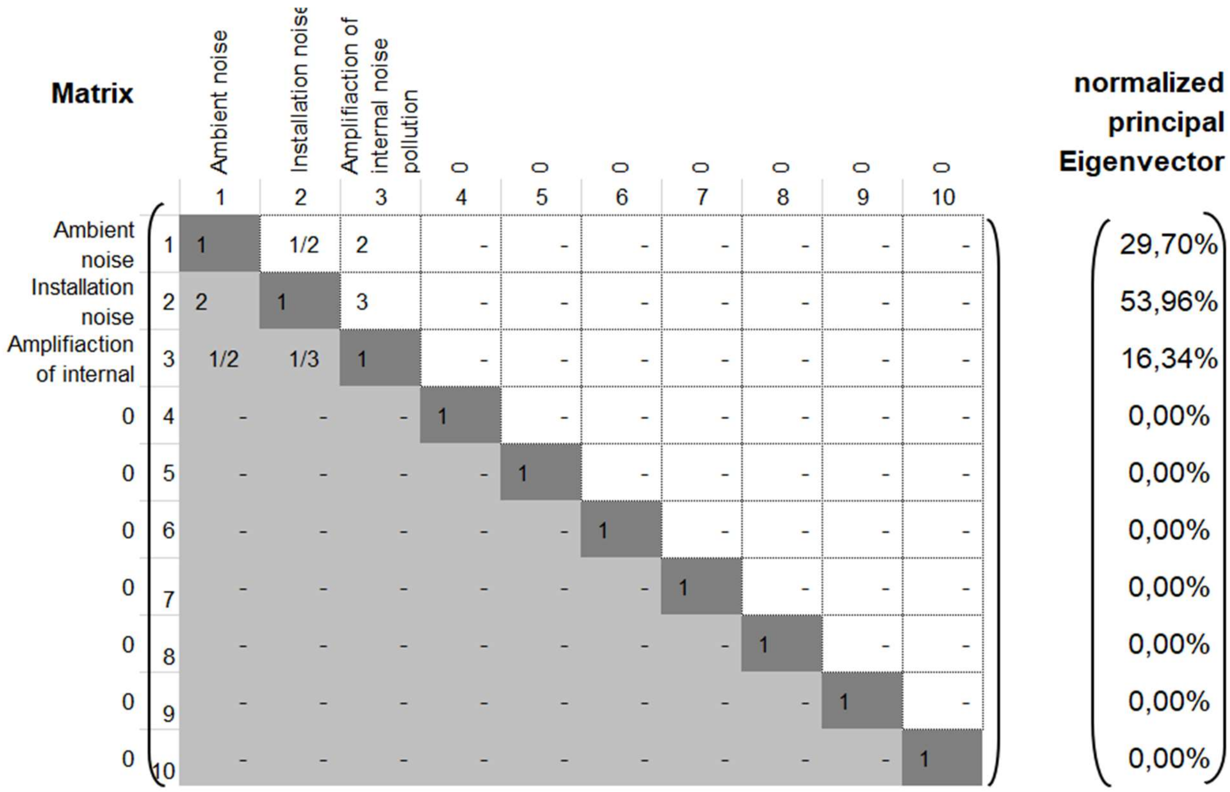
Matrix		Thermal comfort 1	Sound comfort 2	Air quality comfort 3	0 4	0 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
Thermal comfort	1	1	1	2	-	-	-	-	-	-	-	40,00%
Sound comfort	2	1	1	2	-	-	-	-	-	-	-	40,00%
Air quality comfort	3	1/2	1/2	1	-	-	-	-	-	-	-	20,00%
0	4	-	-	-	1	-	-	-	-	-	-	0,00%
0	5	-	-	-	-	1	-	-	-	-	-	0,00%
0	6	-	-	-	-	-	1	-	-	-	-	0,00%
0	7	-	-	-	-	-	-	1	-	-	-	0,00%
0	8	-	-	-	-	-	-	-	1	-	-	0,00%
0	9	-	-	-	-	-	-	-	-	1	-	0,00%
0	10	-	-	-	-	-	-	-	-	-	1	0,00%

2. Thermal comfort



Matrix		General thermal comfort 1	Draught 2	Thermal radiation 3	Temperature gradient 4	Floor temperature 5	0 6	0 7	0 8	0 9	0 10	normalized principal Eigenvector
General thermal	1	1	3	5	5	4	-	-	-	-	-	47,77%
Draught	2	1/3	1	4	4	3	-	-	-	-	-	26,23%
Thermal radiation	3	1/5	1/4	1	1	1/2	-	-	-	-	-	7,06%
Temperature gradient	4	1/5	1/4	1	1	1/2	-	-	-	-	-	7,06%
Floor temperature	5	1/4	1/3	2	2	1	-	-	-	-	-	11,88%
0	6	-	-	-	-	-	1	-	-	-	-	0,00%
0	7	-	-	-	-	-	-	1	-	-	-	0,00%
0	8	-	-	-	-	-	-	-	1	-	-	0,00%
0	9	-	-	-	-	-	-	-	-	1	-	0,00%
0	10	-	-	-	-	-	-	-	-	-	1	0,00%

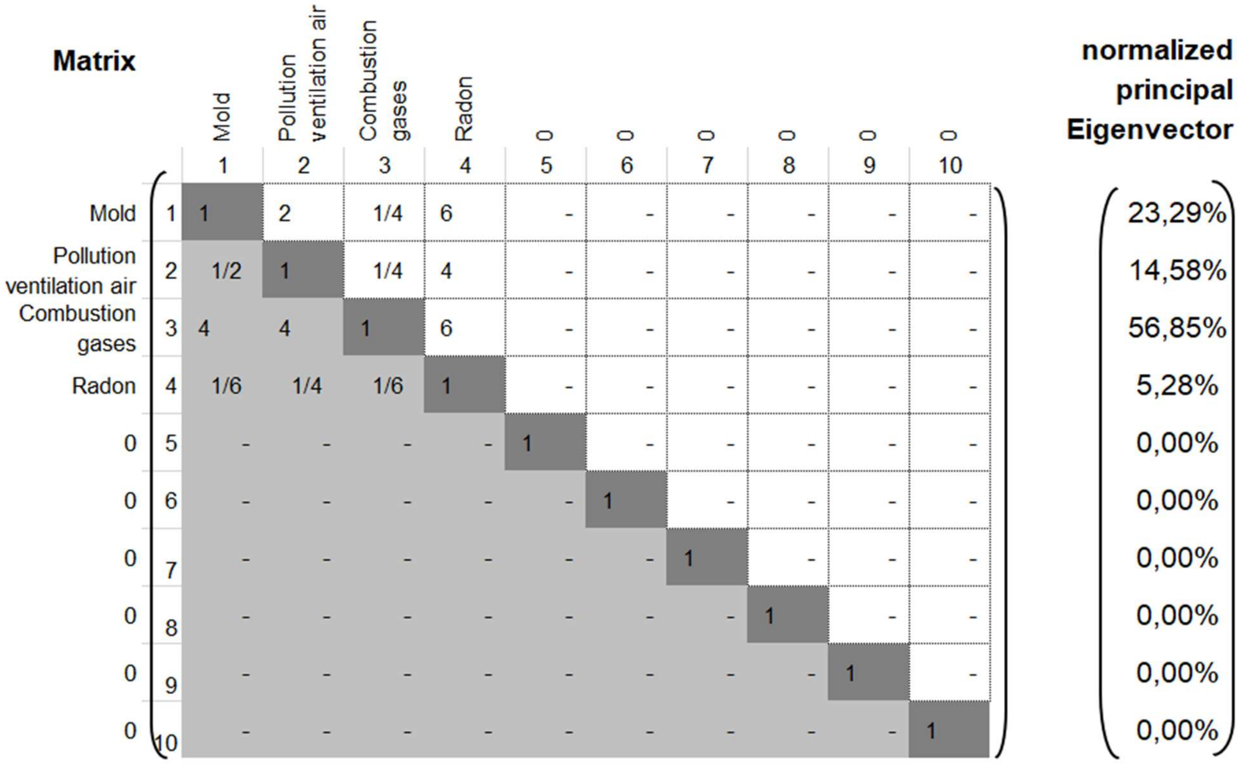
3. Sound comfort



Matrix

		Ambient noise	Installation noise	Amplifiaction of internal noise pollution	0	0	0	0	0	0	0	normalized principal Eigenvector
		1	2	3	4	5	6	7	8	9	10	
Ambient noise	1	1	1/2	2	-	-	-	-	-	-	-	29,70%
Installation noise	2	2	1	3	-	-	-	-	-	-	-	53,96%
Amplifiaction of internal	3	1/2	1/3	1	-	-	-	-	-	-	-	16,34%
0	4	-	-	-	1	-	-	-	-	-	-	0,00%
0	5	-	-	-	-	1	-	-	-	-	-	0,00%
0	6	-	-	-	-	-	1	-	-	-	-	0,00%
0	7	-	-	-	-	-	-	1	-	-	-	0,00%
0	8	-	-	-	-	-	-	-	1	-	-	0,00%
0	9	-	-	-	-	-	-	-	-	1	-	0,00%
0	10	-	-	-	-	-	-	-	-	-	1	0,00%

4. Air quality comfort

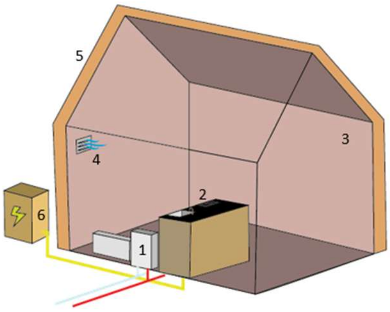


Matrix

		Mold	Pollution ventilation air	Combustion gases	Radon	0	0	0	0	0	0	normalized principal Eigenvector
		1	2	3	4	5	6	7	8	9	10	
Mold	1	1	2	1/4	6	-	-	-	-	-	-	23,29%
Pollution ventilation air	2	1/2	1	1/4	4	-	-	-	-	-	-	14,58%
Combustion gases	3	4	4	1	6	-	-	-	-	-	-	56,85%
Radon	4	1/6	1/4	1/6	1	-	-	-	-	-	-	5,28%
0	5	-	-	-	-	1	-	-	-	-	-	0,00%
0	6	-	-	-	-	-	1	-	-	-	-	0,00%
0	7	-	-	-	-	-	-	1	-	-	-	0,00%
0	8	-	-	-	-	-	-	-	1	-	-	0,00%
0	9	-	-	-	-	-	-	-	-	1	-	0,00%
0	10	-	-	-	-	-	-	-	-	-	1	0,00%

Appendix V: Installation renovation phases

1. District heating MT



District heating MT - 1

1. Insulation label D
2. Insulation label B

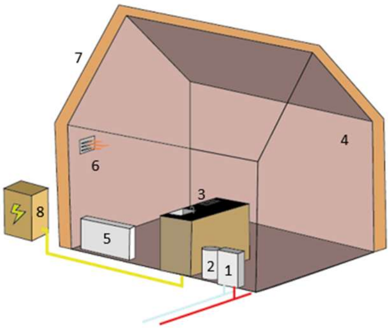
District heating MT - 2

1. Delivery set district heating
2. Electric cooking
3. Remove gas connection
4. Install mechanical ventilation
5. Increase electricity connection

District heating MT - 3

1. Solar panels

2. District heating LT



District heating LT - 1

1. Insulation label B

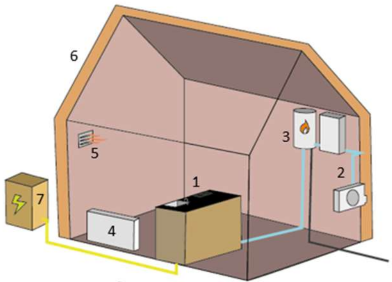
District heating LT - 2

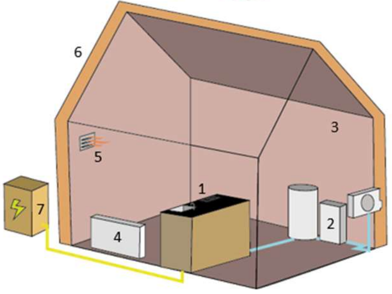
1. Delivery set district heating
2. Booster heat pump
3. Electric cooking
4. Remove gas connection
5. LT radiator
6. Ventilation with heat recovery
7. Increase electricity connection

District heating LT - 3

1. Solar panels

3. All-electric 1





All-electric 1 - 1

1. Insulation label B

All-electric 1 - 2

1. Electric cooking
2. Hybrid heat pump
3. HR boiler
4. LT radiator
5. Ventilation with heat recovery
6. Increase electricity connection

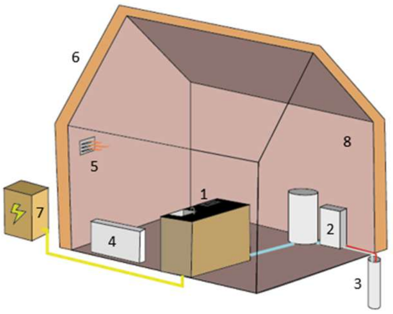
All-electric 1 - 3

1. Solar panels

All-electric 1 - 4

1. Air-water heat pump
2. Remove natural gas connection

4. All-electric 2



All-electric 2 – 1

1. Insulation label B (2023)

All-electric 2 – 2

1. Electric cooking
2. Ground heat pump
3. Ground heat source
4. LT radiator
5. Ventilation with heat recovery
6. Increase electricity connection
7. Remove gas connection

All-electric 2 – 3

1. Solar panels

Appendix W: Comparison with the selected CBAs

Overview of the selected CBAs compared the LCBA *(CE Delft, 2018; M. Mulder & Hulshof, 2021; Tieben et al., 2020)*

	Tieben et al. (2020)	Mulder & Hulshof (2021)	CE Delft (2018)	Current research
Goal	The study calculates the social costs and benefits of various heat options aimed at making the heat supply in the built environment and greenhouse horticulture in West Brabant and Hart van Brabant more sustainable.	The objective of this policy paper is to show how a social Cost-Benefit Analysis can be conducted for district-heating systems, which may help policymakers in their discussion of the social desirability of this policy option to reach their climate-policy objective.	In this study, a social Cost-Benefit Analysis (SCBA) is performed for a heat network in Zaandam-East, based on the concrete business cases drawn up by Alliander DGO and Engie.	The study determines the costs and benefits of various heating techniques for the homeowners of a selected housing cluster.
Region (population)	West-Brabant and Hart van Brabant	Neighbourhoods Vinkhuizen-Noord & -Midden, Paddepoel-Noord & Midden, and Selwerd-West. The area includes 3200 residential buildings.	Municipality Zaanstad	Selected housing cluster
Household types	The averages of several housing types are used in the CBA.	12 types of buildings are used. The housing types are distinguished based on housing type, construction period, energy label and natural gas consumption.	Corporation homes, new-build homes and other buildings.	Type of dwellings included in the selected housing cluster
Horizon Scenario's	2020-2050 The scenarios of the welfare and living environment of the planning offices, as prescribed in the SCBA guidelines, are used for the CO2 prices.	2022-2080 Three scenarios: S1: Modest climate policy S2: Intermediate climate policy S3: Intensive climate policy	2018-2068 Two scenario's: High: combines high population growth with high economic growth. Low: a more moderate demographic development and a more modest economic growth.	2020-2050 Multiple scenarios are used in the research the scenario's include: S1: Natural gas costs S2: Electricity costs S3: Deveopmentr costs S4: Detachment heat price S5: Reduction connection costs district heating due to cluster size
Baseline alternative	Natural gas will remain the primary fuel for heating homes. Some households will switch to heat pumps. By 2050 75% of the households depend on natural gas for heat supply. The energy-saving pace in the baseline alternative is 0.5% per year.	The households will continue to heat their home using natural gas.	The most likely situation without a heat network. 1) tenants of housing associations and public buildings in Zaandam continue to use gas-fired boilers, 2) new-build homes will be 'all-electric' or will have a high-efficiency gas boiler, and 3) the residential complexes will be renovated over time.	The dwelling will remain heated with natural gas. The small interventions that are expected are: 1) boiler needs to be replaced after 10 years. 2) Current boiler is 10 years old. 3) the insulation will be improved to level B in 2036.

Policy alternatives	1) regional heat network (focussed on biomass, geothermy or a mixture), 2) local heating source (with or without the use of the existing regional heat network), 3) Individual heating technique (using solar thermal/green gas or all-electric)	The policy alternatives all include district heating but vary in the heat source for the network (which results in a different source temperature). Main difference homeowner delivery temperatures (30°C, 50°C and 70°C)	All policy alternatives all include the same implementation of a district heating network but differ in the heat source of the network: 1. biomass power plant, with SDE subsidy 2. biomass power plant, without SDE subsidy, and 3. gas-fired peak boiler.	The policy alternatives are: 1. District heating MT 2. District heating LT 3. All-electric individual A/W heat pump 4. All-electric collective ground heat pump.
Findings	None of the policy alternatives has a positive balance. Project alternative 3A (in which green gas is used) provides relatively the most favourable balance. The most expensive alternative is 2B which focuses on local heat networks fed by local heat sources.	Variant V1 (delivery temperature 50°C) has the most negative welfare effect and V2 and V3 (both delivery temperature 70°C) do not differ strongly although V2 performs better.	The CBA is positive for district heating with existing and new construction dwellings. The CBA without new construction dwellings is negative but can be made positive if extra dwellings are added.	Comparing the total costs there are no big differences between the baseline alternative and the policy alternatives. Taking the costs and benefits of the LCBA into account, both alternatives DH1 and AL1 both have a positive balance.

Appendix X: Comparison of expected results and the results of the LCBA

	District heating 1		All-electric 1	
	Expected results	*Results LCBA*	*Expected results*	*Results LCBA*
Effect	*Scenario low (variable natural gas price +40%, electricity price -34%)*			
Investment costs (in € k)	▼	€ 2,34	▲	€ 14,07
Maintenance costs (in € k)	▼	€ 1,04	▲	€ 0,77
Replacement cost (in € k)	▼	€ - 1,90	▲	€ 1,21
Energy costs (in € k)	▲	€ 1,96	▼	€ -17,20
Total costs (in € k)	▲	€ 3,44	▼	€ -1,15
Comfort (index 0-31)	▼	-0,06	▲	+0,04
Required space (in m^3)	▼	-0,53	▲	1,91
Impact renovation process (in days)	▲	1	▲	3
Energy price volatility (index --/++)	▼	+	▼	+
Freedom of choice of energy supplier (index --/++)	▼	--	▲	+
Safety (index --/++)	▼	++	▼	+
Climate (in tonnes CO_2 emission)	▼	-0,22 tonnes	▼	-0,30 tonnes
	Scenario high (variable natural gas price +103%, var electricity price 17%)			
Investment costs (in € k)	▼	€ 2,34	▲	€ 14,07
Maintenance costs (in € k)	▼	€ 1,04	▲	€ 0,77
Replacement cost (in € k)	▼	€ - 1,90	▲	€ 1,21

Energy costs (in € k)	▼	€ 5,62	-	▼	€ -23,01
Total costs (in € k)	▼	€ 4,14	-	▼	€ -6,96
Comfort (index 0-31)	▼	-0,06		▲	+0,04
Required space (in m^3)	▼	-0,53		▲	1,91
Impact renovation process (in days)	▲	1		▲	3
Energy price volatility (index --/++)	▼	+		▼	+
Freedom of choice of energy supplier (index --/++)	▼	--		▲	+
Safety (index --/++)	▼	++		▼	+
Climate (in tonnes CO_2 emission)	▼	-0,22 tonnes		▼	-0,30 tonnes

Appendix Y: Number of cases for type of heating in the WoON 2018 dataset

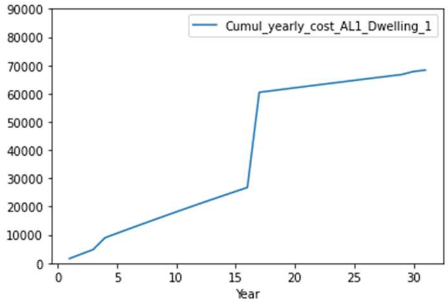
Type of heating	Percent
Natural gas boiler	90.9
Wood-fired heating device	6.6
Pellet stove	0.7
Gas stove	4.1
Heat pump	1.2
Bock district heating	1.5
District heating	3.4
Other	1.2

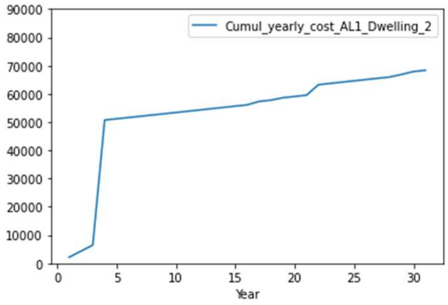
Appendix Z: Output optimization models

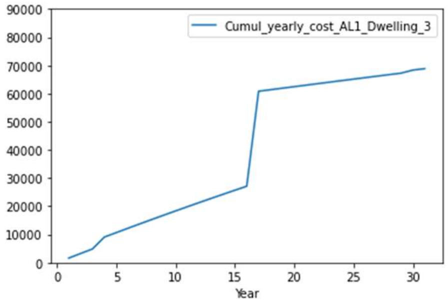
Costs including the net present value

Dwelling 1	Dwelling 2	Dwelling 3

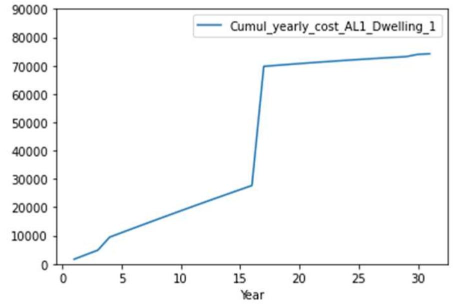
Scenario low

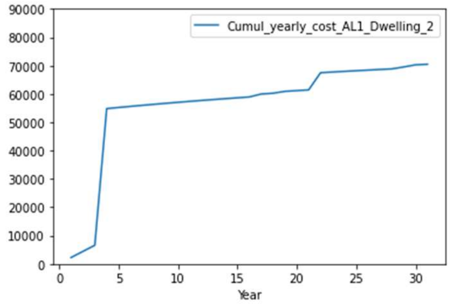


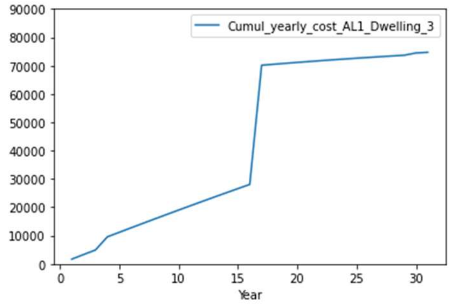




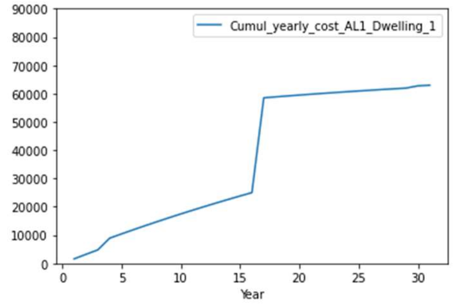
Scenario high

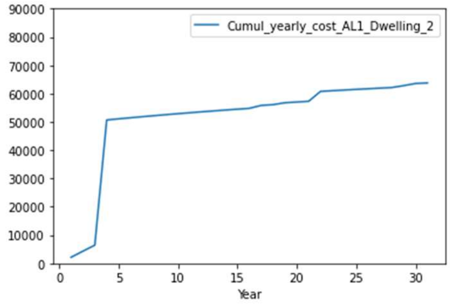


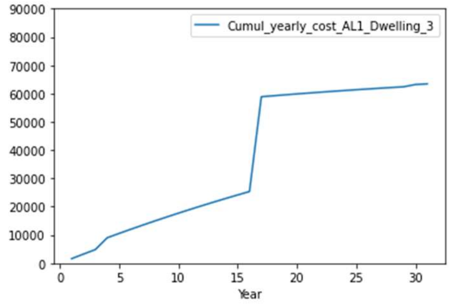




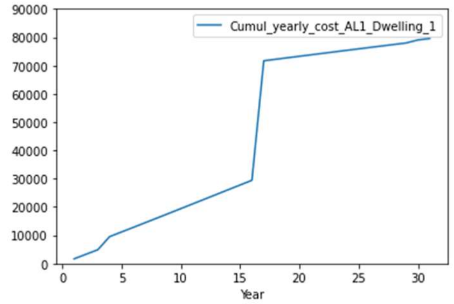
Scenario 3

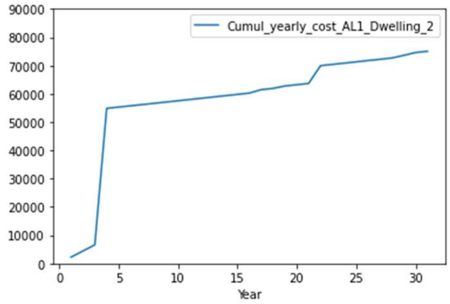


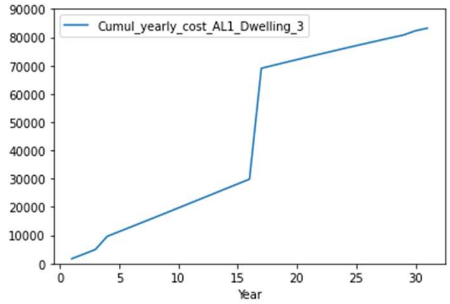




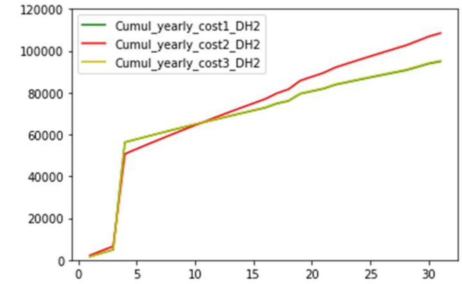
Scenario 4



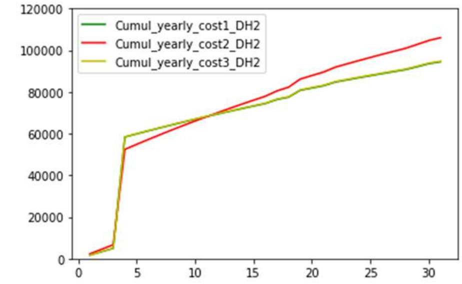




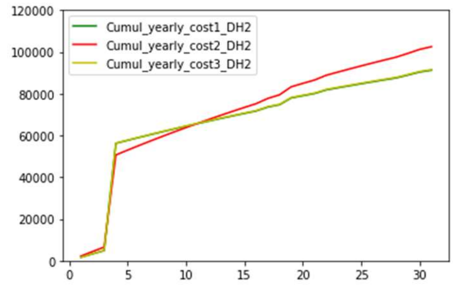
Scenario low



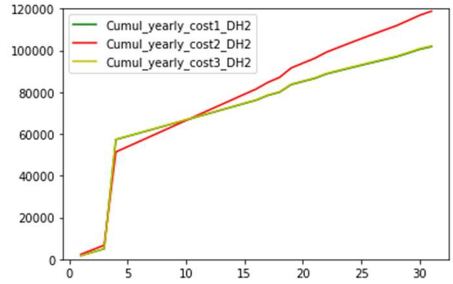
Scenario high



Scenario 3


120000
100000
80000
60000
40000
20000
0
0
5
10
15
20
25
30
Cumul_yearly_cost1_DH2
Cumul_yearly_cost2_DH2
Cumul_yearly_cost3_DH2

Scenario 4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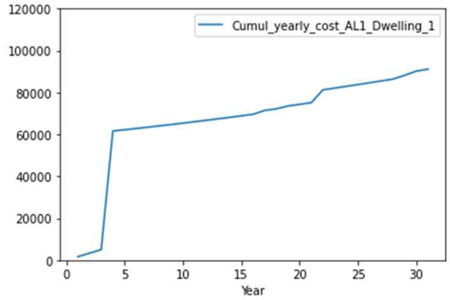
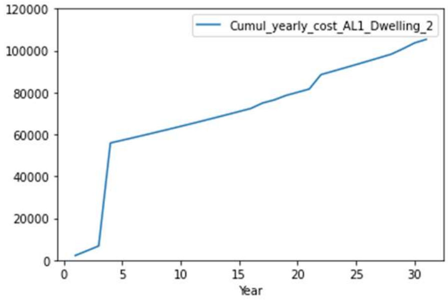
80000
60000
40000
20000
0
0
5
10
15
20
25
30
Cumul_yearly_cost1_DH2
Cumul_yearly_cost2_DH2
Cumul_yearly_cost3_DH2

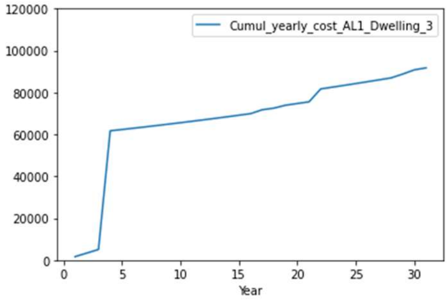
Costs excluding net present value

Dwelling 1 Dwelling 2 Dwelling 3

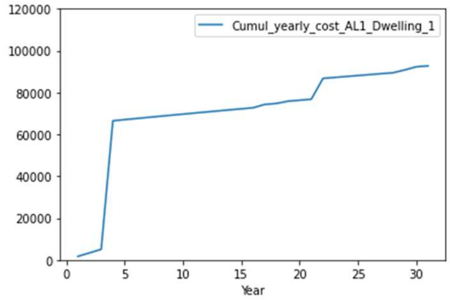
Scenario low

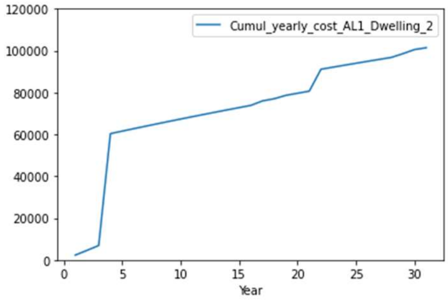


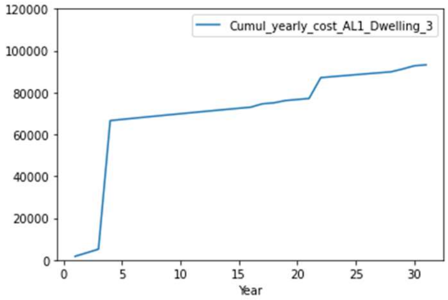




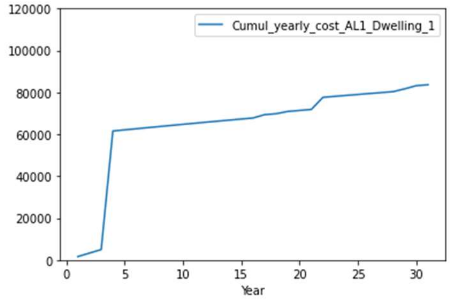
Scenario high

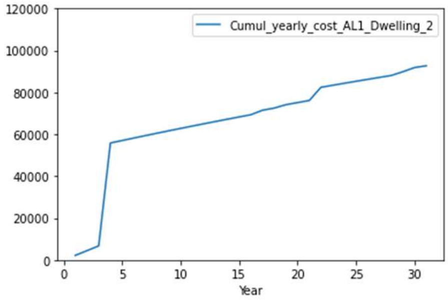


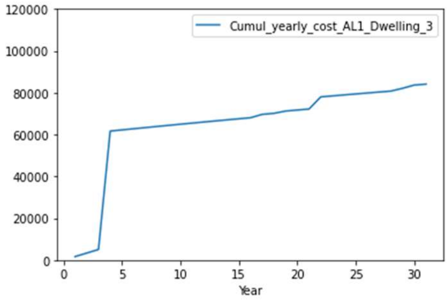




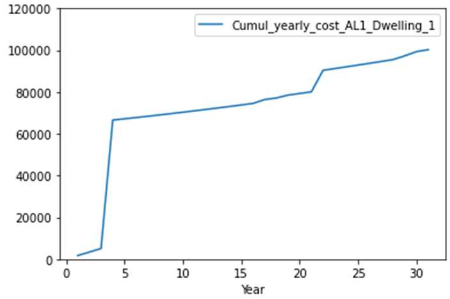
Scenario 3

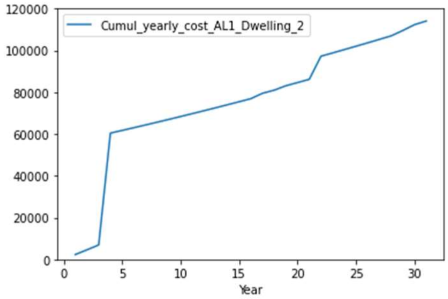


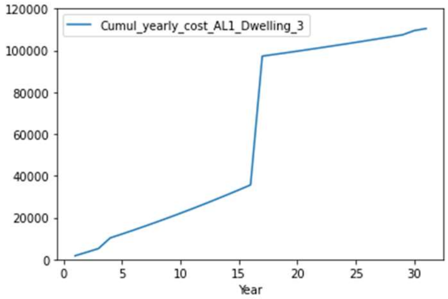




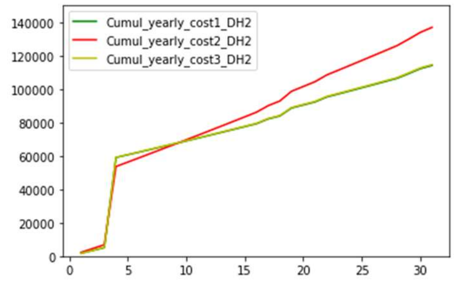
Scenario 4







Scenario low



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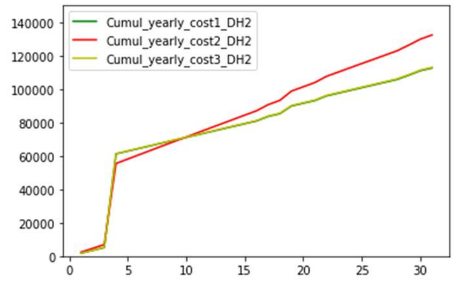

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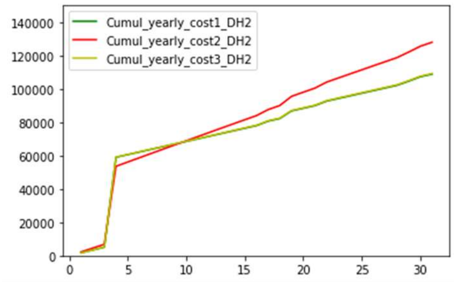

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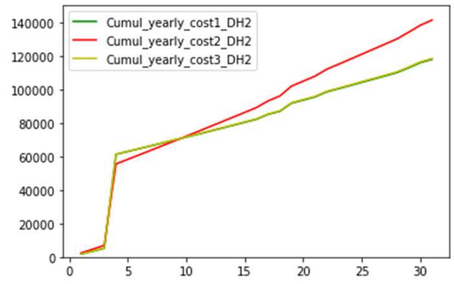
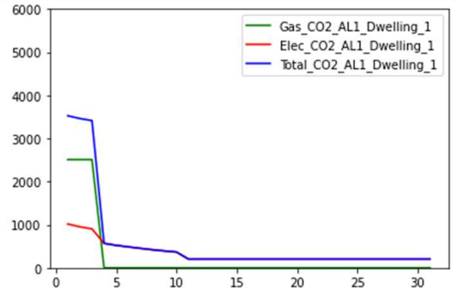
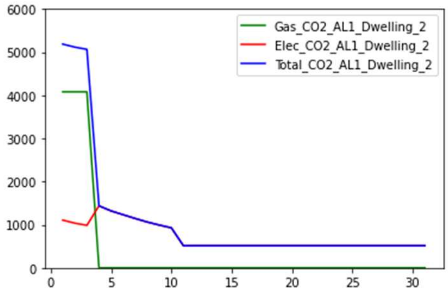
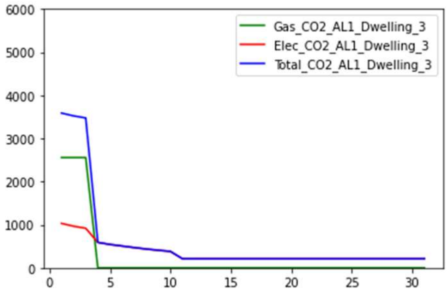


Dwelling 1	Dwelling 2	Dwelling 3

CO_2 emmission







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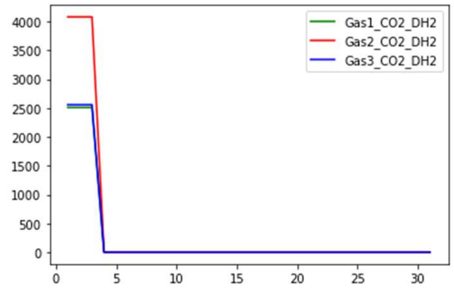

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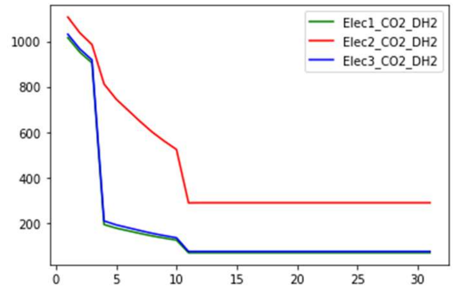
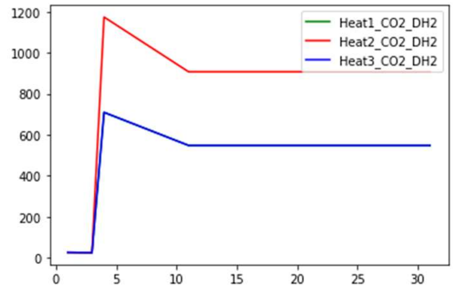
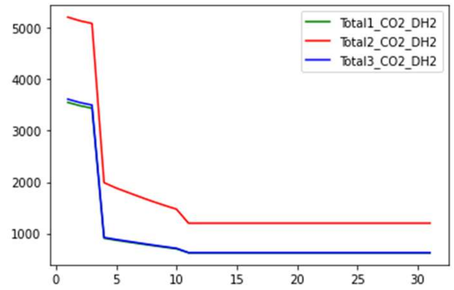
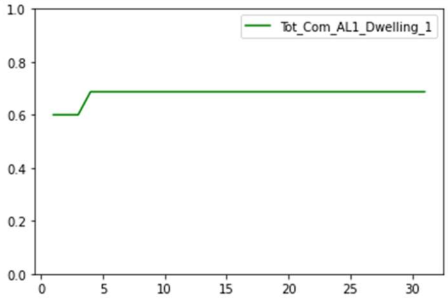
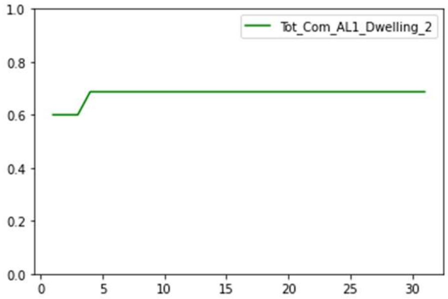
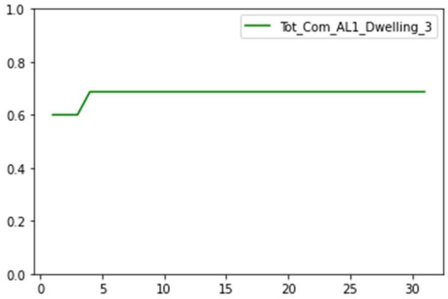


Scenario 3

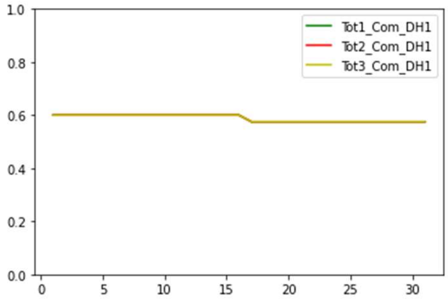


Scenario 4



Dwelling 1	Dwelling 2	Dwelling 3
Comfort		
		

Comfort



Appendix AA: Tasks user validation

The task that needed to be executed during the user validation:

1. Select cluster consisting of 3 dwellings, consisting of housing types: 1. Corner house, 2. Terraced house and 3. Terraced house.
2. What are the reinvestment costs for the heating technique natural gas of dwelling 1 of the selected housing cluster?
3. What are the average energy costs for the technique district heating (MT) for dwelling 2 and scenario high energy costs? What is the advised switching year?
4. What is the difference in total costs of district heating (MT) compared to the heating technique natural gas for dwelling 1?
5. Select your own optimization preferences.

Additional questions:

1. What is your opinion of the dashboard?
2. Did the dashboard inform you about the implementation of heating techniques?
3. Do you have comments or recommendations?